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THE UTILIZATION OF 6G IN INDUSTRY 4.0

Abstract

The sixth-generation (6G) communication technology has potential in various applications, for instance, industrial automation, intelligent transportation, healthcare systems, and energy consumption prediction. On the other hand, the concerns of privacy measures and security measures in 6G-enabled networks are considered critical issues and challenges. The integration of 6G with advanced technologies for example computing, Artificial Intelligence (AI), and Internet of Things (IoT) is a common theme in this paper. Additionally, the paper discusses the challenges and advancements required for 6G technology to be utilized with other technologies, involving edge technology, big data analytics, and deep learning. In this review paper, the authors overview the integration of 6G with cutting-edge technologies like IoT, IoMT, AI, and edge computing that address human requirements and issues. In addition, to make values for new technologies like Big data, federated learning machine learning, deep learning, and multiple aspects are merged collectively to offer a network for the machine and human growing era. These integrations can be utilized for monitoring energy consumption in real-time, intelligent transportation solutions, improved security in industrial applications, signal reconstruction, and industrial automation. Additionally, the authors illustrate the critical considerations and challenges that face the integration of 6G for instance, performance requirements, security, and privacy concerns. Overall, this paper suggests that 6G communication technology can revolutionize different sides of our society, and enhance efficiency and accuracy in various future industrial automation and sectors.

1. INTRODUCTION

Mobile communication networks have developed across varied generations, starting in the 1980s with the first generation (1G) which provides voice calling services for subscribers (Kuruvatti et al., 2022). In 1990, significant developments were added to the networking industries and telecommunication during second-generation (2G), third-generation (3G), and fourth-generation (4G) cellular networks (Y. Wang et al., 2021). Where, 2G networks changed the transmitted signal from analog to digital, which offers services like Short Messaging Service (SMS) so it is not necessary for callers and receivers to be online

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simultaneously (S. Wang et al., 2021). In 3G the data rate was increased, it delivers with data rate better than 2G. 4G was developed to handle broadband services of mobile with significantly higher data rates (Nashwan & Nashwan, 2021). The year 2020 was the deployment phase of 5G wireless technologies, and it is yet to be adapted chiefly on software-driven until 2025 and with the total coverage (Porambage et al., 2021). The key marked characteristic of 5G is cloudification networks with micro-service-based design. 5G represents key technology to empower an assortment of innovations such as IoT, self-driving vehicles, and smart urban areas. Currently, 5G is in the deployment phase, meanwhile research activities in addition to standardization efforts toward prospective 6G communication systems are in progress (Uusitalo et al., 2021). In 6G, the framework of 5G will be further developed and expanded. However, concerning user quality of service (QoS), and performance, the 6G network which goes beyond 5G, besides offering certain features involving low-latency connectivity through many devices, massive high-speed, enabling real-time data availability for smart cities, intelligent transport systems, Industries 4.0, and more (Liu & Zhang, 2021; S. Wang et al., 2021; Zhang & Zhu, 2020). These aforementioned advances can expand data collection in real-time without any wired connection requirements or interference concerns (Rao, 2021). 6G technologies will enable new applications over many fields, which will result in a bigger data explosion, for example, future industries, autonomous vehicles, connected vehicles, intelligent cities with a network of wide sensors, utilities, security and surveillance, healthcare, etc. (Rao, 2021; Shahraki et al., 2021).

