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Review

Sixth-Generation (6G) Networks for Improved Machine-to-Machine (M2M) Communication in Industry 4.0

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Abstract: The sixth generation of mobile networks (6G) has the potential to revolutionize the way we communicate, interact, and use information for machine-to-machine (M2M) communication in Industry 4.0 and Industry 5.0, while also improving coverage in places that were previously considered difficult to access and/or digitally excluded, and supporting more devices and users. The 6G network will have an impact through a combination of many technologies: the Internet of Things (IoT), artificial intelligence/machine learning, virtual and augmented reality, cloud computing, and cyber security. New solutions and architectures and concepts for their use need to be developed to take full advantage of this. This article provides an overview of the challenges in this area and the proposed solutions, taking into account the disruptive technologies that are yet to be developed.

Keywords: 6G networks; IRS; XL-MIMO; cell-free mMIMO; massive MIMO; 6G visions and requirements; deep learning (DL); emerging technologies; machine learning (ML); reinforcement learning (RL); sixth generation (6G) communication; wireless communications

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1. Introduction

The demand for wireless connectivity has been growing exponentially over the last 15 years. In five years' time, there will be approximately 17 billion devices connected to the mobile network, generating a flow of one thousand exabytes of data per month. It will also be necessary to transition from fifth-generation (5G) to sixth-generation (6G) systems to meet the growing demand for services and requirements for innovative applications, including in industry. Sixth-generation (6G) networks, which are intended to support mass connectivity and ensure an increase in efficiency and quality of service for all users, including industrial ones, will have to supply effective solutions to many technical problems. This is particularly the case with multiple antennas and multiple-input multiple-output (MIMO) technologies for 6G networks, namely massive MIMO (mMIMO), extremely large MIMO (XL-MIMO), intelligent reflecting surface (IRS), and cell-free mMIMO (CF-mMIMO) [1]. The characteristics of 6G networks include ultra-reliable low-latency communications (URLLC), ultra-high throughput, high energy and spectrum efficiency, ultra-dense connectivity, integrated sensing, and secure communications. Given the high load and computational complexity, technologies are already working to provide 6G communications to mass users: IRS, unmanned aerial vehicles (UAVs), non-orthogonal multiple access (NOMA), etc. Optimizing the functionality of a 6G system may be difficult or even impossible using traditional mathematical methods—instead, machine learning (ML), deep learning (DL), and reinforcement learning (RL) are increasingly being proposed (Figure 1) [2].

This article aims to provide an overview of the challenges in the area of 6G networks for improved machine-to-machine (M2M) communication in Industry 4.0 and the proposed solutions, taking into account the disruptive technologies that are yet to be developed. M2M uses the Industrial Internet of Things (IIoT) to communicate between machines for collaborative automation and intelligent optimization. This requires high-quality connections, ubiquitous communication, and interoperable interactions. Manufacturing IIoT applications are focused on collaboration through M2M messaging (CoM2M). The scalable interoperability of production applications is necessary for machine cooperation and data interoperability at the communication and semantic levels. The novelty and contribution of this work lie in the emphasis on 6G technologies, which are still being developed and are planned to be implemented in the next five years. A coherent look at these development areas can reveal gaps or unevenly developing areas, as well as opportunities for development in subsequent substantive areas and time steps. However, we would like to draw attention to the fact that this is a one-sided view: from the point of view of M2M and Industry 4.0/5.0. Therefore, we focus not on what 6G is, but what it can be in Industry 5.0 after 2030, if we take advantage of all the opportunities associated with it. Perhaps engineers and scientists from research areas such as the Green Deal or smart technology will have different expectations and priorities that are not necessarily contradictory to ours. The market for Industry 5.0 networks and technologies is focused on people and their environment and is more than a set of visions, concepts, and technologies that did not fit into the 5G concept—it is the opportunity to shape the intelligent industry from scratch to solutions that will appear on the market after 2030 as products, services, or processes.

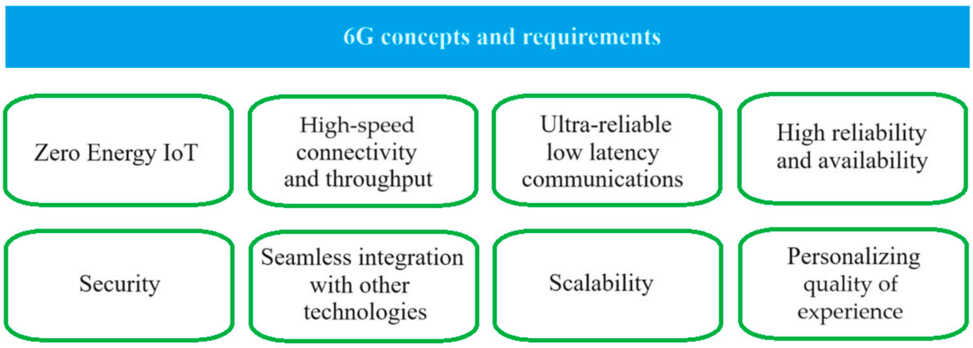

Figure 1. 6G visions and requirements [2].

To improve readability, all acronyms appearing in the article are explained in Table 1 below (in alphabetical order).

Table 1. Acronyms appearing in the article.

