Cellular Connectivity and Wearable Technology Enablers for Industrial Mid-End Applications

Salwa Saafi, Gabor Fodor, Jiri Hosek, and Sergey Andreev

***Abstract*—Industrial digital transformation through efficient automation hinges largely on the deployment of communication infrastructures that meet the requirements of smart factory use cases. These infrastructures involve multiple devices that utilize different communication technologies to increase the overall operational efficiency. Rooting from the key implementation requirements of a smart factory environment, this article focuses on the role of cellular connectivity and wearable technology in enabling new industrial applications. Specifically, we shed light on a novel category of services — industrial mid-end wearable applications — by positioning their requirements among the 5G service classes. We then identify features that can complement cellular connectivity to further support the given requirements. More precisely, we review cellular network-aided device-to-device communications and reduced-capability devices. Our performance evaluation results justify the choice of these features and show that they can work in concert with cellular connectivity to enhance spectral efficiency and reliability in industrial mid-end wearable applications.**

I. INTRODUCTION

Industrial digital transformation has been at the top of many business agendas. However, the tight restrictions imposed on economic activity by the global pandemic situation have made it increasingly urgent for manufacturers to rethink their digital strategies. Hence, enterprises often take advantage of this opportunity to achieve sustainable business development by speeding up automation initiatives, which under normal circumstances could have taken years longer. These automation efforts are being conducted within the framework of Industry 4.0 and practically involve many industrial verticals, including automotive, manufacturing, healthcare, logistics, field services, retail, construction, power grid, and transport.

One of the key concepts within Industry 4.0 is smart factory. It corroborates a fully connected manufacturing system, in which industrial processes are improved through automation [1]. In such automated systems, the involved devices generate, exchange, and process the necessary data to perform tasks related to preventive maintenance, workforce management, machine utilization optimization, risk management, remote asset control, and worker health monitoring. Therefore, employing intelligent assistant systems with appropriate connectivity solutions is a key component of the automated operations in a smart factory. This understanding underpins the scope of the present article.

In what follows, we provide an overview of cellular connectivity and wearable technology enablers for the smart factory. Further, we extend the 3GPP efforts in supporting wearable use cases by introducing a novel category of services that involve cellular-enabled wearables with so-called 'mid-end' requirements, namely, *industrial mid-end wearable applications (IM-EWA)*. We then review network-aided device-to-device (D2D) communications and reduced-capability (RedCap) operations as part of the cellular features for supporting IM-EWA requirements. Finally, we provide first-order analysis and system-level performance evaluation of industrial setups where the conventional cellular connectivity is complemented by the discussed capabilities.

II. SMART FACTORY ENABLERS

Manufacturing sites rely on factory automation to enable more efficient and sustainable production processes. However, these benefits are the result of not only deploying advanced manufacturing operations, but also exploiting information and communication technology capabilities [1]. Augmented/virtual reality (AR/VR), Internet of Things (IoT), private LTE/5G networks, machine learning, robotics, wearables, big data, artificial intelligence, and cloud services are among the key enablers behind the factory automation use cases [2]. Within the scope of this work, cellular connectivity and wearable technology are the smart factory enablers that are in focus.

A. Cellular Connectivity

A fully connected manufacturing system, in which workers and machines communicate at each stage of the production process, is the foundation of a smart factory. Historically, industrial Ethernet has been deployed in fixed-cable networks that are mainly targeted to support critical applications for stationary workers and machines [2]. However, the key to smart manufacturing is a communication platform that enables mobility for connected devices, agility in operations, and scalability of the network. Hence, manufacturing is shifting toward wireless connectivity solutions like Wi-Fi, LoRa, ZigBee, Bluetooth, and ultra-wideband (UWB) [2]. Not limited to the economy of scale and interoperability issues at both the infrastructure and the end-device sides, a constraint on the deployment of these solutions can be in the uncontrolled interference produced by the unlicensed spectrum options. However, unlicensed-band solutions can complement licensed-band technologies to boost system capacity and offload non-critical traffic from licensed to unlicensed frequencies.

The limitations of legacy technologies deployed in industries drive the convergence toward the use of cellular connectivity [2]. Specifically, 5G New Radio (NR) is considered as a key enabler for the implementation of Industry 4.0. With the 3GPP recommendation of three service classes (ultra-reliable low-latency communications (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communications (mMTC)), 5G NR networks are rapidly gaining momentum as an all-inclusive communication platform for the provisioning of dissimilar application requirements defined by the smart factory use cases [2].