6G is envisioned to be the backbone of intelligent industry infrastructure in the future. Particularly, an integration of 6G technology and emerging technologies will pave to the future growth of the Industry 4.0 (I4.0) systems (Han et al., 2021). Several visions for 6G are being proposed and highlighted (Liu et al., 2020; Jiang et al., 2021). Overall, it is predicted that 6G will cover each corner of the world (Tariq et al., Aug. 2020,), not just delivering data, but additionally reliable automated services with outstanding performance (Liu et al., 2020). Moreover, growing concerns related to climate change and the energy crisis are motivating people to point out sustainability as a core 6G value (Alshahrani et al., 2023; Feng et al., 2021). To fulfill real-world needs, it is expected that 6G can continuously support applications in vertical industries, encompassing building automation and factories, e-health, manufacturing, agriculture, transportation, smart grid, and surveillance. These applications are essential to ‘industry 4.0. (Abdulazeez & Askar, 2023, 2024; Dohler et al., 2017; Faouzi et al., 2023). Industry 4.0 is founded based on the past historical progression of various revolutions in industry. The revolution in industrial began in the 18^{th} century with the first revolution in industry which was manual machining using water and steam (Industry 1.0), then after a century, powered machining using oil, fuel, and energy (Industry 2.0), and after that computerized machining by incorporating computers, data analysis, and advanced telecommunications (Industry 3.0) and followed by the current start of Industry 4.0 paving to the era of smart and autonomous industrial operations. The aim of Industry 4.0 is to enhance operations, minimize costs, and enhance quality by optimization, the use of intelligent services, and industrial automation. In general, Industry 4.0 targets to automate and autonomies the industry it services (Al-Jaroodi et al., 2020). In Industry 4.0, data is considered the key to generating current information and is used to predict or contribute to making decisions according to the estimations of the futuristic state of the system (Sarker, 2021).

In the present world economy context characterized by increasingly demanding markets and globalization, industries are compelled to enhance the efficiency and performance of production lines to satisfy customers (Bécue et al., 2021; Pallathadka et al., 2023). Connectivity, inventory reduction, data, customization, new devices, and controlled production are all contributing to the birth of Industry 4.0, which today sounds unstoppable (Ghobakhloo, 2020). This indicates the demand to deploy techniques of automation to incorporate each of the modern technologies which will raise productivity subsequently (Ghildiyal et al., 2023; Hussein & Askar, 2023; Ibrahim & Askar, 2023). The potential transformation of integrating I4.0 with other technologies offers various benefits, involving: 1) Efficiency enhancement where I4.0 technologies like Big Data and IoT, enable data collecting and analysis in real-time, resulting in enhanced operational productivity and efficiency (Silvestri et al., 2020). 2) Increased competitiveness: via leveraging technologies of I4.0, the companies' competitiveness can be strengthened by enhanced production processes, decreased waste, and improved product quality (Silvestri et al., 2020). 3) Improved decision-making: The integration of AI methods and cyber-physical systems enables informed decision-making, and can result in optimized production processes and better resource allocation (Achouch et al., 2022). 4) Customization and personalization: I4.0 allows companies to respond rapidly to market changes and provide more customized products, fulfilling the requirements of growing demanding markets. 5) Reduced downtime: where the models of predictive maintenance in I4.0, can minimize downtime of machines and related costs, as well as maximize the machine's life cycle (Assad et al., 2021; Pech et al., 2021).

The combined impact of both 6G and the emerging technologies for instance AI, Machine Learning, Blockchain, and Digital twin, and other technologies, in particular, lead to accelerate the future revolution of I4.0 systems (Gui et al., 2020). 6G networks will allow to use of frequencies higher than 5G networks, which means significantly higher capacity and minimized latency (Akhtar et al., 2020). For the mentioned purposes, this review paper is focused on the 6G communication system from the perspective of Industry 4.0 and the integration of developed technologies like edge computing, AI, and IoT is a common theme in this paper. As well as the paper discusses the challenges and advancements required for 6G technology.

The objective of this paper is to explore how integrating 6G with advanced technologies like AI, IoT, and edge computing can revolutionize various domains and industries such as transportation, healthcare, manufacturing, and smart systems. By reviewing the present research studies, the goal is to investigate the significance of 6G technology on Industry 4.0, its potential applications, benefits, and challenges to be solved to fully utilize the power of 6G technology, benefits, address key challenges and create the path for advancements and future research in the industrial automation and communication technology field. In summary, this review targets to present the understanding of how 6G technology can lead to a more connected, intelligent, and efficient future over variety industries.

2. REVIEW METHODOLOGY

A literature search is performed to response to research queries.

