Enabling Human-Machine Interfaces with 5G RedCap: Architecture, Key Requirements, and Challenges

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***Abstract*—5G wireless communication protocols introduce a new paradigm for Human Machine Interface (HMI), allowing for a seamless user experience everywhere. HMI applications require low latency, balanced data rate, low energy consumption, and cost efficiency. The recent development of 3GPP-based 5G NR Reduced Capability (RedCap) may serve as the solution to fulfill this objective. This article focuses on the compatibility of the RedCap protocol with developing HMI. We have studied numerous previous research works by other authors related to the requirements of various HMI use cases and conducted a secondary study on how the capabilities of RedCap can satisfy these requrements. We examine the application cases of HMI, such as virtual reality (VR), augmented reality (AR), industrial collaborative robotics (Cobots), and wearables, as well as the RedCap requirements for HMI deployment. Furthermore, we discuss potential technological architectures and characteristics. Comparing the HMI link level requirements with the RedCap link level performance offerings, we observe that RedCap can be a suitable solution to meet the HMI communication demands. Finally, we discuss challenges and potential research directions for accomplishing this goal such as security, privacy, scalability, interoperability, and large level integration.**

***Index Terms*—RedCap, HMI, 5G, VR, AR, Cobots, Wearables**

I. Introduction

The Human Machine Interface (HMI) has become a common aspect of modern life and continues to have a growing influence. This is true for consumer-based products as well as professional and industrial applications. One significant application of HMI in professional and personal applications is Extended reality (XR). XR contains several emerging technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) [1]. In recent years, XR has shown the potential to increase productivity, particularly in office environments, by removing the necessity of being physically present in various scenarios. This can reduce the overhead for office space and other associated costs. XR is already playing a major role in the entertainment industry, i.e., multimedia and gaming applications. The wearable device industry is another area that has seen massive growth in the past decade, with its future prospects looking even brighter. Though this is mostly useful for personal use cases, it is an essential part of propelling us toward a more interconnected future. Another important and effective application of HMI is to make industries more competitive by implementing advanced human-machine collaborative solutions for manufacturing [2]. Robot and human collaboration is common practice in this day and age, particularly in use cases where repetitive but highly precise tasks need to be performed. By utilizing the strengths of both human and machine entities, we can enable an increase in manufacturing flexibility and efficiency [3]. In order to do this, we need an intuitive solution for humans to work with machines and for them to be able to use machines to maximize productivity. The constant advancement of the interface through which we interact with these devices ensures more widespread adoption and diverse applications. An essential aspect of HMI, which ensures the viability of its application in commercial and industrial use cases, is the performance over wireless communication methods. There are various wireless Internet of Things (IoT) communication protocols that are currently in use today. Among them, an emerging standard is the Reduced Capability (RedCap) 5G. Reduced Capability 5G NR devices, unveiled in 3GPP Release 17, move a further step forward in support of IoT by NR by optimizing the operation of device types typically found in Industrial IoT (IIoT) services [4]. RedCap promises unprecedented performance in terms of QoS while ensuring acceptable power efficiency for battery-operated devices [5].

For the use cases mentioned above, we investigate the potential of RedCap to be the most suitable communication protocol for the foreseeable future due to its lucrative middle ground between power efficiency and data rate. Figure 1 shows an overview of the three general areas targeted by 5G, which are enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (uRLLC), and massive Machine Type Communications (mMTC). eMBB use cases demand very high data rates and spectral efficiency. uRLLC devices demand very low latency and reliability. mMTC use cases require long coverage and battery life. A limitation for 5G NR-based protocols for IoT applications has historically been the power constraints of edge nodes. Due to the higher power consumption of regular 5G NR protocol, its use has been limited thus far. The principle contributions of this article are the following:

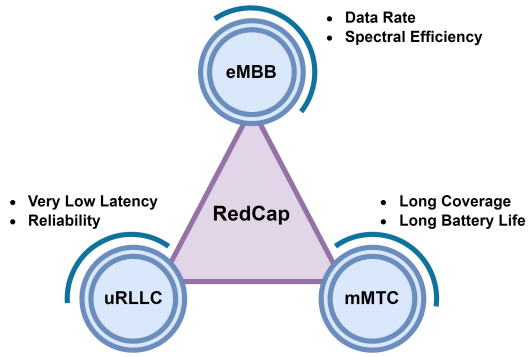

Fig. 1. High-level overview for KPI requirements and use cases for 5G NR-Lite

- As per our knowledge, we are the first to show the usability and requirements of RedCap in the emerging HMI field.
- We discuss a comprehensive architectural overview and key performance parameters of RedCap for HMI applications such as XR, wearables, and collaborative robots (cobots).
- We discussed the viability and effectiveness of RedCap for HMI use cases.
- We also discuss some challenges and research directions regarding RedCap in HMI.

The rest of the article is organized as follows. In section II, various use cases of HMI and its requirements are described. Section III presents an overview of RedCap architecture and its performance parameters. In section IV, we discuss the performance feasibility of RedCap for real-world HMI use cases, described in section II. Section V states multiple technical challenges that need to be resolved in order to deploy RedCap effectively for HMI. Finally, we conclude our work in section VI.

II. HMI Requirements and Use Cases

Computers are involved in almost every aspect of human life today. We constantly interact with machines in order to operate various day-to-day tasks. And with the emerging industry 4.0, the level of interaction will only increase. These interactions take place via device interfaces that we use to tap into the machine-driven world. They are termed as Human Machine Interface (HMI). Some upcoming HMI application criteria are robots, wearables for different usage, and XR. Table I presents a concise summary of the most prominent HMI use cases and their link level requirements, such as latency, data rate, mobility, scalability, and range.

A. Extended Reality

Extended reality (XR) encompasses technologies like virtual reality (VR) and augmented reality (AR) [7]. It integrates the actual and virtual environments to generate a virtual HMI environment [1]. It is becoming more and more popular day by day, and to accommodate the necessary requirements, 3GPP-developed 5G technology has become the main option. XR is the human-machine interactive gateway to the metaverse and digital twin, which will take flight soon [1, 8]. The communication aspect of XR is one of the most important things to look into, as its requirements are very demanding. These demands need to be met by mostly wireless networks.

1) Augmented Reality: AR adds extra computer-generated three-dimensional information to the real-world experience [7]. It is a type of mixed reality. AR may run on mobile devices, which rely on HMI. The inputs include various sensors, companion devices, etc., and the outputs include display screens like Head Mounted Displays (HMD), projection-based displays, handheld displays, contact lenses, audio outputs, haptic outputs like game controllers, etc. The devices are mostly connected wirelessly, which can utilize cellular IoT networks. AR technology is suitable in industrial, healthcare, entertainment, and educational settings. It will be used for academic and professional education, video games, navigation, path finding, medical procedures and training, collaborative visualization of space and design, and many more applications [7].

2) Virtual Reality: Virtual reality is a simulation experience that provides the user an immersive experience [14]. Its immersive live videos will be used for Metaverse, which can be presented as texts, pictures, movies, virtual worlds, video games, VR chats, etc. [15, 16]. It uses various near-eye devices and pose-tracking technologies to create an experience for the user. VR devices include HMD, motion controllers, motion sensors for tracking body parts, wired gloves, etc. This is where HMI comes into play. Humans need to interact with these devices in order to use VR. And these devices demand high data rates and low latency [14]. Error-free transmission through touch is essential for the VR haptic interfaces to run properly [14].