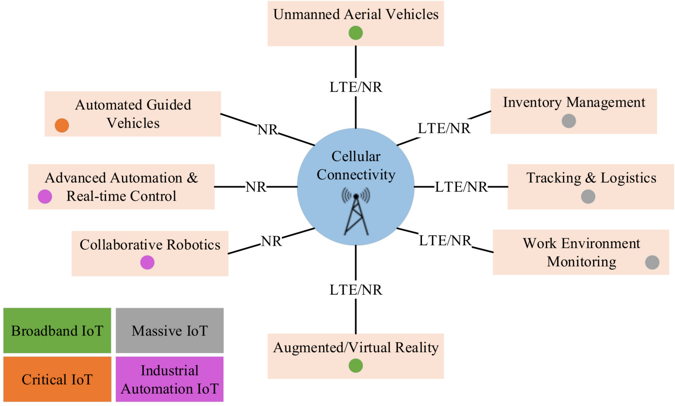

Fig. 1. Overview of cellular-enabled services in smart factory environment

In Fig. 1, we select the main services that illustrate the possible forms of automation in a cellular-enabled smart factory. These use cases have been identified and trialed by several manufacturing sites to assess the impacts of the introduced factory automation processes [2]. Being part of a broader IoT ecosystem, the connectivity needs of the smart factory use cases can be addressed by the four multi-purpose IoT segments that can co-exist in a single 5G-enabled network [3]. These are developed by the 3GPP community and include Massive IoT, Broadband IoT, Critical IoT, and Industrial Automation IoT. Each cellular IoT segment addresses multiple requirements such that, when combined within one network, the four segments together provide cellular connectivity with the capability to meet the extremely diverse requirements of the smart factory use cases [3].

B. *Wearable Technology*

An important component of the smart factory paradigm is related to the employment of intelligent assistant systems. In a smart factory, workers and production processes are supported by computer-aided systems to ensure a seamless flow of operation for increased performance and safety [1]. Examples of industrial intelligent assistant systems are provided in Fig. 1 and include automated guided vehicles, drones, sensors, wearables, and mobile robots. Among these "smart helpers", industrial wearables are gaining attention as the key driver on the wearable market, next to consumer wearables. According to a Markets and Markets report on the "Industrial Wearables Market", the latter is projected to grow from USD 1.1 billion in 2019 to USD 8.6 billion by 2024, thus reaching the compound annual growth rate of 50.2%.

The increased attention toward industrial wearables can be supported further by the involvement of wearable devices into several smart factory use cases that are illustrated in Fig. 1. For instance, the AR/VR category includes wearable-based applications, such as quality inspection and troubleshooting of products using AR-enabled wearable devices [2]. Accordingly, workers are equipped with AR headsets to inspect the quality of the manufactured products in a hands-free fashion. Therefore, replacing documents and manuals with visualized high-quality information helps reduce the fault detection times, and thus better handle the high troubleshooter workloads [2]. This application becomes an example of the many benefits that can be brought by the use of wearables in smart factories. With cloud native technologies becoming central to the 5G core architecture, the network can provide wearable devices with the necessary storage capacity and processing power. Hence, 5G-enabled wearables will be able to host more sensors, collect more data, and enable new industrial applications.

Although the initial deployments of smart factory solutions that involve wearable devices focus on mobile broadband (such as AR/VR), critical (for example, real-time control of manufacturing), and massive (such as monitoring of warehouse logistics) scenarios, other services target predictive safety improvements and increased productivity. These applications have mid-end requirements that do not strictly fall under the three 5G service classes (eMBB, URLLC, and mMTC). Motivated by the promise of wearable technology in these emerging applications, our contribution is built around the industrial mid-end wearable use cases, requirements, and technology enablers.

III. INDUSTRIAL MID-END WEARABLE APPLICATIONS

Advanced movement assistance using wearable exoskeletons and monitoring smart watch-equipped employees in high-risk working environments are examples of applications that (i) are associated with relaxed requirements in comparison to broadband and critical applications and (ii) engage wearable devices equipped with more elaborate features and audio/video capabilities as compared to massive low-end wearables. These characteristics are common to the new category of applications that we refer to as IM-EWA.

To better position the IM-EWA class among the existing smart factory services, we revise the 5G spider diagram that incorporates the emerging applications on top of the three other 5G service classes. The outcome is depicted in Fig. 2 and is based on (i) the technical performance requirements for International Mobile Telecommunications-2020 (IMT-2020) radio interfaces and (ii) the communication requirements of wearable devices provided in [4] and [5]. We further offer a classification of the potential IM-EWA examples and their performance requirements, mainly in terms of the data rate, latency, and reliability.