2.1. Search strategy

To obtain related research, various academic online search engines were utilized for instance Scopus, Science Direct, IEEE Xplore, Research Gate, and Google Scholar were utilized to obtain related studies. The keywords used to find the relevant works were: ('6G' or '6 Generation technology', and 'IoT), ('6G' or '6 Generation technology', and 'Deep Learning), ('6G' or '6 Generation technology', and 'Machine Learning), ('6G' or '6 Generation technology', and 'AI' or 'Artificial Intelligent'), ('6G' or '6 Generation technology', and 'Blockchain), ('6G' or '6 Generation technology', and 'Industry 4.0' or I4.0'), ('Integration of 6G in Industry 4.0', or I4.0), ('Integration of 6G in edge computing), etc.

2.2. Inclusion and exclusion criteria

Only the relevant studies published in English language have been selected. The inclusion and exclusion criteria that have been considered for related studies are as follows:

Inclusion criteria:

1. Studies that present at least one application of 6G in advanced technologies like IoT, AI, etc.
2. Studies that discuss at least one issue/ challenge by integrating 6G in advanced technologies.
3. Studies that are relevant to the topic of "6G in Industry 4.0" or relevant topics mentioned in the sub-section (2.1 Search strategy).
4. Types of the studies covered are empirical studies, reviews, and case studies.

Exclusion criteria:

1. Studies published before 2020.
2. AI, IoT, Machine Learning, and Deep learning-based techniques mentioned in studies that are not associated with 6G.
3. Issues/ challenges mentioned in a study that does not utilize integration of 6G with one of the advanced technologies.

2.3. Selection of the study

The study selection process is based on (sub-section 2.2 Inclusion and exclusion criteria). According to the search strategy mentioned earlier, the primary relevant studies were selected in this step. Where 91 research works were initially identified and selected. In the next phase, the duplicated works were removed resulting a total of 70 studies. Then, during the screening process, 40 studies were excluded. The studies were filtered based on abstract analysis and inclusion and exclusion criteria. A total of 30 studies became eligible to be full-text analyzed via the screening process. After that, these 30 studies were reviewed, and 14 were eliminated. Finally, a total of 16 studies were remained for review.

2.4 Data extraction

After the studies selection process, data extraction is crucial to properly analyze and interpret the studies. A table with some key attributes was created, and different data from the studies were added to the tables to extract meaningful findings from the studies The attributes of the table are: “Ref” includes the authors’ name with publication year. The second attribute “Focus Area” is the field of the studies. The third one is “Key Technologies” which describes the advanced technologies integrated with 6G. The fourth attribute “Application” is the application of the integration in the third attribute. Finally, the last attribute is “Findings/Results” which mentions the main outcomes of the studies.

2.5. Research questions (RQs)

The primary aim of this review paper is to answer subsequent research questions:

RQ1: What can result in integrating 6G technology with advanced technologies such as AI, IoT, and edge computing?

RQ2: What are the applications of 6G technology in industries?

RQ3: Are there any challenges/ barriers that obstacle the adoption of 6G technology in I4.0? how can these challenges be addressed?

3. LITERATURE REVIEW

The 6G networks development stands at the top in the quest for more reliable and faster communication technologies. It offers speed up to one hundred times faster than 5G, it is expected that 6G can make revolution in different sectors notably AI, deep learning, and IoT. Therefore, this literature review focuses on the intersection of 6G technology with these advanced technologies, paying attention to present research, applications, and the future trends, perspectives, and challenges.