TABLE I
HMI USE CASES AND THEIR LINK LEVEL REQUIREMENTS

Features	Latency (ms)	Data Rate (Mbps)	Mobility	Scalability	Range
VR	10	30-210 for video transmission 0.2 for motion control	Low to medium	Number of user	Typical factory floor size
AR	<10-20	50-200 for video transmission 0.2 for motion control	Low to medium	Number of user	Typical factory floor size
Cobots	<10	<2	High	100-10000 nodes	<1 km
Wearables	<10	50-150	Medium to high	-	-
References	[6, 7, 8, 9]	[6, 7, 9, 10]	[7, 11, 12]	[11, 13]	[11, 13]

B. Wearables

Wearables are becoming increasingly popular every day. These smart devices include smartwatches, fitness trackers, exergame devices, health monitoring medical devices, location tracking devices, smart glasses, etc. These devices rely on touchscreens or voice-controlled mechanisms to interact with its user. So, these HMI-reliant instruments demand good data rates and low latency [9].

C. Industrial Cobots

Robot-based collaborative systems will be a staple part of Industry 4.0. A factory running on collaborative devices consists of a dense network that requires a highly scalable communication network varying from a small to a large area. The data rate requirements are not too much, but very low latency is required. In an industrial setting, human-robot collaboration is becoming more prominent. These robots, also sometimes termed as cobots, rely on context-aware contact in shared spaces with humans in order to complete shared tasks. So, these robots are good examples of HMI use cases and desire mobility and scalability. They use visual sensors and touchscreens to convert perception to real-time action [17]. They can be deployed in assembly, packaging, weight handling, moving and placing objects, remote control of risky tasks [18, 19] in heavy industrial factories, chip fabrication industries, vehicle manufacturing and assembly factories, remote missions, etc. Figure 3 shows a graphical interpretation of the HMI use cases and some prominent examples where they are deployed.

III. REDCAP OVERVIEW

There were more than a billion cellular IoT connections in 2020, and according to forecasts, there will be around 5 billion connections by 2025 [5]. A significant portion of the exponential increase in cellular IoT connections will come from distinct fields such as Industrial IoT and Industrial Wireless sensor networks (IWSN) [20], surveillance [21], and wearables [22]. These applications require a particular feature set where the data rate requirement is higher than other existing cellular IoT protocols like Narrowband Internet of Things (NB-IoT) and Long-Term Evolution Machine Type Communication (LTE-M) and lower than full 5G New Radio. RedCap 5G standard was unveiled in Release 17 with a specific focus to tackle this middle ground [5] and it has the potential to enable new functionalities and capabilities in the above-mentioned applications. It was developed not necessarily to replace NB-IoT, but it has the potential to replace existing IoT communication protocols like NB-IoT for certain use cases due to some of its characteristic advantages. It offers moderate latency and high reliability due to its 5G backbone [23]. Figure 2 illustrates an overview of RedCap's architecture, starting from HMI and to RedCap IoT servers.

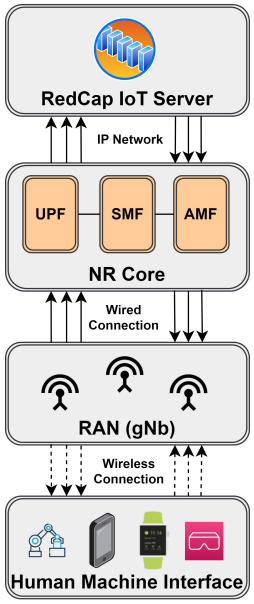

Fig. 2. Network architecture for 3GPP 5G NR based RedCap protocol

RedCap is able to provide data rates around 150 Mbps in DL/UL [9]. Also, RedCap's latency can be less than around 10ms [9, 24]. Utilizing the 5G NR core, RedCap offers good mobility [25, 26]. Using the Frequency Range 2 (FR2) spectrum also allows the building of sophisticated private networks with the help of its limited range and high spatial reuse [27]. Besides, RedCap's transmission range allows it to be deployed for close settings at around 30m [28]. Additionally, RedCap has been designed to be a lot less power consuming and cost less compared to regular 5G NR according to its target use