- **Process Management Services**: this category comprises applications aiming to ensure the appropriate execution as well as surveillance of the industrial workflows in various parts of a factory, such as warehouses and production lines. Examples of services under this category include workforce resource management, progress report exchange using smart watches, and streaming video tutorials using wearable headsets without the need for an

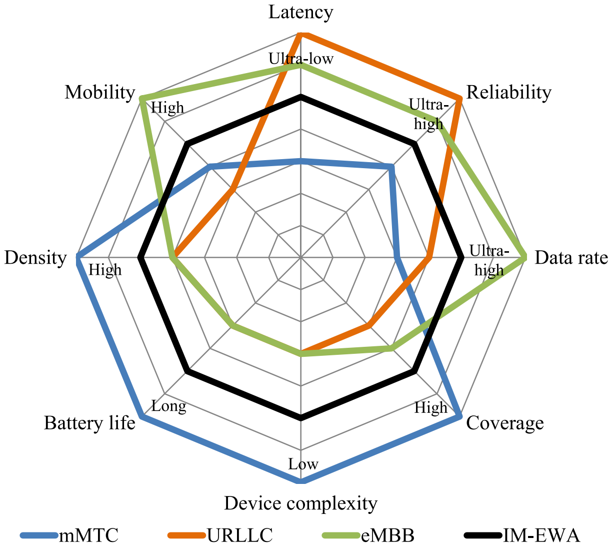

Fig. 2. Requirements of IM-EWA in relation to 5G service classes

expert to be present in the field. The common feature of these examples is that the expected amount of exchanged data and the required data rates are higher as compared to mMTC services but lower in comparison to eMBB applications, as illustrated in Fig. 2. For this category of IM-EWA, the ranges of 2 to 5 Mbps and 5 to 50 Mbps are considered for the uplink (UL) and the downlink (DL) data rates, respectively.

- **Work Safety Services**: deploying mechanisms for preventing work accidents allows factories to equip their workers with real-time safety measures. Wearable devices can play a crucial role in these mechanisms, especially by promoting hands-free operation. For instance, working with potentially dangerous power tools can be controlled by wearable wristbands, wearable headsets can alert truck drivers in case of sensing fatigue or distraction in real time, certain industrial exoskeletons are designed today for supporting manual labor tasks, and smart watches can also be used to transmit voice messages in critical situations. These examples of mission-centric applications require very low latency values ranging from 5 to 10 ms.
- **Healthcare Monitoring Services**: the mental and physical health conditions of workers directly affect their performance. Therefore, it is necessary for factories to ensure healthy workplaces where the well-being of all employees is considered to be a priority. Equipping workers with various wearables like smart watches, fitness trackers, as well as glucose, blood pressure, and heart rate monitors, and then processing the collected health data allow providing these workers with insights around monitoring their health conditions and also their insurance and billing statements without the need for going through the usual administrative burden. For this category of applications, ultra-high reliability values between 99.9% and 99.99% are required, since they involve exchanging health data.

In the above classification, we emphasize the main requirement of each application category (i.e., data rate in process management, latency in work safety, and reliability in healthcare monitoring services). However, we also review other application requirements. Specifically, in work safety and healthcare monitoring services, the ranges of 0.25 to 2 Mbps and 0.25 to 5 Mbps are required in terms of UL and DL data rates, respectively. Low latency values ranging from 10 to 100 ms are demanded in process management and healthcare monitoring applications. In terms of reliability of process management and work safety services, the range of 99 to 99.9% is typical.

Admittedly, the considered categories of applications promise not only enhanced productivity of employees, but also improved safety and health conditions. Taking into account these important factors, wearable devices have to be provided with the required connectivity levels in 5G-enabled smart factories, especially in the scenarios where the success of industrial tasks can be affected by the communication system performance and device capabilities. Therefore, complementing the traditional cellular connectivity with appropriate NR features enables the industrial 5G networks to cover these scenarios and meet the requirements imposed by the novel IM-EWA use cases.

IV. EMERGING 5G NR CONNECTIVITY FEATURES

A. Cellular Network-Aided D2D Communications

D2D communications are characterized by direct data exchange between proximate mobile devices under the control of the base station. Employing this type of connections in cellular networks has demonstrated improved performance in terms of several metrics, including throughput, latency, reliability, and spectral and energy efficiency [6]. To exploit these benefits and serve the developing market of proximity services, 3GPP has proposed the use of D2D communications in LTE systems by specifying a D2D interface known as sidelink.

