Interference Burden in Wireless Communications: A Comprehensive Survey From PHY Layer Perspective

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***Abstract*—Interference represents one of the most common barriers for the wireless communications society to bring the fully connected world to life, where everybody and everything is connected at any time, aiming to support a wide range of services and applications with increasing demand in terms of data rate with a higher degree of reliability and security, while keeping an affordable overall system capacity, complexity, and latency. Essentially, interference clearly explains the primitive nature of the wireless communications systems, where there is always an unwanted physical signal that disrupts the communication link, occurring from the physical layer (PHY) architecture of transmission signal, its interaction with the wireless channel and transceiver architecture in particular. Therefore, in past wireless technologies, waveform design along with wireless channel impairments and handset architecture define the main sources of interference, leading to inter-symbol interference (ISI), inter-carrier interference (ICI) and co-channel interference (CCI) types. In this line, recent advances in wireless technologies have revealed unprecedented interference types including inter-numerology interference (INI), inter-antenna interference (IAI), inter-waveform interference (IWI), cross-link interference (CLI) and inter-Doppler interference (IDI), while additional unique interference types are expected in near future. Consequently, a broader view of the interference has become a crucial need in order to avoid and relax its impact towards beyond 5G radio access technologies. Despite the extensive research in the literature performed by academia and industry, to the best of the authors' knowledge, there is no work that provides a comprehensive taxonomy framework of interference sources and types, and a review of management techniques from the perspective of the PHY layer. This work aims to fill this gap in the literature. With this notation, in this survey, we propose an intuitive, generic, and expandable framework that categorizes the interference sources and their corresponding management solutions. In particular, we split the interference sources into two main groups by taking into account the user of interest such as self-user-interference (SUI) and other-user-interference (OUI), which we further classify considering the user's intention about the presence of interference named intentional SUI (I-SUI), unintentional SUI (U-SUI), intentional OUI (I-OUI), and unintentional OUI (U-OUI). In line with this, we offer a classification of the interference management techniques regarding the source of interference. Lastly, the survey presents open research perspectives for beyond 5G wireless systems and concluding remarks.**

***Index Terms*—Interference sources, unintentional interference, intentional interference, pulse shaping, channel impairments, RF imperfection, coexistence, unlicensed bands, OMA, NOMA, MIMO, IM, RIS, UAV, RSMA, OTFS, WD-NOMA, ML, MPA.**

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I. Introduction

OVER the past decade, the world of wireless technology has been experiencing revolutionary advances mainly with the emergence of a broad range of applications, which will continue increasing at a rapid pace in the fifth generation (5G) and beyond (5G-B) [1], [2], [3]. Early generations of wireless systems have been designed considering the needs of human users where system throughput has been the primary concern [4], [5]. Besides human-centric networks, the emergence of machine user equipment (UE) has brought unprecedented demands on data rate, system capacity, security, transmission latency, coverage area, and reliability, in 5G New Radio (5G NR) [6], [7]. According to International Telecommunication Union (ITU), these requirements have been categorized into three main services; enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC) [8], [9], [10]. High data rate services, such as broadband Internet access, high-definition video streaming, and virtual reality, mainly determine the eMBB use-cases, which can be considered as an extension of the conventional 4th generation (4G) Long Term Evolution (LTE) technology. Applications with mMTC are expected to support a massive number of machine UEs with sporadic transmission, low power consumption, wide coverage area, and moderate data payloads. Differently, URLLC services represent the most challenging ones due to conflicting requirements of ultra-reliability and low-latency. In addition to the above demands, new application families, such as NR-Lite and secure URLLC (SURLLC), have been envisioned in beyond 5G [11], [12]. This unprecedented global trend, where everything and everyone is expected to be connected at any time on our planet with real-time data exchange from a wide variety of services, requires efficient use of radio resources (RRs) by wireless operators and adaptation of new communication techniques. Hence, future radio access technologies need to support UE while performing transmission when traveling in public transportation, in crowded environments, and in unexpected traffic jams [4]. Basically, the ultimate goal is to offer a

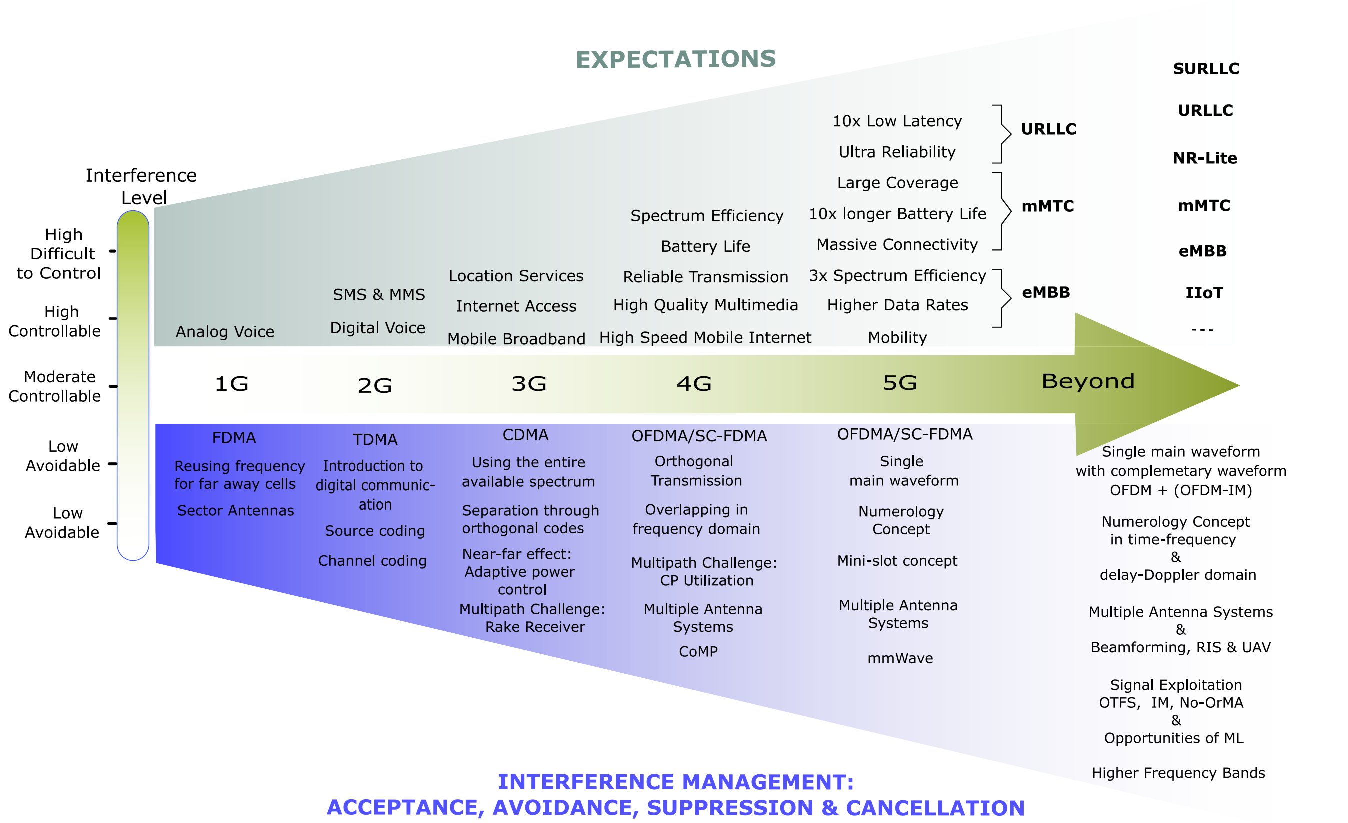


Fig. 1. An overview of wireless communications transition from 1G to beyond 5G.

society where people, vehicles, drones and sensors will be able to connect with each other through terrestrial and non-terrestrial deployments in order to support innovative services such as smart cities, self-driving cars, remote surgery, and smart homes [13].

A. Interference vs. New Considerations in Wireless Networks

With the urge to be always connected to the network along with data-hungry applications, the evolution of traditional wireless deployments toward the coexistence of a wide range of services and use-cases has become a necessity; starting from the early times of wireless technology history such as General Packet Radio Service (GPRS), Enhanced Data rates for Global Evolution (EDGE), High Speed Packet Access (HSPA) and ending up with the most prominent today's wireless technologies such as Wireless Fidelity (Wi-Fi), LTE, LTE-Advanced (LTE-A), and 5G NR [14]. Moreover, an intelligent integration of these technologies with heterogeneous networks (HetNet), millimeter wave (mmWave) based schemes, multiple-input-multiple-output (MIMO) signaling, and potential future wireless systems that recently have been attracting attention of both academia and industry such as reconfigurable intelligent surfaces (RIS), rate-splitting multiple accessing (RSMA), unmanned aerial vehicle (UAV), index modulation (IM), orthogonal time frequency space (OTFS) modulation and machine learning (ML) are expected to carry the society of wireless communications to the stages of 5G-B, as illustrated in Fig. 1 [15], [16], [17], [18]. Consequently, the presence of various wireless systems in the network, high conjunction of using the same RRs per square meter, and broadcast nature of the medium is highly expected to expose the transmission from the desired UE to external interference leaking from other sources (i.e., different UEs and wireless networks) and internal interference coming from its own communication link. In line with this, interference between UEs indeed dominates the noise power and results in interference-limited wireless systems, which represents a critical challenge towards accomplishment of ambitious UE requirements in future wireless systems [19]. Importantly, new interference types and models have been revealed with the emergence of multi-functional applications, multi-tier networks, utilization of unlicensed bands, different derivatives of waveforms, and novel waveforms [20]. It is worth mentioning that the future of interference will not be the same with what we have seen in the past last decades. Interference is becoming a major area that will shape the future of wireless systems by disclosing research opportunities and future direction.

With this motivation, there is a need more than ever to understand, model, avoid, control, and generate interference, since it is becoming and will be essential to the performance of wireless communications realm for the better. Consequently, we believe that a holistic perspective indeed which considers the interference sources and potential management techniques

TABLE I
DEFINITIONS OF INTERFERENCE TYPES ELABORATED IN THIS WORK

Interference Type	Definitions
CCI	It happens when multiple UEs transmit simultaneously non-orthogonal radio signals by using the same channel.
ICI	Refers to the signal leakage between adjacent subcarriers in multi-carrier systems, leading to signal degradation.
ISI	It occurs when the energy from one symbol leaks into the symbols that follow up.
ACI	Defines the signal leakage between adjacent channel carriers.
INI	It arises as energy leakage between adjacent channels with different numerological systems.
IWI	It is defined as a CCI with UEs performing communication via different signal waveforms.
IAI	It represents the signal leakage between antennas in a multi-antenna-based communication system.
IDI	It refers to the signal leakage between adjacent subcarriers in delay-Doppler domain, due to fractional Doppler.

(i.e., interference control, mitigation and cancellation) towards 5G-B wireless communications systems has become a need for academia and industry. Additionally, to the best of authors' knowledge a work that reveals the deficiencies of the existing interference solutions alongside with recommendations and future designs in order to accomplish the aforementioned demands of beyond 5G is missing in the literature.

B. Interference as an Inevitable Reality

Interference and noise indicate two fundamental phenomena and critical limiting factors in the world of wireless communications that are placed at the denominator part of Shannon's capacity formula, known as signal-to-interference and noise ratio (SINR), and cause degradation in the system capacity [46]. Different from noise that shows random behave, interference has deterministic characteristics, which are mainly inherited from the statistics of the transmitted signal (i.e., pulse shape, time, frequency and space properties), its interaction with the physical wireless channel, handset architecture and radio access protocol. Hence, in order to have insights about unique features of interference and how it differs from noise, an extensive research is performed by academia and industry. To have an explicit view of the interference problem, we found it useful to chart its evolution following the used wireless technologies starting from the 1st generation (1G) up to today, as illustrated in Fig. 1, and its prominent types are given in Table I. In this context, it is worth mentioning that orthogonal multiplexing/transmission has been the key to the wireless communications realm regardless of ever-increasing interference sources. In particular, frequency division multiplexing (FDM), time division multiplexing (TDM), code division multiplexing (CDM), and lastly orthogonal frequency division multiplexing (OFDM) represent the basic signal formats that have been used and modified within the industry of wireless communications up to 4G [47].

In early cellular communication systems with analog voice services, adjacent channel interference (ACI) and co-channel interference (CCI) have been avoided via the use of guard band among adjacent channels and frequency reuse (FR) through geographical separations. With the introduction to digital communication systems in 2nd generation (2G), Global System for Mobile (GSM) technology has paved the way for SMS and mail services. Specifically, digital channel coding schemes have been designed aiming to protect the system reliability against inter-symbol interference (ISI) due to *frequency selectivity* of wireless channel [48]. Later, broadband systems have been integrated to achieve high data rates and capacity. Hence, in 3rd generation (3G) with Universal Mobile Terrestrial Systems (UMTS) standard, each UE has been allowed to use the entire available time and frequency RRs for communication with the aid of distinct orthogonal codes. Adaptive power control and rake receiver (Rx) have been introduced to avoid near-far effect and achieve diversity gain, respectively [49]. OFDM-based LTE has been the breakthrough technology for both achieving high spectral efficiency (SE) and serving multiple UEs via a simple frequency domain equalizer (FDE) in 4G [50], [51]. Unfortunately, this multi-carrier scheme is highly sensitive to inter-carrier interference (ICI) mainly because of channel and hardware impairments, i.e., *time selectivity* of wireless channel, wider band transmission, and radio frequency (RF) handset imperfections, that will be more frequently faced in the near future towards smaller equipment sizes and higher data rate transmission (wider spectrum such as mmWave bands) [52], [53], [54], [55].

In contrast to the above-mentioned communication technologies relying on stringent criteria of orthogonality, in 5G-NR, basically scalable OFDM with multi-numerology (15kHz, 30kHz, 60kHz subcarrier spacing) has been adopted to fulfill the needs of UEs, which are defined by the International Telecommunication Union-Radiocommunication Standardization Sector (ITU-RSS) [4], [56]. For this reason, the presence of various numerologies inherently leads to an unprecedented external interference named inter-numerology interference (INI) due to the loss of orthogonality between the subcarriers [57], [58]. Moreover, MIMO-based UE specific has become a key component of 5G-NR, suffering from multi-link inter-antenna interference (IAI) and becoming more intense with UE-specific beamforming. Over the last decade, non-orthogonal transmission has been actively elaborated as a potential alternative for multiple accessing such as power domain non-orthogonal multiple access (NOMA), where all UEs utilize the same signal format over the same RRs [59], [60], [61]. Moreover, the recent interest of wireless communications society in the concept of NOMA is shifting towards non-orthogonal transmission based on the coexistence of multiple waveforms with distinct features named waveform domain NOMA (WD-NOMA), leading to a new interference type that we name inter-waveform interference (IWI) [62], [63], [64]. In WD-NOMA, different signal formats coexist over the available RRs, aiming to serve various demands of UE. In line with this, we expect that WD-NOMA will become more attractive to serve multiple wireless systems simultaneously, such as joint radar-sensing and communication (JRC) in mmWave bands [65]. Essentially, the strength of orthogonal transmission schemes continues with the maintenance of orthogonality between RRs. Consequently, this limited flexibility of orthogonal transmission has opened the

TABLE II
MAGAZINE PAPERS ON INTERFERENCE IDENTIFICATION AND MANAGEMENT

Type	Ref.	Year	Interference Types								Description
			CCI	ICI	ISI	ACI	INI	IWI	IAI	IDI	
Magazine Articles	[21]	2009	✓								A summary of potential techniques that can coordinate and mitigate inter-cell interference in 4G OFDM-based LTE technology.
	[22]	2012	✓								Dynamic configuration of RRs in TDD-LTE-based technology can help to control CCI regarding the scenario requirements.
	[23]	2014	✓								Joint utilization of network interference and desired signal can mitigate the impact of CCI via design of advance Rxs.
	[24]	2013	✓								This work provides an overview of CoMP technology and its capabilities of managing inter-cell interference.
	[25]	2014	✓								Power control and cell association are discussed to manage CCI in 5G multi-tier networks with a shared access link.
	[26]	2016	✓								An overview of various interference alignment and neutralization methods are provided for the network architecture.
	[27]	2018	✓								A revision of ICIC architecture is needed to better benefit from the unique opportunities brought by 5G NR vision and demands.
This Survey		2024	✓	✓	✓	✓	✓	✓	✓	✓	Within this study, we aim to offer a thorough classification of interference sources and management techniques. We cover various approaches such as interference avoidance, mitigation, and cancellation, focusing on various emerging wireless technologies.

door for integration of complementary modulation schemes and waveforms including IM and OTFS for beyond 5G mobile technologies [66]. The inherent characteristic of signal sparsity introduced by IM concept (i.e., time, frequency and space) and exploitative feasibility of *frequency/time selectivity* offered by OTFS shows immunity against different interference sources. On the other hand, these emerging technologies are associated with new interference characteristics and types, such as inter-Doppler interference (IDI) in OTFS transmission. Besides physical (PHY) layer approaches, a wider perspective towards interference has been introduced via inter-cell interference coordination (ICIC) and coordinated multi-point (CoMP) transmission and reception [67], [68], [69]. Briefly, Fig. 1 illustrates that as the UE demands increase, a high interference level and new interference types occur which require intelligent management solutions, as we discuss in the following sections.

C. Review of Related Magazines and Surveys

In this section, we briefly revise the existing magazines and surveys and compare with this work, listed in Table II and Table III, respectively. A rich literature on the interference concept exists since it is the main limiting factor of the overall system capacity of wireless systems. Importantly, the majority of the presented survey and magazine articles mainly address aspects of medium access control (MAC) layer-based CCI management schemes with a focus on 4G OFDM for LTE/LTE-A technology [21], [27], [30]. For instance, in [22], Shen et al. investigate CCI management through ICIC with the aid of uplink-downlink time-division duplexing LTE (TDD-LTE) in HetNet. Similarly, in [28], Kwan and Leung emphasize the importance of correct estimation of channel state information (CSI) and exploitation of RRs reuse concept via ICIC in order to enhance fairness between center and edge UE in LTE systems. In [25] and [27], authors discuss that management of CCI needs to be readdressed for UEs with different channel access priorities in 5G multi-tier networks. Moreover, in [39], Chen et al. elaborate in-depth CCI between wireless local area networks (WLANs) and wireless personal area networks (WPANs) in 2.4 GHz Industrial, Scientific and Medical (ISM) band. Different from the aforementioned system-level cases, recent works discuss the management and exploitation of interference from a link-level perspective via proper precoder designing in multiple antenna-based systems [34], [38]. Miridakis and Vergados [31] discuss the performance of different successive interference cancellation (SIC) Rxs under several interference types in downlink LTE/LTE-A technology, as listed in Table III. Motivated by recent developments in computer communication, in [45], Kazim considers Software Defined Networking (SDN) as a potential routing-based inter-network interference mitigation concept. In [42], Oyedare et al. emphasize the utilization of deep learning (DL) tools against interference. Sadjina et al., in [37], discuss the impact of self-interference caused by transceiver limitations in LTE-A and 5G NR wireless systems. Moreover, in [40], Motz et al. discuss the introduction of interference in frequency division duplexing (FDD) transceivers caused by RF imperfections, with a specific emphasis on carrier aggregation (CA) in the context of 4G and 5G NR wireless technologies. In [41], Chen et al. provide an overview of the state-of-the-art interference cancellers from an implementation and comparison perspective, considering both RF and baseband scenarios. In [44], Siddiqui et al. offer a thorough demonstration of interference issues, such as inter-slot, inter-slice, and inter-service, for URLLC use-cases in

TABLE III
SURVEY PAPERS ON INTERFERENCE IDENTIFICATION AND MANAGEMENT

Type	**Ref.**	**Year**	**Interference Types**								**Description**
			CCI	**ICI**	**ISI**	**ACI**	**INI**	**IWI**	**IAI**	**IDI**	
Survey Articles	[28]	2010	✓								UE CSI-based scheduling and CCI mitigation via FR are considered as the two key features of success for LTE technology.
	[29]	2010	✓								A survey of interference models that are revised and categorized considering the radio capture phenomenon.
	[30]	2013	✓								Potentials of ICIC concept in order to manage and mitigate CCI due to energy leakage between cells is revised and discussed with the focus on prominent OFDM-based LTE/LTE-A technology only in downlink transmission.
	[31]	2013	✓	✓	✓	✓			✓		Performance of SIC is investigated for OFDM-based communication systems i.e., OFDM, spread OFDM, and MIMO-OFDM. The efficiency of SIC Rx is assessed in terms of BER performance and detection complexity.
	[32]	2013	✓		✓						Interference management techniques i.e., interference rejection Rxs, RR scheduling, and dynamic ICIC are discussed for femtocell-femtocell scenario and femtocell-macrocell leading to co-tier and cross-tier interference, respectively.
	[33]	2016		✓	✓						A classification of research publications on ISI and ICI caused by time and carrier frequency synchronization is provided regarding various wireless technologies.
	[34]	2016	✓								Integration of interference alignment schemes with cooperative precoding is considered as a promising to explore CCI or INeI.
	[35]	2017	✓								A comprehensive survey of interference exploitation as a potential power source combined with energy harvesting technology is presented.
	[36]	2019	✓			✓					The escalating threat of interference to GNSS-based system and an encompassing overview of corresponding interference management methods are elaborated.
	[37]	2020	✓	✓							The degradation of the Rx sensitivity due to increased transceiver complexity against RF impairments, i.e., intermodulation and phase noise, is discussed from an interference perspective.
	[38]	2020	✓		✓						A tutorial of symbol-level precoding is offered in multi-antenna wireless communications systems with known CSI at the BS.
	[39]	2021	✓								A detailed review of CCI in ISM band due to coexistence scenarios between Bluetooth, IEEE 802.15.4 and Wi-Fi, and spectrum sharing issues have been discussed.
	[40]	2021	✓			✓					An introduction of interference in FDD transceiver due to RF imperfections is provided with a focus in CA for 4G and 5G NR wireless technologies.
	[41]	2021	✓			✓					An overview on implementation and comparison of various interference cancellers is presented from both an RF and a baseband perspective.
	[42]	2022		✓		✓					A comprehensive overview of the advantages of DL tool towards mitigation of various interference types have been discussed.
	[43]	2022	✓								The escalating concern of the CCI due to coexistence of multiple wireless technologies in ISM band is discussed.
	[44]	2023	✓	✓			✓				Authors revise and discuss interference issues associated to services utilizing URLLC access technologies in beyond 5G.
	[45]	2023	✓								A routing-based interference mitigation for mobile systems is examined, considering past, present, and future approaches towards INet.
This Survey		2024	✓	✓	✓	✓	✓	✓	✓	✓	Within this study, we aim to offer a thorough classification of interference sources and management techniques. We cover various approaches such as interference avoidance, mitigation, and cancellation, focusing on various emerging wireless technologies.

beyond 5G wireless networks. Hasan and Khan in [43], shed light on the CCI caused by the coexistence of various wireless technologies in ISM band. In [36], Morales-Ferre et al. examine interference characteristics within Global Navigation Satellite System (GNSS) systems in the context of satellite and aviation technologies.