Acronym	Explanation
1G	First generation of mobile networks
2G	Second generation of mobile networks
3G	Third generation of mobile networks
3GPP	Third generation partnership project
4G	Fourth generation of mobile networks
5G	Fifth generation of mobile networks
6G	Sixth generation of mobile networks
AI	Artificial intelligence
AKA	Authentication and key agreement
AP	Access point
AR	Augmented reality
AS	Angular spread
BCDID	Blockchain-based collaborative distributed intrusion detection

Table 1. *Cont.*

Acronym	Explanation
BER	Bit error rate
BFSK	Binary frequency shift keying
BLE	Bluetooth low energy
CF-mMIMO	Cell-free massive multiple-input multiple-output
CIR	Channel impulse response
CoM2M	Collaboration through M2M messaging
CPS	Cyber-physical system
CRSN	Cognitive radio sensor network
DS	Delay spread
DL	Deep learning
DTS	Dynamic bandwidth throttling
eMBB	Enhanced mobile broadband
ERLLC	Extremely reliable and low-latency communication
eSIM	Embedded subscriber identity module
FA	Factory automation
FP	Fractional programming
GEO	Geostationary earth orbit
HAP	High altitude platform
HCS	Human-centric services
ICS	Industrial control system
IIoT	Industrial Internet of Things
IMS	Intelligent multi-surface
IoD	Internet of Drones
IoE	Internet of Everything
IoMT	Internet of Medical Things
IoRT	Internet of Remote Things
IoT	Internet of Things
IoV	Internet of Vehicles
IP	Internet protocol
IRS	Intelligent reflecting surface
ISO/OSI	International Organization for Standardization/Open Systems Interconnection
IUABP	Intelligent-reflecting surface-user equipment association based on pilots
LAP	Low altitude platform
LEO	Low earth orbit
LOS	Line-of-sight
LTE	Long-term evolution
M2M	Machine-to-machine
MAC	Media access control
MEO	Medium earth orbit
MIMO	Multiple-input multiple-output

Table 1. *Cont.*

Acronym	Explanation
MIMO-OFDM	Multi-input, multi-output wireless orthogonal frequency division multiplexing
ML	Machine learning
mMIMO	Massive multiple-input multiple-output
MMSE-OSIC	Minimum mean squared error ordered successive elimination constellation
mMTC	Massive machine-type communication
mRSU	Mobile roadside unit
NRZ	Non-return-to-zero
NOMA	Non-orthogonal multiple access
NTN	Non-terrestrial networks
OOK	On–off keying
OPL	Optical path loss
PA	Process automation
PBAS	Pilot-based access point selection
RF	Radio frequency
RL	Reinforcement learning
RSMA	Rate-splitting multiple access
RSU	Roadside unit
RTBC	Real-time broadband communication
SDMA	Spatial division multiple access
SDN	Software-defined network
SHA	Smart home automation
SNR	Signal-to-noise ratio
THz	Terahertz (communication)
UAVs	Unmanned aerial vehicles
UCBC	Uplink centric broadband communication
uHDD	Ultra-high data density
uHSLLC	Ultra-reliable low latency communications
uMUB	Ubiquitous mobile ultra-broadband
URLLC	Ultra-reliable low-latency communications
V2X	Vehicle-to-everything
VANET	Vehicular ad hoc network
VLC	Visible light communication
VLEO	Very low earth orbit
VR	Virtual reality
WSN	Wireless sensor network
XL-MIMO	Extra-large multiple-input multiple-output
XR	Extended reality

The article consists of the following sections: after the introduction, the methodology of the review is described, followed by the results relevant to show 6G support for M2M within the Industry 4.0 and Industry 5.0 paradigms, followed by a discussion of the main limitations of the research to date and key directions for further research and conclusions.

2. Materials and Methods

For the purpose of this review, six main bibliographic databases (Web of Science, Scopus, ACM Digital Library, CiteSeer, DBLP, and Pubmed) were analyzed using specified keywords in English (M2M, 6G, IoT, IIoT, Industry 4.0, Industry 5.0, and related). The inclusion criteria were defined so as to return scientific articles and chapters in monographs (including post-conference materials) published in the last 10 years. Letters to the editor were excluded. The identified publications underwent content analysis, and duplicate studies were removed. The results of the analysis are presented below.

The following presentation of the results stems from the way in which the introduction and diffusion of 6G networks will affect M2M—initially mainly in the area of communication and only later in the area of production, creating conditions favorable to completely new solutions, perhaps not yet known or defined. This approach also stems from the gradual planned development of 6G, which will be fully defined only in the years to come.

3. Results of the Review

In line with the latest knowledge and experience, the key purpose of IIoT is to interconnect machines, anywhere and anytime, within the production system in order to improve its productivity, efficiency, safety, and intelligence (also as part of the implementation of previously unused solutions, such as 3D printing). IIoT has unique types of built-in intelligent devices (production, control/design, sensors, effectors, as well as e-commerce for cooperation with the customer in order to select the final shape and configuration of the product, service, or process), network technologies, quality of services, and command and control processes. The IIoT architecture becomes the basis for IIoT applications—factory automation (FA) and process automation (PA)—in three areas: control, network, and IT. Industrial control systems, including those based on 6G, provide M2M communications, software-defined networks (SDNs), and—from a computing perspective—cloud and edge and hybrid platforms in cloud and edge computing. In the context of a cyber-physical system (CPS), control, network, and computing systems are interactively built and shaped into IIoT systems to achieve the operator's design goals. Automation in dynamic industrial operations uses techniques such as reinforcement learning for the faster and more efficient automatic reconfiguration of control systems and networks in dynamic industrial environments.

3.1. The 6G-Based Revolution of Industry 4.0/5.0

Sixth-generation networks are expected to revolutionize M2M communications in the context of Industry 4.0/5.0, offering the following significant improvements over previous generations:

- Ultra-reliable low-latency communications (URLLC): 6G networks are expected to provide ultra-reliable low-latency communications, which are crucial for real-time M2M interactions in industrial settings. This means machines can communicate with each other with minimal latency and high reliability, allowing users to respond quickly to changing conditions on the factory floor.
- Massive machine-type communication (mMTC): With 6G networks, the ability to connect a huge number of devices simultaneously is expected to improve significantly. This capability is essential to support the wide range of sensors, actuators and other devices found in modern industrial environments. mMTC facilitates seamless communication between these devices, enabling efficient coordination and automation.
- High-bandwidth transmission: Industry 4.0 applications often involve the transmission of large amounts of data, such as high-resolution sensor data, video streams, and virtual reality (VR) environments. Sixth generation networks are expected to support significantly higher data rates than previous generations, facilitating the smooth trans-

mission of bandwidth-intensive data in real time. This enables advanced analytics, remote monitoring, and predictive maintenance in industrial systems.
- Sixth-generation networks are expected to introduce network slicing capabilities, enabling the creation of virtualized, dedicated network slices tailored to specific industrial applications. This enables enterprises to tailor network resources to their requirements, ensuring optimal performance, security, and reliability of M2M communications across a variety of Industry 4.0 use cases.
- Integration with edge computing, which is increasingly used in Industry 4.0, to process data closer to the source, reducing latency and bandwidth utilization. Sixth-generation networks will likely integrate seamlessly with edge computing infrastructure, enabling distributed M2M data processing and analysis at the edge. This facilitates real-time decision-making and enables rapid responses to a dynamic industrial environment.
- Improved security and privacy: As cyber threats evolve, ensuring the security and privacy of M2M communications in Industry 4.0 is of paramount importance. Sixth-generation networks are expected to include advanced security features such as robust encryption, authentication mechanisms, and intrusion detection systems to protect M2M communications from unauthorized access and cyber attacks.