Historically, the term sidelink was first introduced in 3GPP Rel-12 as a complementary enabler for public safety proximity services provided by LTE networks. Subsequently, two LTE sidelink communication modes were designed specifically for vehicle-to-vehicle communications in Rel-14 to improve traffic safety by allowing vehicles to exchange accurate knowledge of their surrounding environment [7]. The evolution of sidelink communications in 3GPP specifications continued through Rel-16 by introducing NR sidelink, a 5G NR feature that supports D2D connectivity over the sidelink. Similarly to Rel-15 LTE sidelink, the main use cases of NR sidelink are vehicle-to-everything (V2X) and public safety.

Beyond public safety and V2X services, the more recent use cases of D2D communications include commercial applications, such as maritime and wearable services [8]. Motivated by the fact that wearables are often paired with a smart phone using a short-range radio technology to connect to the network, 3GPP evaluated in [9] the benefits of using an enhanced form of LTE sidelink for D2D-aided services with the focus on wearable and IoT applications. The primary objective of that technical report is to study user equipment-to-network (UE-to-network) relay scenarios for low-end devices.

In these particular setups, the aim of using D2D communications for wearables is limited to providing proximity-based energy-efficient communications. However, with the definition of two transmission modes for NR sidelink in 3GPP Rel-16 [10], deploying D2D communications in 5G-enabled wearable networks for industrial mid-end applications has the potential of three types of gains (i.e., proximity, hop, and reuse) and multiple performance improvements (for example, availability, latency, reliability, and spectral efficiency).

B. New Radio Reduced-Capability Features

With first discussions held in March 2019, 3GPP Rel-17 is believed to bring further opportunities for cellular systems to address novel IoT use cases that can include advanced meters, industrial sensors, surveillance cameras, and wearable devices in smart home, smart city, and industrial applications [11]. However, these new use cases should be addressed with additional considerations, especially in terms of device capabilities (i.e., complexity and cost). Even though it is technically feasible, reusing the high-end UE capabilities of Rel-15 NR devices is economically inefficient since the device capabilities may exceed the service requirements [11].

The said gap has motivated several 3GPP-involved partners to launch 3GPP Rel-17 study and work items for the support of the new requirements that emerge in-between the well-defined performance objectives of the 5G communication classes. As a result of these efforts, a new 3GPP technical report was released in December 2020 to characterize the required technical capabilities for the novel "mid-end IoT" applications [4]. The NR support for RedCap devices was initially named NR-Lite, subsequently re-named to NR-Light, and finally established as NR RedCap. Specifically, RedCap wearables include glasses, headsets, and watch-type devices that are capable of not only monitoring healthcare information but also enabling access to advanced applications [11].

The impact of reduced capabilities on network performance, UE power saving, identification, and access control are among the study objectives that were identified by NR RedCap-related 3GPP documents. Therein, device complexity reduction is the priority topic due to the need for defining RedCap device types that represent a combination of terminal capabilities [12]. Compared to Rel-15 NR UEs, RedCap devices have to support reduced UE bandwidth, smaller number of Tx/Rx antennas, half-duplex FDD operation, relaxed UL/DL modulation orders, reduced number of DL MIMO layers, and lower UE processing times. The recommended ranges of these radio-frequency and baseband parameters for RedCap terminals as compared to Rel-15 NR devices are provided in the feature description parts of 3GPP TR 38.875 [4]. Concerning the number of device categories, ratifying a device type for each specific use case was not preferred due to the risk of market fragmentation. Hence, two RedCap device categories were recommended based on the utilized frequency range (FR1 or FR2) [12].

V. D2D-AIDED NR REDCAP FOR IM-EWA

The key requirement that was excessively considered by the wearable market solutions and overly studied by the research works related to wearable applications is energy efficiency [13]. However, and as reviewed in Sections III and IV, the emerging industrial mid-end applications involving reduced-capability wearables target various scenarios that eventually go beyond the sole requirement of energy-efficient communications. This observation is supported by the findings of our technology background and the future trends in wearable technology, namely, (i) the network-controlled and autonomous transmission modes ratified by 3GPP for the extension of NR sidelink operating scenarios, (ii) the power saving techniques defined among the study objectives of the NR RedCap technology, and (iii) the research efforts targeting battery-free or zero-energy devices, wireless power transfer, and energy harvesting mechanisms [14]. Hence, this section discusses the multitude of scenarios, where NR RedCap-enabled wearables can employ network-aided D2D communications to complement the conventional cellular connectivity in smart factory environments.