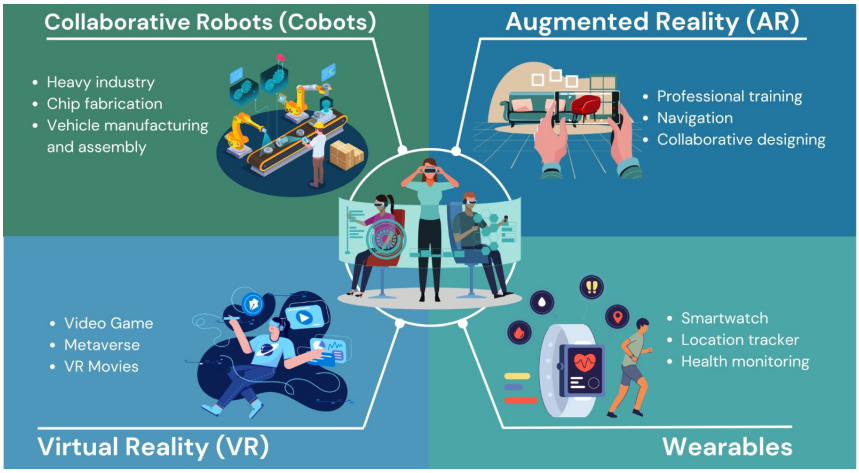

Fig. 3. 5G NR based Reduced Capability potential use cases for Human Machine Interface

criteria [5]. Table II summarizes major RedCap's key performance parameters that can fulfill HMI link level requirements.

IV. Discussion

Researchers in [22] talked about the possibility of cellular IoT technologies in the wearable devices sector, but they only mentioned NB-IoT and LTE-M, whereas RedCap is the most recent development in the cellular IoT domain. Researchers evaluated the possibility of 5G NR to meet some Key Performance Indicators (KPI) regarding XR communications in [10]. They showed 5G NR's ability to meet the data rate and latency of the XR interfaces from the video stream, motion/control stream, and audio stream requirements in detail. In [29], researchers discussed the wifi-reliant existing private networks among industrial robots and how 5G can perform much better latency and reliability wise due to its cellular radio access network. But these researchers talked about regular 5G NR technology, whereas our work discusses RedCap, the less expensive and more power efficient version of 5G-NR [5], to meet these KPI demands. Our work focuses specifically on RedCap and whether its performance parameters can meet these HMI use case requirements of the emerging technologies. From a data rate perspective, XR is the most demanding HMI application, followed by wearables and industrial robots [6, 7, 9, 10, 10, 12].

To fulfil such HMI demands with IoT devices, a protocol with very high data rates and very low latency is necessary. We can see from table I and table II that for XR use cases, RedCap can meet the high data rate demand of the entry level XR devices, whereas it easily meets wearables and robots' data rate requirements [9]. Secondly, all of the XR, wearables devices and industrial robots demand stringent latency [6, 7, 8, 9] and RedCap is the only IoT communication protocol that can fulfill this demand [9, 24]. XR devices need to accommodate mobility to some extent as to successfully carry out user movements of the HMIs. On the contrary, when it comes to wearables and industrial robots, connectivity with high mobility is essential [7, 11, 12]. RedCap supports full mobility, which can be good for these HMI use cases [12, 25]. It also is highly scalable from a load and structural perspective, making it more than enough to be deployable in factories. Typically, XR use cases consist of a lower number of user devices compared to the other use cases. So their structural scalability demand may be lower, but due to the data rate and low latency needs, the devices need to be highly load scalable [11]. This can be properly done by cellular IoT technologies like RedCap. Finally, HMI application criteria do not require too much range, as it is the interface itself where humans interact with the machines [11].

TABLE II
Performance Metrics of RedCap

Features	Metrics [5, 9, 24, 25, 28]
Data Rate	150 Mbps
Latency	10ms
Mobility	Good
Scalability	High
Transmission Range	30m
Device Cost	<5G NR Legacy devices
Power Consumption	<5G NR Legacy devices

As a result, RedCap's range [28] is good enough for it to be considered in these scenarios. Our work focuses on these essential HMI requirements and RedCap's ability to meet them. It also gives an overview of RedCap's suitability for link-level HMI requirements.