Sixth-generation promises extremely high data rates (in terabytes), artificial intelligence (AI), very low latency, low energy consumption, and a huge number of simultaneously connected devices. This will improve connectivity, sustainability, and credibility and will provide new services: extended reality (XR), mobile holograms, and next-generation entertainment. The upcoming 6G technology is expected to be ready in 2030. Sixth-generation systems combine up to 11 different communication technologies, including terahertz (THz) communication, visible light communication (VLC), multiple access, coding, CF-mMIMO, IRS, and artificial intelligence/machine learning (ML) in wireless transmission [3]. Table 1 lists the key capabilities of 6G that render it highly attractive [3].

Sixth-generation systems are popular for their key capabilities (Table 2).

Table 2. Comparisons of capabilities of 4G, 5G, and 6G systems [3].

Parameter	Fourth-Generation (4G)	Fifth-Generation (5G)	Sixth-Generation (6G)
Mobility [km/h]	350	500	>1000
Latency [ms]	<100	<10	<0.1
Connectivity density [devices/km^2]	10^5	10^6	10^7
Area traffic capacity [Gbps/m^2]	0.001	0.01	1
Peak data rate [Tbps]	0.002	0.02	>1
User experiences data rate [Gbps]	0.01	0.1	1

3.2. Transition from 5G to 6G

A comparison of 5G and 6G networks in terms of services, key technologies, and communication techniques is given in Table 3.

The sixth-generation spectrum covers several bands from 410 MHz to 71 GHz and THz frequencies [3]. Sixth-generation technologies will operate on the same frequencies as 4G long-term evolution (LTE) (410 MHz to 6 GHz) and 5G new radio (410 MHz to 7.125 GHz and 24.25 to 71 GHz), plus additional frequencies (7.125 to 24.25 GHz) and sub-THz frequencies. The key enabling technologies for 6G are:

- THz communications;
- Holographic beamforming;
- Cell-free MIMO,
- AI/machine learning (ML);
- Blockchain;

- Quantum communications;
- Enhanced edge computing;
- Intelligent reflecting surface;
- New multiple access techniques;
- Zero energy interface [3].

Table 3. Comparison of use cases for 5G, 5.5G, and 6G systems [3].

Technology	5G	5.5G	6G
Ultra-reliable and low-latency communications (URLLC)	+	+	
Massive machine-type communications (mMTC)	+	+	
Enhanced mobile broadband (eMBB)	+	+	
Uplink centric broadband communication (UCBC)		+	+
Real-time broadband communication (RTBC)		+	+
Human-centric services (HCS)		+	+
Ubiquitous mobile ultra-broadband (uMUB)			+
Ultra-high data density (uHDD)			+
Ultra-reliable low latency communications (uHSLLC)			+

Despite advanced research on 6G wireless network technology, it is expected that it will be implemented around 2030 and will allow the expansion of mobile communication to all fields of use, including the IIoT for the needs of Industry 4.0 and 5.0 (with people and the environment at the focus of attention). The development and standardization of 6G specifications is planned for 2025–2029, with the first laboratory tests and 6G pilots scheduled to begin in 2028, preparing 6G for commercial launch in 2030. It appears that the closeness of this date to deadlines for targets under the Green Deal is intentional. Additionally, these changes are leading to reconsideration of traditional security and privacy methods (innovative authentication, encryption, access control, communication, and malicious activity detection), as well as the use of AI/ML [4].

3.3. Target M2M Communication in 6G Networks

The fully connected, automated Industry 4.0/5.0 smart factory powered by 6G improving production processes and efficiency must evolve from the current hierarchical model towards a fully connected vertical model. Possible gaps at the levels of industrial control systems (IT/OT ICS) and IIoT M2M communication also need to be filled. It will be advantageous to deploy the 6G networks, autonomous networks, and converged data security technologies described later in this article. It is also worthwhile to assess the impact of vulnerabilities or risks that may be exploited by attackers (Table 4).

Improvements in the 6G security architecture may include:

- In the physical layer: 6G-authentication and key agreement (AKA) protocol, physical layer authentication, novel user subscription models (eSIM), and novel authentication protocols for non-third generation partnership project (3GPP) networks.
- In the connection layer: end-to-end security services and policies and user security using biological characteristics of individuals.
- In the application layer: novel security applications and novel privacy schemes [4].

6G visible light communication technology attacks and threats include:

- Authentication attacks;
- Access control attack;
- Jamming attacks;
- Data modification attack;
- Eavesdropping attacks [4].

Table 4. The security evolution of mobile communications from 1G to 6G [4].

Generation	Network Services	Security Solutions
1G	Voice services	Unencrypted telephone services
2G	Voice services and short messages	One-way authentication, unauthorized access
3G	High-speed Internet, web browsing	Internet protocol (IP) privacy, wireless interface threats
4G	Improved spectrum efficiency, reduced latency	Media access control (MAC) layer attacks, threats from new devices
5G	High-speed Internet, more secure systems	Non-terrestrial networks (NTN), software-defined networks (SDN), cloud threats
6G	Ultra-low latency, variety of applications, extremely reliable and low-latency communication (ERLLC), Internet of Everything (IoE)	AI/ML threats, system attacks

The high performance of MIMO mass systems will be ensured by the use of intelligent multi-surface (IMS) and IRS, AI/ML, terahertz (THz) communications, cell-free architectures, wireless location and sensing, vehicular communications, extraterrestrial communications, remote sensing, and interplanetary communications [5].