In smart factories enabling automated operations, any interruptions to the industrial processes may result in high downtime costs. Hence, the network must be made sufficiently reliable, so that workers are able to continuously access the provided services without the risk of downtime. This availability challenge is even more critical for NR RedCap-enabled wearables, where a potential loss of coverage is caused by the simplifications to the radio-frequency and baseband capabilities as compared to those of Rel-15 NR devices. As shown in Fig. 3, in outdoor industrial tasks that might lead to out-of-coverage situations, workers can be provided with the required radio connectivity by establishing direct D2D connections. Such scenarios illustrate the benefits of exploiting the proximity of wearable devices by 5G networks not only in offering low delays but also in compensating for the coverage reduction and guaranteeing uninterrupted access to applications. The resultant network availability and latency enhancements are valuable especially for mission-critical services, such as work safety-related applications.

Signal strength is another essential and challenging parameter for wearables, especially when considering near-body communications and the peculiarities of radio propagation in industrial environments where multiple objects can cause signal fluctuations. As a result, signal strength degradation and radio link intermittence can be expected due to the non-line-of-sight (NLOS) propagation. These considerations directly affect the reliability requirement of IM-EWA. Hence, and as illustrated in Fig. 3, a UE-to-network relay can be deployed in NLOS scenarios to provide alternative propagation paths for the signal. Consequently, improving the signal strength helps delivering reliable services in industrial wearable networks.

Similarly to the availability, latency, and reliability enhancements, spectral efficiency boost is considered as an essential benefit of network-aided D2D communications being a direct implication of the reuse gain. The latter implies that radio resources can be simultaneously used by cellular as well as D2D links. This link diversity helps reduce the cellular network load without the need to deploy denser fixed infrastructure, which is considered to be a valuable asset for industries seeking to scale and adapt their networks for future growth targets without increased capital expenditures.

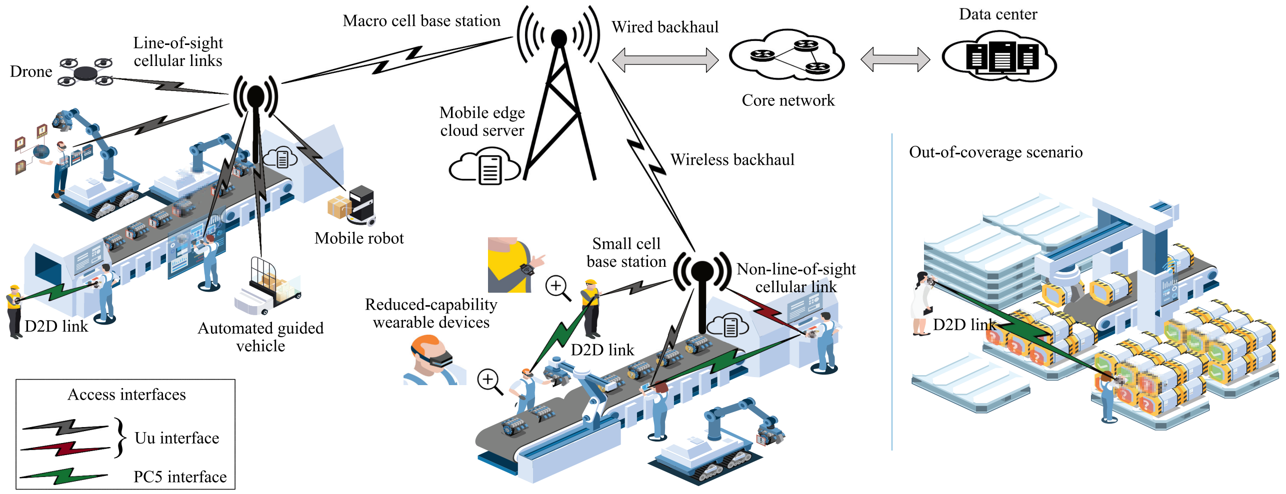

Fig. 3. Cellular-based D2D-aided communication scenarios for mid-end wearable applications in industrial setups

Furthermore, a mobile edge cloud server can be deployed next to each base station (BS) as depicted in Fig. 3. Mobile edge computing can enable NR RedCap wearable operations at lower delays even when D2D relaying is employed. The considered scenarios suggest that network-aided D2D communications can work in concert with cellular links to enhance the connectivity options for RedCap-enabled wearables and to meet the emerging IM-EWA requirements.

VI. SYSTEM-LEVEL PERFORMANCE EVALUATION

In this section, we investigate the performance of network-controlled D2D-enhanced cellular connectivity for IM-EWA. More precisely, we examine the performance of D2D-aided NR RedCap wearable networks in specific industrial scenarios and in terms of essential performance metrics.