Although there is a rich literature on interference, it is worth mentioning that the existing surveys are application specific, i.e., ICIC management for HetNet, and do not encompass the full spectrum of new emerging needs in 5G-B wireless communications society. Surveys that discuss the interference from the perspective of emerging new applications and use-cases in 5G and beyond wireless systems are scarce. Specifically, we shed light on the most challenging interference sources and associated limitations in 5G wireless technologies, and thus, we establish a precedent for the need of interference management techniques (i.e., interference suppression, avoidance and control) in order to relax the gaps in the existing solutions. Moreover, in this work, we have attempted to follow the natural and intuitive flow by pointing out the communication reliability, system complexity, communication latency and energy efficiency (EE) issues associated with the interference types and the corresponding management schemes. In line with this, we have discussed the most common solutions and then we have identified potential gaps that need solutions from a link or network level perspective. Importantly, this work not only considers classical system models of interference but also is more up-to-date in terms of surveying the recent interference-based references and the new system models of interference within. In a nutshell, although the interference problem has been covered from the aspect of ICIC, the overall picture of interference from the PHY layer perspective is missing, illustrating the interference as an inseparable truth for current and upcoming standard technologies in wireless communications realm. To fill this gap, in this work, we have conducted a comprehensive work on the interference sources, models, and control schemes considering the perspective of the UE of interest. This article aims to present a comprehensive overview of interference from a PHY layer perspective, focusing on providing a thorough understanding rather than listing and discussing every work related to the interference in the literature, which may exceed hundreds of thousands.

D. Contributions

Considering the above discussions, the main contributions of this work are listed as follows.

- In this work, we provide a unique and comprehensive taxonomy framework that categorizes the interference types according to their source of origin, so that researchers, system designers and engineers can easily understand the possible interference types, taking into account their system architecture.
- This framework, first defines two primary groups of interference sources, including UE of interest and other UEs named as *self-user interference* (SUI) and *other-users interference* (OUI), respectively. Moreover, SUI and OUI groups are divided into two other classes each as *intentional* and *unintentional* interference. Thus, interference taxonomy is split into a total of four interference classes named *unintentional* SUI (U-SUI), *intentional* SUI (I-SUI), *unintentional* OUI (U-OUI), and *intentional* OUI (I-OUI).
- In this way, the interference types are differentiated and matched with the corresponding interference sources, such as frame design, radio access schemes, channel impairments, and hardware limitations.
- This framework provides a comprehensive categorization of interference management techniques, including interference avoidance, mitigation and cancellation, regarding the interference types and sources to guide the readers on smart utilization of RRs by taking into account the UE demands.
- Limited temporal and angular dispersion of the wireless channel can alleviate U-SUI ISI and U-SUI ICI, respectively, while a controlled spreading of the signal's energy across the spatial domain relaxes the effect of U-OUI CCI. Methods such as filtering, windowing, and adaptive guard techniques aid in signal localization within the transmission domain, providing resilience against potential U-SUI ICI, ISI, and U-OUI ACI.
- In addition, this work places special emphasis on the interference perspective of emerging wireless technologies including RIS, UAV, OTFS, IM and non-orthogonal and overlapped multiple accessing (NOOrMA) based solutions to shed light on potentials and limitations of interference in 5G-B.
- Effective exploitation of diverse time and frequency characteristics of wireless channel (i.e., RIS and UAV), and distinct signal-related features (i.e., OTFS, IM, OFDM, SC-FDE, and NOOrMA) can assist in estimation, mitigation or avoidance of not only conventional interference types (i.e., CCI, ISI, ICI, and ACI) but also emerging INI, IWI and IDI on the intended UE.
- Intelligent integration of the aforementioned technologies, GF-access with ML and signal processing techniques for interference management can significantly contribute towards dense deployments, increased capacity, and coexistence of diverse wireless networks serving a wide range of UE demands.
- To the best of authors' knowledge, the categorization of interference sources is missing in the literature, and the existing articles in the field of interference management only focus on system-level approaches, such as ICIC and CCI, as summarized in Tables II and III. This article is the first comprehensive survey on the interference types, sources and management techniques from the perspective of PHY layer, with a special emphasis on new interference sources and potential solutions in 5G-B systems.
- Finally, we discuss future directions and potential challenges to shed light on the interference exploitation in next-generation wireless communications along with its management.

E. Organization of the Survey

The organization of this work is illustrated in Fig. 2. Section II offers an essential background with respect to transmission domains in this work. Section III describes and categorizes the core interference sources of current and

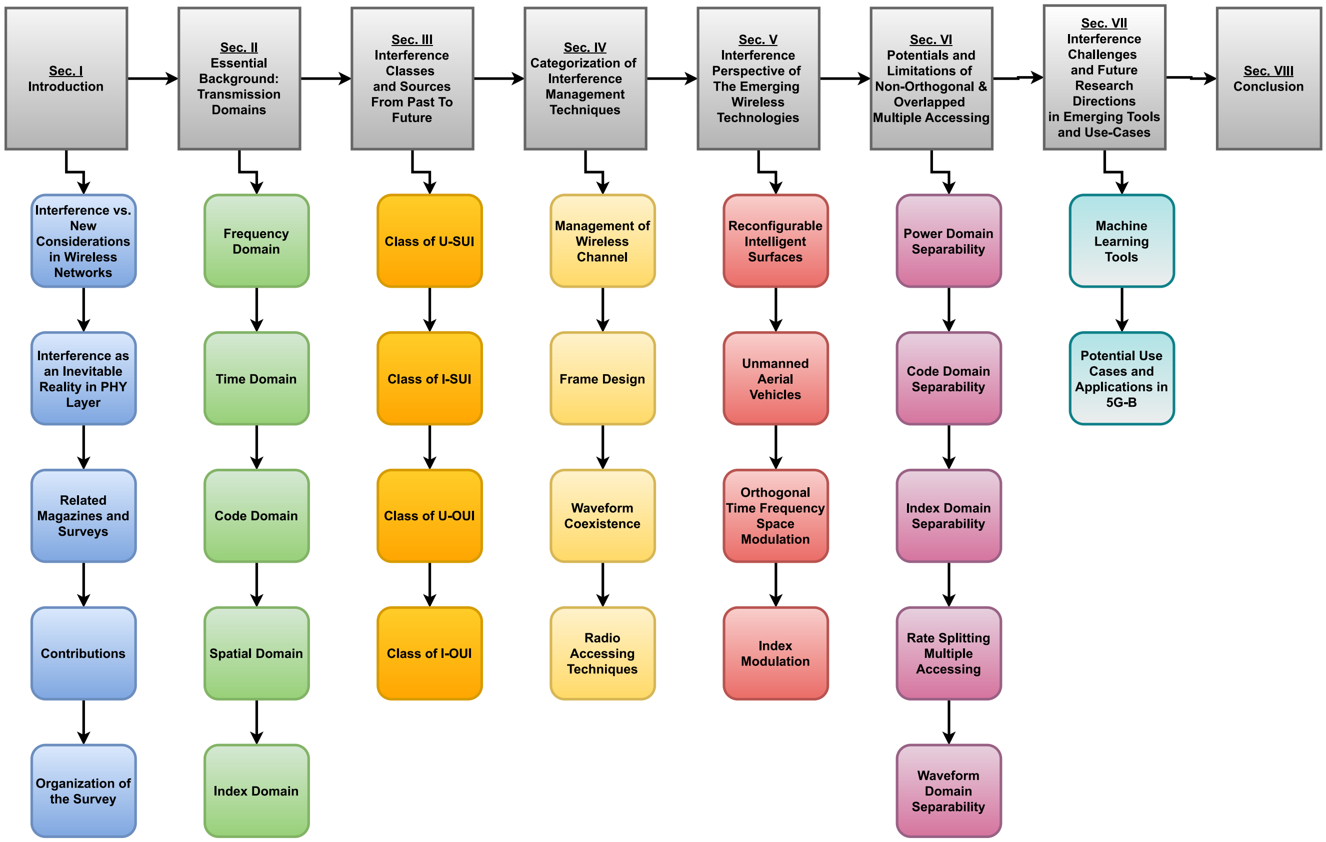


Fig. 2. Outline of the survey paper.

future wireless technologies. In this line, Section IV surveys and groups the interference management techniques in accordance with the potential interference sources. Section V explores the interference perspective of potential emerging wireless technologies, while Section VI focuses on NOOrMA-based techniques, shedding light on their role in addressing interference. Section VII elaborates on potential challenges and future directions with a focus on interference for prominent communication networks. Finally, Section VIII provides the concluding remarks of the work.

II. Essential Background: Transmission Domains

This section revises the basic concepts of prominent wireless communications technologies from a transmission domain perspective, aiming to provide an essential background for the remainder of the work.

A. Frequency Domain

1) Frequency Division Multiplexing: It splits the entire frequency spectrum into multiple RF carriers, where each carrier is assigned to a particular UE. Moreover, a frequency guard band is utilized in between to avoid signal emission between adjacent channels and maintain the orthogonality. FDM is one of the most common analog technologies of 1G for mobile phones known as frequency division multiple accessing (FDMA). FDM is characterized by a large symbol duration (T_s) compared to the delay spread (τ_{max}) of wireless channel. It reduces the impact of ISI at the cost of a lower data rate. Unfortunately, insertion of the guard band leads to a waste of SE. Moreover, the hardware impairments become a critical factor due to the implication of narrow-band filter in the transceiver architecture.

2) Orthogonal Frequency Division Multiplexing: OFDM represents the most popular multi-carrier technology, which has been adopted in the wireless standards, such as IEEE 802.16, WLAN, 4G LTE, and Wi-Fi [70]. In particular, this technology splits a wide-band fading channel into several narrow-band subchannels. Occasionally, interference on the desired channel can be bandwidth-limited. Consequently, this will avoid impacting all subchannels, hence not affecting all the data. As a result, it is resilient against CCI interference. OFDM can avoid ISI which is associated with the frequency selectivity of wireless channels and the presence of multiple narrow-band subchannels. As shown in Fig. 3, data information X[k] (i.e., M-ary quadrature amplitude modulation (QAM)/phase shift keying (PSK) symbols) are defined in the frequency domain. In Fig. 3, the red box labeled "subcarrier mapping block" illustrates the allocation of available resources to multiple UEs in the case of multiple accessing. "S-to-P" and "P-to-S" denote the conversion of serial data into a parallel format and vice versa, respectively. Unfortunately, OFDM signal is highly sensitive to ICI occurring among subchannels and caused by the strict frequency synchronization demands. Hence, it is very sensitive to phase noise (PN) and corrupted RF-front-end. Asynchronous transmission leads to crucial ICI in case of OFDMA, where

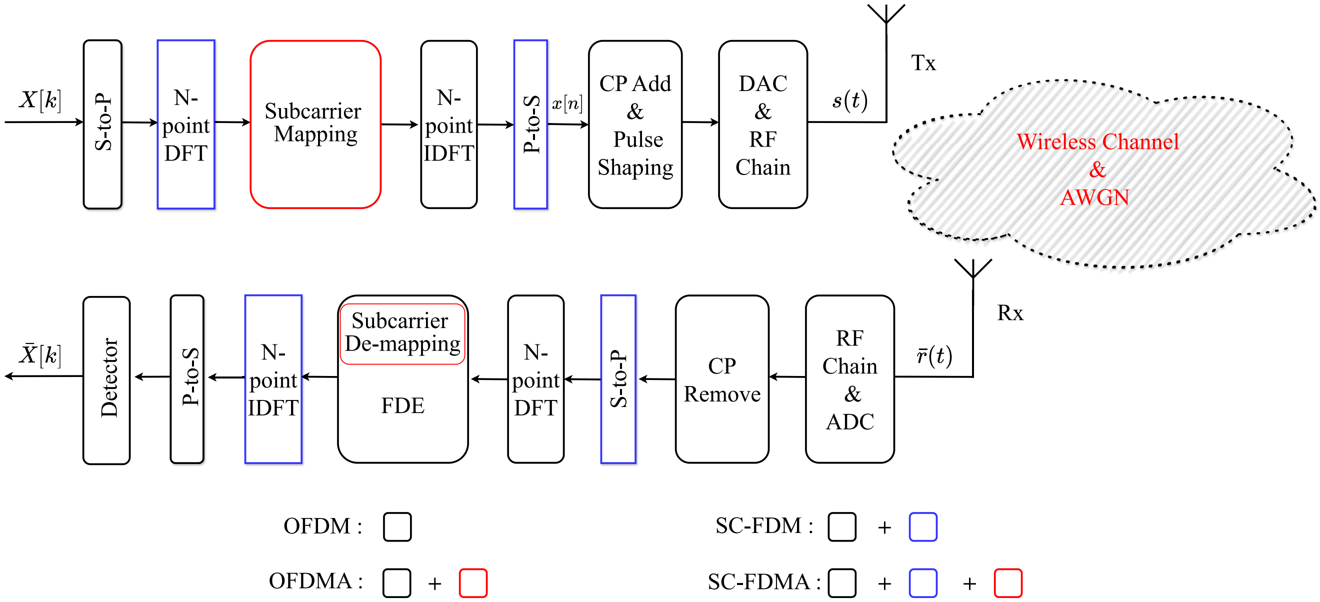


Fig. 3. Transceiver model for conventional wireless technologies utilizing FDE methodology.

OFDM subchannels are split between different UEs via the subcarrier mapping scheme properly.

B. Time Domain

1) Time Division Multiplexing: In contrary to FDM, in TDM, the entire bandwidth has been used for transmission or shared among the UEs, i.e., which is the case of time division multiple accessing (TDMA), while utilizing pre-determined time slots or dynamic time slots. Due to fast time slots, the data rate is higher than FDM, and thus, the transmission bandwidth is much higher, allowing much more flexible rates. Importantly, due to shared bandwidth access, no guard band is needed. Thus, this removes the necessity for narrow-band filter processing and implementation. On the other hand, wireless systems performing broadband communication require advanced equalization techniques, since T_s gets smaller. Consequently, complex signal processing techniques are required to overcome ISI and relevant synchronization problems within the TDMA frame.

2) Single Carrier - Frequency Division Multiplexing: Inspired by the simple structure of OFDM, single carrier-frequency division multiplexing (SC-FDM) is introduced in the literature [71], as shown in Fig. 3. It is characterized by a similar structure as classical OFDM. It is adopted as the uplink transmission named single carrier-frequency division multiple access (SC-FDMA) for the 3rd generation partnership project (3GPP) LTE technology, offering a lower level of envelope fluctuation than the OFDM-based scheme. Different from the OFDM transmission, additional DFT with P-to-S at transmitter (Tx) and additional IDFT with S-to-P at Rx are implemented to facilitate the FDE [72]. In other words, a sequential transmission of the subchannels is achieved instead of parallel transmission as in OFDM at the cost of a moderate system complexity enhancement to achieve a low PAPR. SC-FDM can be considered as an OFDM system with an additional DFT mapper, and thus, it is also called DFT spread OFDM (DFT-s-OFDM) in the literature. This shows that in SC-FDMA, the information of any symbol is carried by each subchannel, while OFDM based subchannel conveys only a single data symbol information. Therefore, SC-FDM reduces the sensitivity to ICI while losing immunity against multi-path fading, i.e., limiting the frequency selectivity.

C. Code Domain

Code Division Multiplexing: CDM has been adopted in 3G wireless communication networks, where orthogonal codes are assigned to the desired signal $x[n]$, spreading it over the entire spectrum [73]. In other words, different CDM based signals share the RRs in both time and frequency dimensions but are orthogonal in the code domain. Hence, in the case of code division multiple accessing (CDMA), each UE has a unique de-spreading sequence to recuperate the information at the Rx side. CDM technique provides satisfactory performance under the conditions of low SNR through achieved processing gain via spread-spectrum technology. Therefore, CDM-based technologies have been used in military applications for confidentiality. CDMA offers better multi-path resolution due to the wide-band transmission. Moreover, RR sharing among multiple UEs allows a high SE alongside a relaxed CCI handoff problem that has been a major problem in cellular systems. On the other hand, the near-far power issue arises while utilizing CDMA techniques. Even though different UEs are allowed to coexist over the same RR, the number of orthogonal codes and their corresponding lengths are governed by orthogonality and latency constraints, making code selection a tedious process.

D. Spatial Domain

Multiple-Input Multiple-Output: MIMO concept has gradually evolved from a controversial theoretical idea to a mainstream technology, making its way into the family of standard technologies such as WiFi with IEEE 802.11n, LTE, and 5G-NR. MIMO is a radio antenna-based technology that utilizes spatial domain via multiple antennas at both Tx and Rx to perform data communication. MIMO enhances the power of the signal captured by the Rx since it enables the Rx to properly combine the transmitted energy coming from different paths and different time instances. In particular, MIMO can explore the fading channels and provide spatial diversity gain or spatial multiplexing gain. The robustness of the communication increases by securing the success of the transmission with the aid of multiple realizations to reduce the probability of failure. Different from spatial diversity, in spatial multiplexing, different signals associated with multiple UEs simultaneously broadcast over a group of antennas by taking advantage of the fact that each antenna is characterized by a specific spatial signature. Nevertheless, irrespective of its application as spatial multiplexing, spatial diversity, beamforming, or as a smart antenna system, the primary disadvantage of any MIMO scheme is the escalation in both complexity and cost.

E. Index Domain

The idea behind IM is to convey additional data bits via different transmit entities in time, frequency, space, and code domains to provide reliability and EE without compromising SE [66]. At first, IM concept is combined with MIMO systems, i.e., spatial modulation (SM), and OFDM systems, i.e., OFDM-IM, by transmitting additional information bits through antenna and subcarrier indices, respectively [74], [75]. For instance, OFDM-IM partially activates subcarriers to convey the data bits by both activated subcarriers and *M*-ary symbols [75]. In this line, SC transmission with IM (SC-IM), generalized frequency division multiplexing GFDM with IM (GFDM-IM), and code-domain IM (CD-IM) through direct-sequence spread spectrum (DSSS) are introduced in the literature [76], [77], [78]. Incoming information bits are divided into subblocks and each subblock is split into two parts, where the first part decides the status of information-bearing entities, i.e., active or inactive, and the second part is conventionally modulated. Consequently, the IM concept introduced the utilization of RR in a sparser manner, diverging from classical communication schemes, while maintaining a significant level of SE. To emphasize, our main focus is on elaborating the potential advantages of IM schemes in managing and mitigating various types of interference.

III. Interference Classes and Sources From Past to Future

Within this section, the primary interference sources have been identified and categorized into four different interference classes named U-SUI, I-SUI, U-OUI, and I-OUI. This categorization serves as a comprehensive taxonomy framework, providing researchers and engineers with valuable guidelines when addressing PHY layer-based interference issues. Basically, in the realm of the PHY layer, interference arises from either the UE itself or other UEs. The term "interference" in most literature studies traditionally refers to disturbances from unintended sources. However, with the emergence of promising technologies like grant-free (GF) access, the coexistence of technologies over available RR, and in-band full-duplex (IBFD) communication, this perspective has evolved and changed. In addition, these new concepts have brought flexibility in terms of SE, increased system capacity, and reduced system latency, while also introducing new interference sources and types. These interference classes are illustrated in Fig. 4 and discussed in detail as follows.

A. Unintentional Self-User Interference (U-SUI)

U-SUI denotes the interference types stemming from uncontrolled sources that only affect the UE itself. Mainly, these interference sources include wireless channel, as shown in Fig. 5, and hardware limitations.