V. Research Challenges

A key limitation of our current work is the lack of real time testing of RedCap in practical HMI scenarios. Also, RedCap is a relatively new technology. So, it needs a large level implementation, which is not available at the moment. Several technical challenges need to be solved to deploy RedCap successfully in HMI. A few possible concerns are briefly discussed below and summarized in Table III.

TABLE III
RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Topic	Challenges	Future research direction
Security and privacy [1, 30]	Personal private data and real time data flow	Include blockchain technology
Scalability [31, 32, 33]	Spectrum bottleneck, packet collision, interference	multiple clustering, peer-to-peer transmission, mobility management, dynamic frame structure
Complexity and interoperability [34, 35, 36]	Lack of defined architectural standard, maintain low computing delay, end to end transmission	Protocol standardization, fog or edge computing,
Integration [1, 26]	Data management, multiple HMI integration, multimodel transmission	Unified database management, hybrid and AI based integration

A. Security and privacy

Wearables and XR technologies offer an extensive amount of data, but they also raise serious concerns about privacy. AR/VR devices have the capability to gather biometric data such as voice, gestures, and facial expressions from users, in addition to real-time location and surrounding environment information. Additionally health, physiological, and behavioral data can be recorded by wearables. It's critical to assess if the privacy protection methods in place are strong enough to satisfy the demanding specifications of these gadgets [30]. Blockchain, with its encryption, consistency, and anonymity features, is a promising technology for tackling security and privacy challenges. It presents a potential avenue for future research [1].

B. Scalability

A Low latency and high data rate operated system is necessary for HMI to continuous and steady communication. Spectrum congestion, packet collision, and non-line of sight (NLOS) interference often hinder this, making it a pressing issue that requires immediate attention. Research focusing on peer-to-peer communications, mobility management, and dynamic frame structure is crucial to overcome these challenges [31, 32].

C. Complexity and interoperability

HMI devices, with their motion sensitivity, time sensitivity, rendering virtual environment, and high mobility concerns, present a complex and challenging landscape. The lack of defined architectural standards and computational delays further compound these issues. This underscores the need for research to focus on avoiding end-to-end transmission and maintaining low computing delay to ensure the smooth operation of these devices [34, 35, 36].

D. Integration

It is a key challenge for the cellular network to integrate a large range of bandwidth-consuming and latency-sensitive HMI applications with different QoS requirements. Also, data management, multiple HMI integration, and multimodal transmission are further hindrances [1]. Unified database management, hybrid, and AI-based integration can be the possible solutions and future research agendas to solve the problem.

VI. CONCLUSION

This article summarizes the HMI use cases of 5G NR-based RedCap protocol and the requirements for such applications' adaptability with IoT networks. Accordingly, we described the detailed architecture and key performance parameters of RedCap that are suitable for HMI applications. Utilizing RedCap, the 5G NR network can adapt to support devices needed for wearables, AR, VR, industrial cobots, and more HMI applications, all the while maintaining a lower power consumption and lower deployment cost. The ability to bolster HMI device types in a unique network brings additional features to network operators and service providers. In turn, it can contribute to the triumph of future IoT-based businesses. In addition, we addressed some key challenges and potential future research directions to overcome them. Despite these challenges, RedCap can offer a cost and power efficient exclusive wireless protocol solution for emerging HMI devices in the era of 5G.

REFERENCES

[1] Z. Huang, C. Xiong, H. Ni, D. Wang, Y. Tao, and T. Sun, "Standard evolution of 5g-advanced and future mobile network for extended reality and metaverse," *IEEE Internet of Things Magazine*, vol. 6, no. 1, pp. 20–25, 2023.

[2] C. Krupitzer, S. Müller, V. Lesch, M. Züfle, J. Edinger, A. Lemken, D. Schäfer, S. Kounev, and C. Becker, "A survey on human machine interaction in industry 4.0," *arXiv preprint arXiv:2002.01025*, 2020.

