

IoT Connectivity Technologies and Applications: A Survey

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ABSTRACT The Internet of Things (IoT) is rapidly becoming an integral part of our life and also multiple industries. We expect to see the number of IoT connected devices explosively grows and will reach hundreds of billions during the next few years. To support such a massive connectivity, various wireless technologies are investigated. In this survey, we provide a broad view of the existing wireless IoT connectivity technologies and discuss several new emerging technologies and solutions that can be effectively used to enable massive connectivity for IoT. In particular, we categorize the existing wireless IoT connectivity technologies based on coverage range and review diverse types of connectivity technologies with different specifications. We also point out key technical challenges of the existing connectivity technologies for enabling massive IoT connectivity. To address the challenges, we further review and discuss some examples of promising technologies such as compressive sensing (CS) random access, non-orthogonal multiple access (NOMA), and massive multiple input multiple output (mMIMO) based random access that could be employed in future standards for supporting IoT connectivity. Finally, a classification of IoT applications is considered in terms of various service requirements. For each group of classified applications, we outline its suitable IoT connectivity options.

INDEX TERMS IoT connectivity technologies; 5G; massive MTC; massive connectivity; compressive sensing; NOMA; massive MIMO; machine learning; IoT applications.

LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project	CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
4G	The 4th Generation	CSS	Chirp Spread Spectrum
5G	The 5th Generation	DBPSK	Differential Binary Phase Shift Keying
BLE	Bluetooth Low Energy	DPSK	Differential Phase Shift Keying
BLER	Block Error Rate	DQPSK	Differential Quadrature Phase Shift Keying
BPSK	Binary Phase Shift Keying	FDMA	Frequency-Division Multiple Access
BS	Base Station	GFSK	Gaussian Frequency Shift Keying
BS-ILC	Beam-Steered Infrared Light Communication	GSM	Global System for Mobile Communication
CDM	Code-Domain Multiplexing	HTC	Human Type Communications
CDMA	Code-Division Multiple Access	IR	Infrared
CP-OFDM	Cyclic-Prefix Orthogonal Frequency Division Multiplexing	ISM	Industrial, Scientific, and Medical
CS	Compressive Sensing	ITU	International Telecommunication Union
CSMA	Carrier Sense Multiple Access	IoT	Internet of Things
		LD	Laser Diodes
		LED	Laser Emitting Diode
		LPWAN	Low Power Wide Area Networks
		LTE	Long-Term Evolution
		LTE-A	Long-Term Evolution-Advance

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LTE-M	Long-Term Evolution Machine Type Communications
LiFi	Light Fidelity
LoRa	Long Range
ML	Machine Learning
MTC	Machine Type Communications
NB-IoT	Narrow-Band IoT
NOMA	Non-Orthogonal Multiple Access
OCC	Optical Camera Communication
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
OOK	On-Off Keying
OQPSK	Offset Quadrature Phase-Shift Keying
OWC	Optical Wireless Communication
PDM	Power-Domain Multiplexing
POS	Point of Sale
PRACH	Physical Random Access Channel
PRBs	Physical Resource Blocks
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
QoS	Quality of Services
RA	Random Access
RFID	Radio Frequency Identification
RL	Reinforcement Learning
RRC	Radio Resource Control
SC-FDMA	Single-carrier Frequency-Division Multiple Access
SIC	Successive Interference Cancellation
SINR	Signal-to-Noise-and-Interference Ratio
TDMA	Time-Division Multiple Access
TTL	Time-To-Live
UAV	Unmanned Aerial Vehicles
UNB	Ultra Narrow-Band
UV	Ultraviolet
VL	Visible Light
VLC	Visible Light Communication
WLAN	Wireless Local Area Networks
WPAN	Wireless Personal Area Networks
WSN	Wireless Sensor Networks
cGFRA	Compressive Grant-Free Random Access
eDRX	Expanded Discontinuous Reception
mGFRA	Massive Multiple-Input Multiple Output based Grant-Free Random Access
mMIMO	Massive Multiple-Input Multiple Output
mmWave	Millimeter Waves

I. INTRODUCTION

In 1999, the MIT Auto-ID center coined the term of the Internet of Things (IoT), for the first time, where the “things” can be any physical object that sends data and communicates with a network [1]. At the beginning, radio frequency identification (RFID) systems were the first deployed technologies for simple IoT applications that had enabled objects to communi-

cate with other objects or a server without human interaction [2]. Since 2003, Walmart 24, a retailer for the first time in the vertical market, has deployed RFID tags in all stores around the world [3]. In 2009, European Commission proposed a framework, with financial support of governments, to start an extensive research on a compatible IoT network for all available and future applications [4]. Throughout the last few years, with the introduction of the 5th generation (5G) wireless technology [5], the IoT has drawn much attention in particular with the emergence of machine type communications (MTC), which refers to automated data communications among devices or from devices to a central MTC server or a set of MTC servers [6].

The IoT is projected to grow significantly with a remarkable economic impact. It is expected that there will be more devices and sensors that are to be connected to the Internet for the IoT and various new IoT applications will be emerged (e.g., smart cities and industrial IoT). According to Gartner, it is estimated that more than 8.4 billion connected devices were in use worldwide in 2018, more than 31% from 2016. By 2020, it is predicted that the number will exceed 20.8 billion and the exponential growth is expected to continue in the future [7].

As the number of things or devices to be connected is growing, their connectivity becomes an important issue. A number of IoT applications are used in a small coverage area and their connectivity can rely on short-range wireless technologies such as Bluetooth, Zigbee, WiFi, and optical wireless communication (OWC) [8], [9]. On the other hand, as there are more IoT applications that require a wide coverage area, long-range wireless connectivity technologies are required. For example, outdoor sensors for environmental monitoring and unmanned aerial vehicles (UAV) need long-range connectivity to be connected to networks. As a result, various long-range wireless technologies are developed. For example, there are Sigfox [10] and LoRa [11] that use the unlicensed bands and have their own base stations (BS) so that things/devices can be connected to one of them, similar to conventional cellular networks. In general, Sigfox and LoRa support applications of low data rates with low power consumption so that most devices can have long life cycle (about 10 years). There are also different low-power long-range connectivity technologies that are based on cellular systems. For example, there are long-term evolution (LTE) standards, e.g., narrowband IoT (NB-IoT) and LTE MTC (LTE-M), which are developed for MTC connectivity within LTE systems [6], [12]. Unlike Sigfox and LoRa, NB-IoT and LTE-M employ licensed bands and can support devices with the existing cellular infrastructure. In addition, 5G is proposed to not only enhance traditional mobile broadband communications, but also expected to fulfil diverse connectivity requirements of new IoT applications like low latency and ultra-high transmission reliability. In fact, each wireless connectivity technology has different advantages and disadvantages. In general, if IoT applications require low latency, medium to high data rates, and a wide

coverage, cellular IoT connectivity technologies become suitable.

In this survey, we emphasize on the state-of-the-art wireless technologies for IoT connectivity and their applications. We first provide an overview of the most dominant existing connectivity technologies that are widely debated in the literature and 3rd generation partnership project (3GPP) documentation. It is noteworthy that the selected existing and conventional connectivity technologies are widely used in different industry sectors and current applications. We outline their different specifications along with their fundamental limits for enabling massive IoT connectivity. Then, promising emerging technologies are discussed to address the issue. Indeed, the scale of massive connectivity varies. For example, with NB-IoT, about 50,000 devices per cell are to be connected [31]. However, in the future, the number of devices per cell will exponentially increase, which means that the existing IoT connectivity technologies may not be able to accommodate increased device connectivity without sacrificing quality of services (QoS). Therefore, new approaches are required to be developed and employed for future IoT connectivity. These new approaches should provide high spectral efficiency as spectrum resources are limited. Furthermore, it is expected that they are able to support low latency for delay-sensitive applications such as smart vehicles and collaborative IoT [32]. There are several survey papers that have discussed various approaches for enhancing the IoT connectivity [14], [20], [27], [33]. For example, intelligent resource management was considered in [33] and non-orthogonal multiple access (NOMA) technology was reviewed in [27]. In [14], spectrum sharing solutions for the existing IoT technologies by taking advantages of their basic features were reviewed and discussed. Different from the existing survey papers, we provide a more comprehensive overview for the cutting-edge connectivity technologies such as Compressive Sensing (CS), NOMA, massive Multiple-Input Multiple-Output (mMIMO), and Machine Learning (ML) based random access (RA). We elaborate on their abilities of enabling massive connectivity and also discuss their limitations that need to be addressed. These outlined technologies have the potential to be employed together with the existing IoT technologies to further enhance their performance. In a nutshell, in this study, we provide the latest reviews on existing and emerging technologies along with their strengths and limitations and also new directions in terms of research topics. To further elaborate on the contribution of this survey, we summarize the features of existing key survey papers on IoT connectivity in Table 1 while highlighting the benefits of our survey paper. As given and explained in Table 1, we emphasize that despite the existing key surveys, our survey mainly focuses on providing a broad overview on not just the existing IoT connectivity technologies but also diverse state-of-the-art technologies that can be used to provide connectivity for various types of IoT applications. In addition, unlike classic utilization-domain application classification, we consider a different classifica-

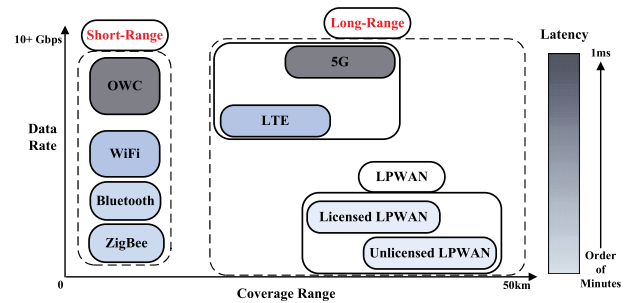


FIGURE 1. Illustration of features of the IoT connectivity technologies in terms of data rate, coverage, and Latency.

tion approach for IoT applications with respect to their general requirements and then identify the feasible connectivity technologies for each application group.

II. WIRELESS IoT CONNECTIVITY TECHNOLOGIES

Since there will be billions of different kinds of connected devices in future IoT applications, it is urged to develop various technologies to support their connectivity. In this section, we discuss the existing wireless technologies for IoT connectivity and classify them into two categories in terms of coverage range, namely short-range technologies and long-range technologies. For short-range technologies, dominant technologies like Bluetooth, ZigBee, WiFi and the emerging OWC technologies are to be discussed. For long-range technologies, depending on service features and requirements, LTE and 5G, and LPWAN technologies including unlicensed and licensed LPWAN, are introduced. In Figure. 1, we illustrate a diagram including the existing IoT connectivity technologies with respect to data rate, coverage range, and latency.

A. SHORT-RANGE TECHNOLOGIES

Short-range wireless technologies for IoT applications are usually used to support connectivity within a small coverage area. There are a number of short-range technologies with different features and performance for given application requirements. Bluetooth, ZigBee, WiFi and OWC, as the mainstream technologies of this kind, are briefly reviewed as follows.

1) BLUETOOTH

Bluetooth, standardized by the Institute of Electrical and Electronics Engineers (IEEE) 802.15.1 [34], is originally created by Nokia during the late 90's as an in-house project. However, it quickly became a popular wireless technology that is primarily used for communications between portable devices distributed in a small area (a maximum of 100m coverage range [35]). Technically, Bluetooth sends short data packets over several channels of bandwidth 1MHz between 2.402GHz to 2.480GHz and its data rate varies from 1Mbps to 3Mbps [35]. Nevertheless, the high power consumption of classic Bluetooth makes it impractical for some emerging

TABLE 1. Summary of key survey papers in the areas of IoT/MTC connectivity. LPWAN: low power wide area networks.