Massive MIMO increases throughput by grouping antennas at both the transmitter and receiver, providing high spectral and energy efficiency with relatively simple processing. This includes processes related to pilot contamination, channel estimation, pre-encoding, user scheduling, energy efficiency, and signal detection [6]. Factors contributing to greater growth in wireless data traffic include:

- Smart factories;
- Smart homes;
- Smart cars;
- Unmanned aerial vehicles (UAVs);
- Smartphones, smartwatches, and smartbands;
- Wearable devices;
- Broadband access [6].

The Internet of Remote Things (IoRT) provides the opportunity to expand the Internet of Things, producing and providing services in remote and geographically isolated areas where traditional Internet connectivity is a challenge. Non-terrestrial networks (NTNs) are a solution that enables the integration of satellites and UAVs with cellular networks. The 3GPP activities have addressed the problem of standardizing the NTN network to provide an energy-efficient IoRT environment in 6G networks (Figures 2–5) [7].

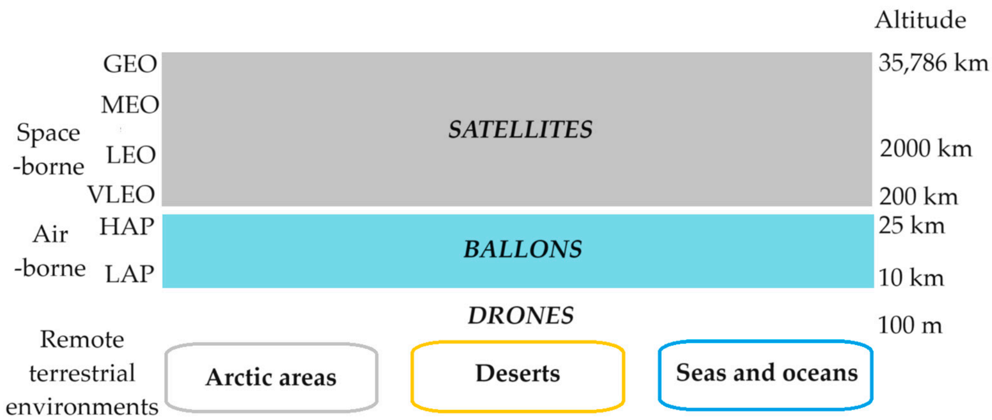

Figure 2. Non-terrestrial networks [7].

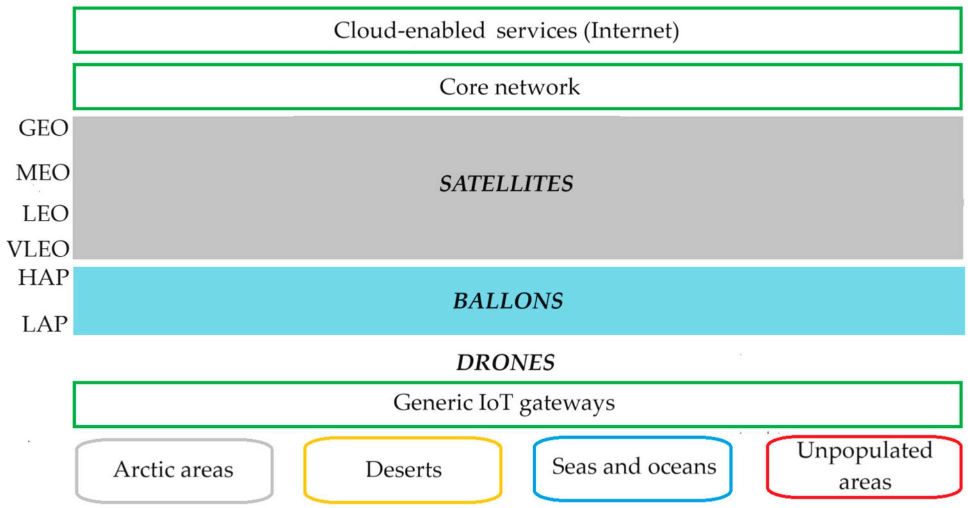

Figure 3. Generic IoRT system model [7].

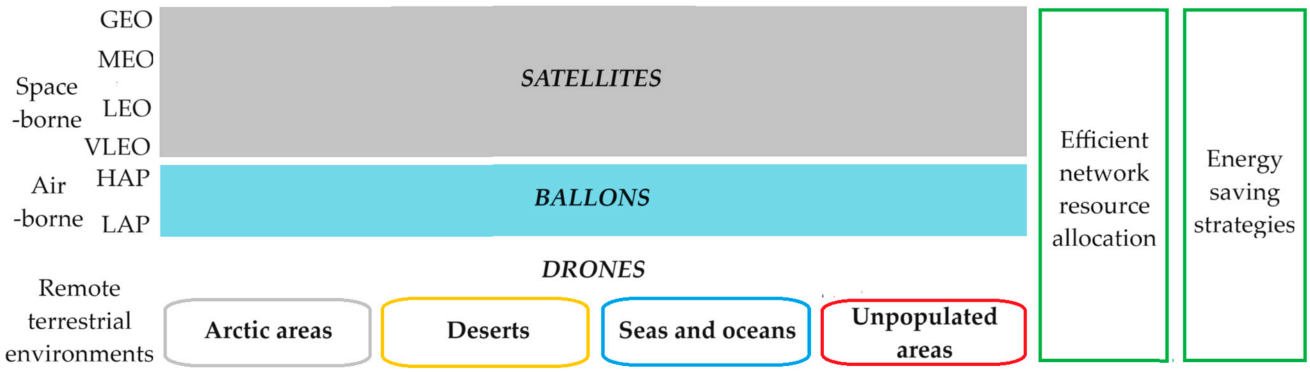

Figure 4. Challenges in NTN-based IoRT systems [7].