[3] M. Brettel, N. Friederichsen, M. Keller, and M. Rosenberg, "How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective," *International journal of information and communication engineering*, vol. 8, no. 1, pp. 37–44, 2014.

[4] B. Bertenyi, "5g evolution: What's next?," *IEEE Wireless Communications*, vol. 28, no. 1, pp. 4–8, 2021.

[5] "Redcap - expanding the 5g device ecosystem for consumers and industries.," *Ericsson Whitepaper*, 2023.

[6] F. Hu, Y. Deng, W. Saad, M. Bennis, and A. H. Aghvami, "Cellular-connected wireless virtual reality:

Requirements, challenges, and solutions," *IEEE Communications Magazine*, vol. 58, no. 5, pp. 105–111, 2020.

[7] Y. Siriwardhana, P. Porambage, M. Liyanage, and M. Ylianttila, "A survey on mobile augmented reality with 5g mobile edge computing: Architectures, applications, and technical aspects," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 1160–1192, 2021.

[8] T. Q. Duong, D. Van Huynh, S. R. Khosravirad, V. Sharma, O. A. Dobre, and H. Shin, "From digital twin to metaverse: The role of 6g ultra-reliable and low-latency communications with multi-tier computing," *IEEE Wireless Communications*, vol. 30, no. 3, pp. 140–146, 2023.

[9] N. Varsier, L.-A. Dufrène, M. Dumay, Q. Lampin, and J. Schwoerer, "A 5g new radio for balanced and mixed iot use cases: Challenges and key enablers in fr1 band," *IEEE Communications Magazine*, vol. 59, no. 4, pp. 82–87, 2021.

[10] M. Gapeyenko, V. Petrov, S. Paris, A. Marcano, and K. I. Pedersen, "Standardization of extended reality (xr) over 5g and 5g-advanced 3gpp new radio," *IEEE Network*, vol. 37, no. 4, pp. 22–28, 2023.

[11] S. Gangakhedkar, H. Cao, A. R. Ali, K. Ganesan, M. Gharba, and J. Eichinger, "Use cases, requirements and challenges of 5g communication for industrial automation," in *2018 ieee international conference on communications workshops (icc workshops)*, pp. 1–6, IEEE, 2018.

[12] T. H. Moges, D. S. Lakew, N. P. Nguyen, N.-N. Dao, and S. Cho, "Cellular internet of things: Use cases, technologies, and future work," *Internet of Things*, p. 100910, 2023.

[13] M. Noor-A-Rahim, J. John, F. Firyaguna, H. H. R. Sherazi, S. Kushch, A. Vijayan, E. O'Connell, D. Pesch, B. O'Flynn, W. O'Brien, *et al.*, "Wireless communications for smart manufacturing and industrial iot: Existing technologies, 5g and beyond," *Sensors*, vol. 23, no. 1, p. 73, 2022.

[14] D. Milovanovic, Z. Bojkovic, M. Indoonundon, and T. P. Fowdur, "5g low-latency communication in virtual reality services: Performance requirements and promising solutions," *WSEAS Trans. Commun*, vol. 20, pp. 77–81, 2021.

[15] J. Yang, A. Andersson, and S. Sanders, "5g-nr latency field performance for immersive live video," in *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*, pp. 1–5, IEEE, 2022.

[16] F. Tang, X. Chen, M. Zhao, and N. Kato, "The roadmap of communication and networking in 6g for the metaverse," *IEEE Wireless Communications*, 2022.

[17] R. Jahanmahin, S. Masoud, J. Rickli, and A. Djuric, "Human-robot interactions in manufacturing: A survey of human behavior modeling," *Robotics and Computer-Integrated Manufacturing*, vol. 78, p. 102404, 2022.

[18] S. El Zaatari, M. Marei, W. Li, and Z. Usman, "Cobot programming for collaborative industrial tasks: An overview," *Robotics and Autonomous Systems*, vol. 116, pp. 162–180, 2019.