Ref.	Main Focus	Discussion of Existing IoT Technologies?		Discussion of Emerging Technologies for Massive Connectivity?			
		Short-range	Long-range	CS based	NOMA based	mMIMO based	ML based
This Survey	State-of-the-art IoT connectivity technologies and their applications	✓	✓	✓	✓	✓	✓
[5]	Cellular evolution challenges towards 5G	×	×	×	×	×	×
[13]	IoT platforms for massive connectivity	×	×	×	×	×	×
[14]	Spectrum sharing solutions for IoT connectivity	✓	✓	×	×	×	×
[15]	Short-range technologies and architectures for IoT	✓	×	×	×	×	×
[16]	IoT communication technologies and challenges	✓	✓	×	×	×	×
[17]	Comparison of Low-power technologies for IoT	✓	✓	×	×	×	×
[18]	IoT enabling technologies, protocols, and applications	✓	×	×	×	×	×
[19]	Different LPWAN technologies and their applications	✓	✓	×	×	×	×
[20]	LoRa for smart city applications	✓	✓	×	×	×	×
[21]	LoRA, NB-IoT, and semantic web	×	✓	×	×	×	×
[22]	NB-IoT and its open issues	×	✓	×	✓	×	×
[23]–[25]	Comparison of different LPWAN from various perspectives	×	✓	×	×	×	×
[26]	CS based IoT Applications	×	×	✓	×	×	×
[27]–[29]	NOMA for massive IoT connectivity	×	×	×	✓	×	×
[30]	mMIMO for massive IoT connectivity	×	×	×	×	✓	×
[31]	ML based solutions for massive MTC	×	✓	×	×	×	✓

IoT use-cases that require low-power transmissions for small and battery-limited devices [36]. To this end, Bluetooth Low Energy (BLE) has been introduced in Bluetooth 4.0 specifically for low-powered IoT devices [37]–[39]. Unlike classic Bluetooth optimized for continuous data streaming, BLE is optimized for short burst data transmissions. BLE defines 40 usable channels. These 40 channels are divided into 3 primary advertisement channels and 37 data channels. In general, BLE employs two multiple access schemes, i.e., frequency division multiple access (FDMA) and time division multiple access (TDMA) based polling. In Bluetooth 5.0, enhancements upon BLE’s data rates and range were presented by using increased transmit power or coded physical layer. Compared to Bluetooth 4.0, maximum 4x transmission range increase is expected and a maximum data rate of 2Mbps can be achieved (as twice as fast) [37]. In the latest Bluetooth 5.1, direction finding feature of BLE was enhanced to better

understand signal direction and achieve sub-meter location accuracy [40]. To enable large-scale IoT device networks that support many-to-many device communications, BLE mesh networking has been adopted in 2017 [41], [42]. BLE mesh topology operates on a managed flood routing principle for forwarding messages from one device to another. The maximum number of devices in any given Bluetooth mesh network is 32,767, with up to 16,384 groups. In this model, only devices that have the enabled relay feature forward received messages further into the network. In addition, a message cache is introduced to ensure that a relay device only relays a specific message once and a time-to-live (TTL) is used to address the issues that arise with routing loops. A relay device only relays a message if the message is not in the cache and its TTL is greater than 1 [43]. Each time message is received and retransmitted, TTL will be decremented by one. If the TTL reaches zero, the message will be discarded

at the relay device, eliminating endless loops. The maximum TTL supported in Bluetooth mesh is 127 [44]. In addition, the backwards compatibility feature and friendship feature are also defined in BLE mesh for BLE devices. In particular, the backwards compatibility feature enables the BLE devices that do not support BLE mesh to be connected to a mesh network. Furthermore, the friendship feature enables power-limited BLE devices to become part of a mesh network with the help of battery-powered devices [43]. Classic Bluetooth and BLE have been currently adopted by a number of use-cases including audio streaming, health and wellness monitoring, low-cost indoor positioning, and controlling and automating [45]–[47].

2) ZigBee

ZigBee is another short-range wireless technology for wireless personal area networks (WPAN), which is built on top of IEEE 802.15.4 [48]. Currently, ZigBee has been widely considered for a variety of IoT applications including home automation, industrial monitoring, and health and aging population care [49]–[52]. Similar to BLE, Zigbee is also a low-power technology. Zigbee operates in the unlicensed bands, i.e., mainly at 2.4GHz and optionally at 868MHz or 915MHz, and its default operation mode at 2.4GHz uses 16 channels of 2MHz bandwidth. ZigBee is able to connect up to 255 devices at a time with a maximum packet size of 128bytes. Depending on the blockage of environments, the transmission ranges between devices vary from a few meters up to 100 meters [53]. ZigBee supports star and peer-to-peer topologies for connecting devices. In ZigBee, three types of devices are defined as follows: coordinator, router, and end device. In particular, coordinator and router are normally mains-powered and end device can be battery-powered. The coordinator is the most capable device in ZigBee, which coordinates the actions of a network and might connect to another network as a bridge. The routers form a network for packet exchanges. The end devices are logically connected to a coordinator or routers. However, these end devices cannot directly communicate with each other. To enable large-scale IoT device networks, Zigbee can be extended as generic mesh where devices are clustered with a local coordinator and connected via multihop to a global coordinator [54], [55]. Unlike BLE, ZigBee uses carrier sense multiple access with collision avoidance (CSMA/CA) to avoid packet collisions (please refer to Appendix B for more details and explanations on CSMA). In addition, while BLE allows four different data rates varying from 125kbps to 2Mbps, ZigBee can only support data rates from 20kbps to 250kbps. According to the performance evaluation in a realistic home automation scenario in [55], [56], BLE is superior to ZigBee in terms of service ratio thanks to its higher bit rate and dedicated data channels. In terms of delay, both technologies have similar performance in a basic scenario, but BLE is more delay-sensitive to the traffic load than ZigBee. It was also shown that BLE devices consume less energy to set up the same network,

which indicates the BLE devices may have a comparably longer expected lifetime.

3) WiFi

WiFi, standardized by IEEE 802.11 [57], is a family of technologies commonly used for wireless local area networks (WLAN). Different from Bluetooth and Zigbee that provide connectivity between devices, WiFi provides the last mile wireless broadband connections for devices to the Internet with a larger coverage and higher data rates [8]. In fact, WiFi has been evolved several generations to support higher throughputs. Specifically, IEEE 802.11a and IEEE 802.11b were introduced in 1999, where IEEE 802.11a can support a data rate up to 54Mbps in 5GHz, and IEEE 802.11b makes it up to 11Mbps in 2.4GHz. In 2003, IEEE 802.11g was released with a maximum data rate of 54Mbps in 2.4GHz. However, IEEE 802.11a/b/g standards were not able to meet the growing demand of hypermedia applications over WLANs due to their relatively low throughputs and capacity. Therefore, new generations of WLANs, i.e., IEEE 802.11n [58] and IEEE 802.11ac [59] have been released in 2008 and 2014, respectively. These new generations can achieve much higher data rates (up to 600Mbps in IEEE 802.11n and 7Gbps in IEEE 802.11ac) with a wider coverage compared to previous ones (IEEE 802.11a/b/g) by using dense modulations and MIMO technology. In addition, IEEE 802.11ah (WiFi HaLow) was introduced in 2017 to support IoT with extended coverage and low-power consumption requirements. It operates in the unlicensed sub-1GHz bands (excluding the TV white-space bands) and its bandwidth occupation is usually only 1MHz or 2MHz, while in some countries, wider bandwidths up to 16MHz are also allowed. Compared to high-speed WiFi generations, the IEEE 802.11ah aims to provide connectivity to thousands of devices with coverage of up to 1km but its maximum data rate is about 300Mbps utilizing 16MHz bandwidth [31], [60], [61].

4) OWC

Another emerging short-range wireless technology developed to support the indoor IoT device connectivity is the OWC [9], [62]. OWC is a promising architecture that can be used to resolve the issues arising from high bandwidth and low latency indoor IoT applications. In OWC, visible light (VL), infrared (IR), or ultraviolet (UV) spectrum are used as propagation media in comparison to radio frequencies used in WiFi and other WLAN technologies [57], [62]. To date, different research groups from academia and industry have demonstrated low-complex optical wireless links that can operate at multi-gigabits per second data rate in an energy-efficient manner under a typical in room environment to support various applications [63]–[65].

The high-speed OWC links are proposed to provide connectivity for many IoT application where we have limited or poor WiFi/other wireless connectivity [66]. The application includes Tactile Internet, wireless body area networks that consist of body placed sensors, in airplanes, and also

connecting bandwidth demand latest medical instruments at hospitals [67]. Furthermore, OWC links are proposed to provide connectivity for remotely operated underwater vehicles, dense urban environments, autonomous vehicle communications, and connecting sensors in chemical and power plants where usage of radio frequency is restricted [62].

Among different types of OWC technologies have been developed, there are two major categories of OWC technologies that can be identified as potential tools to provide high bandwidth and low-latency connectivity for emerging IoT applications [62]. These categories are visible light communication (VLC), and beam-steered infrared light communication (BS-ILC) [68].

- 1) VLC: VLC uses the laser emitting diode (LED) illumination infrastructure to provide multi-gigabit wireless connectivity by employing diverse modulation scheme ranging from simple on-off keying (OOK) to quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM) [69], [70]. In 2011, VLC was initially standardized as IEEE 802.15.7 [71]. This standard was further developed in two directions based on the data rate requirements of diverse applications. For low data rate applications, IEEE 802.15.7m [72] standard was developed using the optical camera communications (OCC) that support connectivity for a range of 200m. On the other hand, for high data rate application, IEEE 802.15.13 [73] was developed enabling multi gigabit data rate connectivity over few tens of meters. Recently, 100 Gbps VLC links have demonstrated using laser diodes (LD) instead of using LEDs [74]. The popular technology, light fidelity (LiFi) is also developed based on VLC technology [75]. To date, there are several commercial VLC products are available in the market such as pureLiFi to support diverse IoT applications.
- 2) BS-ILC: Infrared light communication was first standardized by IrDA and IEEE in early 90's. In particular, infrared light communication was included in the initial WiFi standard (IEEE 802.11) [57]. In comparison to VLC, in BS-ILC systems, the IR beams are turned on when needed, for example when there are applications/users to be served. In this system, multiple beams can be used to serve several users in the same room. In term of the coverage of a single beam, there are two different types of BS-ILC systems available. In the first type, a single beam is used to serve a single user application/user within a room and hence the implementation of medium access control protocols can be avoided as no shared medium is used [76]. In the second type, multiple users are served within a wide IR beam and hence implementation of the medium access control protocols has also been investigated [77], [78]. To date, different types of BS-ILC systems have demonstrated their ability to provide multi-gigabit connectivity for a range of 3m

using diverse modulation formats and different beam-steering techniques that use either active beam steering devices [64], [79], [80] or passive beam steering devices [76], [81].

In Table 2, the technical specifications of Bluetooth, Zigbee, WiFi, and OWC are summarized. As discussed, different technologies have different advantages. For example, the IEEE 802.11ac and OWC are focused on supporting high-speed transmissions, while BLE, Zigbee and the IEEE 802.11ah are targeting at low-power and low-cost communication. Among these low-power consumption candidates, the IEEE 802.11ah can provide higher data rates and wider coverage range.

Although these technologies are able to provide connectivity to various data rate use-cases, they are not suitable for the use-cases that require a wide coverage. As a counterpart of the short-range technologies, existing paradigm of long-range technologies is introduced in the following.

B. LTE AND 5G

LTE and 5G are the essential parts of cellular IoT technologies. As the standardized technology of the 4th generation (4G), LTE/LTE-Advance (LTE-A) has now been deployed successfully worldwide, which was mainly designed to support the conventional human-type communications (HTC) for high-speed transmissions. Since 2016, the 5G standardization has been progressed by the international telecommunication union (ITU) and 3GPP [82]–[84]. Technically, the main advantage of 5G over LTE is its ability of providing 100x higher data rate, 10x lower latency, and supporting 100x more connected devices [85] by utilizing a new air interface that includes much higher frequencies such as millimeter wave (mmWave) and using more advanced radio technologies, e.g., massive multiple-input multiple-output (mMIMO), edge computing, full duplex, and Polar codes [86]. Compared with LTE, 5G is expected to not only enhance HTC by handling far more traffic at much higher data rate, but also to support unprecedented mission-critical applications [85], [87]. In Table 3, comparison of the specifications of LTE and 5G is presented. Indeed, the current LTE has a nominal latency of 15ms and a target block error rates (BLER) of 10^{-1} before retransmission [88]. In future, various mission-critical applications, such as haptic communication and smart transportation, will gradually merge into our daily life. These applications are normally insensitive to power consumption and have very restrictive requirements in terms of latency (1ms or less) and transmission reliability (BLER as low as 10^{-9}) [89]. Therefore, one of the key tasks of 5G is to address the challenges of low latency as well as ultra-high reliability transmissions. In fact, low latency and ultra-high reliability are two conflicting requirements. On one hand, it is necessary to use a short packet to guarantee low latency, which however may have a severe impact on the channel coding. On the other hand, users usually need more resources to satisfy high transmission success rate requirements, while

TABLE 2. Comparison of Bluetooth, Zigbee, WiFi and OWC [8], [37], [62]. GFSK: Gaussian frequency shift keying; DQPSK: differential quadrature phase shift keying; DPSK: differential phase shift keying; BPSK: binary phase shift keying; OQPSK: offset quadrature phase-shift keying; QPSK: quadrature phase shift keying; CDMA: code-division multiple access.