1) Wireless Channel: Typically, the dispersion of the signal $s[n]$ in time and frequency are imposed by *small-scale fading* propagation characteristics of the mobile wireless channel known as *frequency selectivity* and *time selectivity*, respectively, and thus, causing ISI and ICI, in particular [79], [80], [81], and given in Table IV.

a) Time dispersion (frequency selectivity): The small-scale fading is represented as a multiplicative propagation mechanism, where the transmitted signal reaches the Rx via different propagation paths, as illustrated in Fig. 5 via $h[\tau]$ [82]. This phenomenon happens by reflections of the radio waves from the surrounding buildings, various objects, or other obstacles in the environment, and it causes distortion on the emitted signal via some amplitude modulation, phase rotation, and change in the angle-of-arrival (AoA). Specifically, each multi-path component has a different propagation delay, gain attenuator, and phase shifter, where a vectorial combination of all paths results in a filtering type of effect on the received signal. Hence, a spread in time of $s[n]$ is observed and becoming inevitable towards wider bandwith transmission such as mmWave bands and ever-increasing metropolitan areas [83]. Considering the time difference between the first tap and the last one denoted as maximum excess delay (τ_{max}), and the symbol duration T_s, the channel is categorized as *frequency selective* or *frequency flat*. The arrival time of $s[n]$ from the initial channel path is labeled as τ_0, the second path is indicated by τ_1, continuing until the final path denoted by τ_{max}, as given in Fig. 5. The wireless channel is *frequency selective* if the bandwidth of the transmitted signal $\mathrm{B_s}$ exceeds the coherence bandwidth of the channel $\mathrm{B_c}$ over which the channel remains flat. In other words, $\tau_{max} > \mathrm{T}_s$ in case of frequency selectivity. It is worth noting that $\mathrm{B_s}$ and $\mathrm{B_c}$ are inversely proportional to T_s and τ_{max}, respectively. Consequently, different frequency components of the desired signal $s[n]$ are exposed to various amounts of attenuation. Importantly, the frequency variation of the wireless channel, caused by the time dispersion of the transmitted signal $s[n]$, induces U-SUI at the Rx due to ISI, while leaking into previous/past data transmissions, as illustrated in Fig. 5 via blue colored signal propagation paths within the blue region. Differently, $s[n]$ does not experience time dispersion in case τ_{max} does not exceed the T_s, i.e., $\tau_{max} < \mathrm{T}_s$. As a result, a similar effect is experienced by all the frequency components

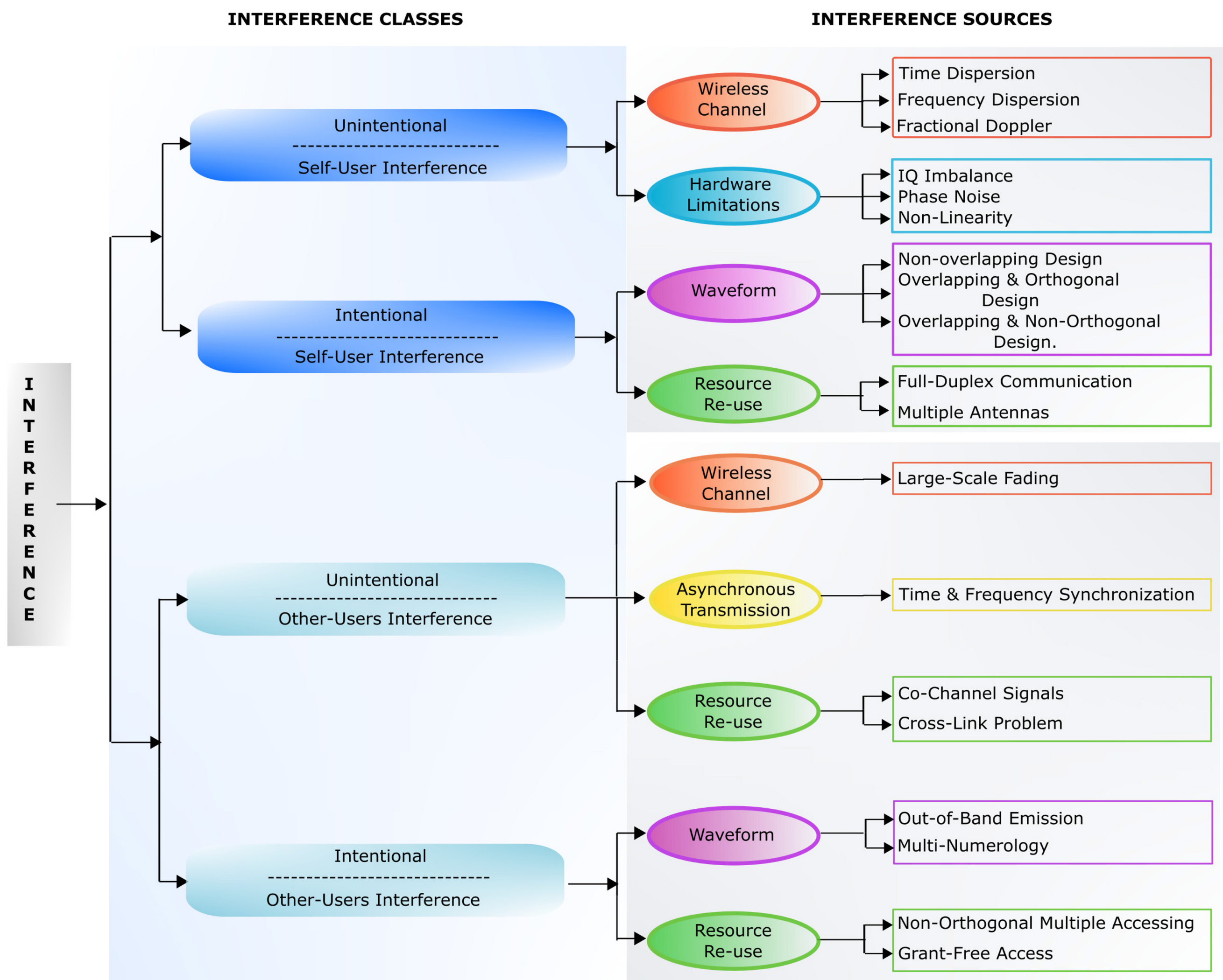


Fig. 4. Interference classes and sources in 5G-B wireless systems.

of the transmitted signal at the cost of limiting not only the transmission rate but also the stringed latency demands in 5G-B wireless networks since τ_{max} becomes the time domain RR boundary [84].

b) Frequency dispersion (time selectivity): While the *time dispersion* of s[n] leads to ISI, its *frequency dispersion* causes U-SUI of ICI type, which poses a significant burden for multi-carrier wireless technologies. Basically, this is caused by time variation of the wireless channel that is related to the mobility of Tx, Rx, or the environmental motion [85], as visualized in Fig. 5 via $h[t,\tau]$ within the magenta region. Here, $h[t_1,\tau]$ and $h[t_2,\tau]$ depict two distinct channels received by the intended UE at times t_1 and t_2, respectively. Essentially, the channel impulse response is associated with time-varying excess delays and attenuation of individual multi-path components within the symbol duration T_s. The nature of the channel's variation determines whether it is considered *fast fading* or *slow fading*. *Fast fading* occurs when the channel experiences rapid changes, with a *coherence time* (T_c) shorter than T_s, which is the time during which the channel remains nearly static. An example of problematic interference in *fast fading* is U-SUI ICI in multi-carrier-based transmissions like OFDM. ICI arises due to the Doppler effect, causing *frequency dispersion*, also known as *time selectivity* [86]. This phenomenon contributes to the lack of established self-driving vehicles and robust vehicle-based communication systems, as the presence of high ICI results in low link reliability [87]. Conversely, in slow fading, the channel undergoes slower changes within the symbol duration, making ICI more manageable. In the forthcoming sections, various potential approaches to address channel-based interference sources will be categorized and discussed.

c) Fractional doppler: Transmission in the delay-Doppler domain significantly enhances channel sparsity, which is critical for handling *time selective* environments. Most research in the literature focuses on integer Doppler indices, which maximize channel sparsity and simplify Rx design. However, if the time and frequency resolution of the desired signal is not inversely proportional to the Doppler indices of the wireless channel, channel sparsity is lost, leading to severe ICI in the delay-Doppler domain, known as IDI. Fractional Doppler disrupts channel sparsity by spreading across the

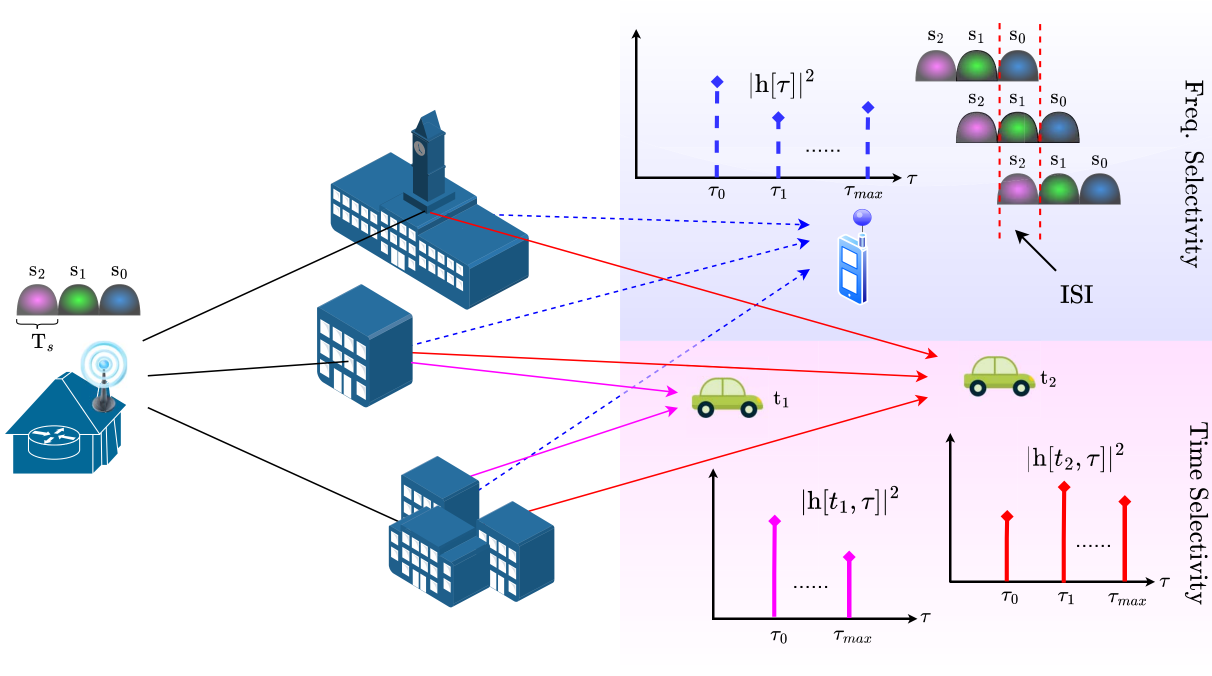


Fig. 5. Dispersion characteristics of the wireless channel as a source of interference.

TABLE IV
CATEGORIZATION OF INTERFERENCE SOURCES AND TYPES, RESULTING IN SUI

Interference Class	Interference Sources	Interference Types							
		CCI	ICI	ISI	ACI	INI	IWI	IAI	IDI
Unintentional-SUI	Time Dispersion			↑					
	Frequency Dispersion		↑						
	Fractional Doppler								↑
	Phase Noise		↑	↑	↑				
	IQ Imbalance	↑			↑				
	Non-linearity		↑						
Intentional-SUI	Non-Overlapping Design		↓	↓					
	Partial Overlapping & Orthogonal Design		↑	↓					
	Overlapping & Non-Orthogonal Design		↑	↑					
	Full-Duplex Communication	↑							
	Multipe Antennas	↑						↑	

Interference Potential- ↑: High ↓: Low

entire Doppler axis. Specifically, this paper discusses IDI in detail for OTFS transmission under Section V-C. IDI is one of the main challenges for waveform types that perform transmission in the delay-Doppler domain.

2) Hardware Limitations: Many promising technologies have been developed to support human needs over the past few decades, and many more will need to be developed and incorporated into future wireless networks. Nevertheless, the theoretical advantages are not always achievable because of limitations induced by RF impairments observed after the physical implementation [88]. These impairments arise as a result of non-idealities in the hardware of transceiver front-ends, e.g., filters, amplifiers or oscillators, due to component mismatch and manufacturing errors [89], mainly leading to U-SUI. Among the most critical RF impairments discussed in the literature are PN, in-phase and quadrature imbalance (IQI), and non-linear power amplifier (PA), being discussed as follows [90].

a) Phase noise: It determines the frequency stability of an oscillator. Basically, the existing active devices within the oscillator cause phase modulation distortion or noise, which inherently differs from the classical noise of electrical systems [91], [92]. This phenomenon has a direct impact on the frequency stability of the oscillator. For example, in the case of a tone transmission, the spectra of the original signal is no longer a single spectral line, but a spread of spectral lines, leading to spectral regrowth, decreased Rx sensitivity, and enhances bit error rate (BER). Hence, this spectral growth significantly boosts the amount of U-SUI ACI between the adjacent bands. The mathematical model of the received signal under the impact of PN is given in [93] as

$$\mathrm{y}[n] = \mathrm{h}[n] \otimes \mathrm{x}[n] e^{j\phi[n]} + \mathrm{w}[n], \tag{1}$$

where $\mathrm{h}[n]$ is the channel impulse response, $\mathrm{w}[n]$ denotes the additive white Gaussian noise (AWGN) random variable with $\mathcal{CN}(0, \sigma_0)$, $\otimes$ denotes the convolution operation, and $\phi[n]$ is the PN as a random sequence, being a function of time. The spectrum growth becomes critical in conventional multi-carrier-based technology, i.e., LTE with OFDM, where it leads to U-SUI ICI [94]. This loss of orthogonality among the carriers in OFDM-based multi-carrier transmission is modeled at k-th subcarrier as follows

$$\mathrm{Y}[k] \approx \mathrm{H}[k]\mathrm{X}[k] + \Phi + \mathrm{W}[k] + \underbrace{\frac{j}{N} \sum_{\substack{r=0 \\ r\neq k}}^{N-1} \mathrm{H}[r]\mathrm{X}[r] \sum_{n=0}^{N-1} \phi[n] e^{j\frac{2\pi n}{N}(r-k)}}_{\text{ICI}}, \tag{2}$$

where $\Phi = (1/N)\sum_{n=0}^{N-1} \phi[n]$ is the *common phase* that can be estimated and compensated due to its deterministic characteristics of being identical for all subcarriers. $\mathrm{H}[k]$, $\mathrm{X}[k]$ and $\mathrm{W}[k]$ represent the frequency response of $\mathrm{h}[n]$, $\mathrm{x}[n]$ and $\mathrm{w}[n]$, respectively. Different from Φ, mitigation of ICI caused by PN is infeasible because of its random nature. In addition, the severeness of ICI plays a critical role in the estimation performance of Φ. High ICI significantly reduces the accuracy of the correct estimation of Φ, as the former dominates the later [95], [96]. Moreover, the spectrum broadness and the randomness of PN become major concerns in high-frequency bands like mmWave.

b) In-phase and quadrature imbalance: The interest of industry in direct conversion transceivers (DCT) has increased exponentially due to their simple architecture and low power consumption. Furthermore, DCT neither needs image rejection filters nor intermediate frequency to perform frequency translation from baseband to passband and vice versa [97]. Hence, it can be easily integrated into new technologies serving a massive number of devices with a wide range of applications. Unfortunately, DCT introduces unintentional distraction and image rejection interference (IRI) in the desired signal, as illustrated in Fig. 6. This happens due to the imbalance between in-phase and quadrature signal branches, where in the case of ideal DCT, carriers of each branch have the same power level and 90° phase difference [98]. The mathematical model of the received baseband signal under Rx IQI is given as

$$\mathrm{y}[n] = \alpha \mathrm{h}[n] \otimes \mathrm{x}[n] + \underbrace{\beta(\mathrm{h}[n] \otimes \mathrm{x}[n])^*}_{\text{IRI}} + \bar{\mathrm{w}}[n], \tag{3}$$

where $\bar{\mathrm{w}}[n]$ is the amplified noise with $\mathcal{CN}(0, \bar{\sigma}_0)$, while $\bar{\sigma}_0 = (1+\epsilon^2)\sigma_0$. $(\cdot)^*$ denotes complex conjugate operator of $(\cdot)$, $\alpha = \cos\Delta\phi + j\epsilon\sin\Delta\phi$ and $\beta = \epsilon\cos\Delta\phi + j\sin\Delta\phi$. ϵ and $\Delta\phi$ represent gain and phase imbalance, respectively. In case of OFDM-based transmission, the positive frequency spectrum, i.e., f_c region introduces IRI on the mirror region of spectrum,

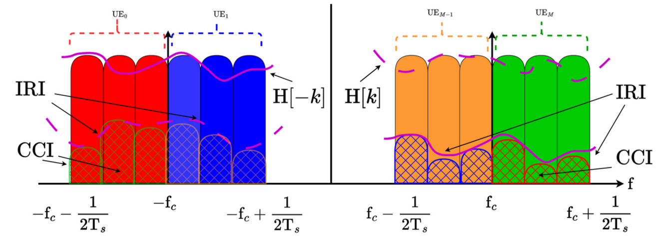


Fig. 6. IQI as a source of interference.

i.e., $-f_c$, and vice versa. From (3), it is clear that IQI at Rx causes U-SUI CCI on UE_0 coming from UE_M, while reducing its strength by α, as illustrated in Fig. 6. Similarly, while the signal strength is reduced by α for UE_0, it induces U-SUI CCI on UE_M. The same relation exists between UE_1 and UE_{M-1} if the Rx side suffers from IQI. In case of multiple UEs, IRI can turn into U-OUI in the form of CCI or ACI. Moreover, IQI impacts not only the desired signal $\mathrm{x}[n]$ but also the statistics of noise $\bar{\mathrm{w}}[n]$. Different from SC systems, IQI leads to a cross-talk form of interference between the mirror frequencies in multi-carrier systems, i.e., OFDM, mathematically modeled as

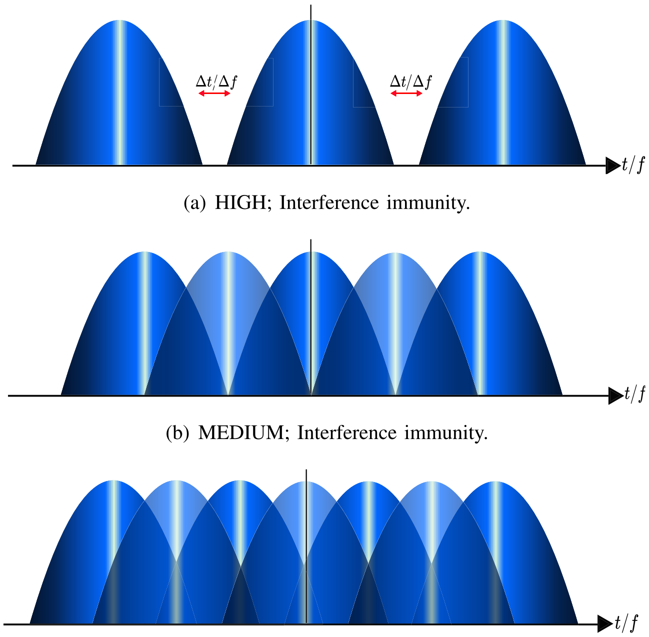
$$\mathrm{Y}[k] = \alpha \mathrm{H}[k]\mathrm{X}[k] + \underbrace{(\beta \mathrm{H}[-k]\mathrm{X}[-k])^*}_{\text{IRI}} + \mathrm{W}[k], \tag{4}$$

where $-k$ represents the mirror frequency index of the k-th subcarrier and vice versa. It is important to highlight that the effect of IQI becomes particularly critical when it occurs as IQI Rx or IQI Tx-Rx. The random influence of the channel mirror H[-k] adds to the issue of IRI and poses challenges in accurate channel estimation.

c) Non-linearity: Different from the scenarios involving imperfect design of the RF front-end such as PN and IQI, the inevitable interaction of the physical signal with the handset itself can introduce distortions to the desired signal, resulting in degradation of BER. This distortion is dependent on the PA operating in the nonlinear region [99]. Specifically, when the transmitted signal contains high peaks, it may get clipped due to the limited linear range of the PA. This clipping generates in-band noise and spectral regrowth [100]. In the literature, peak-to-average power ratio (PAPR) for a given signal is mainly used to assess the impact of non-linearities during signal transmission. The PAPR of baseband signal $s[n]$ is given in [101] as follows

$$PAPR \triangleq \max_{0\leq n<N-1} \frac{|s[n]|^2}{P_{av}}, \tag{5}$$

where $P_{av} = \mathrm{E}\{s[n]\}$ denotes the average power of $s[n]$, where $\mathrm{E}\{\cdot\}$ is the expectation operation. Regarding (5), peak characteristics of time domain $s[n]$ determine the value of PAPR. Consequently, SC-based wireless technologies are robust against the PA nonliterary due to constant envelope transmission. On the other hand, in multi-carrier systems, PAPR becomes a major problem due to the non-constant envelope with high peaks. Due to the inclusion of independently modulated subcarriers, the instantaneous signal power exceeds the average signal power by a significant margin.



(a) HIGH; Interference immunity.

(b) MEDIUM; Interference immunity.

(c) LOW; Interference immunity.

Fig. 7. Interference immunity of the waveform design.

Consequently, the effect of the saturation region becomes more pronounced with an increasing number of subcarriers [102].

B. Intentional Self-User Interference (I-SUI)

Different from the U-SUI, I-SUI denotes the interference types stemming from controllable sources that only affect the UE of interest itself, as shown in Table IV. Basically, this interference class depends on the intentional will and the way how we utilize the given RRs, including the architecture of the transmitting waveform and the RR assignment schemes.

1) Waveform: In the wireless communications realm, the main constituent of PHY layer is the waveform, which describes the physical shape of the signal in time and frequency dimensions. It is one of the core elements that determine the characteristics of the transmission system in order to address the requirement specified by the application. For instance, the robustness of the waveform in the dispersive communication medium, accessing abilities, and hardware implementation feasibility are just a few example cases. It would not be wrong to say that waveform is directly or indirectly connected to approximately all aspects of a communication system. Similarly, waveform design has a significant impact on interference sensitivity and immunity. With this motivation, in order to visualize interference resilience due to waveform design, a symbol or subcarrier is illustrated by blue pulse shape in Fig. 7(d). The way how pulses of the UE are located in the transmission domain is used to categorize I-SUI potential into three main groups.

a) Non-overlapping design: Performing transmission via a non-overlapping design refers to zero energy leakage among pulses in the transmission domain at Tx side. A scenario of the non-overlapping and orthogonal waveform is illustrated in Fig. 7, where Δt and Δf represent guard in time and frequency, respectively. This scenario is endorsed until Δt or Δf reaches zero. Despite the high system reliability of orthogonal transmission, SE of systems decreases with the increase of guard portion. The design of an orthogonal pulse at Tx does not mean that it satisfies the condition of perfect recovery on the Rx side. In other words, there is no assurance that there will be no contribution from other pulses on the part of a given pulse after it undergoes the wireless channel. Essentially, transmission with non-overlapping pulses only provides high immunity against potential I-SUI ISI and I-SUI ICI considering the time and frequency domain, respectively.

b) Partial-overlapping & orthogonal design: In order to enhance the SE, the overlapping of pulses is considered. Thus, in case of no guard $(\Delta t, \Delta f < 0)$ allocation between consecutive pulses in the transmission domain, energy leakage of the pulse into its neighbors leads to partial overlapping, as illustrated in Fig. 7(b). The presence of energy leakage between pulses is not a sufficient condition for loss of orthogonality among the signal shapes within a waveform. Unfortunately, partial-overlapping and orthogonal pulses are associated with a lower interference immunity against potential ISI and ICI than non-overlapping pulses. Removing the guard, i.e., $\Delta t, \Delta f < 0$ among the pulses exposes the transmitted waveform to a moderate interference risk at the Rx side. As an example, *sinc* pulse-shaped subcarriers of an OFDM block are partially overlapped among each other and there is zero interference on the index (bin) of orthogonality [103]. Thus, the OFDM signal is time-limited which makes it infinitely long in the frequency domain. Consequently, it becomes very sensitive to residual frequency ICI coming from the frequency dispersion of the wireless channel, PN, or hardware non-linearity [104], [105].

c) Overlapping & non-orthogonal design: The third category includes pulses that are overlapping and non-orthogonal, where there is a severe energy leakage on the bin of orthogonality. Despite the low utilization of the RRs associated with high SE, it makes waveform interference inevitable. Hence, Rx side needs proper interference localization, estimation and mitigation techniques. For instance, filter-bank multi-carrier (FBMC) is an overlapping non-orthogonal waveform [106]. Compared with classical OFDM, FBMC performs subcarrier-based filtering by utilizing different pulse-shaping functions to form the time-frequency features of the waveform. In FBMC, individual subcarriers are more localized in frequency domain and more spread in time domain. Hence, frequency domain localization is achieved at the cost of orthogonality loss [107].

