Multi-Gigabit Millimeter-Wave Industrial Communication: A Solution for Industry 4.0 and Beyond

Abdul Jabbar, Muhammad Ali Jamshed, Mahmoud A. Shawky, Qammer H. Abbasi, Muhammad Ali Imran and Masood Ur Rehman

James Watt School of Engineering, University of Glasgow, UK

{abdul.jabbar; muhammadali.jamshed; mahmoud.shawky; qammer.abbasi; muhammad.imran; masood.urrehman}@glasgow.ac.uk

***Abstract*—Industry 4.0 and 5.0 are paradigms of digitalization and intelligentization. The huge available bandwidth and the least spectral interference in millimeter-wave (mmWave) band can pave the way for a wide range of new industrial automation capabilities. Sophisticated industrial applications such as industrial Internet of Things, time-sensitive networking (TSN), intelligent logistics, product tracking, remote visual monitoring and surveillance, image-guided automated assembly and automatic fault detection require high bandwidth, reliability and low latency which can be ensured using the mmWave band. In this paper, we address the physical layer (PHY) requirements of industrial communication from the viewpoint of Industry 4.0 and beyond, while highlighting the key performance indicators. This paper proposes a 60 GHz millimeter-wave antenna system with high reliability and low latency, making it ideally suited for industrial IoT and communication. The proposed novel antenna system is designed to cover the entire 9 GHz bandwidth of the 60 GHz standard spectrum (57 to 66 GHz). It provides high gain and efficiency across all four channels of 60 GHz communication from 57.24 GHz to 65.88 GHz, each channel with 2.16 GHz of bandwidth. Moreover, the simulated achieved beamforming gain of the proposed antenna system reaches 16.1 dBi, which satisfies the high gain requirement for 60 GHz multi-gigabit industrial communication. The proposed antenna system is a promising physical layer candidate suitable for communication standards such as WiGig IEEE802.11ay, IEEE802.11ad, IEEE802.15.3c, ECMA-387 and WirelessHD to ensure multi-gigabit wireless communication at 60 GHz ISM band for factory automation and industrial applications.**

Keywords— Industrial IoT, Industry 4.0, Industry 5.0, Millimeter-wave, 60 GHz communication.

I. Introduction

The utilization of the millimeter-wave (mmWave) band has become a physical layer (PHY) enabling technology for fifth-generation (5G) as well as sixth-generation (6G) wireless communication [1], [2]. Industrial wireless communication has also embraced mmWave bands due to huge available bandwidth required for many sophisticated industrial applications such as smart manufacturing and factory automation. The Internet of Things (IoT) combined with advanced analytics capabilities can facilitate automated and flexible processes that can be monitored in real-time, lowering production and maintenance costs [3], [4]. The industry 4.0 regime is concerned with the digitalization of the industrial sector, with the ultimate goal of optimizing existing processes and creating the so-called smart factory (see Fig .1).

Amongst the mmWave bands, the 60 GHz Industrial, Scientific and Medical (ISM) band possesses immense future potential in industrial communication and control [3]. It provides huge bandwidth of 9 GHz (57-66 GHz) available in many countries of the world (such as Australia, Singapore, Japan, Russia and some European countries), while 14 GHz of bandwidth has been acquired in Unites States (57-71 GHz) [5]. This huge bandwidth is far more than the combined bandwidth of sub-6 GHz ISM bands (2.4 and 5 GHz). Moreover, sub-6 GHz ISM bands provide very low bandwidth, are spectrally congested and suffer from interference which are major limiting factors in the performance of modern industrial applications. On the other hand, since mmWave band applications are not much acquired as compared to sub-6 GHz ISM band applications, thus interference mitigation is an inherent property of the mmWave bands along with huge available bandwidth. Thus the major limiting factor is the noise generated by the radio system. As a result, mmWave communication can be considered *noise-limited* instead of interference-limited [6]. This property of mmWave bands can be employed as inherent security to develop secure indoor industrial communication and sensing networks [4], [7].

On a broader aspect, industrial applications are usually categorized into two areas, namely factory automation and process automation [8], [9]. Factory automation applications include sensing, robots, production of materials and manufacturing, and intelligent logistics to list but a few. These applications produce bursty data and the latency requirement is quite stringent. Process automation

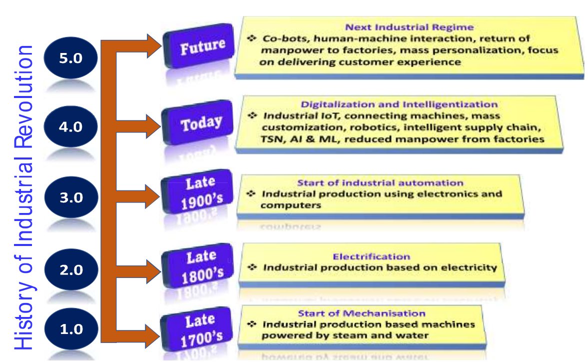

Fig. 1. Industrial revolutions from Industry 1.0 to Industry 5.0.

.