3.1 Applications of 6G in AI

The development of edge computing, IoT, and mobile AI can be beneficial for urban authorities in using the quantity of the collected data via Connected and Autonomous Vehicles (CAV) to develop intelligent transportation solutions to tackle smart city challenges. Timely and effective road infrastructure repair is a key challenge. The vital role of using 6G technology is highlighted, which can facilitate data collection from a multitude of road-user devices (Harahap et al., 2024; Sharma et al., 2023). Hijji et al. (2023), proposed a novel approach to exploit 6G technology, mobile edge AI training approaches, and deep learning techniques to overcome the challenges of road infrastructure maintenance and automate pothole detection in smart cities. The system utilizes various CAVs to collect data and use these data for training the model of pothole detection in an efficient, scalable, and secure way. A Federated AI training approach ensures that CAV data is kept private (route and position of the drivers) while allowing the local model to be continually updated and improved. The local model updates are gathered in an embedded local server founded on signs of smart road to create new locally gathered models and the latter are sent to a global server in which all other local models are gathered to make a new more intelligent global model. Then in a backward process, the global model is distributed to the end users in fixed period intervals, as shown in Figure 1. This multi-bi-directional (intensive) communication is supported by 6G technology. As a result, the system prioritized key maintenance works by notifying relevant authorities in real time regarding potholes found on the road. Thus, it will address the challenge of accomplishing required maintenance work in a cost-effective and timely way and optimize the scheduling and distribution of resources and services(Hijji et al., 2023).

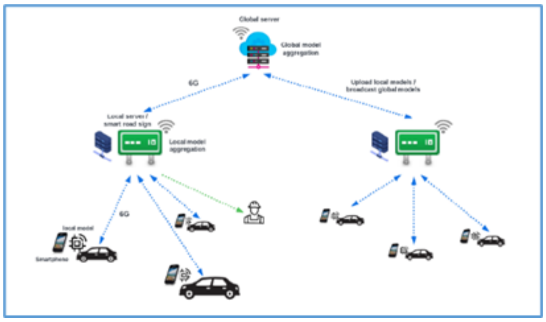

Fig. 1. Hierarchical model architecture(Hijji et al., 2023)

The integration of 6G and AI-based technology can be utilized in a ship energy consumption estimation system, that provides real-time transmission of ship energy consumption data to users. This can improve the monitoring and management of ship energy consumption. Deng et al. (2021), adopted 6G technology, IoT, and AI technology to propose a system to assess and anticipate the efficiency of ship energy consumption. The authors targeted to address the issue that the ship's energy consumption has not been monitored and managed for a long period because of the absence of efficient technical tools. Applying 6G communication technology in the proposed system can provide the users with the data of ship energy consumption in real-time, which is a more realistic to manage the ship energy consumption. The performance of the system is good, and the variation between both actual predicted values is small, with a relative error of about (0.017 % - 0.074 %) i.e. superiority and accuracy of the prediction model of ship energy consumption. The system also facilitates the storing of ship information resources, which means improving the overall management capability of China’s shipping (Deng et al., 2021).

Ahammed and Patgiri (2020), promoted the merging of 6G communication networks and AI to create an era of innovation in digital communication technology. Where it predicts a future in which 6G driven by AI, will revolutionize different aspects of society, particularly transportation, industry automation, logistics, and smart cities creation. The authors underlined the future promise for 6G and AI technology that could improve the quality of life, enhance efficiency, and accelerate the economy to an entirely automated industry. Furthermore, they highlighted the significance of addressing, privacy secrecy, and security issues in the advancement of 6G communication technology (Ahammed & Patgiri, 2020).

3.2. Applications of 6G in Machine Learning

Sliwa et al. (2021), introduced a novel approach used for efficient resource opportunistic data transmission in applications with delay-tolerant vehicular sensor data. The proposed method includes a hybrid approach of machine learning 1) Supervised Learning to predict possible data rates, and 2) Unsupervised Learning to identify geospatial uncertainties in the prediction model. The real-world evaluations in German cellular networks show an improvement of up to 223% in average data rates, a 73% decrease in transmission-related power consumption, an 89% reduction in occupied network resources, and a 73% reduction in transmission-related power usage. However, it leads to increasing the Age of Information (AoI) of the sensor data. Based on the results, the authors derived recommendations for 6G networks in the future using client-based intelligence which are: 1) non-cellular-centric networking approaches: where end edge cloud coordinated intelligence enables the exploiting of network clients' computational and sensory capabilities to contribute to comprehensive network optimization. 2) To minimize end-to-end prediction errors considerably, cooperative data rate prediction which includes actively sharing knowledge about network load, should be expressly enabled by network architecture. 3) Increasing data acquisition efforts to generate massive open data sets, as more data frequently results in higher performance gains than model modification (Sliwa et al., 2021).