	Bluetooth	Zigbee	WiFi	OWC
RA protocol	TDMA based polling FDMA	CSMA/CA	CSMA/CA	CSMA/CA TDMA/CDMA
Modulation type	GFSK/DQPSK/DPSK	BPSK/OQPSK	BPSK/QPSK/QAM	OOK/OFDM
Maximum data rate	Classic: 3Mbps BLE: 2Mbps	250kbps	7Gbps	10Gbps using LED 100Gbps using LD
Coverage	Classic: 100m BLE: 240m	100m	Conv.: 100m 802.11ah: 1km	200m

it may simply increase the latency for other users [90]. Although research works have recently investigated and proposed the potential solutions to this technical challenge from various perspectives [91]–[96], there are open issues that still need to be addressed to enable mission-critical applications and make them practical [97]. For example, resource allocation becomes particularly challenging with the introduction of haptic communication into 5G and flexible resource allocation approaches need to be investigated to enable the coexistence of haptic communication with other types of applications. Specifically, the latency of data transmission is influenced by how quickly wireless resources can be allocated when a data packet arrives at the radio interface. Because of stringent latency requirements of haptic communication, wireless resources must be provided for it on a priority basis. Furthermore, since the available wireless resources will be shared between haptic communication and HTC or MTC and these applications have different and often conflicting application requirements, existing resource allocation approaches only designed for typical HTC or MTC may not result in optimal resource allocation outcome to accommodate different application with various QoS requirements. Thus, 5G requires flexible dynamic approaches for wireless resource management so that the utility of various applications can be maximized by ensuring efficient and intelligent wireless resources allocation [98]. In addition, accurate and fast traffic prediction approaches need to be developed in urban scenarios for smart transportation [91]. Specifically, traffic prediction enables the early identification of traffic jams and allows the smart vehicles or traffic authorities to take prompt measures to avoid the congestion on the roads [99]. Therefore, accurate real-time traffic prediction is one of the most important component to enable traffic efficiency services in smart transportation. Nevertheless, most existing traffic prediction approaches were developed for highway networks, which may not suitable for more complicated urban networks. In urban scenarios, traffic environments and patterns are more unpredictable and complex, which makes it difficult to use simple traffic models to predict traffic in a fast and accurate manner. Thus, some advanced and complex modeling tools are required to design effective approaches for accurate, fast, scalable traffic prediction in urban scenarios so that accurate reaction to the change in traffic flows can be carried out promptly [99], [100].

TABLE 3. Specifications of LTE and 5G [87], [88], [101]. SC-FDMA: single-carrier frequency division multiple access; CP-OFDM: cyclic-prefix orthogonal frequency division multiplexing.

	LTE/LTE-A	5G
Round trip latency	15ms	1ms
Peak data rate	1Gbps	20Gbps
Available spectrum	3GHz	30GHz
Channel bandwidth	20MHz	100MHz below 6GHz 400MHz above 6GHz
Frequency band	600MHz to 5.925GHz	600MHz to 80GHz
Uplink waveform	SC-FDMA	Option for CP-OFDM

C. LPWAN TECHNOLOGIES

Currently, LPWAN has been driven to fulfill the demand of emerging IoT applications to offer a set of features including wide-area communications and large-scale connectivity for low power, low cost, and low data rate devices with certain delay tolerance [102]. In general, LPWAN can be divided into two categories, namely unlicensed and licensed LPWAN. In the sequel, we review the most prevailing LPWAN technologies.

1) UNLICENSED LPWAN

The unlicensed LPWAN technologies refer to the LPWAN technologies that employ unlicensed spectrum resources over the industrial, scientific, and medical (ISM) band. Thanks to the usage of the unlicensed band, the unlicensed LPWAN providers do not necessarily pay for spectrum licensing, as a result it reduces the cost of deployments. For the unlicensed LPWAN, LoRa and Sigfox are the two biggest competitors [103], [104].

- 1) LoRa: LoRa, stands for Long Range. It is a physical layer LPWAN solution that modulates signals using a spread spectrum technique designed and patented by Semtech Corporation [11]. Technically, LoRa employs the chirp spread spectrum (CSS) modulation that spreads a narrow-band signal over a wider channel bandwidth, thus enabling high interference resilience and also reducing the signal-to-noise-and-interference ratio (SINR) required at a receiver for correct data decoding [105]. The spreading factor of the CSS can be varied from 7 to 12, which makes it possible to provide variable data rates and tradeoff between throughput and coverage range, link robustness, or energy consumption

[19], [22]. Specifically, a larger spreading factor allows a longer transmission range but at the expense of lower data rate, and vice versa. Depending on the spreading factor and channel bandwidth, the data rate of LoRa can vary between 50bps and 300kbps. In 2015, a LoRa-based communication protocol called LoRaWAN was standardized by LoRa-Alliance [106]. LoRaWAN is organized in a star-of-stars topology, where gateway devices relay messages between end-devices and a central network server [24]. In LoRaWAN, three types of devices (Class A, B, and C) with different capabilities are defined [107]. In particular, Class A is the class of LoRaWAN devices with the lowest power consumption that only require short downlink communication, and Class A devices use pure-ALOHA RA (please refer to Appendix A for more details and explanations on ALOHA protocols) for the uplink. Class B devices are designed for applications with extra downlink transmission demands. In contrast, Class C devices have continuously receive slots, thus always listening to the channel except when they need to transmit. Among the three classes, all the devices must be compatible with Class A [24].

- 2) Sigfox: SigFox is another dominant unlicensed LPWAN solution on the market [10]. SigFox proposes to use an ultra narrow-band (UNB) technology with only 100Hz bandwidth for very short-payload transmission. Thanks to the UNB technology, Sigfox enables less power consumption for devices and supports a wider coverage compared with LoRa at the cost of a lower data rate [109]. Sigfox was initially introduced to support only uplink communication, but later it evolved to a bidirectional technology with a significant link asymmetry [110]. However, the downlink transmission can only be triggered following an uplink transmission. In addition, the uplink message number is constrained to 140 per day and the maximum payload length for each uplink message is limited to 12bytes [22]. Due to these inflexible restrictions, together with its unopened business network model [19], Sigfox has unfortunately shifted the interest of academia and industry to its competitor LoRaWAN, which is considered more flexible and open. In Table 4, the characteristics of Sigfox and LoRa are summarized.

2) LICENSED LPWAN

As a counterpart of the unlicensed LPWAN above mentioned, we briefly review the licensed LPWAN technologies in this subsection. The licensed LPWAN refers to the LPWAN technologies using the licensed spectrum resources. They are standardized by the 3GPP. For the licensed LPWAN, LTE-M and NB-IoT are the two most promising standards that are introduced in 3GPP Rel-13 in 2016 [6], [12].

Since both standards are developed based on LTE, their RA procedures are compatible with that in LTE. Generally speaking, the RA procedure refers to all the procedures when

a device needs to set up a radio link with the BS for data transmission and reception. In LTE, a contention-based RA procedure used on physical random access channel (PRACH) is specified for initial access [111]. The PRACH consists of four-handshaking steps. In step 1, each accessing device randomly selects a preamble from a predetermined preamble pool of size 54. Preamble collision may occur since multiple devices may select the same preamble. However, the BS can only detect if a specific preamble is active or not in this step. In step 2, the BS sends a RA response corresponding to each detected preamble. After receiving the RA response in step 3, each device sends a radio resource control (RRC) request for its data transmission. In the case of preamble collision, all the collided devices use the same resource to send their RRC request and this collision will be detected by the BS. In step 4, contention resolution procedure is employed to resolve the collision, where all collided devices need to make a new access attempt with backoff. Since the PRACH operation is based on ALOHA-type access, its capacity is very limited [111], [112].

In the following, we briefly review the two licensed LPWAN technologies for long-range connectivity.

- 1) LTE-M: LTE-M is fully compatible with existing cellular networks [113]. It can be considered a simplified version of LTE intending for low device cost and low power consumption IoT applications [114]. The key features of LTE-M are the support of mobile MTC use-cases and voice over networks [115]. LTE-M uses orthogonal frequency division multiple access (OFDMA) in the downlink and multi-tone SC-FDMA in the uplink. To reduce hardware cost and complexity, LTE-M has a bandwidth of 1.4MHz and typically supports one receive-antenna chain and half-duplex operations (full-duplex operations are also allowed). In 3GPP Rel-14 and Rel-15, new features have been proposed to enhance the performance of LTE-M in terms of data rate, latency, positioning, and voice coverage [116], [117]. For example, in 3GPP Rel-15, coverage enhancement for higher device velocity (e.g. 200km/h) was proposed and techniques such as wake-up signal/channel and relaxed monitoring for cell reselection during RA were used to reduce latency and power consumption.
- 2) NB-IoT: Compared with LTE-M, NB-IoT is a system built on the existing LTE functionality with a single narrow-band of 200kHz with low baseband complexity, which aims at supporting wider coverage, lower device cost, longer battery life, and higher connection density [119], [120]. To be more specific, we compare the characteristics of LTE-M and NB-IoT in Table 5. Like LTE-M, NB-IoT can coexist with the existing LTE networks, which can utilize the existing network hardware and reduce the deployment cost therefore [121], [122]. NB-IoT also uses OFDMA with 15kHz subcarrier spacing in the downlink and SC-FDMA with

TABLE 4. Comparison of Sigfox and LoRa [22], [24], [108]. DBPSK: differential binary phase shift keying.

	Sigfox	LoRa
RA protocol	ALOHA	ALOHA/Slotted-ALOHA
Modulation type	GFSK/DBPSK	CSS
Frequency	Unlicensed ISM bands	Unlicensed ISM bands
Bandwidth	100Hz	125kHz and 250kHz
Bidirectional	Limited/Half-duplex	Half-duplex
Link budget	156dB	164dB
Maximum data rate	100bps	50kbps
Maximum payload length	12bytes	243bytes
Coverage	10km (urban), 50km (rural)	5km (urban), 20km (rural)
Interference immunity	Very high	high
Battery life	10 years	10 years
Localization	Yes	Yes
Mobility	No	Yes

TABLE 5. Comparison of LTE-M and NB-IoT [22], [115], [118], [119].

	LTE-M	NB-IoT
RA protocol (based on PRACH)	Slotted-ALOHA	Slotted-ALOHA
Modulation type	QPSK/QAM	BPSK/QPSK
Frequency	Licensed LTE bands	Licensed LTE bands
Bandwidth	1.4MHz	200kHz
Bidirectional	Full/Half-duplex	Half-duplex
Link budget	153dB	164dB
Maximum data rate	1Mbps	250kbps
Maximum payload length	1000bits	1000bits
Coverage	Few kilometers	1km (urban), 10km (rural)
Interference immunity	Low	Low
Battery life	10 years	10 years
Localization	Yes	Yes
Mobility	Yes	Yes

both 15kHz and 3.75kHz subcarrier spacings in the uplink [123]. Different from LTE-M, both single-tone and multi-tone SC-FDMA can be used for NB-IoT [14] but only half-duplex operations are supported by NB-IoT. Compared to LTE-M and legacy LTE, NB-IoT has extended coverage and deep penetration in buildings and hard-to-reach areas, thanks to its narrow bandwidth and low data rate. Technically, the coverage target of NB-IoT has a link budget of 164dB, whereas the LTE link budget is 142dB [118], [124]. The 20dB link budget margin can significantly increase the coverage range in an open environment and compensate the penetration losses caused by walls of a building to ensure high quality communication. In addition, NB-IoT has three operation modes such as in-band, standalone, and guard-band, as illustrated in Figure 2. In in-band mode, one or more LTE physical resource blocks (PRBs) within an LTE carrier are reserved for NB-IoT. In standalone mode, NB-IoT can be deployed within one or multiple global systems for mobile communications (GSM) carriers. In guard-band mode, NB-IoT can be utilized within the guard-band of an LTE carrier [125]. To prolong battery life, two main power-efficiency mechanisms are supported in NB-IoT and LTE-M, namely power saving mode (PSM) and expanded discontinuous reception (eDRX) [113], [123]. In particular, PSM keeps a device registered with network, but allows it to turn off the functionalities

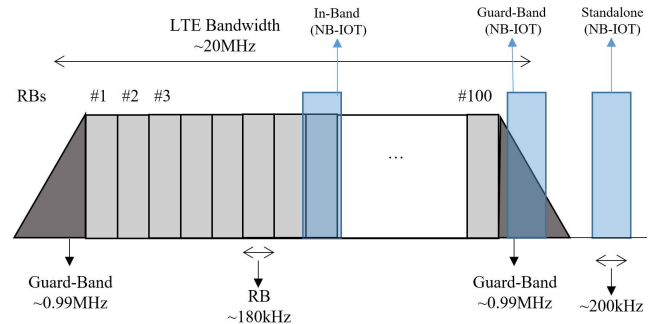


FIGURE 2. In-band, standalone, and guard-band deployment of the NB-IoT in an LTE component carrier with 20MHz bandwidth [123].

of paging listening and link quality measurements for energy saving. On the other hand, eDRX allows a device to negotiate with a network when it can sleep, during which the device can turn off the receiving functionality for energy saving. Both mechanisms allow to repeat transmissions for latency-tolerant devices to extend network coverage [14].