[19] Y. Cohen, S. Shoval, M. Faccio, and R. Minto, "Deploying cobots in collaborative systems: major considerations and productivity analysis," *International Journal of Production Research*, vol. 60, no. 6, pp. 1815–1831, 2022.

[20] M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, "A critical analysis of research potential, challenges, and future directives in industrial wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 39–95, 2017.

[21] S. Moloudi, M. Mozaffari, S. N. K. Veedu, K. Kittichokechai, Y.-P. E. Wang, J. Bergman, and A. Höglund, "Coverage evaluation for 5g reduced capability new radio (nr-redcap)," *IEEE Access*, vol. 9, pp. 45055–45067, 2021.

[22] F. J. Dian, R. Vahidnia, and A. Rahmati, "Wearables and the internet of things (iot), applications, opportunities, and challenges: A survey," *IEEE access*, vol. 8, pp. 69200–69211, 2020.

[23] S. Baker and W. Xiang, "Artificial intelligence of things for smarter healthcare: a survey of advancements, challenges, and opportunities," *IEEE Communications Surveys & Tutorials*, 2023.

[24] R. Ratasuk, N. Mangalvedhe, G. Lee, and D. Bhatoolaul, "Reduced capability devices for 5g iot," in *2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1339–1344, IEEE, 2021.

[25] M. H. C. Garcia, A. Molina-Galan, M. Boban, J. Gozalvez, B. Coll-Perales, T. Şahin, and A. Kousaridas, "A tutorial on 5g nr v2x communications," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 3, pp. 1972–2026, 2021.

[26] M. Islam, H. M. M. Jamil, S. A. Pranto, R. K. Das, A. Amin, and A. Khan, "Future industrial applications: Exploring lpwan-driven iot protocols," *Sensors*, vol. 24, no. 8, p. 2509, 2024.

[27] 3GPP, "Key directions for release 17," *doc. RP-190831*, June 2019.

[28] 3GPP, "Rp 191047 nr-lite for industrial sensors and wearables," Jun. 2019.

[29] P. Sossalla, J. Rischke, F. Baier, S. Itting, G. T. Nguyen, and F. H. Fitzek, "Private 5g solutions for mobile industrial robots: A feasibility study," in *2022 IEEE Symposium on Computers and Communications (ISCC)*, pp. 1–6, IEEE, 2022.

[30] A. Qayyum, M. A. Butt, H. Ali, M. Usman, O. Halabi, A. Al-Fuqaha, Q. H. Abbasi, M. A. Imran, and J. Qadir, "Secure and trustworthy artificial intelligence-extended reality (ai-xr) for metaverses," *ACM Computing Surveys*, 2023.

[31] M. Chen, W. Saad, and C. Yin, "Virtual reality over wireless networks: Quality-of-service model and learning-based resource management," *IEEE Transactions on Communications*, vol. 66, no. 11, pp. 5621–5635, 2018.

[32] O. Semiari, W. Saad, M. Bennis, and M. Debbah, "Integrated millimeter wave and sub-6 ghz wireless networks: A roadmap for joint mobile broadband and ultra-reliable low-latency communications," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 109–115, 2019.

[33] D. GC, F. Bouhafs, A. Raschellà, M. Mackay, and Q. Shi, "Radio resource management framework for energy-efficient communications in the internet of things," *Transactions on Emerging Telecommunications Technologies*, vol. 30, no. 12, p. e3766, 2019.

[34] H. F. Atlam and G. B. Wills, "Iot security, privacy, safety and ethics," *Digital twin technologies and smart cities*, pp. 123–149, 2020.

[35] P. K. Sadhu, V. P. Yanambaka, and A. Abdelgawad, "Internet of things: Security and solutions survey," *Sensors*, vol. 22, no. 19, p. 7433, 2022.

[36] Z. Wang, Y. Zhao, Y. Zhou, Y. Shi, C. Jiang, and K. B. Letaief, "Over-the-air computation for 6g: Foundations, technologies, and applications," *IEEE Internet of Things Journal*, 2024.