2) Resource Reuse: Intentional reuse of RRs in IBFD communication and its inherent interference leads to the I-SUI of CCI type.

a) In-band full-duplex communication: The ultimate goal of IBFD-based technology is to simultaneously transmit and receive data information over the same time-frequency RRs to double the SE compared to classic half-duplex (HD) wireless schemes [108]. In particular, the UE of interest performing IBFD-based transmission receives not only the signal transmitted from the communicating UE but also its own transmitted signal over the same RRs, as we illustrate in Fig. 8. The green signal indicates the propagating signal from the UE of interest

TABLE V
CATEGORIZATION OF INTERFERENCE SOURCES AND TYPES, LEADING TO OUI

Interference Class	**Interference Sources**	**Interference Types**							
		CCI	ICI	ISI	ACI	INI	IWI	IAI	IDI
Unintentional-OUI	Large-Scale Fading				↑				
	Asynchronous Transmission		↑	↑	↑				
	Co-Channel Signals	↑					↑		
	Cross-Link Interference	↑							
Intentional-OUI	Out-of-Band Emission				↑				
	Multi-Numerology				↑	↑			
	Non-Orthogonal Multiple Accessing	↑							
	Grant-Free Access	↑							

Interference Potential- ↑: High ↓: Low

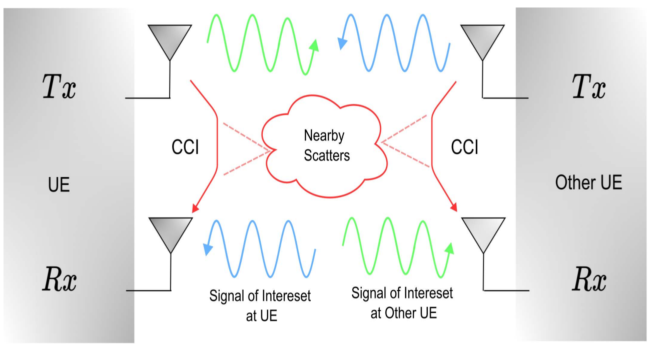


Fig. 8. Interference in IBFD-based wireless communication systems.

and to the other UE while the red arrows depict the back scattered signals by the presence of nearby obstacles in the wireless channel. Consequently, I-SUI of CCI type constitutes among the signal of interest and transmitted one by the other UE that is mathematically given as

$$\mathrm{r}[n] = \mathrm{s}[n] + \underbrace{\sum_{l=0}^{L-1} \mathrm{h}[l]\bar{\mathrm{s}}_i[n-l]}_{\text{CCI}} + \mathrm{w}[n], \tag{6}$$

where $\mathrm{s}[n]$ is the signal of interest and $\bar{\mathrm{s}}_i[n-l]$ is the self interference form the l-th reflector. Even though, the UE of interest knows the interfering signal $\mathrm{s}_i[n]$, cancellation of the CCI also depends on the channel estimation $\mathrm{h}[n] = \sum_{l=0}^{L-1} \mathrm{h}[l]\delta[n-l]$ with $\delta[\cdot]$ denoting Dirac function. Moreover, the impact of CCI becomes severe due to other factors such as hardware imperfections, i.e., PN, IQI, pulse shape of $\mathrm{s}_i[n]$, and the error propagation of imperfect channel estimation. In this sense, the practical implementation of IBFD is limited to the amount of interference caused by transmitted signal [109]. In other words, high SE of IBFD is eroded due to the large power ratio between the transmitted signal and the received one. Moreover, this uncontrolled interference can even reduce system capacity for IBFD that falls below that of HD technology, as shown in [110]. The critical challenge in IBFD systems is the development of new techniques that can alleviate the impact of I-SUI CCI on the reception of the desired signal.

b) Multiple antennas: Spatial domain-based transmission techniques including MIMO, multi-user MIMO (MU-MIMO), and massive MU-MIMO are designed to enhance the capacity and performance of 5G and beyond wireless systems. As in the case of IBFD-based technologies, simultaneous data transmission occurs over the same RRs, but at different spatial directions, achieved by deploying multiple antennas at the panel [111]. Theoretical analysis of the wireless system utilizing massive antennas can deliver significant gains in multiplexing and diversity, resulting in higher data rates and improved reliability. Unfortunately, it encounters various baseband processing challenges, known as inter-antenna interference (IAI) [112]. It occurs when the spacing between antennas becomes significantly smaller than the half-wavelength distance referring to the given carrier frequency, and causing I-SUI IAI. Moreover, in MU-MIMO systems, the presence of multiple antennas can lead to a potential CCI between multiple UEs.

C. Unintentional Other-User Interference (U-OUI)

U-OUI denotes the interference types stemming from uncontrolled sources that lead to interference among multiple UEs, as listed in Table V. Basically, this interference class occurs from the wireless channel, asynchronous transmission, and resource radio reuse.

1) Wireless Channel: Different than small-scale characteristics of wireless channel representing a major source of SUI interference, large-scale is a crucial source of U-OUI CCI.

a) Large-scale fading: Path loss effect determines the received signal power as a function of the distance between Tx and Rx for a clear line-of-sight (LoS) path. The signal strength is inversely proportional to the square of the distance. Differently, *shadowing* denotes the variation of the expected *path loss*-based signal power when prominent terrain contours like buildings, mountains, or forests, block the emitted signal [113]. Hence, *shadowing* is modeled as a log-normally distributed variance around the mean of path loss. Consequently, the power adjustment of the UEs within a cell poses a challenge, as it may lead to signal leakage into neighboring cells. Therefore, the power leakage coming from the multiple UEs in neighboring cells leads to U-OUI CCI, i.e., inter-cell interference, due to transmission over the same RRs [114].

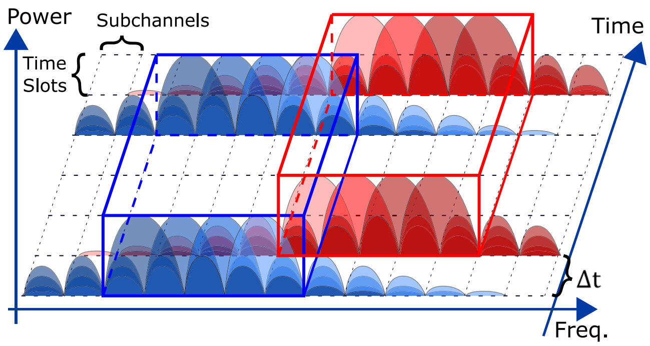


Fig. 9. Asynchronous transmission in OFDM-based systems with time offset.

The concept of channel reuse emerged during the early ages of wireless networks, as the industry faced significant limitations due to the scarce spectrum availability, hindering its expansion. As a result, the number of UEs able to access the network simultaneously was limited, and expanding the network's coverage posed a challenge. The cell-edge UEs suffer the most from CCI, which has become imminent with small-size cells used for higher capacity load and better areal coverage [115].

2) Asynchronous Transmission: Scenarios in which synchronization is lacking among a large number of UEs sporadically communicating with each other or with the base station (BS) represent one of the most challenging problems for massive UE networks, which results on U-OUI [116]. For instance, in multi-UE OFDMA, all UEs require to be aligned in the time and frequency domains in order to maintain the strict orthogonality between the subcarriers. Unfortunately, multi-UE time synchronization is infeasible for asynchronous communications, since signals transmitted from each UE occurs at various time instances and may arrive at the BS with different time delays, as illustrated in Fig. 9. Thus, this time misalignment leads to severe ICI between the subcarrier pulses of UEs [117]. Moreover, the impact of U-OUI ICI gets worse if the power level difference between multiple UE is significant. The rise in the quantity of wireless networks catering to diverse applications exposes them to a greater extent to asynchronous transmission scenarios, and so, potential U-OUI ICI [118].

3) Resource Reuse: Despite the expectation that a controlled utilization of reuse RRs will prevent interference, it remains necessary to discuss it as a potential source of U-OUI.

a) Co-channel signals: The demand for high data rate wireless networks has pushed to new horizons of cellular systems. In early generations of wireless technology, the FR concept is introduced to enhance capacity, where several UE utilize the same RRs in different cells. Moreover, the coexistence of several radio technologies over the same RRs within a given cell is allowed recently, like Wi-Fi 6/6E at 6 GHz or Citizens Broadband Radio Service (CBRS) at 3.5 GHz [119]. Wi-Fi UE in the 6GHz band will need to take steps to avoid outdoor U-OUI on the existing licensed UE. Likewise, CBRS technology is specifically designed to facilitate the sharing of RRs with various incumbent UE, such as radar technology, satellite operators, and other commercial UE [120]. In addition, it will severely affect the system performance for types of scenarios with dense UE deployment. Thus, the overall system capacity can be impacted negatively. Moreover, small cell concept, i.e., picocell, femtocell, and so on, is introduced to further improve capacity and coverage area. However, in HetNets, small cell UE can be exposed to dominant CCI due to macrocell UE operating in the same band [121]. The growing number of co-channel UE with distinct waveform characteristics in HetNets reinforces the presence of IWI as a form of CCI. The features of U-OUI IWI varies by the pair of coexisting waveforms, which are increasing with the wide range of new demands and applications in wireless networks. In a multi-cell scenario, the necessary reuse of RRs for pilots across various cells implies pilot contamination, a type of CCI, whose impact is far greater than AWGN, in MIMO based networks [122]. The bottleneck in fully harnessing the benefits of MIMO based technologies lies in accurately estimating the channel impulse response for each Tx and Rx antenna pair via pilot schemes. For instance, Ngo et al. demonstrates that the impact of uncorrelated interference and rapid Rayleigh fading decreases with the increase of the number of BS antennas, whereas the influence of pilot contamination remains unchanged, becoming severe in HetNets with IWI [123].

b) Cross-link interference: Dynamic time division duplexing (D-TDD) has been considered as an essential concept to cope with the dynamic changes of data traffic, streaming services and various applications in conventional wireless networks [124]. In other words, D-TDD based wireless technologies offer more flexible RR utilization opportunities than classical TDD-based schemes, and thus, these systems have the advantage of being able to vary the transmission rate and transmission time frame in the same spectrum for DL and UL connectivity for each cell UE. Basically, traditional BSs utilize the same frame configuration and strict synchronization constraints considering the whole network demands during DL and UL transmission, which it makes impossible to support the dynamic nature of the network in beyond 5G wireless realm [125]. Hence, D-TDD has been proposed as a potential solution for asymmetric traffic flow. Unfortunately, transmission direction incompatibility occurs due to the change of DL/UL transmission parameters between co-channel UE of adjacent cells, resulting in a new type of interference named cross-link interference (CLI) under U-OUI [126]. In classical cellular technologies, BSs of adjacent cells cause CCI to the UE of interest (i.e., BS-to-UE) and UE of adjacent cells leak interference to the BS of interest (UE-to-BS) in case of DL and UL communication, respectively, as shown in Fig. 10. Different from the scenario of CCI, CLI happens because of link energy leakage from the BSs in the DL transmission while other BSs perform UL transmission (BS-to-BS), and UE in UL interferes with the UE of adjacent cells in DL transmission (UE-to-UE) [127]. In addition, the need for solving the CLI is becoming a critical challenge in B5G wireless realm not only with the transmission direction in harmoniousness but also with the integration of mini-slot concept and various subcarrier spacing (SCS) in the 5G-NR frame design. Consequently, the chances to avoid, mitigate, and cancel CLI become less, since the interference features/characteristics are less predictable and

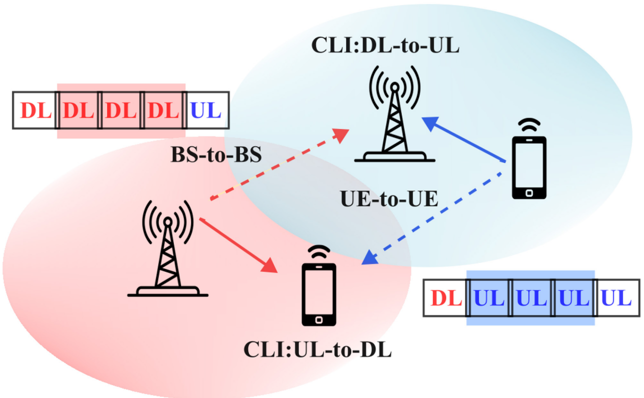


Fig. 10. CLI in D-TDD transmission.

more random if we compare to classical TDD and FDD-based solutions [128].

D. Intentional Other-User Interference (I-OUI)

I-OUI denotes the interference types stemming from controllable sources that lead to interference among multiple UEs, as shown in Table V. Mainly, these interference sources consist of waveform and non-orthogonal multiplexing schemes.

1) Waveform: This subsection discusses I-OUI types caused by waveform, which includes out-of-band emission (OOBE) and INI.

a) Out-of-band emission: OOBE represents the signal energy leakage out of the desired signal bandwidth in frequency domain and causes severe I-OUI ACI on the adjacent bands [129]. Signal localization within the band should be satisfied in order to mitigate OOBE. The classic SC-based transmission signal is well-localized in the frequency domain by means of rectangular and Gaussian filtering, which correspond to sinc and Gaussian pulse shapes in the time domain, respectively. In this way, SC transmission provides low OOBE. Differently, in OFDM-based systems, the use of a rectangular pulse shape in the time domain leads to spreading in the frequency domain due to sinc shape. Consequently, high side lobes of the sinc pulse result in high OOBE in OFDMA types [130]. Unfortunately, the inverse relation of time and frequency domains makes it difficult to have localized signals in both domains simultaneously [131]. OOBE is a challenging task for wireless systems performing data transmission via the frequency domain.

b) Multi-numerology: To fulfill the diverse requirements of 5G including high data rate, low latency, and massive connection, OFDM is enriched with the numerology concept that defines the mini-slot concept and allows the utilization of various SCS in adjacent channels. The shortest transmission time interval (TTI) in 4G-LTE systems is 1 ms that corresponds to 14 OFDM symbols in time domain with a fixed SCS of 15 kHz. The mini-slot concept in 5G-NR shortens the TTI up to 2, 4, or 7 OFDM symbols. Besides, 15 kHz, 30 kHz, and 60 kHz for below 6 GHz, 60 kHz, and 120 kHz for above 6 GHz are adopted to serve different UE demands in 5G and beyond communication systems. Corresponding symbol duration T_s, CP duration and slot duration for a given

TABLE VI
NUMEROLOGY STRUCTURE AND CORRESPONDING OFDM SYMBOL (T_s), CP, AND SLOT DURATION IN 5G-NR

OFDM with Multi-numerology					
SCS (kHz)	15	30	60	120	240
Symbol time (us)	66,6	33.3	16.6	8,3	4,1
CP time (us)	4,69	2,34	4.17/1.17	0.58	0.29
Slot time (ms)	1	0.5	0.25	0.125	0.0625

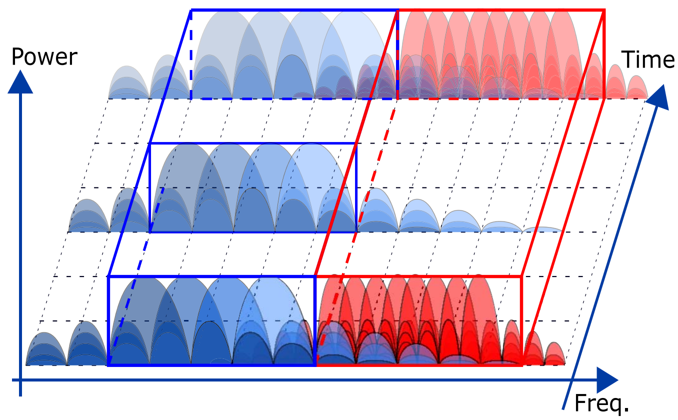


Fig. 11. INI in 5G-B wireless communications systems.

SCS setting are shown in Table VI [132]. In addition, the coexistence of different numerologies in adjacent bands brings challenges and introduces a new type of interference called INI, as in [57]. As shown in Fig. 11, the accommodation of two different numerologies in adjacent bands leads to the loss of orthogonality between the numerologies, while the orthogonality within numerology is maintained. Hence, INI is a form of I-OUI ACI, but different than classical ACI that occurs between multiple adjacent UE using same OFDM SCS, its characteristics, i.e., density and location in spectrum, varies with SCS combinations. To provide a deep understanding of INI and the main factors that contribute to it, extensive research efforts have been devoted in the last few years.

2) Resource Reuse: Intentional reuse of RRs in NOMA and GF access leads to I-OUI, which has gained a large interest in the last few years from both academia and industry.

a) Non-orthogonal multiple access: The exponential growth of data traffic with massive machine-type connectivity increases the need for new technologies in beyond 5G wireless multiple accessing wireless systems [6]. Since insistence on OMA with limited RRs becomes a significant challenge for many applications with high data rates and latency requirements, NOMA with overlapped and non-orthogonal pulses has received special attention as a potential candidate in next-generation wireless networks. In NOMA, multiple UEs perform simultaneous transmission over the same RRs, e.g., time and frequency in order to relax the spectrum scarcity. Consequently, involved UEs are exposed to an I-OUI of CCI type, where multi-UE detection is a need at Rx side. In this line, NOMA can assist in achieving higher connectivity, improving SE, and reducing latency compared to classical

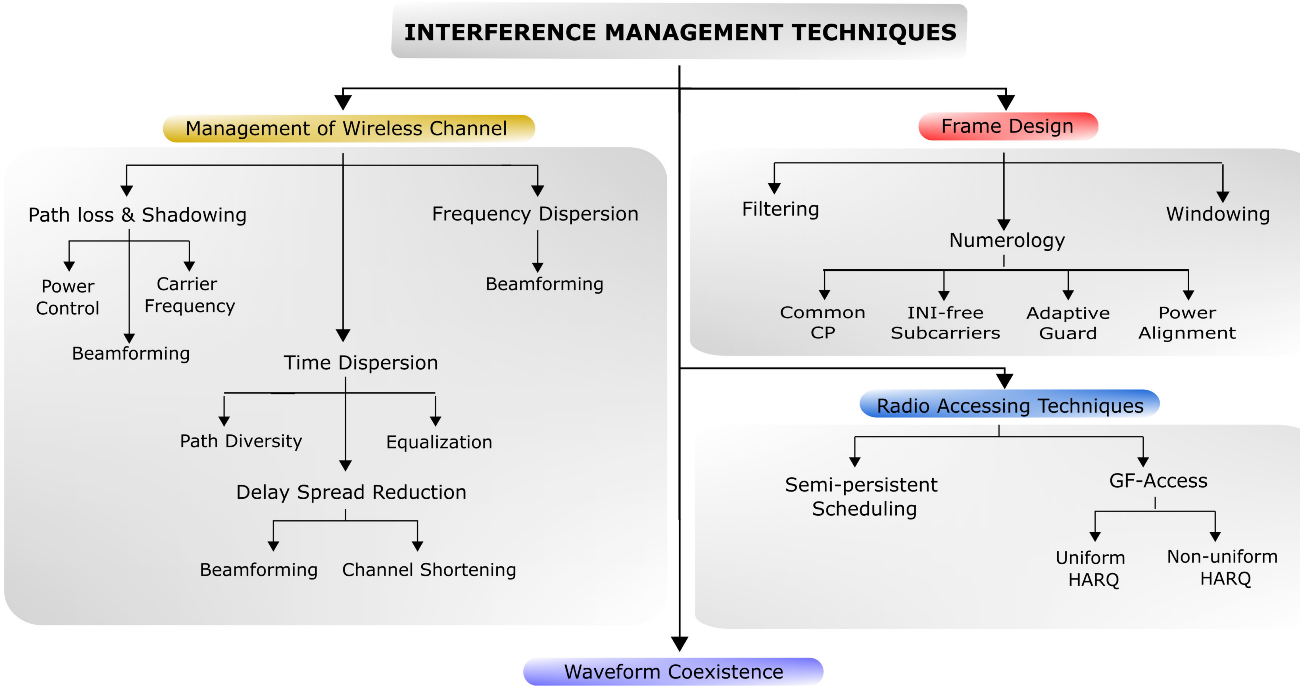


Fig. 12. Categorization of promising interference management techniques for 5G-B wireless systems.

time/frequency-based OMA schemes [133]. It is worth noting that a wide range of different schemes has been proposed and need to be proposed in order to separate multiple UE operating over the same RRs and retrieve the data from a severely CCI interfered signal.

b) Grant-free access: The primary goal of LTE technology along with earlier wireless communication systems is to enhance overall system throughput via scheduled communication, which is known as grant-based radio accessing [134], [135]. Mainly, the BS is always in contact with the UE and provides the required RRs when data transmission is needed. Downlink scheduling is easy for the BS since it knows packet size, transmission requirements, e.g., reliability, and each UE destination in the network. However, this is not the case in uplink communication since UE are isolated from each other and they do not know who wants to communicate, where want to transmit, and what type of data message is being conveyed. According to the current LTE protocol design, each UE needs to send scheduling requests to the serving BS in a dedicated resource, and then wait for the scheduling grant from the BS. After the grant-based access mechanism is successfully completed, a link is established between BS and UE of interest. In this way, the communication link is protected from interference or collision between UE. Although scheduled transmission affords reliable access, it barely can satisfy the latency and massive connectivity constraints of low-latency and machine-critical applications. Moreover, in case of transmission failure, utilization of subsequent grant-based re-transmission becomes infeasible for services with very tight latency constraints. In order to deal with the aforementioned challenges of radio accessing, additional scheduling advances are prompted as a necessity to meet the requirements of new radio communication technologies. Specifically, the concept of GF radio access is introduced in Release 15 and Release 16 by 3GPP standards [136]. Each UE transmits the data in an arrive-and-go manner without performing a handshaking process with the BS that enables a significant latency and excessive packet overhead reduction [137]. Unfortunately, in this case, UEs are exposed to content-based access where collisions are inevitable, leading to I-OUI of CCI type.

IV. Categorization of Interference Management Techniques

In this section, conventional interference management techniques are discussed and categorized with respect to the interference types and sources from a PHY layer perspective, as illustrated in Fig. 12.

A. Management of Wireless Channel

Inherent characteristics of the wireless channel including large-scale fading and small-scale fading represent the major impediments to wireless communication [138]. It is important to mention that, channel management techniques that change the behavior of physical wireless channels are the focus of this section, as given in Table VII.