The two kinds of LPWAN technologies, i.e., unlicensed and licensed LPWANs, have different features and advantages. For example, since unlicensed LPWAN uses ISM bands, this fact favours the deployment of private BSs without the involvement of any mobile operators, but it is difficult to provide guaranteed performance due to the signals that become

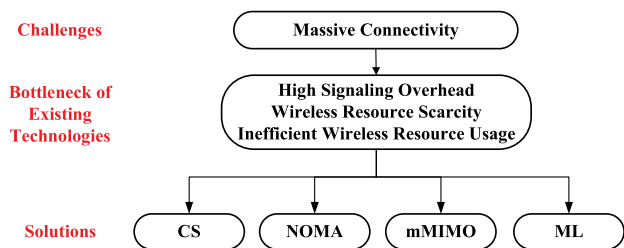


FIGURE 3. Diagram of the challenge for the existing technologies and the promising solutions.

interferers in ISM bands. On the other hand, since licensed LPWAN is part of cellular systems, certain performance can be guaranteed using resource allocation, while its deployment and device cost are comparably higher [22].

As mentioned earlier, both short-range and long-range technologies can be employed for various IoT applications. For example, home IoT applications can be supported using short-range technologies (e.g., WiFi), and small-scale wireless sensor networks (WSN) (e.g., specific indoor health applications) can be implemented using ZigBee. For high data rate and low latency indoor applications such as Tactile Internet, OWC technologies can be used. However, to support a tremendous number of devices deployed over a large area, it is necessary to rely on long-range technologies. For multimedia and ultra reliable low latency applications, LTE and 5G can be effectively employed to support their connectivities. For environmental monitoring and smart farming to cover a wide area (e.g., a city or a suburb), unlicensed LPWAN technologies can be used. Licensed LPWAN technologies would be required for nation-wide IoT applications that require unified supports (e.g., the connectivity for smart meters in smart grid/smart cities).

III. EMERGING WIRELESS TECHNOLOGIES FOR MASSIVE CONNECTIVITY

Although the existing wireless IoT technologies have led to some success in supporting various IoT applications, there are still open issues and difficulties to meet the foreseeable needs of future IoT applications with hundreds of billion objects or things to be connected. One of the critical challenges is to accommodate massive connectivity from IoT devices with small-sized transmission payloads and sporadic features [33], [126]. In fact, the RA protocols of the existing technologies are mainly based on ALOHA or CSMA/CA [127], which is highly likely to cause severe access collision, increased latency, and high signalling overhead for IoT devices. Moreover, only limited wireless resources are allocated for IoT connectivity and these resources are used in an orthogonal manner, which results in wireless resource scarcity and inefficient wireless resource usage for massive connectivity. In Figure 3, we summarize the main bottleneck of existing technologies for enabling future IoT connectivity. To address these issues, ongoing efforts have been made to develop new technologies that can address the shortcomings

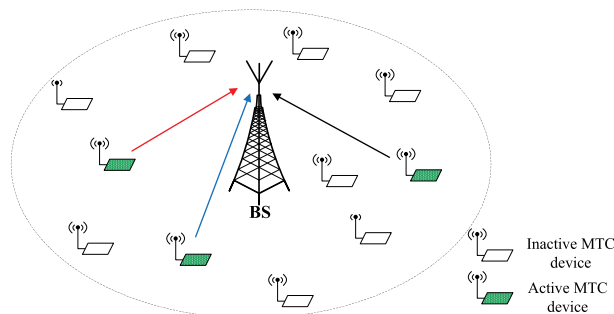


FIGURE 4. Illustration of sparse user activity in massive MTC.

of the existing technologies while maintaining their good characteristics. In this survey, an overview of four promising technologies such as CS, NOMA, mMIMO, and ML that can effectively resolve wireless resource scarcity and enhance spectrum usage efficiency is provided.

A. CS BASED IoT CONNECTIVITY

In order to reduce signalling overhead, grant-free RA has been proposed [128], which does not employ handshaking process that is employed in existing licensed LPWAN standards, i.e., LTE-M and NB-IoT (the request-grant procedure is thus omitted). In general, the grant-free RA enables IoT devices to contend with their uplink payloads directly by transmitting preamble along with data. By utilizing the natural feature of sporadic traffics in MTC, as shown in Figure 4, various compressive grant-free RA (cGFRA) schemes have been proposed [129]–[133], where the sparse device activity is exploited to develop efficient multiple signal detection schemes based on CS algorithms (please refer to Appendix C for more details and explanations on CS principle) [134], [135]. In particular, cGFRA schemes have been studied where the wireless signal of each device is spread by a unique sequence [129], [130]. In [131], sparse sequences were used instead of binary sequences for data signal spreading in order to increase the number of MTC devices and allow device identification. In [132], multiple resource blocks were used to reduce the preamble collision and improve the mGFRA throughput. In [133], another cGFRA scheme was proposed where each device’s channel impulse response is used as a unique signature to differentiate signals that are simultaneously transmitted.

Although cGFRA is well-suited to MTC with low signalling overhead to some extent, its high complexity resulted from the CS algorithm is still an issue to be addressed. In general, the complexity of cGFRA algorithm is proportional to the total number of MTC devices in a cell. In massive access with a large number of MTC devices, its complexity would be prohibitive. Thus, a low-complexity cGFRA is highly desirable for massive access. In addition, cGFRA usually requires a bandwidth expansion to increase the number of MTC devices that can be supported simultaneously. To efficiently utilize wireless resources and also to address

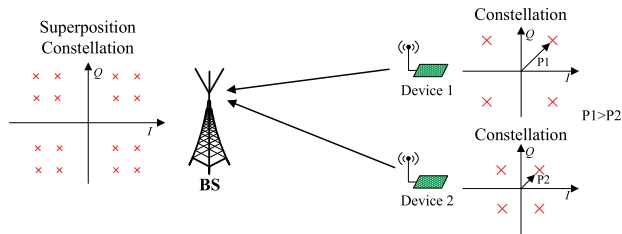


FIGURE 5. Simplified power-domain NOMA systems.

the wireless resource scarcity for supporting massive access, advanced technologies such as NOMA and mMIMO have been developed, which will be introduced in the following.

B. NOMA BASED IoT CONNECTIVITY

NOMA has recently been identified as a promising technology to make more efficient use of wireless resources [136]–[141]. The key idea of NOMA for massive access is to allow overlapping among signals over the same time-frequency resource via power-domain multiplexing (PDM) or code-domain multiplexing (CDM), and to employ successive interference cancellation (SIC) at a BS to perform a separate decoding for each device [26], [27], [142]. Figure 5 illustrates the basic principle of power-domain NOMA in uplink transmission. Specifically, at the BS, the strong signal from device 1 is first decoded and removed by using SIC in the presence of the interfering signal from device 2, which is a weak signal. Then, the weak signal, i.e., the signal from device 2, is decoded (please refer to Appendix D for more details and explanations on NOMA principle). The main benefit of power-domain NOMA for MTC is enabling multiple devices to perform grant-free access in the same time-frequency resource simultaneously without bandwidth spreading [143]–[149]. Specifically, in [143] and [144], NOMA-based RA has been investigated with multichannel ALOHA to improve the throughput for MTC. It was shown that the NOMA-based RA with multichannel ALOHA is suitable for MTC when the number of multiple access channels is limited. This is mainly due to the fact that NOMA can effectively increase the number of multiple access channels without any bandwidth expansion. In [145], the energy efficiency of NOMA for MTC was studied, and it was shown that transmitting with minimum rate and full time is optimal in terms of energy efficiency. In [146], a power control algorithm of NOMA was proposed to improve the energy efficiency by employing game theory. In [147], a MIMO-NOMA strategy has been designed for MTC, where two users are clustered to meet the service demands of one user while the other user is served opportunistically. In [148], a joint sub-carrier and transmission power allocation problem were considered and solved to maximize the number of MTC devices and satisfy the transmission power constraints. In [149], NOMA to cGFRA was adopted to improve the performance of cGFRA and it was revealed that the number of incorrectly detected device activity can be reduced by applying NOMA to cGFRA.

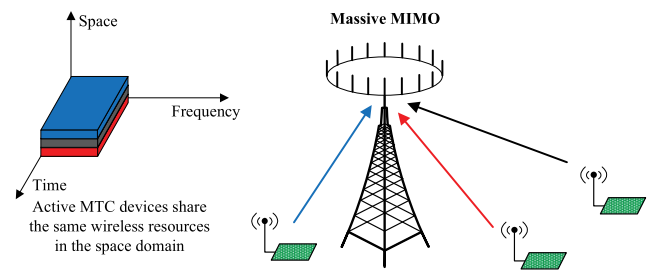


FIGURE 6. Illustration of mMIMO systems.

In [150], a low-complexity dynamic cGFRA for NOMA was proposed to jointly realize user activities and data detections. It was shown that the proposed scheme can achieve much better performance than that of the conventional cGFRA.

Although all these works indicated that NOMA is a promising technology to enable grant-free massive access for emerging MTC standards, there are still challenges to be addressed to enable its implementation [26]. For example, designing appropriate detection algorithms and decoding strategies to increase the number of pairs of devices and suppress the error propagation is important at the stage of SIC in power-domain NOMA. On the other hand, optimizing factor graph needs to be considered for a good trade-off between overloading factor and receiver complexity in code-domain NOMA.

C. mMIMO BASED IoT CONNECTIVITY

Besides NOMA, mMIMO is another promising technology to mitigate wireless resource scarcity and handle the rapid growth of data traffics for 5G and future wireless communications (please refer to Appendix E for more details and explanations on mMIMO principle) [151]–[155]. Compared to NOMA, mMIMO exploits wireless resources in the spatial domain that can afford a large number of MTC devices, as shown in Figure 6. In a typical mMIMO, a great number of antennas are employed at the BS. Thanks to it, the channel responses between different devices tend to be orthogonal to each other. By taking advantage of this property, a large number of devices in the same time-frequency resource could be simultaneously accommodated in an efficient way. Diverse research works have shown that mMIMO can significantly improve the performance of HTC in terms of spectral efficiency [156], [157], energy efficiency [158], [159], and coverage [160]. For example, as shown in [152], when the BS employs 100 antennas to serve 40 users, mMIMO can increase the spectrum efficiency 10 times or more and simultaneously, improve the radiated energy-efficiency in the order of 100 times by using conjugate beamforming, compared to the single-antenna single-user counterpart. Several modifications and improvements of traditional PRACH by using mMIMO have also been proposed to support MTC [29], [161]–[164]. These works validate the effectiveness of mMIMO in resolving access collision, reducing access delay, and enhancing RA capacity in MTC. To more efficiently accommodate massive access with low signalling overhead

TABLE 6. Summary of strengths and limitations of the promising technologies for massive connectivity.

Technologies	Strengths	Limitations
CS	Efficient multiple signal detection schemes can be developed by exploiting sparse device activity in MTC.	1) High complexity in massive access with a large number of MTC devices; 2) bandwidth expansion required to increase the number of MTC devices that can be supported simultaneously.
NOMA	Allowing overlapping among signals over the same time-frequency resource via PDM or CDM.	1) Error propagation at the stage of SIC in power-domain NOMA; 2) trade-off between overloading factor and receiver complexity in code-domain NOMA needs to be optimized
mMIMO	Thanks to favorable propagation, wireless resources in the spatial domain can be exploited to support a large number of devices simultaneously.	1) preamble that has large preamble space but low mutual correlation needs to be designed; 2) array dimensions and hardware cost need to be considered when the number of antennas is large.
ML	Dynamic patterns of the wireless environment that are too complex to be modelled could be effectively explored.	1) Trade-off between the algorithm's computational requirements and the learned model's accuracy needs to be well designed; 2) it could be time consuming, which may not suitable for highly dynamic environments.

and access delay, mMIMO based grant-free RA (mGFRA) has been proposed as a compelling candidate for future IoT [165]. Recently, performance analyses on mGFRA have been conducted with respect to spectral efficiency [166]–[168], success probability [165], user activity detection and channel estimation [169], [170]. Although all these research works confirmed that mMIMO is a viable and effective enabler for emerging MTC applications in IoT, they also revealed that preamble is of prime importance in mGFRA because it not only enables RA device differentiation but also dominates the accuracy of channel estimation, which is essential for successful data transmissions of RA devices. In general, there are two types of preambles considered in mGFRA, namely orthogonal [165], [166] and non-orthogonal preambles [169], [170]. Compared with the non-orthogonal counterpart, orthogonal preamble detection is much more simple and effective and the channel estimation is relatively more accurate, thanks to the orthogonality of preambles. Nevertheless, preamble collision constrains its performance due to the limited orthogonal-preamble space. On the other hand, non-orthogonal preamble can alleviate the preamble collision since it has larger preamble space, but its channel estimation would be affected due to non-orthogonality of preambles. Thus, designing preamble that has large preamble space but low mutual correlation is desirable in mGFRA.