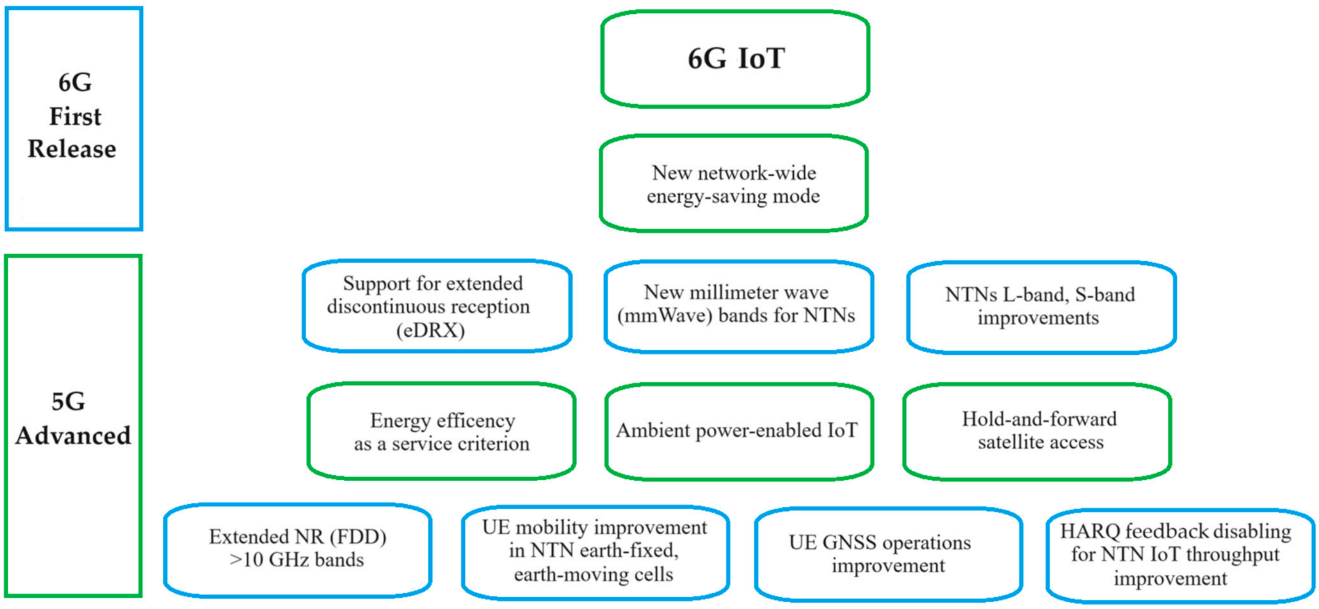

Figure 5. Planned 3GPP standard releases on NTN [7].

It has also been necessary to develop 6G-oriented waveguide and microstrip linear filters operating in the frequency range from 2 GHz to 65 GHz with increased resistance to design imperfections [8]. IRS controls the propagation of electromagnetic waves by changing their properties [9].

3.4. Key Issues to Be Addressed

The key problem in 6G networks is the scarcity of spectrum, resulting from the unprecedented load generated by the large number of devices and communication between them. VLC is a viable high-speed alternative or complement to radio frequency (RF) technologies. This is important because VLC is cost-effective, energy-efficient, and safe, using current infrastructure, both in indoor environments (factory halls, offices) and underwater environments. VLCs face a number of limitations: restricted LED bandwidth, dimming, flicker, line-of-sight (LOS) requirements, impact of severe weather conditions, noise, light interference, shadows, transmitter and receiver alignment, signal decoding complexity, and mobility issues. Non-orthogonal multiple access (NOMA) has been introduced as an answer to these issues (Figure 6) [10].

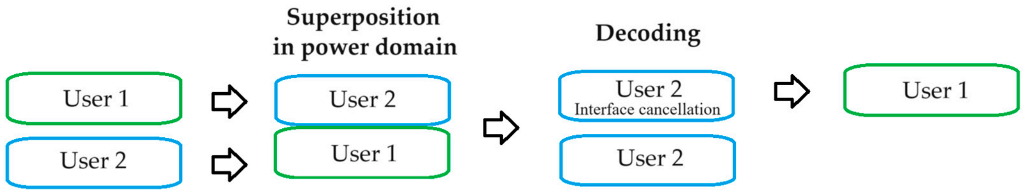

Figure 6. Downlink NOMA-VLC [10].

The problem of optimizing energy consumption in IIoT must be solved in view of the limited energy resources of IIoT 6G devices. The total consumption of millions of devices, even of the energy-saving type, translates into significant energy use. The radio subsystem, properly managed, can significantly improve the energy efficiency of IoT networks [11].

Fleet networks are an extension of fixed infrastructure, using a vehicular ad hoc network (VANET) in which vehicles communicate in infrastructure mode via roadside units (RSUs). The services of disseminating emergency messages and vehicle updates about the traffic situation are performed using sparsely deployed RSUs by constantly switching between them despite frequent interruptions in RSU operation. A mobile RSU (mRSU) has been proposed to complement stationary sRSUs. This solution improves packet delivery rates, increases throughput, reduces end-to-end latency, and reduces hop counts but also leads to a 2% increase in energy consumption [12].