1) Path loss & Shadowing: In cellular communication, SINR is the parameter that defines the performance of the intended UE in a certain location. Although the distance of UEs to their connected BS is the same, i.e., the same level of path-loss, their SINR value is not the same due to the irregular shadowing effect and potential exposed CCI. Power control mechanisms, such as fractional path loss compensation and full path loss compensation, are used to optimize transmission power to achieve the target received power while minimizing

TABLE VII
INTERFERENCE MANAGEMENT SCHEMES AGAINST THE WIRELESS CHANNEL

Ref.	Type	Effect	Management Tech.	
[139]–[141]	Large Scale Fading	Path loss and Shadowing	Adaptive power control mechanism	
[142]			Beamforming	
[143]			FR	Fixed FR
[144]				Dynamic FR
[145]				Fractional FR
[146], [147]	Small Scale Fading	Frequency Selectivity	Equalization	TDE
[148]				FDE
[149]			Rake Rx in CDMA Systems	
[150]–[152]			Channel shortening	
[153]–[155]			Beamforming	
[156]	Small Scale Fading	Time Selectivity	Beamforming (Limited AoA)	

the interference effect [139], [140], [141]. Additionally, beamforming is also considered as a way of controlling interference by concentrating the signal energy in a certain direction, and so reducing the space of U-OUI CCI presence [142]. In essence, beamforming and MIMO employ multiple antennas to manipulate the direction of a wavefront by adjusting the magnitude and phase of individual antenna signals within an array of antennas. Beamforming is anticipated to address coverage challenges associated with mmWave propagation by enhancing beam directivity towards the intended UE, thereby mitigating propagation limitations. Therefore, a limited propagation and being narrower towards a given direction reduces U-OUI due to CCI. However, there are significant challenges associated with beamforming [157]. The substantial amount of signaling needed for beam calibration in the UE's direction, as well as the control signaling for UE and cell detection, can be considerable. These processes are intricate and may result in increased latency during link establishment. Different from microwave frequency bands, a high path-loss level in mmWave frequency bands allows short-distance communication that avoids energy leakage to neighboring cells [142]. In case when energy control of CCI becomes untraceable, FR is used as a solution [158]. Within multi-carrier systems, the fundamental concept of the FR technique is to partition the overall bandwidth into multiple smaller sub-bands and allocate them to different spaces within the cell with the aid of directional antennas [159]. In addition, these sub-bands are reused by UEs located in other zones of the neighboring cell, ensuring a significant separation distance to prevent U-OUI CCI [144]. Hence, sectorization offered via FR can alleviate congestion and CCI in cellular deployments by subdividing cells into smaller sectors, each assigned a distinct set of subchannels, especially in densely populated regions. Conventional FR involves fixed sectorization including three or six sectors of equal size, which effectively manages CCI interference within cells under uniform traffic patterns. Unfortunately, in case of non-uniform traffic, utilizing uniform fixed FR schemes results in inefficiency, since different regions may experience heavy congestion while others remain underutilized [160]. For instance, in [143], Attia et al. introduced an optimization algorithm capable of adaptive adjustment of RRs to align with traffic demand and channel conditions. This resulted in a notable enhancement of system's SE via dynamic FR. Different from fixed and adaptive FR schemes, the main goal of fractional FR is to mitigate CCI particularly at the edge cell UEs, where the interference levels escalate, as discussed in [145]. Moreover, in [161], He et al. explore the combined utilization of FR based techniques and SIC at Rx in a complementary fashion. The findings indicate that FR schemes and SIC can largely enhance network performance, even with a limited number of SIC stages across a few sectors.

2) Time Dispersion: Generally, prior knowledge of signal propagation in an environment is not available at the Rx. Various signal processing techniques are adopted at Tx and Rx to combat the effect of small-scale fading. Time dispersion, called delay spread, leads to ISI type of U-SUI.

The first method that comes to mind for solving ISI is equalization at Rx. It is investigated under two groups: time-domain equalization (TDE) and FDE. Different types of TDE are studied in the literature, such as maximum likelihood sequence estimator (MLSE), linear equalizer (LE), and decision feedback equalizer (DFE). However, TDE suffers from high complexity, which is proportional to the span of ISI in terms of the number of symbols [146], [147]. On the other hand, TDE can be utilized for path diversity as achieved by Rake Rx in CDMA systems. Rake Rx demodulates received paths independently, and diversity gain is achieved by their proper combination [149]. Moreover, ISI span can be limited by the use of localized filters, which can facilitate using TDE. For instance, Gaussian filtering can be applied to signal before its transmission in order to control ISI [52]. FDE used in OFDM-based systems, such as OFDM and

TABLE VIII
ROBUSTNESS OF WAVEFORM DESIGNS AGAINST VARIOUS SUI AND OUI TYPES

BENCHMARK						
Ref.	**Waveform**	**Design**		**Interference Types**		
		Orthogonal	**Overlapping**	**ICI**	**ISI**	**ACI**
[70]	OFDM	✓	✓	↓	↑	↓
[71]	SC-FDE	✓	✗	↑	↑	↓
ALTERNATIVES						
Ref.	**Waveform**	**Design**		**Interference Types**		
		Orthogonal	**Overlapping**	**ICI**	**ISI**	**ACI**
[164]	FMT	✓	✗	↑	↓	↑
[164]	FBMC	✗	✓	↑	↓	↑
[165]	GFDM	✗	✓	↑	↑	↑
[166]	UFMC	✗	✓	↑	↓	↑

Robustness against interference- ↑: High, ↓:Low

DFT-S-OFDM, allows to perform a single-tap equalization in frequency-domain, as mentioned in Section IV-B, [148]. Channel shortening (CS) is also used to mitigate the ISI effect in the presence of insufficient guard time or to reduce the loss caused by long guard size [150]. The main idea behind the shortening techniques is to localize channel energy within the first taps of the channel so that dispersion in time is reduced. In this way, effective channel with shortened impulse response is the combination of the channel effect and CS [151]. Moreover, in [152], utilization of sparse filters is proposed to further reduce the required number of operations for equalization. Beamforming techniques are also exploited in order to control ISI in a given environment [153]. Transmission of energy to a certain point reduces the number of paths caused by far reflectors. Moreover, in [154], [155] beam pattern of Tx and Rx is adjusted to prevent the reflections coming from dominant-far reflectors.

3) Frequency Dispersion: In order to control frequency dispersion, i.e., Doppler spread, stemming from time selectivity of the wireless channel, Erturk et al. [162] propose a beamforming-based separation of individual paths. Three effects that determine the spreading in frequency domain are the presence of multi-path, mobility, and AoA of the paths. Beamforming restricts the AoAs of incoming paths due to its directivity. In this way, the Doppler spread is transformed into a Doppler shift, since paths in an environment come from the same direction. Similarly, in [163], Stamoulis et al. has proposed time-domain mitigation techniques against U-SUI ICI for OFDM-based scheme while utilizing spatial capabilities of MIMO technology. The compensation of ICI caused by Doppler shift can be performed by the conventional methods [156].

Remark 1: A controlled spread of the signal's energy over the space domain relaxes the impact of U-OUI CCI. A limited time dispersion and AoA dispersion of the wireless channel for a given T_s and T_c can mitigate U-SUI ISI and U-SUI ICI, respectively. Hence, the developers of emerging wireless communication systems must prioritize the characteristics of system design to align with UE's demands and address exposed interference types.

B. Frame Design

The main component of the smart frame design is the waveform that decides the interference immunity, the necessity of the guard and its size in time and frequency, and potential filtering/windowing techniques to satisfy the UE in a network. In Section III-B, possible waveform structures and their potential to be source of interference are discussed. During the preparation for 5G systems, new waveform types including filter bank multi-carrier (FBMC), generalized frequency division multiplexing (GFDM), and universal filtered multi-carrier (UFMC) are investigated as an alternative to OFDM, which enables overlapping orthogonal design. Each waveform type provides a different level of robustness against various interference types due to their different realizations, as given in Table VIII.

1) Filtering: The first parameter that distinguishes the waveforms is the pulse-shaping mechanism. FBMC adopts subcarrier-level filtering, which allows easy harmonization with the transmission conditions. FBMC is superior to the conventional OFDM in terms of OOBE due to well-localization in frequency-domain. The early version of FBMC, i.e., filtered multi-tone (FMT), is an example of orthogonal non-overlapping waveform design, where $\Delta f = 0$, as illustrated in Fig. 7(d) [164]. However, it achieves immunity against interference at the cost of high SE loss. FBMC provides a degree of freedom for selecting any kind of pulse shape filter, such as rectangular filter, root raised-cosine (RRC) filter, Gaussian filter, and so on [52]. The utilized filter type decides the overlapping between consecutive subcarriers and so the corresponding interference immunity. In FBMC, the absence of CP can lead to severe degradation of the system performance due to ISI. In the case of pulse shaping through the Gaussian filter, it corresponds to the non-orthogonal overlapping waveform. Moreover, the selection of filter parameters provides further opportunities to satisfy the different UE requirements. To exemplify, the use of a high roll-off factor for RRC filtering eliminates the high sidelobes and results in robustness against time-dispersive channels. Motivated by this, in [167], [168], Esad et al. have investigated adaptive roll-off factor utilization for FMT-based systems. Intentional overlapping between the pulses with the aid of UE-specific filter parameters is introduced to meet the different requirements. GFDM also applies subcarrier-based filtering and provides a well-localized signal in the frequency domain. It adopts the use of non-orthogonal pulse shape filters, and thus it is another example of non-orthogonal overlapping waveforms. GFDM provides lower PAPR due to block-based transmission and reduces the ACI by exhibiting lower OOBE than the conventional OFDM systems. On the other hand, UFMC performs sub-band-based filtering [166]. It provides better localization in the frequency domain and consequently lower OOBE. However, the lack of CP causes a severe U-OUI ISI and requires advanced Rx design. Similarly, filtered-OFDM (F-OFDM) applies sub-band-based filtering in a flexible manner to meet the UE demands and utilizes CP against ISI [169].

2) Windowing: Alongside filtering, windowing has had a crucial impact on waveform shaping. For instance, in order to reduce U-OUI ACI due to high OOBE stemming from rectangular pulse shaping of OFDM signal, windowed-OFDM (W-OFDM) is introduced in [170]. The windowing process provides a smooth transition between the adjacent symbols by means of additional prefix and postfix. Moreover, in [171], Sahin and Arslan introduce edge windowing to further reduce the OOBE for OFDM-based systems. Unlike conventional W-OFDM, where the same windowing size is used for all subcarriers, it proposes a flexible implementation of windowing. Since the edge subcarriers have more impact on OOBE, long and short windowing sizes are utilized for edge and inner subcarriers, respectively. In addition, windowing provides a degree of freedom to control the U-OUI when it is applied at Rx, as in [172]. Peköz et al. [173] introduce adaptive windowing of insufficient CP for minimization of not only ACI but also ISI jointly for the desired UE.

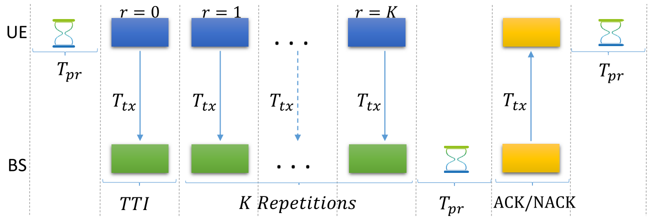
3) Numerology: The presence of multiple UEs with different requirements in a frame and the use of OFDM with multi-numerology require intelligent guard placement to avoid high SE loss while satisfying the UE demands [131]. For instance, latency-critical UEs need a large SCS with a short symbol duration. However, in order to provide satisfactory performance for the intended UE, the impact of INI should be compensated [174]. Kihero et al. investigate the effect of common and individual CP for OFDM symbols [57]. Common CP utilization provides the advantage of having subcarriers with INI-free at the expense of increased INI on the remaining ones, while individual CP utilization leads to INI on all available subcarriers. In this line, Memisoglu et al. provide guard reduction between INI UE, where subcarriers with zero INI are used for transmission, in [175]. Moreover, Yazar and Arslan perform INI-aware scheduling considering the power levels of the adjacent UE in [176].

Remark 2: Techniques including filtering, windowing and adaptive guard help on performing signal localization within the transmission domain, leading to immunity against potential U-SUI ICI, ISI and U-OUI ACI, at the cost of a moderate increase on transceiver complexity, latency and reduced SE.

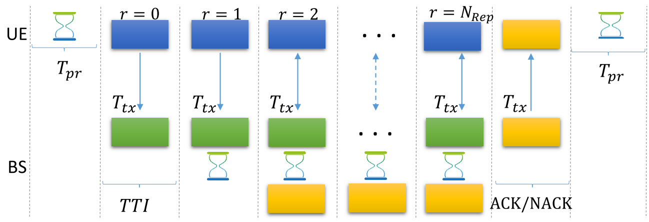
C. Waveform Coexistence

CCI interference is one of the most common interference types in the wireless communication world. In general, several MAC layer solutions including FR, power control, sectorization, ICIC, and CoMP are provided and extensively investigated to manage CCI by academia and industry. Hence, this section gives priority to PHY solutions, which not only avoid but also detect and try to cancel CCI via the utilization of various different signal characteristics of co-channel UEs. In other words, the characteristics of U-OUI IWI vary depending on the pair of coexisting waveforms. Therefore, this a prior information assists in formulating intelligent strategies to address IWI more effectively than merely treating it as classical CCI. For instance, in [177], CCI detection and cancellation between the desired UE with SC-FDE and interferer with SC-FDMA is discussed. Co-channel signals are treated as desired signals, where the UE with SC-FDE causes a partial and dominant interference (DI), which is a IWI type. An iterative blanking scheme is used for DI suppression, reconstruction, and compensation. The use of this technique leads to substantial gain performance improvement in the BER performance as the number of iterations increases at the cost of a slight increase in the complexity of the Rx. Similarly, in [178], Çelebi et al. have proposed to perform a soft window blanking over the region of DI to reconstruct the desired signal from the composite IWI. Differently, in [179], Sahin et al. have discussed the IWI type of CCI due to the coexistence of narrow-band and multi-carrier signals. Each signal is independently demodulated and then regenerated based on the symbol decisions and channel impulse response. The regenerated signal is subtracted from the aggregate signal after a correct detection to obtain an estimation for the interferer. Time-domain misalignment between co-channel signals is used as a signal separability feature to enhance the performance of SIC in TDMA mobile technology, in [180]. Sahin et al. have utilized the RRs of macrocell UEs with OFDM located far away from the femtocell in order to avoid strong CCI in HetNets [181]. A theoretical analysis of IWI between OFDMA and SC-FDMA is provided by Celebi and Arslan in [182]. In addition, the maximum likelihood with successive SIC Rx with power control is evaluated. In [183], Göttsch et al. has introduced sounding reference signal pilot method involving allocation of time and frequency hopping sequence for each UE with the aid of orthogonal latin squares to effectively randomize CCI due to pilot contamination. In [184], Appaiha et al. have conducted time shifting on the pilot positions within the frame for UEs in different cells. This strategy enables them to transmit in partially overlapping and non-overlapping time slots, effectively reducing CCI.

Remark 3: Proper exploitation of different signals with distinct time and frequency characteristics can facilitate IWI



(a) K-Rep GF access scheme.



(b) Proactive GF access scheme.

Fig. 13. Various GF access schemes discussed for 5G-B wireless applications.

estimation and mitigation on the UE of interest. In this line, researchers can also leverage distinct attributes of co-channel signals from the standpoint of application in the evolving wireless domain. As an example, relaxing the complexity and latency constraints for UE with URLLC, while UE with eMBB deals with OUI types.

D. Radio Accessing Techniques

In the literature, several techniques have been proposed and discussed to combat and manage interference due to GF-access. These schemes are categorized as uniform hybrid automatic repeat request (HARQ) and non-uniform HARQ with respect to the performed accessing types.

1) Uniform HARQ: This scheme tries to avoid I-OUI caused by GF access, which is mandatory to achieve low-latency and massive connectivity in next-generation communication systems [185]. In [186], Jacobsen et al. have introduced HARQ-based (K-Rep) and Proactive schemes to meet the requirements of URLLC, as illustrated in Fig. 13(d). T_{pr} is the processing time, TTI is time interval of the transmission, acknowledgment (ACK) is the confirmation signal sent by Rx to signify reception of the message, and negative-acknowledgement (NACK) represents the case of failed reception. Each user with K-Rep is asked to transmit the same packet in K successive time slots without waiting for feedback from the BS, and thus mitigate the impact of I-OUI via proper signal combiner at the Rx side, as shown in Fig. 13. Unfortunately, this scheme can lead to a decrease in SE when the number of required repetitions is exceeded. Thereafter, the HARQ-based Proactive technique is proposed in order to control the number of repetitions, as seen in Fig. 13(c). Different from K-Rep, BS with Proactive scheme is configured not only to autonomously receive the same packet but also to simultaneously process their correctness status. For instance, as shown in Fig. 13(c), once the BS initiates packet reception, it continues to process all received packets collectively until an ACK is reached. Upon successfully completing packet reception in the N_{Rep} iteration, the BS notifies the intended UE via an ACK transmission. This scheme offers improved reliability and higher SE when dealing with inadequate and excessively high K repetitions, albeit at the expense of increased processing complexity on the BS side. It's important to note that the Proactive scheme ensures correct packet detection, which may not always be the case with the K-Rep approach, advantaging its applicability for URLLC based services.

2) Non-Uniform HARQ: Different combinations of GF and grant-based access are proposed in the literature to provide robustness against collision stemming from GF access, and control I-OUI. In [137], Berardinelli et al. have suggested performing HARQ over dedicated resources. Initial transmission is performed over a resource pool that is shared by multiple UEs to maintain both SE and latency requirements, while retransmission is realized over dedicated resources to avoid collision and ensure that UEs are free from I-OUI. Moreover, in [197], Areu et al. have proposed to perform initial transmission and retransmissions on dedicated and shared resources, respectively. *K-Rep* is used for retransmissions. In other words, GF access is performed after grant-based initial transmission. Moreover, in [198], the same authors have discussed the joint optimization of the resource and modulation coding scheme (MCS) for the UEs with GF access. Technically speaking, the UE with strong channel conditions utilizes high-order MCS to enhance the system's SE, while UEs with weak channel conditions perform transmission with low-order MCS. Hence, this enables partial overlapping among UEs simultaneously operating over shared RRs, resulting a low I-OUI. In addition, combination of baseband processing techniques including SIC Rx, interference blanking or rejection, with GF-access can reduce the number of repetitions for correct packet transmission. Allowing higher transmission probability to the UE with lower channel gain reduces its latency and enhances fairness between multiple UEs. Moreover, share of the RR can be performed in accordance with use-cases and applications.

Remark 4: Intelligent GF-access methods allow sharing of I-OUI between multiple UE in a rational manner, aiming to meet requirements of the intended UE. Hence, integrating GF-access schemes with baseband processing techniques such as interference estimation, rejection and cancellation, can relax the necessity for numerous transmissions at Tx and complex Rx to ensure correct packet reception.

V. Interference Perspective of the Emerging Wireless Technologies

Basically, academia and industry have shown substantial and explicit emphasis regarding the interference impact on the link/system reliability and capacity of classical wireless technologies, and thus, plenty of solutions have been proposed, as discussed in the above section. Differently, in this section, potential challenges and future perspectives on suppression, avoidance, and exploitation of the still remaining and newly emerging interference cases in potential beyond 5G wireless technologies are anticipated, as shown in Table IX.

TABLE IX
INTERFERENCE MANAGEMENT OPPORTUNITIES AND RELATED CHALLENGES VIA THE EMERGING WIRELESS TECHNOLOGIES

Technologies	Ref.	Opportunities	Open Issues	Performance Metrics					
				1	2	3	4	5	6
RIS	[187], [188], [189]	RIS devices involve redirecting incident signals towards a desired destination, with the objective of enhancing SNR by circumventing obstacles and obstructions between the Tx and Rx.	To fully exploit the RIS technology, the development of novel RIS control schemes is needed.	↑	↑	↑	↓	↑	↓
UAV	[190], [191], [192]	The utilization of UAV-based systems results in high LoS link probability, which offers promising advantages against ICI and ISI, while exposing the intended UE to major CCI.	UAVs have limited battery life and can be an interference threat for shared spectrum UEs due to LoS.	↑	↑	↑	↓	↓	↓
OTFS	[17] , [193], [194]	By employing the delay-Doppler plane, OTFS achieves a comprehensive depiction of the time and frequency spread exhibited by channel paths, resulting in ICI and ISI immunity.	Design of low complexity and power efficient Rx against potential IDI in practical scenarios.	↑	↑	↑	↓	↓	↑
IM	[67], [75], [195]	Inherent sparse features of IM-base waveforms offer SUI and OUI immunity.	It offers a lower SE than classical schemes for high-order modulation.	↑	↓	↓	↓	↑	↑

Performance Metrics - 1: Interference Immunity, 2: SE, 3: Computational Complexity, 4: Multiplexing Gain, 5: EE, and 6: Compatibility.
Sign - ↑: High, ↓: Low

A. Reconfigurable Intelligent Surface

As discussed in Section IV, the wireless channel represents one of the crucial sources of interference, emerging due to the interaction of the emitted waveform with the large/small-scale characteristics of the environment. When the LoS component, i.e., large-scale characteristic, of the communication link is not as good as it could be, which has become more prominent in current UE applications and use-cases, RIS has been highly proposed across the legacy of communication technologies [187]. RIS works by reflecting incident signals toward an intended destination, aiming to improve the SNR by avoiding obstacles and blockages between Tx and Rx. These devices are conceptually artificial passive surfaces constructed of electromagnetic material that can apply arbitrary phase shifts to signal propagation to alter its propagation, which represents a major interference source in wireless communications realm, associated with its fading characteristics. Moreover, different from classical MIMO and relay-based technologies, RIS does not need power sources and advanced signal processing to digest the impinging signal.

At its beginning, the concept of RIS technology was introduced via intelligent wall design, aiming to control the signal coverage and so the U-OUI in the form of CCI in [199]. It results in a better overall SINR expressed to 80% enhancement of system throughput. Basically, the large scaling characteristics of the wireless channel are significantly influenced by large objects, i.e., walls, for indoor environments [200]. In this line, in [188], authors take a further step and discuss the potential of utilizing the RIS technology against U-OUI in a multi-UE environment, while adjusting the phases of RIS elements and propose to null out the U-OUI. Moreover, since the optimization of the achievable rate for RIS technology under interference channel becomes complex with the increase of UE number and RIS elements, the development of various optimization schemes has been discussed in the literature, as in [201]. Unfortunately, in practical scenarios, each cell is primarily served by a single BS, so UEs near the cell boundary often experience significant U-OUI CCI, differently known as inter-cell interference [202]. Thus, this has motivated authors in [203] to utilize the SIC method and alleviate strong U-OUI CCI due to adjacent cells for passive RIS aided spectrum-sharing wireless networks. Joint precoding of RIS elements has been considered as a potential opportunity to mitigate U-OUI CCI between co-channel UEs, and thus, to enhance network capacity. Unlike traditional precoding that occurs solely at the BS, joint precoding in RIS-based wireless systems involves the simultaneous optimization of both the beamforming vector at the BS and the phase shifts of the RIS elements [204]. For instance, in [205], Yang et al. propose use of RIS in wideband OFDM-based systems, which was explored to maximize the overall network sum rate. However, to further control U-OUI CCI in multi-cell scenarios and enhance overall network capacity, deploying additional distributed RIS panels and BSs towards a cell-free network entails a centralized network.