A. *Evaluation Methodology and Parameters*

For modeling purposes, we employ network simulator 3 (ns-3). Specifically, the system-level evaluation is conducted based on the LTE-evolved packet core network simulator (LENA) updated with the D2D-related capabilities, models, and configurations. Such updates are supported by the research community and were first published in [15]. Further, we extended the LENA module with the features essential for the simulation of industrial reduced-capability wearable devices. In more detail, an empirical off-body propagation loss model was implemented to better capture the signal propagation between different wearable devices and between wearables and the BS. This model is based on an off-body propagation channel that is utilized by the research community as an experimental characterization of UWB communications (from 3.1 to 8 GHz) in body area networks.

Within the above range, we consider a scenario where a cellular network is deployed in the 3.6-3.8 GHz frequency band. This band is used for provisioning cellular connectivity for smart factories in several countries, including Germany, Sweden, and Finland. In terms of device complexity reduction, we utilize the LTE Cat 1bis capabilities as recommended by 3GPP for the NR RedCap devices operating in FR1. We therefore updated the ns-3 adaptive modulation and coding model, where the baseband processing follows the recommendations of the 3GPP specification on physical layer procedures. To summarize the essential parameters collected in Table I, the RedCap-enabled wearables have the maximum bandwidth of 20 MHz, the maximum UL modulation order of 16QAM, the maximum DL modulation order of 64QAM, the transmit power of 23 dBm, and one Tx/Rx antenna.

The sidelink transmission mode is controlled by the network, which is responsible for cellular and sidelink resource configuration. The two main modes that have been defined

TABLE I
SYSTEM-LEVEL EVALUATION PARAMETERS

RedCap-related parameters	**Value**
Max. bandwidth	20 MHz
Max. UL modulation order	4 (16QAM)
Max. DL modulation order	6 (64QAM)
UE transmission mode	1 (1 Tx/Rx antenna)
UE power class	3
UE transmit power	23 dBm
D2D-related parameters	**Value**
Sidelink transmission mode	Mode-1 (network-controlled)
Sidelink MCS	10, 15
PSCCH period	40 ms
Number of PSCCH sub-frames	8
Application-related parameters	**Value**
Traffic model	CBR traffic
Packet size	100–1000 bytes
Inter-packet interval	0.5 s
Other parameters	**Value**
Frequency band	3.6–3.8 GHz
Propagation loss model	UWB off-body channel
Factory floor dimensions	10 x 15 m
Network layout	Single-cell in-coverage and UE-to-network relay scenarios
BS transmit power	33 dBm
BS noise figure	5 dB
BS antenna height	25 m
UE noise figure	7 dB
UE antenna height	1.5 m

for NR sidelink in 3GPP Rel-16 are (i) network-controlled mode, also named transmission mode-1, in which the sidelink configuration is monitored and provided to the UEs by the BS and (ii) autonomous mode, known as transmission mode-2, where UEs rely on sidelink pre-configurations stored by the devices. Based on these definitions, we can assume that while in-coverage UEs can operate in either transmission mode, out-of-coverage users can only utilize the autonomous mode. In either transmission mode, the sidelink grant configuration is based on determining the modulation and coding scheme (MCS), the number of physical resource blocks, and the number of transmission opportunities for each D2D connection. This grant configuration is performed by the network or the UE with a periodicity defined by the Physical Sidelink Control Channel (PSCCH) period parameter.

B. *Spectral Efficiency Results*

To examine the impact of employing D2D communications as an on-demand feature in NR RedCap wearable networks, the first performance indicator that we are considering is the spectral efficiency. Specifically, the area spectral efficiency characterizes the sum of the maximum average data rates achieved per unit bandwidth per unit area in bps/Hz/m^2. The numerical results are provided in Fig. 4 as a function of the total and the D2D user densities. For the user density that is below 2.9 users/m^2, the average area spectral efficiency of a single-cell network increases steadily. Since a degradation of the spectral efficiency performance is observed after that value, one can conclude that it represents the maximum capacity of the cell for the adopted configuration of the user traffic models and the factory floor dimensions.

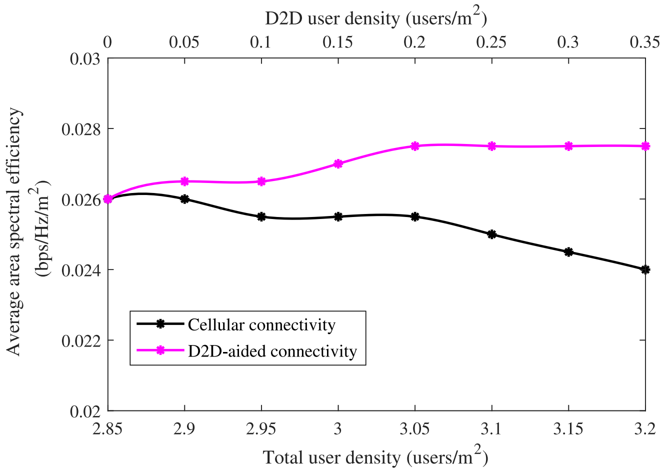

Fig. 4. Average area spectral efficiency (bps/Hz/m^2) in single-cell in-coverage scenario for industrial wearable systems