On the other hand, since the number of MTC devices that could be supported by mMIMO grows with the number of antennas [165], it is expected that hundreds or thousands of antennas are used to support massive access in various IoT applications. However, considering the array dimensions and hardware cost, gathering massive antennas in a centralized way might become impractical. Alternatively, distributed mMIMO [171] could be a viable candidate for future IoT. Specifically, compared with the centralized scenario that a BS is essentially surrounded by devices, in distributed scenario

antennas are distributed over a large geographical area so that each device is surrounded by a few antennas. A number of research works have demonstrated the performance superiority of distributed mMIMO over the traditional centralized mMIMO from different perspectives [172]–[174]. Nevertheless, for emerging MTC applications, only a little research has been done to discover the potential of distributed MIMO for massive access so far, for example, [175] and [176] have provided preliminary analysis on the performance of GFRA in distributed mMIMO.

D. MACHINE LEARNING-ASSISTED IoT CONNECTIVITY

In general, machine learning (ML) algorithms can be divided into four categories, namely supervised learning, semi-supervised learning, unsupervised learning, and reinforcement learning (RL). Each category has its specific applications [177]. Recently, ML algorithms [178]–[180] have drawn much attention to address various issues in wireless communications including link adaptation [181], [182], traffic control [183], [184], and resource allocation [185], [186].

In fact, ML is a very powerful tool that can be used to improve inefficient wireless resource usage in IoT since the resource allocation optimization related problems are usually too complex to be modelled due to the dynamic wireless environments. However, dynamic patterns of the wireless environment could be effectively explored by ML with much lower complexity than using optimization technologies. For this reason, several works have applied ML to address the challenges in the massive access for emerging MTC applications. In [126], an RL scheme was developed to avoid access network congestion and minimize the packet delay by allocating MTC devices to appropriate BSs. In [187], a Q-learning algorithm (one of RL techniques) for the selection

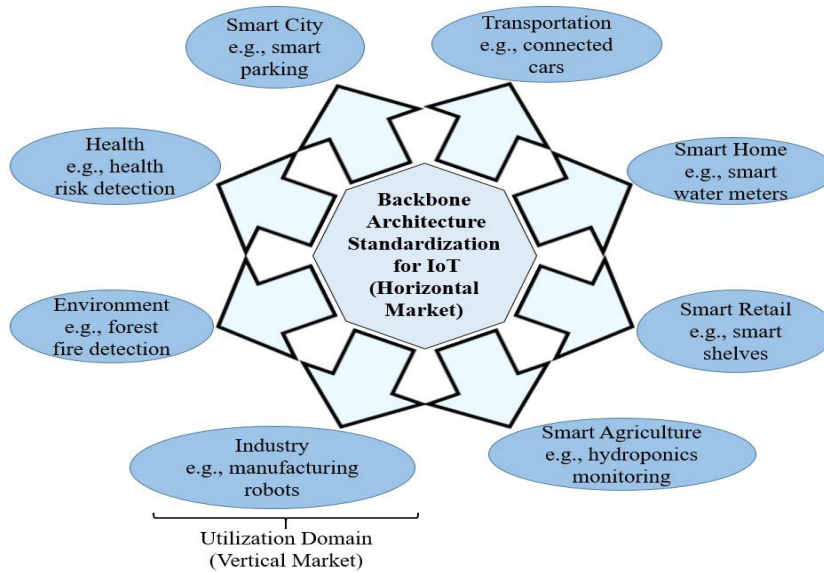


FIGURE 7. Top IoT applications and their utilization domains.

of appropriate BS for the MTC devices was proposed. With the algorithm, MTC devices are able to adapt to dynamic network traffic conditions and decide which BS is the best to be selected based on the QoS parameters. In [188], a Q-learning assisted PRACH scheme was proposed to control MTC traffics with the objective of reducing its impact on the mobile cellular networks. In [189], an online hierarchical stochastic learning algorithm was proposed to determine the access decision for MTC devices. In [190], the authors proposed an adaptive access control scheme by using Q-learning algorithm to solve the massive access problem.

All these research works revealed that RL technique can be used as an efficient resource scheduler to address massive access problems [30]. Nevertheless, there are limitations that need to be considered. For example, a trade-off between the RL algorithm's computational requirements and the learned model's accuracy needs to be well designed, since the higher the required accuracy is, the higher the computational requirements will be, and as a result the higher energy consumption will be. In addition, the learning agent's observations may contain strong temporal correlations and the convergence to the steady state can be time consuming, which may not be suitable for highly dynamic environments.

In summary, all the aforementioned technologies have the potential to be employed in future standards for IoT connectivity. Nevertheless, there are also open issues and limitations that need to be addressed for their implementation. In Table 6, their strengths and limitations are highlighted. Additionally, all these emerging technologies can be not only employed to support massive connectivity, but also can be utilized to provide high reliability and low latency transmissions. In the future, it is expected that more and more advanced technologies can be developed to address various critical challenges for IoT. In the meantime, efforts also need to be made to

smartly merge the existing and emerging technologies to achieve their full potential and maximize the system performance.

IV. CLASSIFICATION OF IoT APPLICATIONS

In this section, we classify the current and future IoT applications with respect to their requirements and then identify the feasible connectivity technologies for each application category. In order to fulfil this task, first, the conventional classification of IoT applications is reviewed and then a different classification is described.

Over the last few years, in the vertical market, most of the applications are classified with respect to their utilization domains (e.g., [18], [191]–[196]). Some examples of the utilization domains in the vertical market are as follows: transportation, smart city, health-care, agriculture, environment, retail, and smart home [197]–[202]. Figure 7 partially illustrates the main utilization domains and their applications. However, the classification of IoT applications based on their utilization domains may result in some conflicts and overlaps [203]. As an example, a sensor for humidity measurement can be considered in multiple utilization domains such as industry, smart agriculture, or even smart environment.

In order to avoid this kind of overlaps and create a straightforward pathway to identify the IoT applications categories based on their technical requirements and consequently find the nominated technologies suitable for them, we consider a different classification of IoT applications. We first focus on end-user-types of applications and then take other application requirements (i.e., data-rate, latency, coverage, power, reliability, and mobility) into account to generalize our classification. The end-user-type classification, similar to the classification used in [203], is illustrated in Figure 8. Contrary to the classic utilization-domain-classification in [18],

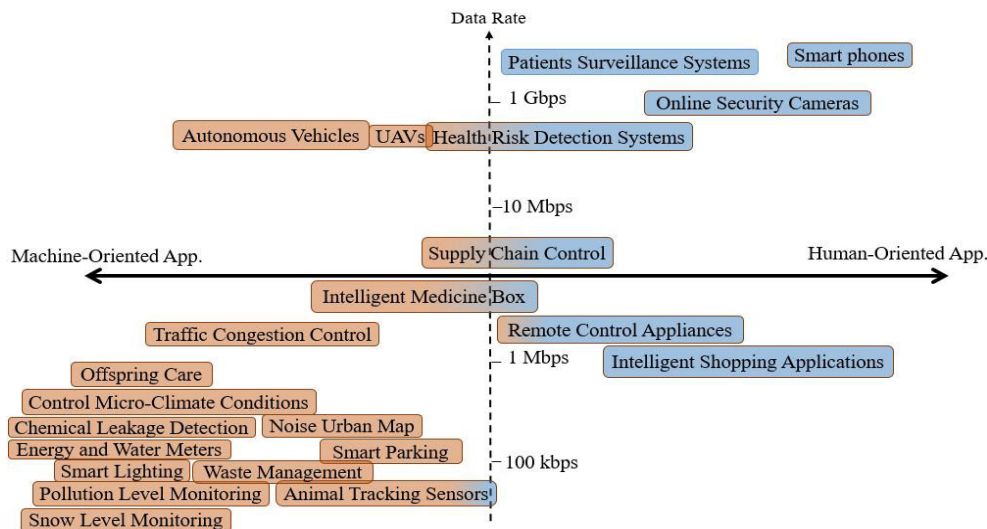


FIGURE 8. Classification of IoT applications based on end-user-type and data rate.

[191]–[196], the classification we use in our paper focuses on end-user-type for each application to classify it into one of the two main categories of human-oriented or machine-oriented applications. Human plays an essential role in human-oriented applications while machine-oriented applications automatically manage their tasks without requiring human intervention. Figure 8 shows that the aggregation of the IoT applications is mostly in machine-oriented applications. As a result, high connectivity density is required that is an important challenging topic in IoT, which comes alongside future massive machine-oriented applications/sensors. It primarily causes a high competition among smart devices to access the limited bandwidth capacity for creating a wireless data delivery link. On the other hand, sharing the available bandwidth among a massive number of devices requires more promising technologies. CS-based IoT connectivity, NOMA, and mMIMO technologies are such emerging technologies that can be deployed for such massive connectivity.

In the following two subsections, the human-oriented and machine-oriented IoT applications are reviewed.

A. HUMAN-ORIENTED IoT APPLICATIONS

Human-oriented IoT applications refer to the applications that require human interaction to communicate with a network. As shown in Figure 8, conventional smartphones, security cameras, patient surveillance systems are three examples of human-oriented IoT applications [204], [205]. Authors in [206], [207] provided a wide range of human-oriented applications and also evaluated the role of the human in interaction with the machines. These applications usually provide a visualization to present information in an intuitive and easy-to-understand way [206], [208] and/or accept interaction based on natural language, e.g., through voice commands, to understand basic human orders and/or respond properly [207]. Human-oriented applications are generally

characterized by high data rates (i.e., from tens of Mbps up to tens of Gbps) [118], [209]. However, there are also a few human-oriented applications that require low data rate (e.g., from 1Mbps up to 10Mbps) like intelligent shopping applications that provide information of all items/interactions in a grocery store to the human as its end-user-type [210]. In addition, one important area in human-oriented applications is pervasive or mobile healthcare like physical activity recognition sensors [211]. Due to the rapid growth in the number of wearable devices and smartphones, healthcare is being evolved from conventional hub-based systems to more personalised healthcare systems [212]. However, enabling these kinds of human-oriented applications referring to the smart healthcare applications is significantly challenging in different issues such as cost-effective and accurate medical sensors, the multidimensionality of data, and compatibility with the current infrastructure [211], [212]. Data fusion techniques or ML-assisted IoT connectivities are potential technologies for classifying types of physical activity and removing the application uncertainty [211].

B. MACHINE-ORIENTED IoT APPLICATIONS

Machine-oriented IoT applications refer to the applications that are able to automatically communicate or interact with each other or a remote server, with minimal human involvement [213], [214]. In the past, they were only characterized by low data rate (i.e., up to hundreds of kbps) and power consumption such as matured WSN and joint power-information transmission technologies (e.g., RFID systems) [215]–[217]. Even today, most of the applications in this class such as monitoring sensors require low data rates (as shown in Figure 8). However, a new set of machine-oriented applications including autonomous vehicles require higher data rates (e.g., tens of Mbps) with relatively more complex designs [218].

It is worth mentioning that some applications such as health risk detection sensors can partially be either machine-oriented or human-oriented application. For instance, a health risk detection sensor can either report the risks to a human as a human-oriented application [219] or interact with medical instruments to modify their performance automatically as a machine-oriented application [220].

C. NOMINATED CONNECTIVITY TECHNOLOGIES FOR IoT APPLICATIONS

In this subsection, first, machine-oriented and human-oriented applications are mapped into certain IoT connectivity technologies. Then, in order to be more specific, the requirements of IoT applications along with their corresponding connectivity technologies are briefly discussed. It is worthwhile to note that the mapping of technologies to the applications is not always unilateral and can be different for a specific application with respect to its unique requirements; however, in this subsection, we focus on general requirements of applications with considering the features of connectivity technologies presented in Sections II and III.