Centralized wireless systems can cause delays, are less flexible, and can be costly for small deployments. Ding and Vincent Poor [206] have proposed the RIS as a solution to manipulate the UE's wireless channel and broaden the application of NOMA technology, which is infeasible via the current techniques. Furthermore, Yang et al. have introduced a low complex scheme on how to maximize the rate of NOMA via joint exploitation of beam transmission and the phase shifting operation of the RIS elements in [189]. As the decoding order increases with UE number, U-OUI CCI cancellation becomes a big challenge in conventional NOMA, which can be further complicated in the presence of RF impairments or imperfect CSI. Differently, since RSMA is flexible towards interference and can be more adaptable against RF misalignment, as in [207], MIMO-RIS with rate splitting under IQ imbalance and improper signaling are evaluated. Moreover, RIS' potential has been investigated across different network scenarios, including energy-efficient beamforming, PHY layer security, wireless power transfer, and indoor positioning, as in [208], [209]. In this context, Melgarejo et al. in [210] have demonstrated enhanced reliability and capacity with RIS-aided GF access compared with the performance of traditional GF access methods, alongside a simplified Rx complexity and enhanced RR utilization by necessitating fewer slots for UE retransmissions.

Even though the aforementioned advantages of RIS technology promise better control over the U-OUI, it also has some drawbacks. Further studies to mature its interaction with wireless technologies are needed. This involves experimentation and validation of RIS performance outside of simulation environments, within a real environment. In addition, these surfaces pose some significant limitations as they are mostly passive. It is a challenge to perform channel estimation and we need more efficient signal processing algorithms, which are critical for the arrangement of RIS devices towards the intended UE's demands and requirements [211]. In RIS technology, CCI and erroneous CSI have become a major concern in different scenarios, leading to both U-SUI and U-OUI. CCI emerges as an undesirable phenomenon stemming from the extensive reuse of frequency channels with high spectrum utilization in emerging wireless networks. CCI significantly impairs the quality of the intended UE, underscoring the significance of assessing its effects [212]. As it is impractical for RIS to entirely eradicate phase errors in real-world scenarios, solutions against potential interference need to be taken into account too [213]. Moreover, the locations of the RIS-based intelligent walls cannot be changed dynamically, which further limits a continuous observation of the environment to relax U-OUI.

Remark 5: RIS functions by redirecting incoming signals towards their desired destination, to enhance SINR by circumventing obstacles and obstructions between Tx and Rx. Leveraging their distinct ability to manipulate the wireless propagation environment, RIS-based technologies offer a compelling and cost-effective approach to control channel based interference types, such as CCI, ISI and ICI. In addition, RIS can also bolster high wireless channel capacity, thereby extending signal coverage effectively and reducing the size and the high demand for energy usage in multi-antenna networks. However, given the impracticality of RIS fully eliminating imperfect CSI in real-world environments, U-SUI and U-OUI still pose a potential threat to the intended UE.

B. Unmanned Aerial Vehicle

Despite all of the potential of RIS technology to control the wireless channel, and thus, the associated interference types such as ICI, ISI, CCI, etc., there still exist some challenges regarding the deployment of these solutions. Differently, UAV-based systems have been predicted dramatically to relax the shortcomings in dense networks and harsh environments by benefiting from promising features of high LoS link probability. Thus, the UAV-based technology offers more deterministic features for CCI than the conventional cellular deployments and inherently can enhance the coverage range [214]. On the one hand, the high probability of LoS presence leads toward wireless channels with dominant large-scale characteristics. Thus, exploitation of the time and frequency selectivity features of the wireless channel protects conventional wireless technologies, i.e., 4G LTE, 5G NR, and WiFi from various interference types such as ISI or ICI. On the other hand, due to the LoS propagation characteristics of UAV-based communication links in the air, the CCI interference problem gets more severe [215]. Motivated by this, Kim et al. have discussed spatial separation as a possible solution in order to minimize the effect of CCI with the aid of directional beamforming in [216]. Following so, from a broader network perspective, authors of [190] have proposed a distributed algorithm to maximize the signal-to-interference ratio (SIR) of the system based on the position of UAVs via message exchange between the adjacent UAVs. Hence, the feasibility of these schemes needs a central network used to coordinate neighbor UAVs, with accurate information on the position of intended UAVs, which represents a challenge for OFDM-based due to the severe Doppler effect leading to U-SUI and U-OUI.

Fading characteristics of the effective channel depend not only on the wireless channel but also on the UE-specific beamforming, strongly supported in 5G-NR MIMO systems [217]. In [218], Kim and Lee advocated that the optimal UAV height increases as the signal strength of interference decreases. Moreover, authors mathematically prove that in case interference dominates the desired signal power, UAVs operating in an NLoS environment offer better link reliability. The authors examined a transmission approach utilizing TDMA for both uplink and downlink scenarios to optimize the data rate between the BS and intended UE via the deployment of multiple UAV-based relaying. A joint optimal strategy encompassing 3D track design and power allocation to maximize the network's throughput while adhering to interference restrictions. In [219], Alzubaidi et al. have introduced a side-lobe mitigation strategy that is suitable for collaboration beamforming in 3D-UAV wireless systems with the aid of the gravitational search scheme (GSS). This scheme reduces not only CCI but also enhances coverage capacity. Simulation results indicate that the proposed approach surpasses the peak side-lobe mitigation strategy in terms of total side-lobe level and performance capacity. However, the capabilities of 5G-NR massive MIMO and the practical implementation of these interference management schemes may be constrained by the substantial side-lobe U-OUI, CCI that arises from a large number of antennas and corresponding generated beams. In [191], Rahmati et al. have proposed a more comprehensive approach to control I-OUI at the legitimate UE with the aid of a 3D trajectory design. Different from trying to control this domain CCI in UAV-based systems via orthogonal-based coordination approaches, the NOMA scheme has been recently proposed for UEs connected to UAV-based BS. Thus, the high probability of LoS presence between the UAV BS and the UEs enhances the chances of power-domain multi-UE separability [192]. For instance, Sohail et al. have proposed a UAV and NOMA-centered technique to optimize both altitude and power allocation, respectively, for maximizing the overall sum-rate in case of a two UE scenario in [220]. UAVs may operate at considerable distances, so coordination between UAV-based NOMA systems must account for the T_c of the wireless channel to ensure a reliable link. In addition to attitude, Nasir et al. have investigated antenna beamwidth, power allocation, and bandwidth allocation to optimize the overall sum rate of the system in [221].

In accordance with the above discussion, there is a need for new protocols, because the number of UAVs, height, number of UEs, and power constraints may limit their ability to communicate, compute, and endure in UAV-based wireless networks. In addition, new interference management scheme needs to be drawn by taking into account small-scale features of the wireless channel, and thus, mitigate interference types such as ICI and ISI. Despite providing people with safety and convenience, UAVs are increasingly being used for illegal activities and crimes. Hence, the military also grapples with the threat posed by foreign military UAVs, underscoring the growing importance of UAV identification technology where interference characteristics play a crucial impact [222].

Remark 6: In UAV-based technologies, high LoS link probability relaxes time and frequency selectivity features of the wireless channel that works as a safeguard for traditional wireless technologies against diverse interference types like ISI and ICI. LoS propagation characteristics of UAV-based communication links intensify the challenge against CCI. It is worth noting that research on UAV-based networks primarily revolves around two key directions: investigating interference stemming from UAV networks and leveraging UAVs for interference management. Key management techniques include directional beamforming, adaptive positioning of UAVs relative to neighboring UAVs, power allocation strategies, and NOMA.

C. Orthogonal Time Frequency Space

In spite of the two most promising technologies based on RIS and UAVs aiming to manipulate the fading features of the wireless channel, it is still not possible to control the characteristics of frequency and time selectivity in a comprehensive manner. The fading characteristics of the environment depend not only on the number of reflectors but also on the transmission features of the propagating signal. Thus, this keeps U-SUI as a concern for seamless and ubiquitous connectivity. In addition, this becomes more severe with the wide range of emerging high-speed services and use-cases in beyond 5G systems [223]. Consequently, designing proper transceiver architectures that deal with small-scale fading limitations of wireless channels has become a challenging task. In this line, an extensive effort from both academia and industry has been put through in order to control and mitigate the impact of doubly dispersive wireless channels on the link reliability via the novel waveform named OTFS, as introduced in [17].

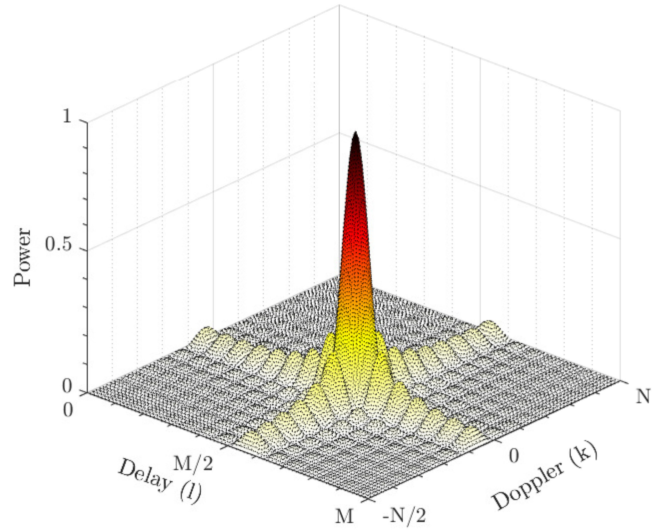
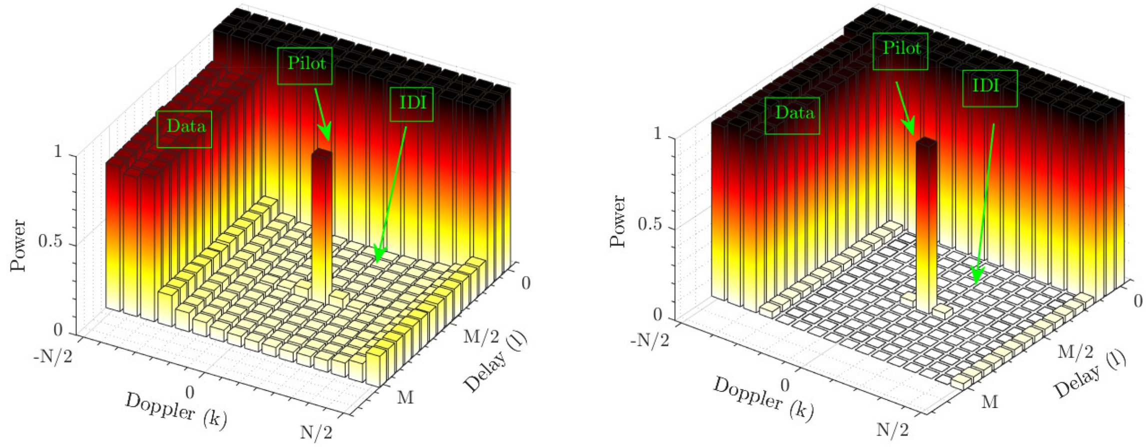


Fig. 14. OTFS carrier in the delay-Doppler domain.

In contrast to classical communication technologies where data information is conveyed by time, frequency, code, and IM domain signals, OTFS utilizes a two-dimensional modulation plane in the delay-Doppler domain for data communication [17]. Basically, data symbols carried via OTFS pulses are spread over both time and frequency domains, while in classical schemes information is spread in either time or frequency domain, as illustrated in Fig. 14. Consequently, OTFS can explore time-frequency domains in contrary to TDM and OFDM architectures that can only explore time and frequency richness of the received signal, respectively [224], [225], [226]. Hence, the delay-Doppler plane achieves a comprehensive representation of delay and Doppler shifts of the channel paths represented via a sparse channel model in accordance with the bandwidth and duration of the signal of interest [227]. When compared to either time or frequency CSI, which exists between Tx and Rx, it provides a more comprehensive description of environmental motion, reflective objects, and AoA [228], [229]. In other words, under frequency selectivity CSI losses its time domain sparsity leading to a severe U-SUI in the form of ISI, while under time selectivity CSI losses its frequency domain sparsity causing ICI. Since performing communication in the delay-Doppler domain prevents wireless channel dispersion, it protects from undesired ICI and ISI interference types at the cost of higher computational complexity at the Rx side. Therefore, in [230], Farhang et al. have proposed the OFDM-based OTFS concept in order to ensure the compatibility of OTFS scheme with the conventional OFDM-based technologies. Moreover, Raviteja et al. have introduced a global CP OTFS scheme emphasizing practical rectangular pulse shaping, which is known as common CP in 5G wireless technologies [193].

Motivated by the resilience of OTFS-based technologies against U-SUI, the delay-Doppler domain has been considered as a potential way for multiple accessing, as in [231], where



(a) Impact of IDI in conventional OTFS frame. (b) IDI suppression for OTFS frame with Rx windowing.

Fig. 15. Received OTFS frame under the presence of fractional Doppler.

different UEs are associated with distinct delay-Doppler RRs. It is worth mentioning that delay and Doppler RR grids are inversely proportional related to pulse symbol duration T_s and SCS $\Delta\hat{f} = \frac{1}{\mathrm{T}_s}$, respectively. Hence, OTFS transmission can offer a different perspective for treating the INI, which has become a bottleneck for the 5G-NR technology [232]. Different from aiming to avoid INI via proper guard band or spectrum allocation, as in [233], [234], the delay-Doppler grid can help with INI estimation and compensation, too. In addition, novel guard band and spectrum assignment schemes can be explored in order to mitigate and control INI in the delay-Doppler domain or other types of U-OUI. For instance, Mary et al. have introduced various UE multiplexing techniques such as the non-continuous method and interleaved method while keeping into consideration UEs' demands [235]. OTFS has been recognized as a promising waveform for JRC and high mobility wireless networks, and has been incorporated into the discussions of the 3GPP meetings [236].

In addition to its potential advantages, the OTFS scheme as a new waveform has brought new challenges for practical consideration from an interference perspective. The advantage of significantly enhancing of channel sparsity in the delay-Doppler domain depends not only on the 2-D structure of OTFS waveform but also on the time and frequency resolution capabilities of the desired signal [237]. If the time and frequency resolution of the desired signal is not inversely proportional to the Doppler and delay indices of the wireless channel, which causes loss of channel sparsity, leads to severe ICI in the delay-Doppler domain. The type of ICI in the delay-Doppler domain is known as IDI [238], where infeasible complex Rx designs become a prerequisite for OTFS-based transmission. IDI within the information symbols, and between information symbols and pilot destroys the link reliability, as shown in Fig. 15. Hence, in [239], Li et al. have discussed jointly performing cross-domain iterative detection and estimation in the time-frequency domain at the cost of moderate Rx complexity. Similarly, Wei et al. have proposed to perform time-frequency domain-based Tx and Rx windowing with the aid of either mercury/water-filling power allocation scheme or Dolph-Chebyshev window technique in order to enhance channel sparsity, and so, reduce IDI [240]. However, prior information on CSI between Tx and Rx is a prerequisite for proper window design, thus, increasing operation latency and system complexity, while performing bisection search. In [241], Qu et al. have introduced a new Rx technique, aiming to jointly perform both symbol detection and IDI mitigation while leveraging the sparsity of the wireless channel in an iterative manner. In addition to the system complexity and time inefficiency associated with iterative detection, the use of channel sparsity as prior information to mitigate IDI, which negatively impacts channel sparsity, may raise new challenges for proper signal detection. Differently, in [194], Tusha and Arslan have proposed raised cosine Rx windowing to mitigate and control the effect of OTFS carrier's side lobes, as shown in Fig. 15(c). Consequently, the impact of IDI on both symbols of information and pilot region is significantly suppressed. In line with the fact that carrier duration determines the Doppler characteristics of the wireless channel, authors perform global Rx windowing over the OTFS frame in the time domain that is followed by only the classical OTFS detector. Finding lightweight approaches for ICI type of IDI has become an imperative need to make feasible integration of OTFS with the current wireless technologies. Moreover, despite OTFS demonstrates superior performance compared to OFDM in time-selective channels, it lacks its own orthogonal transmission pulse in the delay-Doppler domain [242]. Hence, in [243], Lin and Yuan have proposed orthogonal delay-Doppler division multiplexing (ODDM) multi-carrier scheme with realizable pulse shapes, and orthogonal with respect to DD plane's resolution. In this line, ODDM exhibits superior performance compared to OTFS in terms of both OOBE and BER. In addition, in [244], Hunag et al. have assessed the importance of interference via SIC with minimum mean square error (MMSE) that surpasses the performance of the message passing algorithm detector for ODDM in scenarios with imperfect CSI. Likewise, in [245], Li et al. introduce a

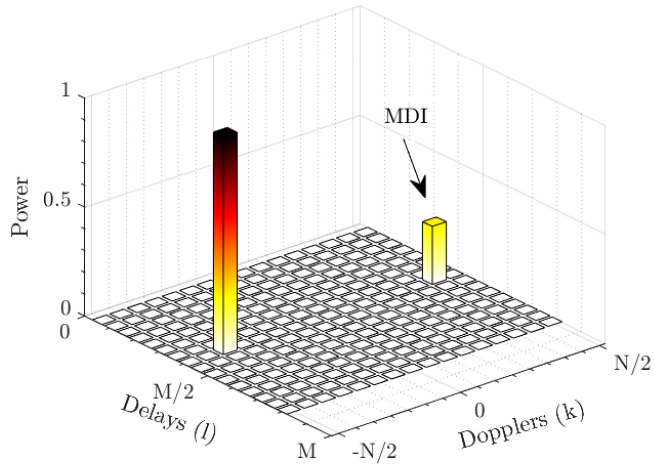


Fig. 16. MDI in delay-Doppler domain caused by Tx IQ imbalance.

novel low-complexity SIC-MMSE detector that outperforms conventional Rx for OTFS scheme.

Similar to any transmission scheme, it is crucial to examine the potential emergence of interference types caused by practical RF impairments in the OTFS scheme as well. In [246], Tusha et al. have found the presence of Tx IQI leads to mirror Doppler interference (MDI) in the delay-Doppler domain, as shown in Fig. 16. Consequently, authors have proposed an energy and spectral-efficient IQI mitigator with the aid of IM in [247]. Moreover, in [248], Tusha et al. have proven that practical IQI does not saturate the error performance of OTFS transmission as in the case of classical OFDM scheme, but only deteriorates the channel diversity gain. In [249], Surabhi et al. have assessed the effect of PAPR on OTFS signal, where different from conventional OFDM, PAPR increases linearly with Doppler indices and not the number of subcarriers. Doppler features of time domain OTFS signal operate in a global manner, and thus, determine the signal peaks. To reduce the PAPR, various companding schemes have been investigated at the expense of link reliability loss, in [250]. In [251], Liu et al. have utilized autoencoder, which is a deep-learning neural network architecture, to suppress PAPR while minimizing the BER loss. This technique performs encoding to offer a low-dimensional representation and the decoder is to reconstruct the desired OTFS signal while minimizing ICI caused by PAPR in the delay-Doppler domain. Moreover, in [252], Sümer et al. have exploited the OTFS signal frame structure by dividing it into subblocks, where a complex constant is found via convex optimization to reduce the PAPR within each subblock, and so, this constant is estimated and removed at the Rx side, while maintaining the link reliability with the conventional OTFS scheme. Differently, in [253], Gao and Zheng have proposed to facilitate from the guard region around the carrier pilot in the delay-Doppler domain and introduce filtered dither signals to not only mitigate PAPR and its potential U-SUI ICI but also to reduce IDI between data and pilot due to the channel at the Rx side. In other words, intelligent interference has been introduced to control both PAPR and overall interference within the OTFS signal. In addition, Francis et al. have performed IM alongside Doppler to enhance the diversity order of OTFS but also reduce PAPR, in [254]. Last but not least, in [255], Surabhi et al. have investigated the performance of OTFS under PN impairment at a carrier frequency of 28 GHz, while simulation results show that OTFS is resilient against PN effects under different Doppler shifts. Hence, OTFS can be considered as a potential technique in future radio frequencies such as mmWave and Terahertz communication. Moreover, Neelam and Sahu have assessed the performance of OTFS under several RF impairments jointly, and they have shown that an increase in pilot power, number of Doppler bins, and presence of windowing schemes enhance the interference immunity, in [256].

Remark 7: The OTFS pulse induces a fast-varying wireless channel to behave as a slow-varying channel, enabling the utilization of both time and frequency richness of the CSI with the received signal in the delay-Doppler domain while rejecting various U-SUI types, i.e., ISI, ISI and ICI. In addition, OTFS posses advantages on dealing against INI, while suffering from IDI and inter-delay interference.

D. Index Modulation

Further investigation and evaluation is required from both academia and industry to assess the integration of emerging technologies, such as RIS or UAV, and the design of advanced waveforms like OTFS. However, considering the existing wireless deployment and aiming to provide robustness against different interference types, the introduction of a complementary scheme with minor modifications can be considered. The application of IM in various domains has provided an attractive trade-off between SE, EE, transceiver complexity, transmission reliability, and most importantly interference immunity. As a result, the adoption of IM has created new opportunities for research in 5G and upcoming wireless systems [67]. For example, due to the integration of IM in the spatial domain SM and activation of a single antenna, the multiple antenna system becomes free of IAI, at the cost of moderate SE, in [74]. Similarly, in [257], Younis et al. have proposed general SM via activating a group of antennas simultaneously and emitting the same data signal, leading to zero IAI.

Basar et al. have shown that frequency domain IM not only is robust against ICI caused by frequency selective channel but can minimize the PAPR impact in OFDM signal due to fractional activation of subcarriers [75]. Tusha et al. have discussed that the level of sparseness in signal design directly affects the impact of I-SUI ICI in IM-based OFDM signal as in [258]. Moreover, the same authors have proposed a novel IQI estimation and compensation scheme by utilizing the sparse features of IM concept in the frequency domain in [195], as shown in Fig. 17. The system parameters used for the simulations consist of N = 256 subcarriers, L = 10 channel taps with CP =16, where each OFDM-IM subblock activates a = 3 out of b = 8 subcarriers per transmission. CRC-ψ represents the cyclic redundancy check technique with ψ-bits. Benchmark is the performance of OFDM-IM for ideal transceiver, i.e., zero IQI ($\epsilon = 0$, $\Delta\phi = 0^o$). Results show that almost perfect mitigation of IQI is achieved even under

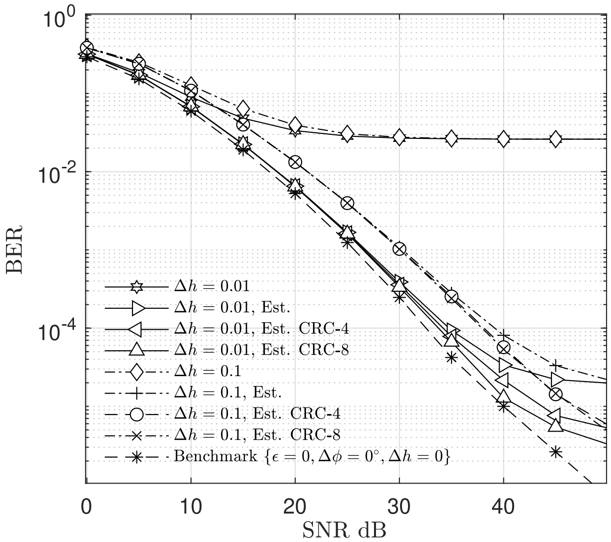


Fig. 17. BER versus SNR performance for OFDM-IM with activation ration (b=8, a=3) and IQ imbalance ($\epsilon = 0.1$, $\Delta\phi = 5°$).