The areas of industrial application of 6G-based IoT include IIoT as well as the Internet of Vehicles (IoV) and Internet of Drones (IoD), offering intelligent communication between a huge number of objects around us, including M2M communication. This requires smooth data flow, uninterrupted communication capabilities, low latencies, and high reliability, based on a network of access points (APs) serving user nodes. Resource control is handled through pilot-based AP selection (PBAS). The PBAS algorithm improves spectral efficiency by 22% at the cell edge and 1.5% at the cell center [13]. Industrial activity also includes the management of vehicle fleets. Vehicle social networks (VSNs), a component of vehicle-to-everything (V2X) services, enable vehicles to create social networks on roads and in garages or warehouses to improve passenger comfort and safety and raise confidence in the transportation of goods and services. Their requirements include lower latency, higher connection density, and up to 100% coverage. Blockchain-based collaborative distributed intrusion detection (BCDID) and dynamic bandwidth throttling (DTS) prevent attacks in VSN networks (involving taking over one of the network devices) [14]. Ensuring high-speed communication between multiple applications and multiple interactive services simultaneously requires a stable propagation environment without connection drops, data loss, or high latency. Distributed IRSs increase the reliability of 6G transmission but cause increased overhead resulting from the use of multiple IRSs, which requires effective resource control (linking IRS sets to the user's equipment, based on the intelligent-reflecting surface-user equipment association based on pilots (IUABP) algorithm, for example). In tests, this resulted in a 30% improvement in the total transmission speed [15]. The error propagation and computational complexity of signal detection in multi-input, multi-output wireless orthogonal frequency division multiplexing (MIMO-OFDM) systems require the development of simpler and efficient iterative feedback signal detection. This can be implemented, for example, by optimizing the feedback point of the minimum mean squared error ordered successive elimination constellation (MMSE-OSIC), which provides an approximation of optimal detection. The vector closest to the received signals is selected based on the maximum likelihood criterion, improving the correctness of the decision in subsequent iterations. For fast operation, however, it requires a reasonable selection of initial parameters (such as the relaxation coefficient) and parallel coarse and fine detection [16]. Sixth-generation network security is also important from an economic perspective—identifying business relationships and business-oriented security analysis by qualitatively assessing the impact of individual security breaches under different business conditions. This means that one can model the effects of security attacks in individual scenarios and their impact on the dynamics of a specific type of business (for instance, a product or service market segment; Figure 7) [17].

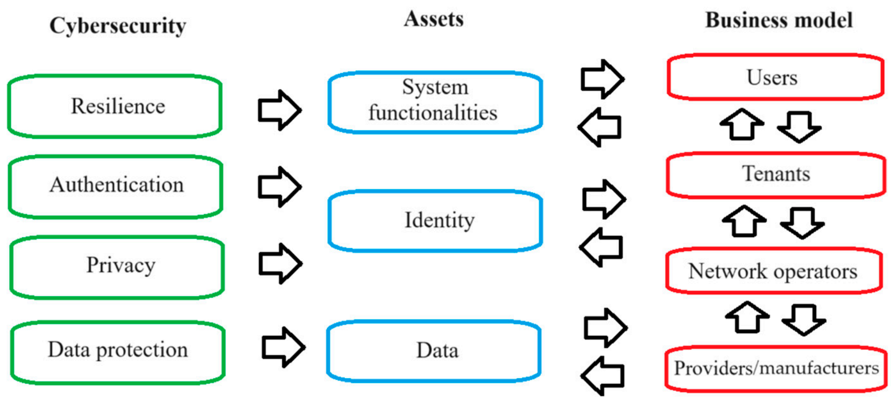

Figure 7. Security requirements, assets, and business relationships model [17].

The capabilities of reconfigurable intelligent surface (RIS) and rate-splitting multiple access (RSMA) technologies extend to 6G and beyond. They provide control of the propagation environment and interference management, as well as the division of a given user's messages into private and shared messages. For further development, progress is needed in optimizing the grouping of RIS elements and power division based on fractional programming (FP) as an alternative to existing spatial division multiple access (SDMA) systems supported by RIS [18]. VLC delivers robust systems that strongly support IIoT connections and throughput, including VLC channel modeling and ray tracing simulation to explore the VLC channel in IIoT scenarios. This makes it possible to analyze large-scale fading and multipath characteristics (channel impulse response—CIR; optical path loss—OPL; delay spread—DS; angular spread—AS) and distance-dependent distribution. The channel characteristics from a single transmitter are proportional to the distance, and the degree of dispersion in the factory floor (temporally, spatially) is higher than in typical office rooms. The density of objects and even the influence of the user's height on the characteristics of the channel are also important. It is necessary to take into account the environment and link adaptation to optimize the multipath interference problem. The signal-to-noise ratio (SNR), RMS DS value, CIR coefficients, and bit error rate (BER) have been proposed as key parameters for the selection of a solution [19]. Wireless sensor networks (WSNs) are increasingly using hybrid RF–VLC cognitive systems, for WSNs with cognitive radio sensor networks (CRSNs) and VLC. This requires a trade-off between performance and complexity, which increases as the number of devices and data rates increase. Further progress requires the development of cognitive radio strategies based on ML and DL while providing large datasets for training the network. This must be reconciled with energy-efficient resource allocation, efficient industrial scenarios, energy harvesting, the effective use of spectrum, and network performance [20]. VLC provides wireless communication in areas where radio frequency (RF)-based technology has limited use, such as in industrial environments due to interference. VLCs offer solutions both inside buildings (including industrial locations) and outdoors, for example for traffic management. Optical noise-tolerant VLC systems based on on-off keying (OOK) modulation and Manchester encoding or binary frequency shift keying (BFSK) and non-return-to-zero (NRZ) modulation can maintain a maximum noise radiation intensity of 3500 μW/cm^2 and provide a 20–25% improvement in indirect exposure to incandescent light sources [21]. It should be noted that IoT is a promising technology not only in the evolution of Industry 4.0 and Industry 5.0 but also in smart home automation (SHA), smart sustainable cities, energy management systems, and municipal resources (water, waste), which will enable better integration of the above-mentioned areas, extending M2M wireless communication beyond smart factories to many other fields, including monitoring of the product life cycle, its carbon footprint, and full recycling. One noteworthy solution is a real-time location monitoring system based on Bluetooth low energy (BLE) technology for wide applications, including even underground communication as part of industrial positioning systems. This allows us to look anew at automatic storage and high-bay systems, which will be able to grow not only upwards but also downwards (Figure 8) [22].