Most of the machine-oriented applications are supported by connectivity technologies such as Bluetooth/BLE, Zigbee, LoRa, and Sigfox, while human-oriented applications usually rely on deployment of cellular technologies such as LTE/LTE-A and 5G technologies. Recently, although cellular networks have mostly been utilized to accommodate human-oriented applications, they are being slowly overshadowed by machine-oriented applications [213]. Therefore, cellular technologies are also being considered the potential candidates to provide connectivity for machine-oriented applications. Today, a majority of cellular machine-oriented applications use legacy cellular technologies due to long-lifecycles of sensors [221]. However, it is expected to be replaced slowly as a broader range of use-cases evolves over time, along with the continued deployment of supporting LTE-based IoT technologies (e.g., LTE-M and NB-IoT) and future capabilities of 5G networks [222].

From the applications standpoint of view, the main disadvantage of LoRa or Sigfox networks deployment over cellular networks deployment is that they rely on their own IoT infrastructure, system model, and data structure, which results in interoperability issues such as difficulty in connecting different IoT applications exposing cross-platform and cross-domain, and also difficulty to use devices in different IoT platforms [223]. As a result, it is difficult to deploy the emergence of IoT technology at a large-scale. Exploiting cellular networks can provide an interoperable and compatible communication network for a large number of IoT applications. It can enable an IoT application to establish an association with a cellular network when the application is activated by an end-user [224]. Consequently, instead of requiring to build a new and private network architecture to host IoT applications (e.g., LoRa and Sigfox), they can piggyback on the same cellular network as smartphones [225].

It is worth noting that both of human-oriented and machine-oriented IoT applications demand some specific requirements including data rate, latency, coverage, power, reliability, and mobility [224], [226]. Note that these requirements overlap with each other and may cause a trade-off for the application's performance. Therefore, in order to generalize our classification and identify the feasible technologies for more specific applications, we take them into account and describe them as follows.

1) DATA RATE

IoT applications can have different data transmission rates from tens of kbps up to tens of Gbps. Three different application groups can be identified in terms of data rate as follows: 1) high data-rate (greater than 10Mbps), 2) medium data-rate (less than 10Mbps and greater than 100kbps), and 3) low data-rate applications (less than 100 kbps) [118].

First, high data-rate applications such as streaming video and web applications, and smartphones are usually supported by 4G (LTE/LTE-A), 5G, OWC, and WiFi. These mentioned applications mostly transmit multimedia contents that require high data rate connectivity technologies. Moreover, mmWave wireless communications – i.e., IEEE 802.15.3c and IEEE 802.11ad – have recently been developed for short-range but very high data rate applications with up to tens of Gbps because of large availability of bandwidth in mmWave bands [227]–[229]. The complexity of the high data rate applications is relatively high and the market share of them is 10% [118]. Second, medium data rate applications such as smart home applications are usually supported by ZigBee, Bluetooth/BLE, and LTE-M technologies [230]. Smart home applications include a set of connected devices in homes such as connected cooking systems with medium data rate requirements [231]. Their design is less complex than high data-rate applications and their market share is estimated to be 30% [118]. Finally, low data-rate applications such as most of the monitoring sensors, goods tracking, smart parking and intelligent agriculture systems are mostly supported by NB-IoT, SigFox, and LoRa technologies [105]. Low power consumption is a critical factor in these kinds of applications and consequently, their design is less complex. Moreover, the market share for this category is estimated to be 60% [118]. Overall, the majority of the future IoT applications require either medium or low data-rate. Therefore, ZigBee, Bluetooth/BLE, WiFi HaLow, LTE-M, NB-IoT, Sigfox, and LoRa will serve as the key connectivity technologies as shown in Figure 9.

2) LATENCY

Most of IoT applications are sensitive to latency. But, the level of sensitivity varies for different applications. Due to this difference, the applications with high and low sensitivity to the latency are categorized into delay-sensitive and delay-tolerant groups, respectively [232]. Autonomous vehicles and health-care systems are two examples of delay-sensitive applications where the shortest possible latency is a critical factor that

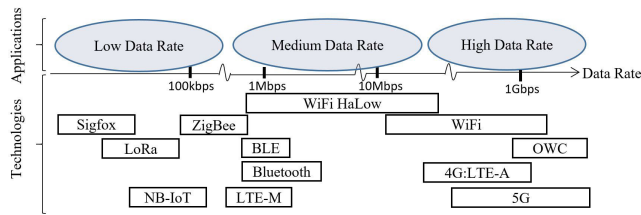


FIGURE 9. Nominated technologies for low, medium, and high data-rate IoT applications.

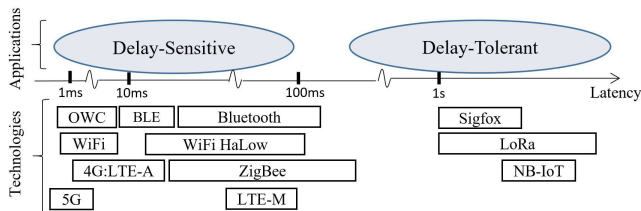


FIGURE 10. Nominated technologies for delay-sensitive and delay-tolerant IoT applications.

affects their performance [224]. To be specific, autonomous vehicles are such driver-less cars that can move automatically and sense their environment to avoid any hazard or accident. Consequently, when the vehicles move at a high speed, latency plays a pivotal role in sensing the environment and make a decision as soon as possible. Likewise, health-care systems (e.g., cardiac telemetry) require to report the possible risks to a distant monitoring station with low latency to assist patients with early treatment. Figure 10 shows the current technologies such as 4G and WiFi can provide a latency up to tens of milliseconds – e.g., the current 4G round-trip latency is about 15ms [101]. Although this range of latency suits most current IoT applications, it is not short enough for future applications such as autonomous vehicles that require a shorter latency. For instance, Tesla company has recently designed a connected autonomous cars system based on current 4G technologies. However, due to high latency, the cars move slowly, maintaining a large car-to-car distance, and forming platoons to cross an intersection [233]. Therefore, moving towards future technologies with low latency such as 5G and OWC technologies is a necessity for these kinds of latency stringent applications. Contrary to the delay-sensitive applications, delay-tolerant applications such as agricultural sensors, waste management systems, and smart parking applications can be supported by existing connectivity technologies as shown in Figure 10. Most of these applications are low duty-cycle applications and the information transmitted by them can be received with relatively large latency (i.e., latency can be greater than 100ms). Therefore, latency, in these delay-tolerant applications, is not as important as in delay-sensitive applications.

3) COVERAGE

The maximum range of communications for IoT applications varies from couple of meters up to tens of kilometres.

The IoT applications which require a communication range of up to tens of meters are categorized as short-range IoT applications. For example, smart home and smart retail applications include a range of connected items/objects in the range of 100m that are considered as short-range applications. On the other hand, the applications with distant connected items/objects (i.e., up to tens of kilometres) are classified as long-range IoT applications (e.g., smart farming and UAV) [118], [234]. For instance, UAV refers to an aircraft without a human pilot onboard and can be used widely in civilian and other applications such as surveillance and product deliveries. UAV may fly long distances while they need to be connected to distant ground control stations. To support the connections in the short-range applications, Bluetooth/BLE, OWC, WiFi, and ZigBee are the nominated connectivity technologies; and for the long-range applications, Sigfox, LoRa, NB-IoT, LTE-M, WiFi HaLow, and 4G/5G are the nominated connectivity technologies as described in Subsections II-A and II-C. In [222], Ericsson forecasts that the number of long-range applications will reach 4.1 billion by 2024 from 1 billion in 2018; and also the number of short-range applications will increase from 7.5 billion in 2018 to 17.8 billion in 2024. The current technologies would not be able to support this massive connectivity. Therefore, the emerging technologies such as NOMA, mMIMO and ML-assisted cellular IoT techniques (as discussed in Section III) can be used in future IoT connectivity paradigms.

4) POWER

Power efficiency is an important requirement that affects the cost of IoT devices. Battery production, recycling, and environmental issues are also important factors that need to be considered in designing IoT applications. For example, even though the smart electric vehicles will not be using the fossil fuel to power the vehicles, they can still cause other environmental problems if the vehicles are not recharged or recycled properly [235], [236]. Therefore, all the IoT applications seek the lowest possible power consumption technologies for low maintenance costs and also for achieving a lower impact on the environment. Most of the human-oriented applications (e.g., smartphones) are able to be charged regularly. However, the most challenging issues appear for ultra-low power consumption applications with LPWAN technologies where they are not able to be charged regularly. For example, applications like agricultural metering sensors normally require the terminal service life with a constant volume battery up to 10 years [118], [237], [238]. Developing such batteries requires careful engineering along with the proper low-power components selection. Besides, the key to achieving good battery life is to ensure that a sensor stays in a low-power standby mode as long as possible and also minimizing the use of wireless communications [239]. PSM and eDRX are two power-saving mechanisms that can be employed by NB-IoT technology to increase the battery lifetime of IoT devices significantly [240]. Additionally, BLE and joint power-information transmission technologies such

TABLE 7. Summary table of IoT applications together with their use-cases and connectivity technologies.

Requirement	App. category	Use-cases (e.g..)	Connectivity technologies
End-user-type	Human-oriented	Smart phone	Legacy cellular technologies, LTE/LTE-A, 5G, WiFi/WiFi HaLow, OWC
	Machine-oriented	Monitoring sensors	Bluetooth/BLE, ZigBee, LPWAN, WiFi/WiFi HaLow, OWC
Data rate	High data-rate	Streaming video cameras	LTE/LTE-A, 5G, OWC, WiFi
	Medium data-rate	Connected cooking systems	Bluetooth/BLE, ZigBee, LTE-M, WiFi HaLow
	Low data-rate	Energy & water meters	NB-IoT, Sigfox, LoRa, ZigBee
Latency	Delay-sensitive	Autonomous vehicles, health-care sensors	LTE/LTE-A, 5G, OWC, WiFi/WiFi HaLow, Bluetooth/BLE, LTE-M
	Delay-tolerant	Waste management sensors	ZigBee, Sigfox, NB-IoT, LoRa
Coverage	Long-range	UAVs, smart farming sensors	LTE/LTE-A, 5G, LoRa, Sigfox, NB-IoT, LTE-M, WiFi HaLow
	Short-range	Smart home appliances	Bluetooth/BLE, ZigBee, OWC, WiFi
Power	Low power	Tracking sensors, smart retail sensors	Bluetooth, ZigBee, LTE/LTE-A, 5G, WiFi
	Ultra low power	Pollution monitoring sensor	BLE, WiFi HaLow, LPWAN: LoRa, Sigfox, LTE-M, NB-IoT
Reliability	Mission critical	Real-time patient surveillance, autonomous vehicles	LTE/LTE-A, 5G, WiFi/WiFi HaLow, OWC
	Mission non-critical	Smart farming sensors	LPWAN: LoRa, Sigfox, LTE-M, NB-IoT
Mobility	High mobility	Autonomous vehicles	LTE/LTE-A, 5G
	Low mobility	Smart traffic lights	LPWAN, Bluetooth/BLE, ZigBee

as backscatter communications have recently been proposed as appealing solutions to ultra-low power consumption IoT applications [241].

5) RELIABILITY

In terms of the reliability of the transmissions, IoT applications can be categorized into two major groups of mission critical and mission non-critical applications [242]. Smart grids, manufacturing robots, autonomous vehicles, and mobile health-care are some examples of mission critical applications [243]. Ericsson forecasts that only a small portion of total IoT applications will be mission critical by 2024 [221]. On the other hand, the majority of IoT applications are mission non-critical IoT applications such as humidity sensors, smart green houses, smart parking, and energy and water meters. Overall, in order to guarantee sufficient reliability for such applications in both critical and non-critical systems, different requirements of end-to-end latency, ubiquity, availability, security, and robustness of the technologies should be assessed [224]. LPWAN and current cellular technologies are the dominant technologies for mission non-critical applications. 3GPP expects that the 5G technologies with support for ultra-reliable low latency communications will enable the first series of mission critical applications such as interactive transport systems, smart grids with real-time control, and real-time control of manufacturing robots by 2020 [221]. Moreover, OWC technologies have also been proposed for short-range but mission critical applications such as real-time patient surveillance systems that report patients movement and vital signs to a monitoring station with high accuracy [62].

6) MOBILITY

IoT applications can be classified into two categories in terms of mobility: low and high mobility applications. Low mobility applications can easily rely on existing connectivity technologies [244]. The challenging issues appear in high mobility applications where the speed can go up to hundreds km/h and consequently they demand for handover, redirection, and cell reselection in connected states. Additionally, high mobility increases the Doppler effect and jeopardizes the reliability of the connectivity technologies [245]. Some examples of high mobility IoT applications are such as vehicles, trains and airplanes demanding enhanced connectivity for in-vehicle/on-board entertainment, accessing the Internet, enhanced navigation through instant and real-time information, autonomous driving, and vehicle diagnostics [224]. In general, high mobility applications utilize cellular connectivity technologies. However, they require significant improvements in current cellular technologies (e.g., 4G and 5G) to overcome high mobility issues for future high mobility applications [246].