W. Wang et al. (2021), anticipated the potential implementation of the incorporated deep learning algorithm into the 6G-based Internet of Medical Things (IoMT) to provide and share medical records and track the outcomes online, aiming to realize effective and convenient diagnosis online. The researchers also examined the evolution of 6G technology and its possible application scenarios, stressing the possibility for 6G to be utilized in varied professions and its qualitative benefits regarding bandwidth and transmission immediacy as compared to 5G. Furthermore, they referenced a few researches that discuss 6G communication systems, technologies, use cases, research directions, and challenges(W. Wang et al., 2021).

Mezair et al. (2022), suggested a sustainable deep learning framework to detect faults in 6G Industry 4.0 variety of data environments. The authors overcame the constraints of the present fault detection techniques by using a combination of Convolutional Neural Networks (CNN), graph CNNs, Long Short Term Memory (LSTM), and a Branch-and-Bound optimization method for tuning hyper-parameter. The suggested framework can enhance the efficiency and accuracy of detecting faults in Industry 4.0, resulting in more sustainable Machine-to-Machine (M2M) communications. They concluded that the combination of 5G and beyond 5G technologies in M2M communications can make Industry 4.0 more intelligent. The development of 6G technologies can benefit industrial automation, maximize productivity, minimize production costs, and create a new industrial environment (Mezair et al., 2022).

3.3. Applications of 6G in IoT

6G cellular IoT should provide precise computation and efficient communication for mass data from terminal devices to enable real-time processing for these data, which represent two fundamental objectives of 6G cellular IoT. Qi et al. (2020), designed a framework integrating Energy, Computation, and Communication (ECC) to handle critical problems in 6G cellular IoT, including energy supply, data transmission, and data aggregation. In the downlink, wireless power transfer (WPT) supplies energy, while Over-the-Air Computation (AirComp) computes and communicates by Non-Orthogonal Multiple Access (NOMA) in the uplink. The study also investigated the effects of transmit and receive beamforming on system performance and suggested an algorithm for minimizing computation distortion while maintaining communication quality through beamforming design and power allocation. The simulation findings revealed that the presented algorithm exceeds the baseline algorithm in 6G cellular IoT (Qi et al., 2020).

Liang et al. (2021), proposed a model called “Convolution-Based Transfer Compressed Sensing (CTCS)” to rebuild the compressed signal in 6G-IoT, specifically when the training sample data is insufficient. After model training on a source domain, the model gets transferred to a target domain that has uncooperative or limited data. The signal recovery is accomplished by refining parameters and reducing the Multi-Kernel Maximum Mean Discrepancies (MK-MMD) loss function in a Multi-dimensional convolution layer. The CTCS’s effectiveness is illustrated using the Mnist dataset (handwritten dataset) and real Ultra Wide Band (UWB) radar echo signals. The findings illustrated that transfer learning can be applied to compressed sensing, and surpass other algorithms such as Orthogonal matching pursuit (OMP), particularly with insufficient measurements or in low Signal-to-Noise-Ration (SNR) situations. The study underlined the use of transfer learning in compressed sensing for signal reconstruction, highlighting its benefits in the context of 6G-IoT. Future papers might aim to adapt the CTCS technique to vital 6G-IoT technologies like addressing high latency and reliability requirements and cognitive spectrum sharing (Liang et al., 2021).

In 6G mobile communication networks, the move toward cloud and edge native infrastructures is expected to continue and the significance of security grows more in the communication system. Darman et al. (2022), brought to light an enhanced User Authentication Key Management Scheme for secure communication in 6G-enabled Network in a Box (iUAKMS-NIB) which is used in industrial applications. A 6G-enabled NIB's major features are a high level of flexibility and low latency, as well as connection services to applications used in uncommon scenarios for instance natural catastrophes or battlefields in the industry. However, most of these applications are not secured appropriately, therefore this scheme is an improved version of 6G-enabled NIB to offer user authentication and management employing a verification key as key features. The study provided various analyses to guarantee security and check the authentication between individuals and smart industrial devices. The suggested scheme offers the most effective security solution against potential 6G attacks. The analytical results revealed that the presented system exceeded the existing schemes. In the future, the suggested scheme will be applied in IoT-based systems(Darman et al., 2022).