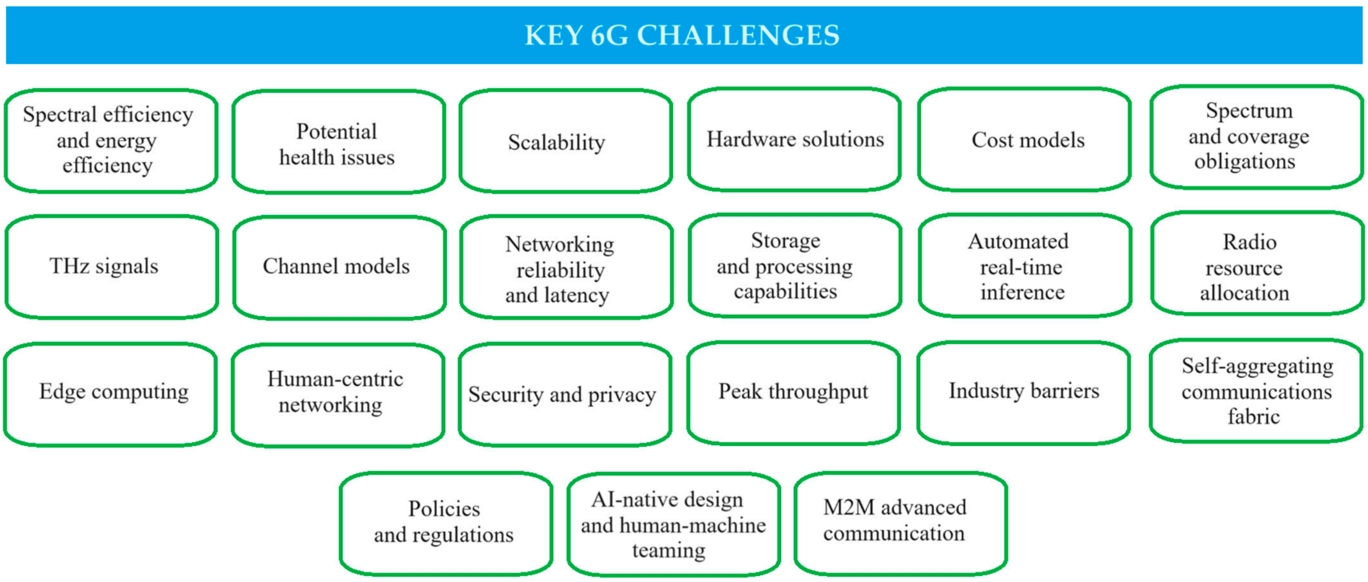

Figure 8. Key challenges of 6G [22].

To sum up, the 5G networks currently in use will not satisfy the requirements expected to be necessary for operation from 2030 onward in terms of delays, throughput, and traffic density [23]. Currently, much research is being carried out on both the physical layer and higher layers of the International Organization for Standardization/Open Systems Interconnection (ISO/OSI) model, the results of which are intended to provide 6G networks with higher performance and the ability to implement new functions in M2M connections, thanks to global coverage, very low delays, high reliability, mass connectivity, improved intelligence and security, non-orthogonal multiple access, MIMO, energy harvesting, hybrid terrestrial and satellite relays, improved IIoT-based automation, millimeter wave band utilization, interference management, hybrid precoding, and statistical shaping beams [24]. Additional requirements for 6G networks are imposed by the sources of industrial data (including medical data, as in the case of the Internet of Medical Things—IoMT) and, on the other hand, by the methods of their use: mass processing, analysis, classification, inference, and prediction from data, including for the purposes of automation, computerization, and technical control as well as analysis of the life cycle of products and carbon footprint of processes [25–27].

4. Discussion

Sixth-generation mobile networks have the potential to revolutionize the way we communicate, interact, and use information M2M communications in Industry 4.0 and Industry 5.0, while also improving coverage in places that were previously considered difficult to access and/or digitally excluded, and supporting a larger number of devices and users.

The development of factories using IIoT and M2M based on 6G technology includes a number of new features. Steps in integrating advanced communication, information, and automation technologies to increase the efficiency, productivity, and flexibility of industrial processes include:

- Understanding 6G technology: 6G is the next generation of wireless communication technology, and is expected to offer significantly faster speeds, lower latency, and powerful device connectivity compared with 5G. Understanding the capabilities and potential applications of 6G technology is crucial to harnessing its benefits in factory automation.
- Use case identification: Identify specific use cases in the factory environment where M2M communication can streamline processes, improve productivity, and reduce operational costs. Examples include predictive maintenance, real-time monitoring, autonomous robotics, and supply chain optimization.
- Network infrastructure: Develop a robust and scalable network infrastructure capable of supporting high-bandwidth, low-latency M2M communications requirements in factory settings. This may include deploying 6G-enabled base stations, edge computing resources, and network slicing technologies to prioritize critical factory applications.
- Sensor placement: Place various sensors throughout the factory floor to collect real-time data on machine performance, environmental conditions, energy consumption, and other relevant parameters. These sensors should be able to wirelessly transmit data to centralized control systems for analysis and decision-making.
- Edge computing: Deploy edge computing capabilities at the edge to process and analyze data locally, reducing latency and minimizing dependency on centralized cloud infrastructure. Edge computing enables real-time decision-making and increases the responsiveness of M2M systems in dynamic factory environments.
- Artificial intelligence and machine learning: Leverage AI and ML algorithms to analyze sensor data, identify patterns, predict equipment failures, optimize production schedules, and improve overall operational efficiency. These AI/ML models can be deployed at the edge or in the cloud, depending on latency and resource requirements.
- Security and privacy: Implement robust security measures to protect sensitive data and prevent unauthorized access to M2M systems. This includes encryption, authentication, access controls, and regular security audits to identify and mitigate potential security vulnerabilities.
- Interoperability and standards: Ensure interoperability between various devices, protocols, and systems in the factory ecosystem by adhering to industry standards and protocols. This facilitates seamless communication and integration between various M2M infrastructure components.
- Scalability and flexibility: Design the M2M factory infrastructure to be scalable and flexible, enabling easy expansion, reconfiguration, and adaptation to changing production requirements and technological advances.
- Testing and optimization: Thoroughly test and optimize the M2M factory system to ensure reliability, performance, and compatibility with existing processes and workflows. Continuously monitor and tune the system based on feedback and performance metrics.

4.1. Limitations of Current Studies

The use of 6G networks to improve M2M communication in Industry 4.0 is associated with certain limitations and challenges, which are presented in Table 5.