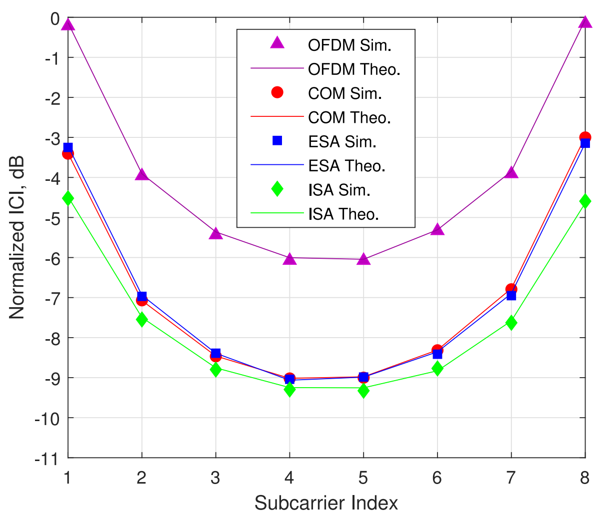
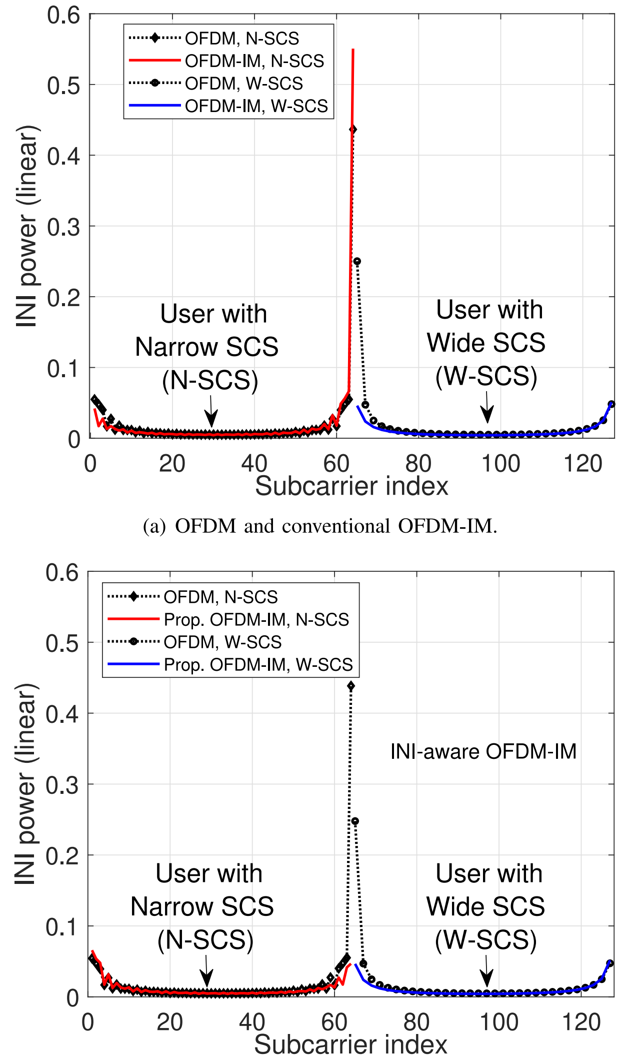


Fig. 18. ACI analysis of various subcarrier mapping schemes in frequency domain under multi-user asynchronous transmission [75], [259].



(a) OFDM and conventional OFDM-IM.

(b) OFDM and INI-aware OFDM-IM.

Fig. 19. INI analysis in OFDM and OFDM-IM systems with conventional and INI-aware subcarrier utilization scheme.

the presence of channel estimation errors Δh in practical scenarios, at a moderate cost of Rx complexity and SE loss which is not possible for OFDM-based technologies.

Dogan et al. have proposed a novel subcarrier mapping technique with high usage probability for the inner subcarrier activation (ISA), and thus alleviates U-OUI of ACI type interference [273]. Fig. 18 assesses ACI of OFDM, combinatorial (COM) OFDM-IM, equal subcarrier activation (ESA) OFDM-IM and ISA OFDM-IM via both theory and simulations, with b = 8 and a = 4. By giving higher activation probability to inner subcarriers limits OOBE, since the majority of OOBSE contribution comes from the edge subcarriers. Therefore, IM mitigates ICI and functions as a windowing or filtering scheme that mitigates OOBE in the frequency domain. Moreover, in [274], the same authors have shown that the INI strength in OFDM-IM systems is highly dependent not only on the number of active subcarriers but also on their position in an OFDM block. Mitigation of U-OUI INI between UE with narrow SCS (N-SCS) and wide SCS (W-SCS) is given in Fig. 19(d), while the ratio of $\Delta\hat{f}$ between the two UEs is 2. Fig. 19 shows the INI level of OFDM compared to conventional OFDM-IM. It shows that N-SCS OFDM-IM has a higher INI level than OFDM, while W-SCS OFDM-IM exhibits a lower INI level. Fig. 19(c) tells that proper subcarrier activation translates into power control for OOBE, allowing to close the gap of INI level difference between W-SCS and N-SCS, and outperforming OFDM. Further suppression of OOBE can be achieved by combining subcarrier activation schemes with windowing and filtering.

Different from the frequency application of IM, time domain IM needs further exploitation as a potential ISI mitigation scheme [77]. Moreover, joined exploitation of IM sparsity in time and frequency helps with a simultaneous mitigation of ISI and ICI, as in [275]. In this line, the advantages of IM in space domain can be used to control and mitigate CCI

TABLE X
INTERFERENCE MANAGEMENT OPPORTUNITIES AND RELATED CHALLENGES VIA NOORMA TECHNIQUES

NOOrMA Schemes	Ref.	Opportunities	Open Issues	Performance Metrics					
				1	2	3	4	5	6
PD-Separability	[59], [260], [31]	Use of simple RF chain at Tx/Rx, ACI free, mitigate CCI and IAI, exploits multi-UE channel gain.	UE selection at Tx and SIC Rx complexity increase with the number of UEs. Error propagation at SIC may limit the data rate.	↑	↑	↑	↑	↓	↓
CD-Separability	[261], [262], [263]	Simple RF chain at Tx/Rx, limited ACI, IAI, and CCI. Exploit multi-UE detection.	Multi-UE detector's complexity increase with the number of UEs. Error propagation at Rx is high because of UE channel gain variations.	↑	↑	↑	↑	↓	↑
ID-Separability	[264], [265], [266]	Immunity against ICI, CCI, and IAI owing to sparse signal representation. It exploits multi-UE channel diversity.	Logarithmic increase on SE with the number of transmission indices. It may require the integration of multiple RF chains at the Tx/Rx side, leading to IAI. Rx feasibility is limited to a low UE number.	↑	↓	↑	↑	↓	↓
RS-Separability	[267], [268], [269]	A moderate number of antennas is used to exploit spatial selectivity. Rx relays not only on the SIC technique, so it is CCI immune.	System capacity is limited by Rx multi-UE separability, latency, and power consumption. Spatial utilization exposes RSMA to potential IAI and CCI.	↑	↑	↑	↑	↓	↓
WD-Separability	[270], [271]. [272]	Simply can be applied to any single-input single-output system. Its diverse architecture allows resilience against a wide range of interference sources.	Proper Tx and Rx designs need to be developed for a wider range of applications and use-cases.	↑	↑	↓	↑	↑	↑

Performance Metrics - 1: Interference Immunity, 2: SE, 3: Computational Complexity, 4: Multiplexing Gain, 5: EE, and 6: Compatibility.
Sign - ↑: High ↓: Low

between adjacent cells and control IAI in case of UE-specific beamforming in MIMO systems [276]. Despite the inherent interference immunity of IM-based transmission schemes, it is characterized by a limited SE in the case of high-order modulation compared to conventional communication schemes. In near future communication systems aiming to achieve higher data rates over higher frequency bands, the need for higher SINR poses a challenge in terms of hardware limitations and impairments, which can be managed by sparse signal designs.

Remark 8: IM-based technologies allow communication over a sparse number of RRs, offering the opportunity to manipulate, avoid, estimate, and develop new exploitative techniques against conventional interference types such as ISI, ICI, INI, and CCI. Moreover, IM-based schemes can inherently benefit from the selectivity features of the wireless channel.

VI. POTENTIALS AND LIMITATIONS OF NON-ORTHOGONAL & OVERLAPPED MULTIPLE ACCESSING

Given the challenging nature of unpredictable interference types originating from I-OUI and U-OUI, it has emerged as a bottleneck for multiple accessing schemes. To exploit and mitigate this issue, the introduction of identifiable signal-related features can enhance the resilience of the UE of interest. Consequently, the literature has seen the proposal of a broad range of NOOrMA-based solutions, which are summarized in Table X.

A. Power-Domain Separability

Power-domain NOMA is a critical concept within NOOrMA, where multiple UEs are fully overlapped over the RRs, firstly inspired by Saito et al. [60]. It started from a basic multi-UE information-theoretic perspective to enhance the SE of the wireless system. Each specific UE is assigned a distinct power allocation factor and multiple UEs emit their signals over the same RRs. Therefore, these UEs engage in fully overlapped NOMA, which can expose the wireless system to low interference immunity. To address this concern, the power factor for each UE is allocated based on the channel conditions of all existing UEs, thus optimizing the overall performance. For instance, a two UE scenario is illustrated in Fig. 20, where a high power level denoted by α_2 is assigned to the UE with poor channel conditions $|h_2|$, while UE exposed to good channel conditions $|h_1|$ utilizes less power α_1. In [59], it is shown that at least 30% capacity enhancement is achieved by proper power multiplexing in NOMA. Moreover, Timotheou and Krikidis [260] show that NOMA can provide better fairness via proper power allocation and provides a higher system achievable rate compared to classical U-OUI/I-OUI free TDMA or OFDMA schemes. As a result, treating interference as a desired signal not only can relax the U-OUI problem but also boosts system capacity while keeping an appreciable UE fairness. By leveraging the power domain separability, the approach of treating interference as a desired signal not only addresses the U-OUI problem but also improves system capacity, all while ensuring a satisfactory level of fairness among UEs.

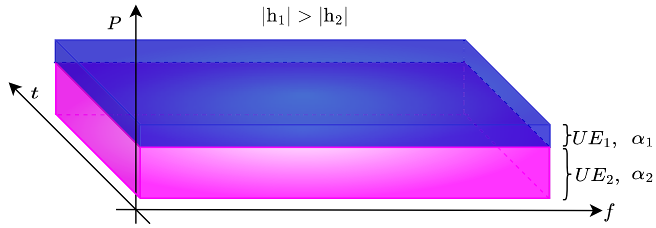


Fig. 20. Exploiting power-domain separability against U-OUI.

On the Rx side, the SIC scheme is used to mitigate interference by exploiting the power difference of UEs and to perform demultiplexing [31]. First, the strong UE is detected by treating the weak UE as noise. After the correct detection of the strong UE, it is removed from the multiplexed signal to detect the data of weak UEs. In the case of multiple UEs, the same process is followed until only the weakest UE is left and the weakest UE decodes its data without interference. Although the SIC process with a few layers seems to be feasible in practice, the complexity and probability of error propagation rapidly increase when the number of UEs is high [61]. Unfortunately, a significant decay of the performance gain is experienced due to SIC error propagation, while UE multiplexing in equal power, i.e., $\alpha_1 \simeq \alpha_2$ scenarios, leading to a sever I-OUI. Therefore, it is necessary to find ways how to reduce the number of SIC layers at each UE and so mitigate I-OUI. Using a SIC-based Rx could be applied to groups of UEs with disparate channels and groups scheduled on orthogonal resources such as beamforming-based NOMA. In [277], an additional clustering and power allocation algorithm is proposed to mitigate I-OUI and enhance the overall sum capacity. This clustering algorithm selects two UEs based on high correlation and a significant gain difference in their channels, effectively reducing interference from other beams, i.e., CCI with respect to other UE, i.e., I-OUI. Similarly, in a two-UE MIMO NOMA, Sun et al. have introduced two power allocation algorithms while utilizing the power domain alongside the spatial diversity [278]. Similarly, Şahin et al. have shown that partial overlapping is a key factor in achieving successful power-domain separability between adjacent UEs [279]. A controlled amount of I-OUI is needed to allow multiple access to various UEs while completing their demands. Moreover, in [280], Lopez-Perez have proposed that via proper power allocation and SIC design at partially overlapped neighboring cell UEs exposed to CCI, it is possible to manage I-OUI CCI within the wireless network at a moderate increase of Rx complexity.

Referring to the above discussion, these algorithms aim to maximize the sum capacity while considering both a total power constraint and meeting the minimum rate requirement for the weaker UE. However, UE grouping can negatively impact link reliability since it shrinks the overall optimization space [133]. Moreover, while performing multi-UE separability via the power domain the SIC Rx becomes challenging with the presence of other potential interference sources which are inevitable for practical wireless systems. Hence, in [281], Chatterjee et al. have proposed power-domain separability in the delay-Doppler domain with relaxed potential ISI and ICI for high mobility UEs.

B. Code-Domain Separability

Motivated by the key idea of CDMA where multiple UEs can share the same RRs via the assignment of specific pseudo-random codes, which are known as signature waveforms, the development of new pseudo-random codes, which expose the intended UE to I-OUI, is developed in the literature. In order to reduce I-OUI, low-density spreading sequences are integrated into the CDMA system and named LDS-CDMA [261]. In LDS-CDMA, each transmitted data symbol by reference UE is spread only over a limited number of resources which means only a few users are exposed to interference coming from reference signal [282]. The sparse structure that characterizes LDS-CDMA helps to improve the robustness of the Rx compared with the classical CDMA systems. On the Rx side, multi-UE detection is performed via message passing algorithm (MPA) [282]. Different from CDMA-based systems, maximum a posteriori (MAP) detector is not necessary. Hence, the implementation of LDS-CDMA with MPA becomes more feasible for practical scenarios. In this way, Hoshyar et al. [262] combined LDS with the classical OFDM as a multiple accessing technique named LDS-OFDM. In LDS-OFDM, multi-UE access is assessed via LDS method, which spreads symbols in the frequency domain. The proposed LDS-OFDM outperforms the conventional OFDM in terms of error performance over a typical multi-path Rayleigh channel due to the inherent frequency diversity gain of LDS technique. MPA Rx is also used for LDS-OFDM. Yuan et al. [283] proposed a new type of spread-sequence-based multiple accessing scheme named multi-UE shared access (MUSA). It spreads the modulated M-ary data symbols of the corresponding UE via some specially designed spreading sequences that make feasible multi-UE detection with SIC implementation, which cannot be facilitated in conventional CDMA-based schemes. Sparse code multiple accessing (SCMA) is presented as a continuation of the LDS-OFDM scheme [263]. Different from LDS-OFDM, the procedure of symbol mapping and spreading are combined together in SCMA, and data bits are directly mapped to different multi-dimensional codewords. Moreover, the use of a multi-dimensional constellation concept to generate codebooks in SCMA leads to extra shaping gain with performance improvement compared to the LDS scheme with fixed M-ary symbol [284]. Recently, SCMA has been combined with the OTFS scheme to facilitate from low-varying characteristics of wireless channels in the delay-Doppler domain, as in [285].

C. Index-Domain Separability

Drawing inspiration from the inherent interference immune features of IM schemes, researchers have proposed integrating the IM concept as a NOOrMA scheme in various studies. One example is the OFDM-IM-based uplink multiple accessing (IMMA) scheme proposed by Lai et al., in [264]. OFDM block is divided into subblocks where more than one user simultaneously performs their transmission over the allocated RRs. It

TABLE XI
WAVEFORM DOMAIN WD-NOMA FOR VARIOUS UE DEMANDS

Ref.	Waveform Pairs		Transmission	Separability	UE	Performance Metrics			
	Waveform 1	Waveform 2	Domain	Metric	App./Demand	1	2	3	4
[286]	TDM	OFDM/CDM	Time, Freq., Code	Partial-Overlapping	HetNet	↓	↓	↑	↑
[270]	OFDM (SCS=$\Delta\hat{f}$)	OFDM (SCS=$2\Delta\hat{f}$)	Time, Freq.	Partial-Overlapping, SIC	URLLC	↑	↑	↓	↑
[271]	OFDM	OFDM-IM	Freq., IM	NB-DI	URLLC	↑	↑	↓	↑
[287]	OFDM	OFDM-IM	Freq., IM	NB-DI, SIC	URLLC, mMTC	↑	↑	↑	↑
[272]	OTFS	OFDM	delay-Doppler, Freq.	NB-DI	High-mobility scenarios	↑	↑	↓	↑

Performance Metrics - 1: Interference Immunity, 2: SE, 3: Computational Complexity, and 4: Compatibility.
Sign - ↑: High ↓: Low

is shown that IMMA outperforms OFDMA in terms of error performance due to higher exploitation of channel diversity. Notably, IMMA exhibits a sparse signal structure that provides immunity against interference. Furthermore, Althunibat et al. in [288] have proven that IMMA can triple the system capacity of OFDMA without compromising communication reliability at the cost of increased Rx complexity. In [265], authors also have combined IM with TDM that corresponds to time-domain IMMA. This multiple accessing scheme utilizes time slots to carry IM data bits, where multiple UEs compete for RRs to perform their transmission, and thus generate a severe I-OUI. In this line, a conventional maximum likelihood detector is used in IMMA in order to separate multiple UEs with I-OUI. To achieve diversity, quadrature IMMA (QIMMA) is introduced in [289]. Despite the advantage of IM-based NOOrMA schemes, utilization of the maximum likelihood decoder on the Rx side limits its feasibility for practical wireless systems with stringent latency and time constraints. Consequently, in order to accommodate maximum likelihood-based detectors, the number of UEs in IMMA needs to be kept low. Furthermore, as the number of UEs operating over the same RRs increases in the IMMA signal scheme, the sparsity of the signal decreases, correct estimation of channel state information because curtail and the possibility of error prorogation increases for multi-UE detection. This reduction in sparsity leads to a decrease in immunity against interference due to RF limitations or wireless channels such as ISI, ICI, and INI. Hence, in [290], Alaca et al. not only have investigated the effect of IQI in IMMA but also have proposed a preamble-based evaluation and compensation method to mitigate IQI interference emerging in a type of U-OUI. In this context, it is essential to investigate the development of decoder architectures that are simpler in terms of complexity, yet capable of preserving the interference immune characteristics of IM-based multiple-access schemes across a broader range of potential interference sources [291]. Furthermore, there is potential for exploring additional transmission domains, such as the spatial domain, to uncover new opportunities, as demonstrated in [266], or delay-Doppler domain as in [292]. The IM design parameters, i.e., activation configuration (b, a), are assigned not only considering the amount of I-OUI but also concerning the capability of benefiting from multi-UE diversity, where the features of wireless channel vary from one UE to another UE, that is different in time, frequency, space or delay-Doppler domain.

D. Rate-Splitting Multiple Accessing (RSMA)

In an effort to overcome the limitations of current multiple accessing schemes, a novel transmission strategy named RSMA which relies on the concept of rate-splitting has been developed and has shown to be compatible with several existing schemes [267]. Technically speaking, splitting multiple UE messages into parts is the basis of RSMA's interference management strategy against I-OUI. At the Tx side, superposition coding is used to encode the split parts, while performing SIC to decode the split parts at Rx side [268]. Hence, RSMA basically represents a NOOrMA scheme. Different from NOMA-based methods mentioned above, RSMA separates the transmitted message parts not only by power as in NOMA, but also via spatial domain as in SDMA, and thus, it manages the I-OUI by adjusting the message splitting and power level simultaneously. Consequently, RSMA approach is able to exploit not only time, frequency, and power resources, but also the spacial domain, too, resulting in a higher degree of freedom and better link reliability [269]. Basically, rate-splitting is an effective interference-management technique that can encompass a range of schemes and technologies, including treating interference as noise, NOMA techniques, SDMA, multicasting, broadcasting, and more. On the other hand, extensive research from both academia and industry is needed to investigate and assess the robustness of the RSMA scheme in performing multi-UE separability, while it is exposed to severe interference sources, such as PN, IQI, and IAI, which directly affects the performance of SDMA-based techniques.

E. Waveform-Domain Separability

Driven by the concept of the waveform design for controlling CCI, hybrid waveform characteristics have been introduced in literature as a means to enable the separation of UEs under NOOrMA. In other words, multi-UE separation is achieved after dealing with the IWI type, while serving a wide range of wireless applications, as briefly given in Table XI.

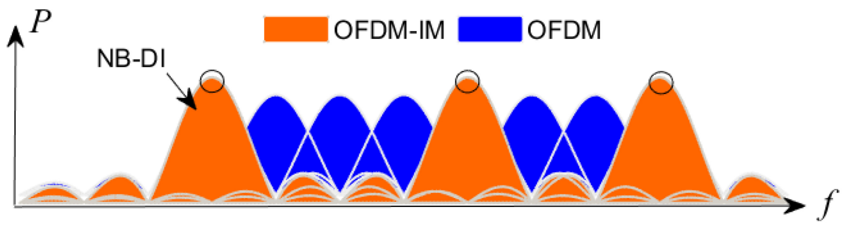


Fig. 21. WD-NOMA via OFDM and OFDM-IM.

For instance, Sari et al. [286] have proposed multiple accessing of UEs in NOOrMA manner via two orthogonal waveforms, which are CDMA and TDMA, for HetNet in time domain. In case there is a single UE utilizing TDMA and being assigned the first time slot in each frame, this TDMA UE introduces I-OUI IWI to the first chip of all CDMA UE symbols with chip period T_s, while the remaining chip periods remain free of interference. Hence, a partial overlapping that enables controllable interference among the UEs is achieved. The intensity of SIR introduced by either UE is critical for performing successful UE detection, which negatively can impact the overall interference immunity and SE of HetNet. Similarly, in [270], the idea of NOMA is investigated under multi-numerology OFDM, from the frequency domain perspective. A new Rx that depends not only on power differences among the power domain multiplexed UEs but also on the used numerology is developed. The I-OUI INI between UEs with different numerologies gets sparse and dominant with the increase in the SCS ratio, i.e., $\Delta\hat{f}_1/\Delta\hat{f}_2$. Hence, utilization of SIC can facilitate interference detection and cancellation, leading toward enhanced system capacity and SE at the cost of computational complexity. Dogan et al. have proposed the sharing of resources between OFDM and OFDM-IM, and thus benefit from the sparse structure of IM-based signals, in [271]. Inherent partial subcarrier activation in OFDM-IM significantly reduces the IWI between the co-channel UEs, while generating a narrow-band and dominant interference (NB-DI) structure, and thus improving interference immunity and SE, as shown in Fig. 21. In this study, the use of a SIC decoder is unnecessary as both the UE employing OFDM transmission and the UE employing OFDM-IM transmission can independently recover the transmitted data via conventional Rx designs, offering potential compatibility and minor computational complexity. In addition, in [287], the same authors show that OFDM-based WD-NOMA with SIC decoder named IM-NOMA outperforms the classical OFDM-based NOMA in terms of both link reliability and achievable sum rate at the cost of moderate system complexity. Furthermore, this scheme exhibits robustness against potential catastrophic error performance when similar power allocations are assigned to the co-channel UEs. In other words, the share of RRs between OFDM and OFDM-IM is always characterized by an inherent power difference between the signals due to the power localization features of the IM concept. This power difference ensures the performance consistency of the SIC Rx. As discussed above, IM-based WD-NOMA offers advantages against other intentional and unintentional interference sources.