Padhi and Charrua-Santos (2021), presented a complete literature review on the 6G technology, IoT, Internet of Everything (IoE), and Industrial Internet of Everything (IIoE), and provided a new theoretical framework for the 6GIIoE system. Where this integration of 6G and IIoE aims to provide advanced communication capabilities and connectivity for industrial applications, like automation, manufacturing, and control systems industries. 6GIIoE is anticipated to provide low-latency, reliable, and high-speed communication, and real-time data transfer and facilitate the establishment of connected intelligent industrial systems. The researchers reviewed the drawbacks of the 5G as an IoE applications enabler, studied IoE transposition into industrial IoE projects, and also discussed the potentials they provided. They intended to fill the research gap and offer a theoretical foundation for the establishment of the 6GIIoE system (Padhi & Charrua-Santos, 2021).

Elaziz et al. (2023), investigated the possibility of enhancing healthcare systems by utilizing advanced technologies like 6G IoT and medical image classifications which can provide efficient and accurate diagnosis of various diseases. The authors presented a framework to extract and analyze medical images using integrated cloud computing and edge devices, as well as a new metaheuristic algorithm to select features. The proposed framework outperformed other techniques for feature selection while testing on four different medical datasets. They also discussed other potential challenges that may arise when implementing such technologies in healthcare environments for instance complexity of the used algorithms, which necessitates specialized expertise to develop and maintain—furthermore, concerns about data security and privacy when storing and analyzing medical data using cloud-based systems. Finally, there might be resistance from some healthcare professionals who encourage traditional methods to diagnose and treat patients because they are unfamiliar with such technologies (Elaziz et al., 2023).

3.4. Overall trends, perspectives and challenges

The envisioning and planning of 6G has begun, intending to provide communication services for future demands. Dang et al. (2020), considered security, secrecy, and privacy the major features of 6G technology which is expected to provide the highest level of privacy, secrecy, and security. THz communication will render 6G snooping and jamming resistant. Similarly, quantum computing will provide unbreakable security to 6G, like quantum cryptography for secrecy. Individuals' privacy is one of their main concerns, and healthcare, in particular, demands the highest level of protection privacy. Blockchain is an extremely important technology for increasing privacy, secrecy, and security(Dang et al., 2020).

Nayak and Patgiri (2020b), proposed implementing intelligent medical services using 5G and 6G technology to enhance response times of emergency. The authors highlighted the challenges that conventional emergency services face and the significance of developing reliable and robust technology to support high-quality service. The study also discussed the essential challenges of integrating intelligent medical services, for instance, establishing Blood Sample Reader (BSR) sensors and accident sensors, and the importance of drones and intelligent vehicles in emergency services (Nayak & Patgiri, 2020b).

Nayak and Patgiri (2020a), discussed the issues and challenges concerning the innovative 6G communication technology. They emphasized the lack of actual technology to fulfill 6G demands, the necessity for advancement in edge technology to enhance performance and preserve Quality of Service (QoS), and the incorporation of Big data analytics and deep learning for self-optimization and advanced automation in communication. The authors also pointed out the importance of envisioning the use cases, techniques, potential applications, and challenges of 6G technology, in addition to addressing various research challenges ranging from devices to softwarization. The researchers explored different alternatives to reach the desired parameters of 6G which include delivering truly AI-driven communication, implementing satellite support with terrestrial communication, supporting 6G with Extended Radio (XR), and changing NR-Lite of 5G, transmitting in TeraHertz (THz) frequency band, relocating portable nodes like satellites, drones, and other mobile nodes to offer effortless service (Nayak & Patgiri, 2020a).