Overall, this section presents a straightforward mapping that nominates the potential connectivity technologies for each application category with respect to requirements and connectivity technologies specifications. It is evident that IoT applications can be mapped into multiple categories at the same time to find the best possible connectivity technology. For example, smart agricultural sensors, [200], are usually considered for machine-oriented, low data rate, delay-tolerant, long-range, low power, non-critical, and low mobility applications. Consequently, we can conclude that LPWAN (e.g., LoRa and NB-IoT) connectivity technologies suit them

well. The classification which is summarized in Table 7 provides a unique opportunity for all IoT applications to find their category and select the suitable connectivity technology for the deployment.

V. CONCLUSIONS

Future IoT is expected to accommodate an exponential growth of connected devices while satisfying their diverse applications' requirements. In this survey, we first reviewed the existing wireless IoT connectivity technologies with their specifications and outlined their fundamental bottleneck and challenges to support massive IoT connectivity. To shed light on addressing the bottleneck, we then reviewed the strengths and limitations of some emerging connectivity technologies, such as CS, NOMA, mMIMO, and ML based random access, that have the potential to be employed in future standards for massive IoT connectivity. We explained that although the emerging CS-based connectivity and grant-free RA protocols are proper options for signalling overhead reduction, their complexity in high-density MTC is still an open issue. We also explained that in emerging NOMA-based connectivity which has been proposed as a key idea for massive connectivity in a spectral-efficient way, the detection algorithms and interference cancellation techniques are still challenging in high-density MTC. In addition, we discussed that different from NOMA, emerging mMIMO connectivity mitigates the interference while providing resource-efficient communication. However, considering the array dimensions and hardware cost, gathering massive antennas in a centralized way might become impractical. Furthermore, we briefly discussed the limitations and strengths of the ML-assisted connectivity for massive MTC. Finally, we presented a classification of IoT applications with respect to different technical domains and also discussed the suitable IoT connectivity technology candidates for supporting various IoT applications.

APPENDIX A ALOHA

ALOHA is a RA protocol [247] that is proposed to share a common radio channel between multiple nodes. In this appendix, we only focus on slotted ALOHA where time is divided into slots and each slot length corresponds to one packet duration (so that a packet can be transmitted within a slot). In slotted ALOHA, it is also assumed that nodes are synchronized and there is a receiver station.

Suppose that each node can transmit a packet for a given slot with probability p , which is called the access probability. Assume that there are K nodes with the same access probability. Then, a node that transmits a packet can successfully transmit its packet if there are no other nodes transmitting simultaneously, which has the following probability:

$$P_S = (1 - p)^{K-1}. \tag{1}$$

If there are more than or equal to 2 nodes that simultaneously transmit packets, it is assumed that no packet is successfully transmitted due to packet collision. Since a node transmits a

packet with probability p and there are K nodes, the number of nodes that can successfully transmit packets, which is called the throughput, is given by

$$\eta(K, p) = KpP_S = Kp(1 - p)^{K-1}. \tag{2}$$

If p is sufficiently low, we have $1 - p \approx e^{-p}$. Thus,

$$\eta(K, p) \approx Kpe^{-p(K-1)} \approx Kpe^{-Kp}. \tag{3}$$

The approximation is reasonable if K is large. Letting $x = Kp$, the throughput becomes xe^{-x} , which is a \cap -shape function of x and has the maximum at $x = 1$. In other words, if K is sufficiently large, the throughput becomes the maximum, which is e^{-1} , when $x = 1$ or $p = \frac{1}{K}$.

In slotted ALOHA, as mentioned earlier, all the nodes need to be synchronized. In addition, it might be necessary for nodes to know whether or not transmitted packets are successfully received at the receiver station. To this end, the receiver station is to periodically broadcast a beacon signal for synchronization and feedback signals to let nodes know the success of packet transmission (using a feedback signal of acknowledgment (ACK) or negative acknowledgment (NAK) at the end of slot. Note that a node that transmits a packet receives a NAK, it can see that collision happens. The collided packet is to be dropped or re-transmitted later. In the case of NAK, since there are other nodes transmit packets an immediate re-transmission results in another collision, which should be avoided. Thus, a random back-off time is required for re-transmissions.

Since slotted ALOHA is a distributed system, there are stability issues. In particular, if each node has a buffer to keep packets before transmissions, a buffer overflow can happen due to frequent packet collisions. Thus, distributed access control and re-transmission strategies are to be carefully designed to keep buffer length (which is also proportional to access delay) stable.

APPENDIX B CSMA

Carrier-sense multiple access (CSMA) is a RA protocol where a node attempts to verify the absence of other traffic (by sensing the presence of carriers or signals) in a common access channel before transmitting. There are different types of CSMA protocols including CSMA with collision detection (CSMA/CD) and CSMA with collision avoidance (CSMA/CA).

In CSMA/CD, suppose that a node wants to transmit a packet. Then, it senses the channel and transmits a packet if the channel is idle. However, multiple nodes can transmit simultaneously and sense a collision. In this case, they abort transmissions after sending a jamming signal to notify collision. As a result, the duration of collision can be shortened and it can result in a better throughput.

CSMA/CD can have the following re-transmission strategies:

- Nonpersistent CSMA: If the channel is idle, the node transmits a packet. If the channel is not idle, the node

waits for a random time (according to a certain distribution).

- 1-persistent CSMA: If the channel is idle, the node transmits a packet. If the channel is not idle, the node waits until the channel becomes idle and transmits a packet immediately. In this case, a collision always occurs if there are multiple nodes (with packets) sensing at the same time.
- p -persistent CSMA: When a node with a packet senses that the channel is idle, it transmits a packet with probability p and delays by τ with probability $1 - p$, where τ is the duration of minislots. A node waiting for a time duration of τ is to repeat the same process above. That is, it senses the channel: if the channel is idle, it transmits with probability p and delays by τ with probability $1 - p$. If the channel is busy, it waits until the channel is idle (and repeats the same process again).

CSMA/CD is usually used for wired networks where a node can simultaneously sense the channel when it transmits a packet. In wireless channels, however, a node cannot sense when it transmits. In this case, CSMA/CA can be used, where collision is to be avoided using a few strategies. In CSMA/CD, inter-frame space (IFS) is introduced to wait a certain period of time although the channel appears idle after sensing as another node may start transmitting, but its signal is not yet reached at the node. If a node is ready to transmit, a random number is generated to wait and the range of the random number is called the contention window. The waiting time is proportional to the random number and the length of the contention window is varying. Initially, the length of contention window is set to 1 and doubled if the node sees that the channel is not idle after the IFS time. In CSMA/CD, although collisions are to be avoided with CS at the sender, they can happen because the collisions happen at the receiver. Thus, feedback signals (ACK or NAK) are given to the nodes to inform collisions. Moreover, in wireless channels, signal strength decreases proportional to the square of the distance and may cause near-far terminal problems in CSMA/CD. Therefore, CSMA/CA usually utilizes two short signaling packets to avoid collisions as follows

- RTS (request to send): a node requests the right to send from a receiver with a short RTS packet before it sends a data packet.
- CTS (clear to send): the receiver grants the right to send as soon as it is ready to receive.

Both of RTS and CTS packets contain information such as node address, receiver address, and packet size. Fig. 11 shows the standard CSMA/CA mechanism. A sender node senses the channel and sends RTS when channel is idle. Other exposed nodes that receive the RTS, hold their requests for a RTS network allocation vector (NAV) period. Receiver receives the RTS and sends the CTS after a short IFS period. Accordingly, other exposed nodes that receive the CTS hold their transmission requests for a CTS NAV period. The sender node receives the CTS and sends its data after a short

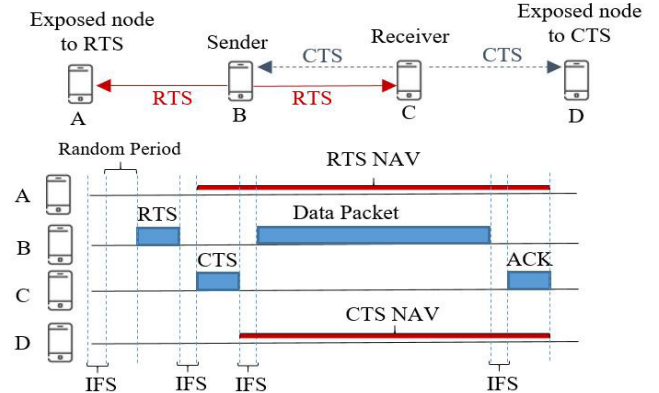


FIGURE 11. Standard CSMA/CA mechanism with RTS/CTS packet transmission.

IFS period. The receiver receives the data and sends ACK to the sender [248]. Consequently, no collision occurs in CSMA/CA. Different variations of this model can be found in IEEE 802.11 as distributed foundation wireless MAC [249].

APPENDIX C CS

Compressive sensing (CS) is to deal with sparse signals [134], [250]. There are a number of applications of CS including image compression and radar systems. In this appendix, we briefly discuss the sparse signal recovery in the context of CS and explain how the notion of CS is applied to RA.

The set of k -sparse signals is defined as

$$\Sigma_k = \{s : \|s\|_0 \leq k\}. \tag{4}$$

A group of signals can have a sparse representation if s can be expressed as

$$s = \Phi c, \tag{5}$$

where $c \in \Sigma_k$ and Φ is a (known) basis. For convenience, we assume that the length of s is n . For a given s , suppose that the following vector is available:

$$y = Cs, \tag{6}$$

where C is an $M \times L$ matrix that is called the measurement matrix. Here, it is assumed that $M < L$ for a dimensionality reduction. In general, it is not possible to recover s from y unless s and C have certain conditions (as (6) is an underdetermined linear system).

Suppose that the sparsity of s is known in (6). For convenience, let $q = \|s\|_0$. Consider the estimation of s based on the ML criterion:

$$\begin{aligned} \hat{s} &= \operatorname{argmax}_{s: \|s\|_0=q} f(s|y) \\ &= \operatorname{argmin}_{s: \|s\|_0=q} \|y - Cs\|^2. \end{aligned} \tag{7}$$

Since C is an $M \times L$ matrix, there are L columns. For a given sparsity q , there can be $L_q = \binom{L}{q}$ possible supports. Denote by \mathcal{I}_i the i th support, where $i = 1, \dots, L_q$. For example, if $L = 4$

and $q = 2$, $L_q = 6$ and $\mathcal{I}_1 = \{1, 2\}$, $\mathcal{I}_2 = \{1, 3\}$, $\mathcal{I}_3 = \{1, 4\}$, $\mathcal{I}_4 = \{2, 3\}$, $\mathcal{I}_5 = \{2, 4\}$, $\mathcal{I}_6 = \{3, 4\}$. In addition, denote by C_i and s_i the submatrix of C and the subvector of s corresponding to \mathcal{I}_i , respectively. Then, for given \mathcal{I}_i , it can be shown that

$$\min_{s: \|s\|_0=q} \|y - Cs\|^2 = \min_{i \in \{1, \dots, L_q\}} \min_{s_i} \|y - C_i s_i\|^2. \quad (8)$$

If $q \leq M$, the inner minimization can be solved by the method of least squares (LS), i.e.,

$$\begin{aligned} \hat{s}_i &= \operatorname{argmin}_{s_i} \|y - C_i s_i\|^2 \\ &= C_i^\dagger y, \end{aligned} \quad (9)$$

where C_i^\dagger is the pseudo-inverse of C_i . If the rank of C_i is q , $C_i^\dagger = (C_i^H C_i)^{-1} C_i^H$. In addition, it follows that

$$\min_{s_i} \|y - C_i s_i\|^2 = \|(I - C_i(C_i^H C_i)^{-1} C_i^H)y\|^2. \quad (10)$$

As a result, the ML solution in (7) can be found if all possible supports are considered. However, the computational complexity becomes proportional to $L_q = \binom{L}{q}$. Thus, for a large L , this approach might be prohibitive.