Essentially, the novelty of NOMA lies in the opportunistic allocation of transmit power to different UEs based on their respective channel strength $|\mathrm{h}[n]|$ conditions. This means that UEs with poorer channel conditions $|\mathrm{h}[n]|$ are allocated more transmission power and vice versa. Not only channel strength conditions but also time and frequency selectivity characterizing the channel, which is a major source of U-SUI, represent a solid key performance indicator [293]. With this motivation, OTFS signaling is considered a potential solution not only against U-SUI and U-OUI scenarios but also against I-OUI. For instance, Ding et al. have proposed an OTFS-based WD-NOMA scheme that multiplexes UE based on their velocity, i.e., channel time selectivity, in such a way that stationary UEs utilize time-frequency domain while high-speed UEs communicated via delay-Doppler domain simultaneously [272]. Basically, different from the aforementioned power/code/index-domain separability and RSMA, Ding et al. have multiplexed various UEs considering the channel Doppler spread over the same RRs, suffering from IWI. UE exposed to time selective channel directly detects its signals in the delay-Doppler plane by treating the NOMA UEs' signals as noise and does not suffer from potential ISI, ICI, or U-OUI because of delay-Doppler domain transmission, ensuring a robust interference immunity. Hence, this method enhances SE without derogating from computational complexity. Furthermore, NOMA-based stationary UE can easily detect and cancel I-OUI IWI from high-speed UE, which could be impossible if high-speed UE operates over a time-frequency domain due to inescapable time-frequency selectivity interference. Proper power assignment in accordance with the channel strength is very difficult in NOMA since the channel $|h[n]|$ may change within the symbol duration T_s. Briefly, OTFS-based WD-NOMA sheds light on new transmission opportunities to perform successful communication for the NOOrMA transmission schemes, which are given in Table XI. Thus, this wide range of existing and emerging waveforms witness the potential of WD-NOMA towards 5G-B with boosted interference immunity, SE, and network compatibility.

Remark 9: The incorporation of identifiable signal-related features and transmission domains can bolster the resilience against IWI, SE and system capacity. Advanced transceiver architecture is need to ensure perfect interference cancellation, decrease of system complexity and processing latency.

VII. Interference Challenges and Future Research Directions in Emerging Tools and Use-Cases

This section delves into a wide range of potential interference challenges and future directions from a practical standpoint regarding emerging tools and use cases in 5G-B wireless networks.

A. Machine Learning (ML) Tools

The following provides a comprehensive overview of the direction of ML tools concerning interference estimation, mitigation, and integration feasibility for wireless networks.

1) Exploiting Stochastic Nature of Interference: The key attribute of the aforementioned domain-based interference management approaches is their ability to adjust or utilize different signal properties, i.e., the domain of transmission, signal envelop, cyclostationary features, channel parameters, and pulse shaping to avoid, identify, and later mitigate various types of interference [294]. Therefore, the reliance on primary knowledge of interference types and transmission domains is a necessity to sustain precise interference detection/management. Unfortunately, due to the stochastic nature of the radio frequency environment, designing a general model for interference management in the wireless realm poses a challenge, and it intensifies with the inevitable emergence of a wide range of coexisting wireless technologies. In this direction, ML-based schemes have been considered as promising solutions, while relaxing the need for interference-related prior information, and thus, offer more feasible practicability [42]. The interference caused by the coexistence of private LTE networks, 5G cellular networks with radar, satellites, and WiFi technologies is a big issue to be sorted, stemming from the emerging need for non-linear time series modeling that is a bottleneck for classical interference solution schemes.

ML-based techniques are better at modeling non-linear time series systems than the conventional signal processing methods, due to non-stationary features [295]. For instance, due to the dynamic nature of radar signaling, accurately estimating or compensating of its interference on coexisting communication signals is highly challenging [296]. In this line, in [297], Wei-Lung have discussed the performance enhancement of GPS signal while performing interference suppression via an adaptive unscented Kalman filter-based Recurrent Neural Network (RNN) design under various types of non-stationary interfering signals. In [298], Rock et al. have introduced a convolutional neural network (CNN) to compress CCI from other radar sensors, while reducing the noise floor and preserving the signal components of intended targets.

2) ML Aided Channel & Waveform Interference Management: Given the utility of ML in signal processing, there has been significant interest from both academia and industry in its potential impact on key interference sources including wireless channels and various waveform designs. In [299], Soltani et al. have studied the impact of pilot location on channel estimation quality, and thus, authors have proposed a ML-based method for pilot locations. In [300], Ye et al. have illustrated the ability of Deep Neural Networks (DNN)-based techniques not only to learn but also to assess the characteristics of wireless channels even under ISI, ICI, or while suffering from possible RF impairments. In [301], Yang et al. have discussed a Deep Learning (DL)-based channel estimation scheme that is first off-line trained with simulated data and then by exploiting additional features from pilots and received data packets. This technique has shown a better channel estimation than conventional schemes such as least square or minimum least square estimator for time-varying environments. Thus, no prior CSI is needed on the Rx side. In addition, to relax the performance limitations from random initialization, a pre-training approach has been proposed to amend the initial system parameters of the estimator. Similarly, in [302], Mohammadian et al. have discussed the system performance of a novel DL-based PN compensator, aiming to perform accurate channel estimation and data detection under ICI, for both orthogonal or non-orthogonal multi-carrier systems, i.e., OFDM and GFDM schemes. Basically, authors not only remove the need for iterative processing associated with conventional estimators but also eliminate the need for additional statistical prior information via exploring the advantages of DL. In [303], Mun et al. have utilized ML via RNN scheme with Gated Recurrent Unit (GRU) in order to perform CCI cancellation and desired signal reconstruction in the time domain. It is important to note that as the GRU technique is characterized to be suitable for processing sequence data, it can be considered for other waveforms or multi-carrier schemes with sequential features to perform interference suppression or cancellation. For instance, the OTFS signal globally represents a repeating sequence pulse in the time domain, and thus, such a feature can be exploited not only for CCI mitigation but also for IDI.

3) RF Imperfections & ML Perspective: ML-based techniques have shown promising solutions for dealing with the diverse range of interference types caused by non-idealities in the hardware transceiver design. In [304], Wong et al. have performed IQI estimation via CNN scheme for SC transmission, while considering frequency-independent IQ imbalance under a simple channel model. Knowing the fact that more than one interference source can be present at the Rx side, in [305], Aygül et al. have proposed an estimator of multiple interference sources from RF imperfections with the aid of DL-based multi-task learning technique. Different from the classical schemes performing individual estimation and compensation of RF impairments, joint interference suppression relaxes the estimation accuracy if multiple impairments exist instantaneously. Pihlajasalo et al. have outlined a variety of technical approaches to improving the EE and the coverage of OFDM-based networks by developing advanced DL-aided PHY layer Rx solutions which can decode signals efficiently even when Tx nonlinear distortion is significant, i.e., mitigating U-SUI of ICI type, in [306]. The multi-tasking concept can be exploited not only from signal feature extraction but also from a wider point of view. In this regard, in [307], Elsayed et al. have discussed a reinforcement learning-based algorithm to mitigate the problem of inter-beam power allocation in a 5G mmWave network, aiming to enhance the system sum rate while mitigating U-OUI and I-OUI of CCI interference via proper user-cell association.

4) Challenges With ML: A crucial point to note is that the primary advantage of ML-based schemes arises from correlating data points, which involves integrating enriched data from various sources to enhance interference related insights. Often referred to as Data Enrichment, this process expands data coverage by integrating essential dimensions from diverse sources. This augmented time-based data can subsequently be leveraged for analytical purposes to enhance the decision-making of ML tool [308]. However, biased data sets can mislead the learning process and high complexity ML models are not feasible for many latency and energy stringed wireless applications. Therefore, ensuring the security of these data sets is crucial to prevent them from becoming a target.

Remark 10: ML-based learning techniques have shown the capability of addressing complex estimation and interference problems since they can exploit the relationship between related interference features through their hidden layer structure. The essential advantages of ML-based methods lie on capability to adapt or employ various signal features, which allows to prevent, detect and subsequently alleviate diverse forms of SUI and OUI, such as CCI, ICI and ISI. The use of ML-based techniques for coexistence in wireless networks is still an open area and requires further research efforts. On the other hand, proper data sustainability is vital to facilitate ML-based tools. These schemes are exposed to over-fitting problem, limiting the sensitivity and effectiveness of ML-based models against inexperienced interference types. System complexity, latency and EE raise as a potential concern for ML-based schemes in 5G-B wireless realm.

B. Potential Use-Cases & Applications in 5G-B

In this section, potential emerging challenges and future directions of interference scenarios in 5G-B use-cases are anticipated.

1) The Need for Inclusive Coexistence in 5G-B Wireless Realm: The U.S. Federal Communications Commission (FCC) approved the use of the CBRS band, spanning from 3.55 to 3.7 GHz, for shared utilization by commercial wireless vendors, while guaranteeing interference-free environment for the incumbent federal UEs, like Navy radar [309]. Spectrum access priority is used to group the CBRS UEs into three different tiers. Tier 1 includes incumbent UE that need to be kept free from CCI of Tier 2 and Tier 3, known as Priority Access License (PAL) and Generalized Authorized Access (GAA), respectively [310]. The Spectrum Access System (SAS) manages access for both PAL and GAA UEs, which perform transmission only after receiving authorization from SAS for channel usage and ensuring protection for UEs of higher tiers. In [311], authors show via comprehensive measurements and analyses that secondary coexistence among GAA UEs, even within the same CBRS network, can hinder optimal performance. This static approach may pose challenges, particularly because the interference environment experienced by low-tier UE can evolve rapidly, requiring swift adjustments to operating channels and avoiding potential CCI [312]. In this line, development of novel channel scheduling schemes, radio FR, modulation, beamforming and GF access methods is an open research field.

The allowed transmit power of Tier 2 and Tier 3 UEs is 30 dBm/10 MHz in indoor and 47 dBm/10 MHz in outdoor. However, the permitted Tx power for vendors is capped at 62 dBm/MHz and 65 dBm/MHz in urban areas and rural areas, respectively, and the operation bands, i.e., 3.45 - 3.55 GHz and 3.7 - 3.98 GHz (C-band), are immediately adjacent to CBRS spectrum. Hence, the Tx power of GAA UEs is much lower than the Tx power of vendor UEs. In [313], Rochman et al. found that a significant ACI occurs among CBRS UEs and C-band vendors in real-world, and thus, introducing a 20 MHz guard band between these bands resulted in a decrease in ACI levels accordingly. Moreover, the power difference between the adjacent bands leads to DI on edge UEs of CBRS band. Thus, a promising direction can be the integration of channel access based approaches with other interference suppression schemes, e.g., multi UE scheduling, windowing and filtering in order to sustain an adequate interference level for both CBRS private 4G and C-band 5G NR technology. ACI leaking on CBRS band is INI which can be managed via exploitation of SCS and location of occurrence, as in [57].

2) Emerging Threat of LoS Satellite Links: There are some extremely challenging ACI and CCI scenarios related to environments with dominant LoS links where the UE of interest operates at a much lower power than the interferer. Numerous ground telescopes are operational worldwide and are constrained within the frequency bands allowed by atmospheric transparency and weather conditions. Due to the weak nature of radio astronomical signals (usually ranging from 10-60 dB below the noise level), radio astronomy systems exhibit high sensitivity to both noise and RF interference (RFI) [314]. Very low-noise amplifies have been designed to address the problem of noise sensitivity [315]. However, the growth of large-scale non-geostationary orbit (NGSO) satellite communication systems with dominant LoS links, such as Iridium, Astra, SpaceX, Telesat, OneWeb, etc., for telecommunication and broadcasting to fulfill the emerging communication requirements leads to unacceptable RFI in the lower frequency bands (L band to Ka band) [316]. In this case, many of the existing interference management techniques such as FR, beamforming, MIMO, waveform feature extraction, etc., will fail to provide interference suppression, estimation and mitigation, since the satellites are moving, dish size of space telescopes is large and the transceiver design is totally different. The need to have potential RFI-free regions around the observer named Radio Quite Zone (RQZ) is introduced in the literature as a solution [317]. However, these methods are limited towards the exponential increase on the number and use-cases of NGSO systems. Consequently, new opportunities that jointly take into account the demands of both NGSO-based communication systems and radio astronomy represent a rich research direction for both academia and industry.

3) A Favorable Trade-Off - Joint Consideration of Reliability, Throughput, Latency and Complexity: Another futuristic and promising future research direction that needs an extensive attention, involves interference approaches from a cross-layer perspective. The performance evaluation of wireless networks is now limited to the Shannon's formula of capacity, but other application based parameters need to be considered, including round trip time of correct data reception, reliability and complexity [318]. This includes interference issues that extend across PHY and MAC layers, PHY and network layers, or encompass all three layers, and beyond. Therefore, there is a need for novel approaches that aim to incorporate the PHY layer along with other upper layers into the design process to address interference issues in next-generation wireless networks. Achieving this objective involves utilizing the functionalities and mechanisms inherent in these layers to enhance interference immunity and exploitation. In [319], Niknam et al. propose a cross-layer interference model considering signal's directionality with random antenna orientation and blockage effect for mmWave band from PHY and MAC layer perspectives. For instance, the flexibility offered by GF access, automatic repeat request at the MAC layer, combined with techniques like maximal ratio combining, FR, filtering, SCS, adaptive modulation, interference suppression, interference detection and other parameters at the PHY layer, can be harnessed for 5G-B applications. Achieving aggressive scale, latency, and throughput targets will require a transition towards deterministic, self-aware, and highly available intelligent systems engineering [320]. For example, in the CBRS band, the performance of edge CBRS UEs is limited by the Tx power of the vendor UEs in the adjacent bands. Hence, minimizing U-OUI ACI via proper windowing, filtering or low probability activation of adjacent band RRs by the vendors will relax the existing power difference between CBRS UEs and vendors. This necessitates an innovative approach from operators, encompassing all aspects from engineering to operations and support [321]. Crucially, this reality entails a gradual mind-shift change from a human controlled environment towards a data-driven and automated architecture empowered by ML technology. The data sharing or flowing into the coexisting operator's networks needs to be enriched and diverse, and not limited to received signal strength indicator (RSSI), SNR and CSI but including reference signal received power (RSRP) and reference signal received quality (RSRQ), which represents the ratio of the carrier power to the interference power [322]. Notably, the generated raw data sets are directed into a data pool for preparation, catering to analytical and ML objectives [323]. Having an enrich prior information about the needs of the intended UE at a specific environment, i.e., time, space, frequency and location, is not something a single network can decide, rather it comes as a result of multiple technologies' alignment with one and other.

4) Ongoing Discussions for 6G and Beyond: Just as in 5G systems, use-cases and applications will continue to be the primary drivers in 6G and subsequent wireless technologies. A plethora of services, including self-driving cars, virtual reality, aerial vehicles, human body communications, and holographic communications are anticipated in 6G [324]. In order to offer satisfactory service in 6G, not only the density of connected devices is expected to increase by a factor of 10 compared to 5G-based networks, but also the area traffic capacity must increase by as much as 100 times [325]. Moreover, exploitation of higher frequency bands like terahertz that are more sensitive to the propagation effect, results in even denser connectivity over a fixed region [326]. Hence, high UE density, increased capacity, wide range of UE demands and coexistence of various wireless technologies makes interference an existential factor, going from mere communication system towards a ubiquitous connectivity with a convergence of multiple functionalities in 6G and beyond wireless communications realm.

VIII. CONCLUSION

This survey presents a thorough examination of various interference sources and potential emerging ones, including channel impairments, waveform design, resource sharing, coexistence scenarios, and hardware limitations. Furthermore, a novel framework for classifying these interference sources into four main groups at the PHY layer is introduced based on the UE of interest. The goal of this work is to provide a simplified, comprehensible, and manageable overview for both academia and industry, facilitating a better understanding of the importance, benefits, and limitations of interference in practical scenarios. On one hand, the first two groups of interference generate from the UE of interest itself, while its intention differs and is named U-SUI and I-SUI accordingly. On the other hand, the last two groups of interference originate from other UEs and differ on the intention of interest UE, and thus named I-OUI and U-OUI. For each interference source, we delve into the corresponding interference types it can generate. It is important to note that an interference source can give rise to multiple types of interference such as INI, IWI, and IDI. From the perspective of the PHY layer, we explore a diverse set of management techniques aimed at mitigating the detrimental effects of interference that significantly impact system performance. Furthermore, we offer a comprehensive overview of emerging wireless techniques beyond 5G, specifically focusing on their implications for interference. Each scheme is accompanied by numerous examples, highlighting recent advancements in interference management and discussing both their advantages and disadvantages. Furthermore, we thoroughly examine the lessons learned, advantages, and disadvantages of each technique to provide valuable insights into the trade-off process between interference and other communication requirements, including reliability, SE, power efficiency, system complexity, and compatibility in comparison to prominent wireless technologies.

NOMENCLATURES

1G	1st Generation
2G	2nd Generation
3G	3rd Generation
4G	4th Generation
5G	5th Generation
5G-B	5th Generation and beyond
5G NR	5G New Radio
6G	6th Generation

3GPP	3rd Generation Partnership Project
ACI	Adjacent Channel Interference
ACK	Acknowledgement
AoA	Angle-of-Arrival
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	base station
CA	Carrier Aggregation
CBRS	Citizens Broadband Radio Service
CCI	Co-Channel Interference
CD-IM	Code Domain IM
CDM	Code Division Multiplexing
CDMA	Code Division Multiple Access
CNN	Convolutional Neural Network
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
CS	Channel Shortening
CSI	Channel State Information
DCR	Direct Conversion Receiver
DCT	Direct Conversion Transceivers
DFE	Decision Feedback Equalizer
DFT	Discrete Fourier Transform
DFT-s-OFDM	DFT spread OFDM
DI	Dominant Interference
DNN	Deep Neural Network
DL	Deep Learning
DSSS	Direct-Sequence Spread Spectrum
D-TDD	Dynamic Time Division Duplexing
EDGE	Enhanced Data rate for Global Evolution
EE	Energy Efficiency
eMBB	Enhanced Mobile Broadband
ESA	Equal Subcarrier Activation
FBMC	Filter-Bank Multi-Carrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FDE	Frequency Domain Equalization
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Accessing
FFT	Fast-Fourier Transform
FMT	Filtered multi-tone
FR	Frequency Reuse
F-OFDM	Filtered OFDM
GAA	Generalized Authorized Access
GF	Grant-Free
GFDM	Generalized Frequency Division Multiplexing
GFDM-IM	GFDM with IM
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GRU	Gated Recurrent Unit
GSM	Global System for Mobile
HD	Half-Duplex
HetNets	Heterogeneous Networks
HSPA	High Speed Packet Access
IBFD	In-Band Full-Duplex
ICI	Inter-Carrier Interference
ICIC	Inter-Cell Interference Coordination
IDI	Inter-Doppler Interference
IFFT	Inverse-Fast Fourier Transform
IM	Index Modulation
IMMA	IM Multiple Accessing
IM-NOMA	Index Modulation NOMA
INI	Inter-Numerology Interference
IQI	In-Phase And Quadrature Imbalance
IRI	Image Rejection Interference
ISA	Inner Subcarrier Activation
ISI	Inter-Symbol Interference
ISM	Industrial Scientific and Medical
ITU	International Telecommunication Union
ITU-RSS	ITU Radiocommunication Standardization
IWI	Inter-Waveform Interference
JRC	Joint Radar and Communications
LDS-CDMA	Low-Density Spreading CDMA
LE	Linear Equalizer
LoS	Line of Site
LTE	Long Term Evolution
LTE-A	LTE Advanced
MA	Multiple Accessing
MAC	Medium Access Control
MCS	Modulation Coding Scheme
MDI	Mirror Doppler Interference
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MLSE	Maximum Likelihood Sequence Estimator
MMSE	Minimum Mean Square Error
mMTC	Massive Machine-Type Communication
mmWave	Millimeter wave
MPA	Message Passing Algorithm
MUSA	Multi-User Shared Access
MU-MIMO	Multi-User MIMO
NACK	Negative Acknowledgement
NB-DI	Narrow-Band and Dominant Interference
NGSO	Non-Geostationary Orbit
NOMA	Non-orthogonal Multiple Access
NOOrMA	Non-Orthogonal and Overlapped Multiple Access
NR	New Radio
N-SCS	Narrow SCS
ODDM	Orthogonal delay-Doppler Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM-IM	OFDM with Index Modulation
OOBE	Out-of-Band Emission
OTFS	Orthogonal Time Frequency Space
PA	Power Amplifier
PAL	Priority Access License
PAPR	Peak-to-Average Power Ratio
PHY	Physical Layer
PN	Phase Noise
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation

QIMMA	Quadrature IMMA
RF	Radio Frequency
RFI	RF Interference
RIS	Re-configurable Intelligent Surfaces
RNN	Recurrent Neural Network
RQZ	Radio Quite Zone
RR	Radio Resource
RRC	Root-Raised Cosine
RSMA	Rate-Splitting Multiple Accessing
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Reference Signal Strength Indicator
Rx	Receiver
SAS	Spectrum Access System
SC	Single Carrier
SC-FDMA	Single Carrier-Frequency Divison Multiple Access
SC-IM	SC with IM
SCMA	Sparse Code Multiple Accessing
SCS	Subcarrier Spacing
SDN	Software Defined Networking
SE	Spectral Efficiency
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference plus Noise Ratio
SIR	Signal-to-Interference Ratio
SM	Spatial Modulation
SURLLC	Secure URLLC
TDD	Time Division Duplexing
TDE	Time Domain Equalization
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Accessing
TTI	Transmission Time Interval
Tx	Transmitter
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UFMC	Universal Filtered multi-carrier
UMTS	Universal Mobile Terrestrial Systems
URLLC	Ultra-Reliable Low-Latency Communications
WD-NOMA	Waveform Domain NOMA
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
W-OFDM	Windowed OFDM
W-SCS	Wide SCS

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