After reaching the maximum capacity of the cell, the natural decision for network designers in smart factories is to densify the cellular infrastructure. However, this option should increase the capital expenditures. Hence, utilizing on-demand network features that can complement the cellular connectivity in high-density scenarios without the need to deploy denser infrastructures is considered as a preferable alternative for factory owners. As depicted in Fig. 4, the obtained results confirm the advantage of complementing cellular connectivity with network-aided D2D communications, specifically for network capacity improvement. These findings gain more importance in factory environments where the number of devices can increase significantly and the cellular network is expected to handle this surge of demand without introducing bottlenecks.

C. *Service Reliability Results*

Complementing the spectral efficiency results, we also consider an application-related performance indicator, which is the packet delivery ratio. This metric is mainly used to evaluate the service reliability in cellular and D2D-aided connectivity scenarios. The target devices in D2D-aided connectivity scenarios are relay UEs and remote UEs that enable UE-to-network relaying depending on the cellular link quality. A single relay UE is responsible for providing its two associated remote UEs with radio connectivity. On the application side, we implement a constant bit rate (CBR) traffic model with the settings (i.e., packet size and inter-packet interval) given in Table I.

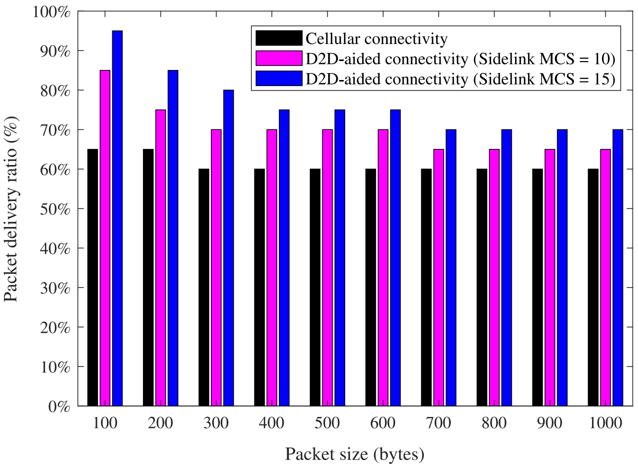

Fig. 5. Packet delivery ratio (%) in cellular connectivity-only and UE-to-network relay setups for IM-EWA

Fig. 5 reports the numerical results for the packet delivery ratio depending on the connectivity scenario and the packet size. In D2D-aided NR RedCap setups, remote wearables deploy D2D links to the relay UEs to improve their service continuity. Therefore, the share of successfully delivered packets is higher than that in the direct cellular connectivity setup. As demonstrated in Fig. 5, the packet delivery ratio can be improved further by adopting sidelink configurations with higher modulation orders. Notably, additional service reliability enhancements can be offered by taking into account the impact of other sidelink-related parameters, such as the PSCCH period, the number of PSCCH sub-frames, and the number of remote UEs per relay.

VII. CONCLUSION

In this article, we provided a summary of the smart factory concept by outlining its main use cases and key enablers.

Among these, we focused on cellular connectivity and wearable technology. Specifically, we presented the emerging category of industrial wearable applications, namely, IM-EWA. We then discussed the cellular features that may be valuable to construct industrial wearable networks and to support the requirements of IM-EWA with reduced-capability devices. The reviewed features included network-aided D2D communications and NR RedCap functions. Further, we analyzed D2D-aided NR RedCap operation in characteristic industrial scenarios and examined, via system-level performance evaluation, the benefits of enhancing cellular connectivity with D2D capabilities.

The understanding of 5G NR connectivity setups that help meet the requirements of the emerging industrial wearable applications allows the standardization community to identify essential improvements to existing 5G NR features. For instance, recognizing the value of D2D communications for RedCap-enabled devices aids in answering the question of whether the network-controlled D2D capability should be a part of the NR RedCap specifications. Such insights can be elaborated further by considering additional aspects related to D2D-aided NR RedCap operation for industrial wearable applications, such as energy efficiency in collaborative communication scenarios.

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REFERENCES

[1] P. Osterrieder, L. Budde, and T. Friedli, "The smart factory as a key construct of industry 4.0: A systematic literature review," *International Journal of Production Economics*, vol. 221, p. 107476, 2020.

[2] "What Industry 4.0 means for manufacturing," Ericsson, Case Study, February 2019.