In the future, industrial applications will include compelling novel uses demanding strict performance guarantees over a wide range of important performance metrics for instance dependability reliability, time synchronization, and latency. This necessitates designing a special-use industrial IoT network. Mahmood et al. (2023), proposed a novel operational architecture for 6G special-use industrial IoT to satisfy the demanding performance needs of the industrial applications in the future for 6G networks. The proposed functional architecture includes seven basic building blocks, which are classified into special-use functionalities and supportive technologies. The target of these building blocks is to provide a complete and resource-efficient solution for future sophisticated and highly challenging industrial applications. The presented architecture emphasizes meeting crucial performance indicators like dependability, reliability, latency, security, and time synchronization. The authors stress the demand for an integrated approach to enable various service necessities for industrial IoT networks. Implementing this architecture has potential benefits for industrial IoT applications in the context of 6G like reliability improved performance, and security (Mahmood et al., 2023).

Mao et al. (2021), discussed the application of numerous technologies in the context of 6G networks including Unmanned Aerial Vehicles (UAVs), satellite networks, and IoT. In their study, they addressed the issues and possible solutions to provide edge computing services and seamless coverage for IoT devices located in remote locations within the scope of 6G networks. The study introduced four essential 6G technologies (energy harvesting, THz, machine learning, and edge computing) and illustrated how they enhance the efficiency of the satellite-UAV-served 6G IoT. It also formulated a computation offloading issue and proposed an AI-enabled offloading strategy. The results showed enhancements in system computation rate and task success ratio. Additionally, the study emphasized the importance of addressing the varied service demands, energy limitations, and latency problems in the framework of 6G IoT systems (Mao et al., 2021).

4. DISCUSSION

The discussed papers illustrate a varied range of advancements and applications in the integration of 6G communication technology throughout different fields for example healthcare, transportation, industry, and IoT. Among the significant contributions mentioned are using 6G for monitoring ship energy consumption in real-time, intelligent transportation solutions, improved security in industrial applications, signal reconstruction, and industrial automation. The integration of 6G with cutting-edge technologies such as IoT, IoMT, AI, and edge computing provides solutions to different challenges. On the other hand, performance requirements, security, and privacy concerns are still critical considerations and represent another challenge, as clarified in Table 1.

The findings of this study response to the predefined research questions as follows:

RQ1: Integrating 6G technology with advanced technologies for instance AI, IoT, and edge computing can pay forward to improve automation, increase bandwidth, provide data analytics in real-time, enhance reliability, which is considered crucial for supporting advanced applications of I4.0, and enhance decision-making in industrial environments.

RQ2: 6G has the power to provide reduced latency, higher capacity, and faster communication that can revolutionize some key industries like healthcare (IoT-enabled devices and supporting AI algorithms for optimization purposes), manufacturing/ smart factories (controlling quality that leads to reducing downtime and enhancing the quality of the product), transportation (providing up-to-date and accurate traffic conditions information, optimal routes, and road hazards), and smart grid systems (real-time controlling and monitoring of energy distribution systems).