From (7), a different approach can be considered by noting that s is sparse (i.e., $q \ll L$). Let us assume that $n = 0$. Then, it is expected to find a sparse solution that satisfies $y = Cs$. Since $M < L$, the resulting system is considered underdetermined (i.e., more unknown variables than equations). Since an underdetermined linear system has either no solution or infinitely many solutions, it is necessary to take into account the sparsity of s . Since the sparsity of s can be measured by the ℓ_0 -norm, in order to find the most sparse solution, the following optimization problem can be formulated:

$$\begin{aligned} \min \|s\|_0 \\ \text{subject to } y = Cs. \end{aligned} \quad (11)$$

Unfortunately, (11) is not a convex optimization problem since $\|s\|_0$ is not a convex function. To generalize (11), the p -norm can be used, which results in the following problem:

$$\begin{aligned} \min \|s\|_p \\ \text{subject to } y = Cs. \end{aligned} \quad (12)$$

If $p \geq 1$, the problem becomes a convex optimization problem. Furthermore, in the presence of error or background noise, the constraint can be relaxed and the following convex-optimization problem can be formulated:

$$\begin{aligned} \min \|s\|_p \\ \text{subject to } \|y - Cs\|^2 \leq \epsilon, \end{aligned} \quad (13)$$

where $\epsilon > 0$. To obtain a sparse solution, it is desirable to have $p \leq 1$ as illustrated in Fig. 12. That is, since the cost function in (13) is spike with $p \leq 1$, the solution of (13) tends to be sparse when $p = 1$ (although ℓ_0 -norm is not used), while the solution with $p = 2$ (which corresponds to the least squares solution of an underdetermined system) is not sparse.

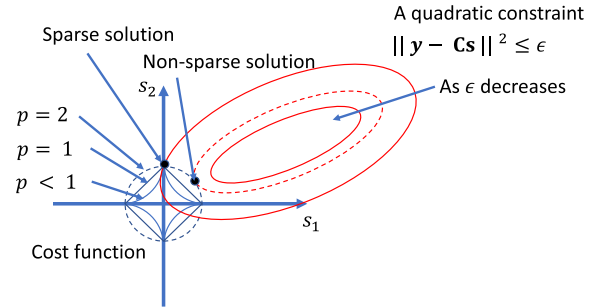


FIGURE 12. Optimization problems with a quadratic constraint.

As mentioned earlier, since the problem in (13) with $p = 1$ is a convex optimization problem, its sparse solution can be obtained by a number of convex optimization tools.

The notion of CS can be applied to the user activity detection in RA. Suppose that there are L users and each user has a unique signature sequence, denoted by c_l . In addition, denote by s_l the user activity variable. That is, if user l is to transmit a signal, it can send its unique signature sequence, c_l . Let the length of c_l be M (if $L > M$, the c_l 's are not orthogonal to each other). Thus, the received signal at a receiver is given by

$$y = \sum_{l=1}^L c_l s_l + n = Cs + n, \quad (14)$$

where n is the background noise. If a few users are active at a time, s becomes sparse. In RA to support a large number of users, it is desirable to have a large L for a fixed M . This shows that the receiver can employ the notion of CS to detect active users when $L > M$ as shown above. The resulting RA (with non-orthogonal sequences, $\{c_l\}$) is referred to as compressive RA [132], [133].

APPENDIX D NOMA

Non-orthogonal multiple access (NOMA) refers to a set of multiple access schemes where multiple access channels are not orthogonal as opposed to orthogonal multiple access (OMA), e.g., time division multiple access (TDMA) and frequency division multiple access (FDMA). While there are various ways to form NOMA schemes, the most popular one is based on the power-domain, which is often called power-domain NOMA [251].

Power-domain NOMA employs the superposition coding where multiple signals are transmitted through a shared channel or radio resource block with different power levels in downlink transmissions. In power-domain NOMA, user pairing is also an important technique where one user is usually close to a BS (the strong user) and the other user is far away from the BS. The former and latter users are referred to as the near and far users, respectively. Due to different distances, the transmit signal power to the near user is lower than that to the far user. Thus, at the near user, the signal to the far user is a strong interfering signal that can be decoded

and then removed using successive interference cancellation (SIC). For convenience, denote by s_1 and s_2 the signals to the near and far users, respectively, and the transmit powers are accordingly denoted by P_k , $k = 1, 2$. The received signal at the near user is given by

$$y_1 = h_1 \left(\sqrt{P_1} s_1 + \sqrt{P_2} s_2 \right) + n_1, \quad (15)$$

where h_1 and n_1 are the channel coefficient and the background noise at the near user, respectively. As mentioned earlier, it is assumed that $P_1 \ll P_2$. Taking s_1 as the interference, the near user can decode s_2 and remove it as follows:

$$\tilde{y}_1 = y_1 - h_1 \sqrt{P_2} \hat{s}_2, \quad (16)$$

where \hat{s}_2 is the estimate of s_2 . If $\hat{s}_2 = s_2$, $\tilde{y}_1 = h_1 \sqrt{P_1} \hat{s}_1 + n_1$. Then, s_1 is to be decoded from \tilde{y}_1 . The above procedure is called SIC.

If the s_k 's are coded signals using a capacity-achieving code, with power-domain NOMA, using the capacity formula [252], the code rate for s_k , denoted by R_k , has the following constraints:

$$\begin{aligned} R_2 &\leq \log_2 \left(1 + \frac{|h_1|^2 P_2}{N_0 + |h_1|^2 P_1} \right) \\ R_1 &\leq \log_2 \left(1 + \frac{|h_1|^2 P_1}{N_0} \right), \end{aligned} \quad (17)$$

where N_0 stands from the noise variance. The first and inequalities in (17) are to successfully decode s_2 and s_1 (after SIC) at the near user, respectively.

At the far user, the received signal is given by

$$y_2 = h_2 \left(\sqrt{P_1} s_1 + \sqrt{P_2} s_2 \right) + n_2, \quad (18)$$

where h_2 and n_2 are the channel coefficient and the background noise at the far user, respectively. The far user is to decode s_2 and requires the following condition for successful decoding:

$$R_2 \leq \log_2 \left(1 + \frac{|h_2|^2 P_2}{N_0 + |h_2|^2 P_1} \right). \quad (19)$$

As a result, the rate constraints from (17) and (19) can be combined as follows:

$$\begin{aligned} R_2 &\leq \min_k \log_2 \left(1 + \frac{|h_k|^2 P_2}{N_0 + |h_k|^2 P_1} \right) \\ R_1 &\leq \log_2 \left(1 + \frac{|h_1|^2 P_1}{N_0} \right), \end{aligned} \quad (20)$$

which plays a key role in the power allocation for power-domain NOMA.

While power-domain NOMA is usually studied for downlink transmissions, it can be naturally applied to uplink transmissions where the received signal at the BS becomes a superposition of transmitted signals from a number of users. For example, with two users, the received signal at the BS is given by

$$y = h_1 \sqrt{P_1} s_1 + h_2 \sqrt{P_2} s_2 + n, \quad (21)$$

where n is the background noise at the BS. Here, s_k is the transmitted signal by user k and P_k is the transmit power at user k . While the BS is able to perform joint decoding to recover s_1 and s_2 , its complexity is usually high. However, by exploiting the notion of SIC, the complexity can be lowered. For example, if $|h_1|^2 P_1 \gg |h_2|^2 P_2$, s_1 is decoded first (where s_2 is regarded as an interfering signal). Then, s_1 is removed and s_2 is decoded from $y - h_1 \sqrt{P_1} s_1$. As a result, the rate constraints are given by

$$\begin{aligned} R_1 &\leq \log_2 \left(1 + \frac{|h_1|^2 P_1}{N_0 + |h_2|^2 P_2} \right) \\ R_2 &\leq \log_2 \left(1 + \frac{|h_2|^2 P_2}{N_0} \right). \end{aligned} \quad (22)$$

We note that the sum rate becomes

$$\begin{aligned} R_1 + R_2 &\leq \log_2 \left(1 + \frac{|h_1|^2 P_1}{N_0 + |h_2|^2 P_2} \right) + \log_2 \left(1 + \frac{|h_2|^2 P_2}{N_0} \right) \\ &= \log_2 \left(1 + \frac{|h_1|^2 P_1 + |h_2|^2 P_2}{N_0} \right), \end{aligned} \quad (23)$$

which implies that power-domain NOMA is also optimal in terms of the sum rate as the sum rate in (23) is also the achievable rate of multiple access channel with (21) [252].

APPENDIX E mMIMO

Massive multiple input multiple output (mMIMO) is an extended form of multi-user MIMO (MU-MIMO) systems where hundreds or thousands of BS antennas simultaneously serve tens or hundreds of users over the same wireless time-frequency resource. In mMIMO, time division duplex (TDD) operation is more favorable than frequency division duplex (FDD) operation since the TDD can take the advantage of reciprocity between uplink channel and downlink channel within a given coherence interval and thus remove the need for downlink channel estimation [253].

Since the number of antennas, M , at the BS is usually much larger than the number of users K , i.e., $M \gg K$, favorable propagation (FP) can be approximately achieved in mMIMO systems due to the law of large numbers [151], which means users' channel vectors are mutually orthogonal/quasi-orthogonal. Under the property of FP, simple linear processing (receive beamforming in the uplink and transmit beamforming in the downlink), such as conjugate beamforming (CB) and zero-forcing beamforming (ZFB), can be nearly optimal to discriminate the signal transmitted by each user from the signals of other users in mMIMO, since the effect of user interference and noise can be eliminated. Furthermore, thanks to the large number of antennas, channel hardening is another key property in mMIMO [152], upon which the channel becomes nearly deterministic. As a result, the effect of small-scale fading is averaged out. This also simplifies the signal processing significantly in mMIMO.

Consider the downlink transmission in mMIMO (the same argument can be used for the uplink transmission), with the

transmit CB, the transmitted signal vector from the BS to all users is given by

$$\mathbf{s} = \sqrt{\frac{P_t}{KM}} \sum_{k=1}^K \mathbf{h}_k^H x_k, \quad (24)$$

where P_t is the total power transmitted by the BS and $\mathbf{h}_k \in \mathbb{C}^M \sim \mathcal{CN}(0, \mathbf{I}_M)$ stands for the channel response vector between the k th user and the BS. \mathbf{h}_k^H is the transmit conjugate beamformer and $(\cdot)^H$ stands for the matrix Hermitian. x_k is the data symbol intended for the k th user with power normalization, i.e., $\mathbb{E}[|x_k|^2] = 1$.

Accordingly, the received signal at the k th user is given by

$$y_k = \underbrace{\sqrt{\frac{P_t}{KM}} \mathbf{h}_k^H \mathbf{h}_k x_k}_{\text{Desired signal}} + \underbrace{\sqrt{\frac{P_t}{KM}} \sum_{j=1, j \neq k}^K \mathbf{h}_k^H \mathbf{h}_j x_j}_{\text{Multiuser interference}} + n_k, \quad (25)$$

where n_k is the additive Gaussian noise with zero-mean and unit-variance.

In mMIMO, when $M \rightarrow \infty$, under the law of large numbers, we have,

$$\frac{\mathbf{h}_k^H \mathbf{h}_k}{M} \xrightarrow{M \rightarrow \infty} 1, \quad (26)$$

$$\frac{\mathbf{h}_k^H \mathbf{h}_j}{M} \xrightarrow{M \rightarrow \infty} 0, \quad k \neq j. \quad (27)$$

Then, we have

$$\frac{y_k}{\sqrt{M}} \xrightarrow{M \rightarrow \infty} \sqrt{\frac{P_t}{K}} x_k, \quad (28)$$

which indicates that the multiuser interference and noise can be eliminated in mMIMO when M is sufficiently large.

In addition, the SINR can be written as

$$\text{SINR}_k = \frac{\frac{P_t}{KM} |\mathbf{h}_k^H \mathbf{h}_k|^2}{1 + \frac{P_t}{KM} \sum_{j=1, j \neq k}^K |\mathbf{h}_k^H \mathbf{h}_j|^2}. \quad (29)$$

Considering $M, K \rightarrow \infty$ with a fixed ratio, under the law of large numbers, we have,

$$\frac{|\mathbf{h}_k^H \mathbf{h}_k|^2}{M} \xrightarrow{M \rightarrow \infty} M, \quad (30)$$

$$\frac{|\mathbf{h}_k^H \mathbf{h}_j|^2}{M} \xrightarrow{M \rightarrow \infty} 1, \quad k \neq j. \quad (31)$$

Thus, the asymptotic deterministic equivalence of the SINR can be obtained as

$$\overline{\text{SINR}}_k = \frac{M}{K} \frac{P_t}{1 + P_t}. \quad (32)$$

Accordingly, the asymptotic sum rate in mMIMO is given by

$$R = K \log\left(1 + \frac{M}{K} \frac{P_t}{1 + P_t}\right). \quad (33)$$

From (33), it can be seen that a huge spectral efficiency and energy efficiency are obtained when M and K are large. Without the need of increase in transmitted power P_t , by increasing

M , we can increase the throughput per user and serve more users simultaneously. On the other hand, given a targeted throughput per user, more power can be saved as M grows.

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