[3] A. Zaidi, A. Branneby, A. Nazari, M. Hogan, and C. Kuhlins, "Cellular IoT in the 5G era," Ericsson, White Paper GFMC-20:000025 Uen, February 2020.

[4] "Study on support of reduced capability NR devices (Release 17)," 3GPP, TR 38.875, December 2020.

[5] R. Djapic, G. Vivier, B. Zhen, J. Wang, J. Lee, and W. Haiming, "Wearables white paper," TNO, White Paper, January 2018.

[6] G. Fodor *et al.*, "Design aspects of network assisted device-to-device communications," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 170–177, 2012.

[7] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications," *IEEE Vehicular Technology Magazine*, vol. 12, no. 4, pp. 30–39, 2017.

[8] S.-Y. Lien, C.-C. Chien, F.-M. Tseng, and T.-C. Ho, "3GPP device-to-device communications for beyond 4G cellular networks," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 29–35, 2016.

[9] "Study on further enhancements to LTE Device to Device (D2D), User Equipment (UE) to network relays for Internet of Things (IoT) and wearables (Release 14)," 3GPP, TR 36.746, April 2017.

[10] S. A. Ashraf, R. Blasco, H. Do, G. Fodor, C. Zhang, and W. Sun, "Supporting Vehicle-to-Everything Services by 5G New Radio Release-16 Systems," *IEEE Communications Standards Magazine*, vol. 4, no. 1, pp. 26–32, 2020.

[11] "Views of Rel 17 NR Light," 3GPP, TDoc RP-192018, September 2019.

[12] "Framework and principles for RedCap," 3GPP, TDoc R2-2009618, November 2020.

[13] S. Seneviratne, Y. Hu, T. Nguyen, G. Lan, S. Khalifa, K. Thilakarathna, M. Hassan, and A. Seneviratne, "A survey of wearable devices and challenges," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2573–2620, 2017.

[14] N. Mahmood, A. Munari, F. Clazzer, and H. Bartz, "Critical and massive machine type communication towards 6G," 2020.

[15] R. Rouil, F. J. Cintrón, A. Ben Mosbah, and S. Gamboa, "Implementation and Validation of an LTE D2D Model for ns-3," in *Proceedings of the Workshop on ns-3*, 2017, pp. 55–62.

BIOGRAPHIES

SALWA SAAFI (saafi@feec.vutbr.cz) is a joint Ph.D. student at the Department of Telecommunications at Brno University of Technology, Czech Republic and the Unit of Electrical Engineering at Tampere University, Finland. She received her engineering degree (2017) in telecommunications from the Higher School of Communication of Tunis, Tunisia. Her research interests include cellular radio access technologies, future wireless architectures, and wearable applications.

GABOR FODOR (gaborf@kth.se) received his Ph.D. degree in electrical engineering from the Budapest University of Technology and Economics in 1998, his Docent degree from KTH Royal Institute of Technology, Stockholm, Sweden, in 2019, and his D.Sc. degree from the Hungarian Academy of Sciences in 2019. He is currently a master researcher with Ericsson Research and an adjunct professor with KTH Royal Institute of Technology. He was a co-recipient of the IEEE Communications Society Stephen O. Rice Prize in 2018. He is serving as the Chair of the IEEE Communications Society Full Duplex Emerging Technologies Initiative and as an Editor for IEEE Transactions on Wireless Communications and IEEE Wireless Communications.

JIRI HOSEK (hosek@feec.vutbr.cz) received his M.S. and Ph.D. degrees in electrical engineering from the Faculty of Electrical Engineering and Communication at Brno University of Technology (BUT), Czech Republic, in 2007 and 2011, respectively. He is currently an Associate Professor (2016) and Deputy Vice-Head for R&D and International Relations at the Department of Telecommunications (2018), BUT. Jiri is also coordinating the WISLAB research group (2012), where he deals mostly with industry-oriented projects in the area of IoT and home automation services. Jiri (co-)authored more than 130 research works on networking technologies, wireless communications, quality of service, quality of experience, and IoT applications.

SERGEY ANDREEV (sergey.andreev@tuni.fi) is an associate professor of communications engineering and Academy Research Fellow at Tampere University, Finland. He has been a Visiting Senior Research Fellow with King's College London, UK (2018-20) and a Visiting Postdoc with University of California, Los Angeles, US (2016-17). He received his Ph.D. (2012) from TUT as well as his Specialist (2006), Cand.Sc. (2009), and Dr.Habil. (2019) degrees from SUAI. He is lead series editor of the IoT Series (since 2018) for IEEE Communications Magazine; he served as editor for IEEE Wireless Communications Letters (2017-19).