Tab. 1. Comparison table of the reviewed papers

Ref	Focus Area	Key Technologies	Application	Findings/Results
(Hijji et al., 2023)	Smart Transportation	6G, AI, Mobile Edge, Deep Learning	Pothole detection, Maintenance of road infrastructure	Real-time alerting, timely and cost-effective maintenance, optimize the scheduling and distribution of resources and services
(Deng et al., 2021)	Ship Energy Consumption Prediction	6G, AI, IoT	Ship energy consumption monitoring in real-time	Enhanced general management capability, small prediction errors
(Ahammed & Patgiri, 2020)	Integration of 6G and AI	6G, AI	Development in digital communication	Revolutionizing society, accelerating the economy to an entirely automated industry, addressing security and privacy, enhancing efficiency
(W. Wang et al., 2021)	6G-Based IoMT	6G, 6G-based IoMT, Deep Learning	Internet of Medical Things	6G's qualitative benefits, convenient and effective diagnosis
(Mezair et al., 2022)	Fault Detection in Industry 4.0	6G, Deep Learning	Sustainable fault detection	enhanced the efficiency and accuracy of detecting faults in Industry 4.0, more sustainable M2M communications
(Qi et al., 2020)	6G Cellular IoT	6G, ECC	Data transmission, energy supply, and data aggregation	Minimized computation distortion while maintaining communication quality, and enhanced the overall system performance.
(Liang et al., 2021)	Compressed Signals in 6G-IoT	6G-IoT, Transfer Learning	Signal recovery	Effectiveness CTCS model, transfer learning surpassed traditional algorithms. They were aiming in the future to adapt the CTCS to vital 6G-IoT like addressing high latency and reliability requirements and cognitive spectrum sharing.
(Darman et al., 2022)	User Authentication in Industrial Applications	6G, User authentication key Management method	6G-enabled NIB with secured communication	Enhanced security against potential attacks of 6G, the system outperformed the existing schemes in flexibility and low latency
(Padhi & Charrua-Santos, 2021)	6GIIoE System	6G, IIoE	Improved communication for applications of industry	6GIIoE is anticipated to provide low-latency, high-speed communication, reliable, real-time data transfer
(Elaziz et al., 2023)	Healthcare Systems Enhancement	6G IoT, medical image classification	Medical diagnosis accurately and efficiently	Metaheuristic algorithm outperformed other techniques for feature selection, explored challenges in data security and algorithm complexity
(Dang et al., 2020)	Security and Privacy in 6G	6G, THz Computing, Blockchain Communication, Quantum	Quantum cryptography, resistance to snooping and jamming	THz communication, Blockchain for privacy, unbreakable security employing Quantum computing
(Nayak & Patgiri, 2020b)	Challenges faced by emergency services and the possible advantages of utilizing 5G and 6G	5G and 6G, AI, IoT	Emergency medical services using intelligent vehicles, wireless communication, and BSR sensors	Revolutionize emergency service delivery, resulting in more rapid response times, more efficient resource allocation, and saving more lives.
(Nayak & Patgiri, 2020a)	Issues and challenges of 6G	Edge technology, 6G, AI, Deep learning, Big data	Lack of current technology to fulfill 6G demands, Big data analytics and deep learning for self-optimization and advanced automation in communication	Various alternatives were explored, ensuring QoS, and resolving research challenges from device to softwarization
(Mahmood et al., 2023)	Special-Use Industrial IoT	6G, Industrial IoT	Industrial applications in the future for 6G networks	Resource-efficient solution for future sophisticated industrial applications, improved performance and security
(Mao et al., 2021)	6G in IoT Systems	6G, Satellite Networks, UAVs, IoT	Seamless coverage, Edge computing services.	AI-enabled offloading strategy, enhanced system computation rate, and task success ratio
(Sliwa et al., 2021)	Vehicular Sensor Data Transmission	6G, Machine Learning	Efficient resource opportunistic data transmission	Recommended 6G network in the future to minimize end-to-end prediction errors, cooperative data rate prediction, increasing data acquisition efforts to generate massive open data sets,

RQ3: There are some challenges to the integration of 6G in I4.0 including infrastructure requirements (upgrading the existing infrastructure to be suitable for higher frequencies signals and data rates which can be time-consuming and costly), security concerns (transmitting data over 6G applications can be threatened by higher risks), and interoperability issues (the ability of various devices and systems to seamlessly communicate and work). These challenges can be addressed by involving significant investment in infrastructure, robust cybersecurity measures, and standardization efforts where industry collaborations play a vital role in standardization bodies to establish common protocols to promote compatibility and interoperability across different applications and devices.

5. CONCLUSIONS

In summary, recent studies on 6G wireless communication technology particularly concerning, machine learning, IoT applications, and energy have been discussed and reviewed in this research. To fulfill real-world needs, it is expected that 6G can continuously support applications in vertical industries, encompassing building automation and factories, e-health, manufacturing, agriculture, transportation, smart grid, and surveillance. These applications are essential to ‘industry 4.0. Future innovations in these fields are envisioned to affect different sides of life in the coming years in a significant way, regardless of industry. This paper also reviewed the key challenges that have to be addressed including big data analytics, edge technology, and deep learning. To address these challenges, it should be the focal point of future research. The results from these reviewed studies collectively emphasized the diverse potential of 6G technology and its power to revolutionize various domains, from the healthcare sector to industrial automation, leading to a more connected and smarter future.

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