Table 5. Limitations of 6G in M2M communication [22–33].

Limitation	Description
Infrastructure deployment	Deploying 6G infrastructure, including base stations and network equipment, will require significant investment and time. Building the necessary infrastructure to support 6G networks in industrial environments can pose logistical challenges, especially in remote or difficult geographic locations.
Systems integration	Many industrial facilities still use legacy equipment and systems that may not be compatible with 6G technology. Updating or upgrading existing infrastructure to support 6G M2M communications may involve additional costs and complexity, requiring careful planning and investment.
Standardization	Sixth-generation technology is still in its early stages of development and standards have not yet been fully defined. The process of developing and standardizing 6G technology could take several years, which may lead to delays in widespread adoption and deployment.
Interference and signal attenuation	The higher frequency bands used in 6G networks are prone to higher signal attenuation and are more susceptible to interference from environmental factors such as buildings, foliage, and weather conditions. This may impact the reliability and performance of M2M communications, especially in outdoor industrial environments with complex topology.
Spectrum availability	Sixth-generation networks are expected to use higher frequency bands, including terahertz (THz) frequencies, to achieve higher data rates and capacity. However, these frequency bands pose challenges in terms of propagation and coverage characteristics, requiring innovative antenna technologies and deployment strategies. Additionally, spectrum allocation and regulatory issues may hinder the availability of appropriate frequencies for 6G deployment.
Power consumption	The higher data rates and increased processing requirements of 6G networks may result in higher power consumption compared with previous generations. This may pose a challenge for battery-powered devices and IoT sensors deployed in industrial settings, where energy efficiency is crucial for long-term maintenance-free operation.
Security and privacy	Sixth-generation networks may be susceptible to security breaches, hacking and privacy breaches. Providing robust security mechanisms and protocols to protect M2M communications in Industry 4.0 environments will be essential to mitigate these threats and build trust in the reliability and integrity of 6G networks.

It is also necessary to be aware of:

- Ethical and social implications: Explore the ethical, social, and regulatory implications of 6G deployment, taking into account factors such as data privacy, algorithmic bias, job displacement, and the digital divide, and develop a framework for responsible deployment and governance.
- Needs for cross-disciplinary collaboration: Supporting cross-disciplinary collaboration between researchers, engineers, policymakers, and industry stakeholders to address multi-faceted challenges, leveraging knowledge from fields such as telecommunica-

tions, computer science, electrical engineering, industrial engineering, and science communities.

Awareness of the aforementioned limitations, and perhaps the inability to overcome some of them, will not only make us aware of the technologically possible development paths for 6G support for M2M but will also allow us to manage the aforementioned development more effectively and choose more cost-effective development models. Particular attention should be paid here to the health and environmental aspects of Industry 5.0, which will soon be the benchmark for meeting the requirements of the Green Deal. Despite these limitations, continuous research and development efforts are aimed at addressing the challenges and realizing the potential benefits of 6G networks for improved M2M communication in Industry 4.0.

4.2. Directions for Further Research

When describing directions for further research, we would like to focus on the development of 6G towards M2M. By focusing on the following research directions, researchers and practitioners can contribute to improving 6G networks and unlocking the full potential of M2M communications to realize the vision of Industry 4.0.

- Spectrum management and allocation: Explore novel spectrum management techniques and principles to optimize spectrum utilization in 6G M2M communications, considering factors such as frequency allocation, dynamic spectrum access, and interference mitigation in industrial environments.
- Propagation modeling and channel characterization: Develop accurate propagation models and channel characterization techniques tailored to 6G frequencies, including THz bands, to better understand propagation characteristics and channel behavior in industrial settings. This research can help design efficient antenna systems and deployment strategies for reliable M2M communications.
- Design energy-efficient network protocols and algorithms specifically optimized for 6G M2M communications, aimed at minimizing power consumption in battery-powered devices and IoT sensors deployed in industrial environments, while ensuring reliable, low-latency communications.
- Edge computing integration and optimization: Learn advanced edge computing architectures and optimization techniques to seamlessly integrate edge computing capabilities into 6G networks, enabling distributed computing, real-time analytics, and intelligent decision-making at the edge for M2M communications in Industry 4.0.
- Security and privacy: Develop robust security mechanisms, encryption techniques, and privacy-preserving protocols to address the unique security challenges of 6G M2M communications, including protection against cyber threats, data breaches, and unauthorized access in industrial IoT deployments.
- Standardization and interoperability: Contribute to 6G standardization efforts, focusing on defining interoperable protocols, interfaces, and data formats to ensure seamless integration and interoperability between heterogeneous devices and systems in Industry 4.0 ecosystems.
- Real-world implementation studies and use cases: Conduct empirical research and field trials to evaluate the performance, reliability, and scalability of 6G M2M communications in real-world industrial environments, identifying practical challenges and opportunities for optimization and improvement.
- Human–machine interaction and collaboration: Explore the role of 6G in enabling advanced human–machine interaction and collaboration paradigms, such as augmented reality (AR), VR, and teleoperation, to enhance productivity, safety, and efficiency in workflow within Industry 4.0 [29–40].

Our vision for the future evolution towards 6G-based M2M support is not a single path but rather a set of parallel paths. Harmonious and simultaneous development in the aforementioned areas is necessary to develop 6G-based M2M as a whole but also to ensure a smooth transition from 5G through 5G advanced to 6G in support of M2M within the Industry 4.0/5.0 paradigms.

5. Conclusions

Sixth-generation networks hold great promise in revolutionizing M2M communications in Industry 4.0/5.0, offering the increased reliability, low latency, high bandwidth, adaptability, and security features that are essential to realizing the full potential of intelligent, connected industrial systems. Sixth-generation networks will have an impact at the intersection of many technologies: IoT, artificial intelligence/machine learning, virtual and augmented reality, cloud computing, and cybersecurity. To take full advantage of this, new solutions, architectures, and concepts for their use must be developed. Joint initiatives between interested investors, standardization bodies, and academia are needed to overcome current limitations and ensure the full use of 6G technology in industrial applications.

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