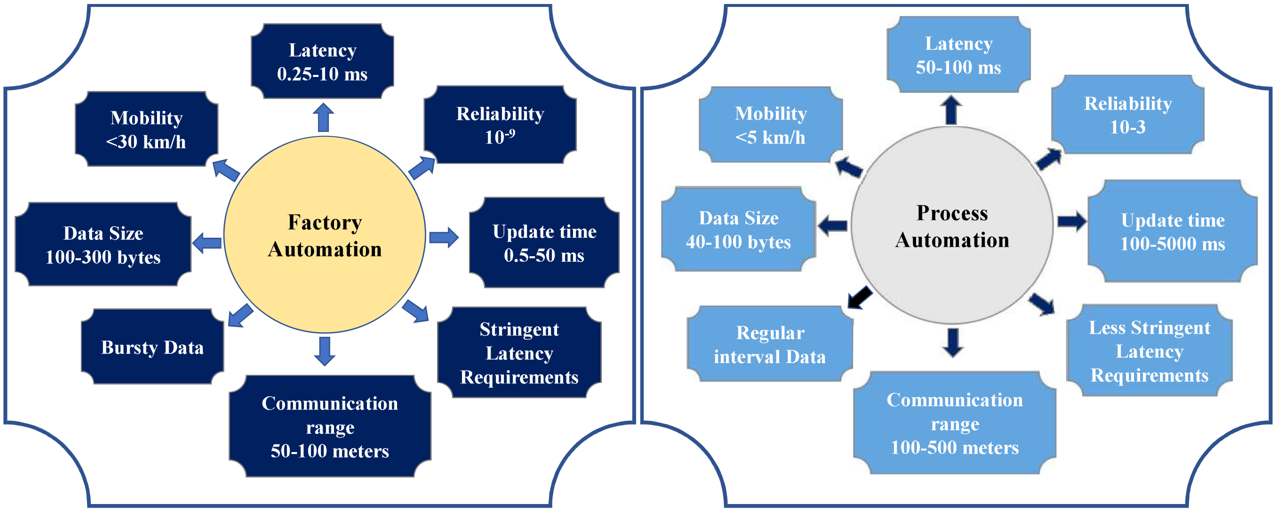

Fig. 2. Key performance indicators and requirements of industrial communication in factory automation and process automation scenarios.

on the other hand, includes non-critical closed-loop controls such as cooling and heating etc with less stringent latency requirements. The key performance indicators for both types are depicted in Fig. 2.

During the past many decades, industrial communication networks relied on wired technology. However, wireless alternatives have become more popular due to their ease of installation, flexibility, scalability and reconfiguration [9]. While various wireless technologies are available at sub-6 GHz ISM bands, important technical issues such as communication dependability and timeliness, security, interoperability, and energy sustainability, as well as the presence of proprietary and fragmented solutions, continue to hinder their adoption in industrial networks [10]. MmWave communication is one of the most demanding area in industrial communication networks to find potential solutions in this regard [4].

A. 60 GHz Industrial Wireless Communication and Motivation

Smart and reliable communication is of paramount importance in Industry 4.0 and beyond. It enables device connectivity and a constant flow of data that can be used to make the factory automation and manufacturing process smarter, more flexible, and adaptable. Manufacturing systems go beyond simple connectivity to leverage the data acquired to drive more intelligent actions and fulfil the demands for increased productivity, green manufacturing, market share, and flexibility. The vast bandwidth available in the 60 GHz mmWave spectrum can be used to implement ultra-reliable low latency communication (URLLC) for time-sensitive networking (TSN) as well as a wide range of new industrial automation capabilities [11]–[13]. For instance, robots and other industrial automation systems can interact appropriately with things and travel safely through their surroundings using mmWave multi-gigabits per second (Gbps) level data rate in vision technology and digital image processing. They can react to changing manufacturing-line circumstances using cameras, vision processors, and software algorithms, offering up a wide range of applications such as remote visual monitoring and surveillance, intelligent logistics and product tracking, automated image guidance with high precision, and automated product problem detection based on images [4], [14]. In this view, Wireless Gigabit Alliance (WiGig) is an international 60 GHz next-generation Wi-Fi standard that aims to unleash URLLC in the indoor industrial environment. This improved standard IEEE802.11ay provides a mechanism for channel bonding and multi-user MIMO [15]. Where IEEE802.11ad (industry consortium) uses 2.16 GHz of bandwidth [16], the improved IEEE802.11ay through channel bonding of 4 such channels is capable of providing 8.64 GHz of bandwidth with MIMO capacity up to four streams. This leads to high throughput of up to 100 Gbps [15]. Furthermore, the Third-Generation Partnership Project (3GPP) is standardizing new radio (NR) access technology (RAT) for 5G networks which supports mmWave carrier frequencies [17]–[19]. Therefore, in this context, consideration to allow NR to access 60 GHz unlicensed spectrum (NR-U) is expected, thereby opening up many new avenues to ensure URLLC in Industry 4.0 and beyond.

The existing industrial wireless standards at sub-6 GHz ISM bands are unable to accommodate the simultaneous transmission of real-time high-resolution video signals as well as other sensor data and control signals generated by the aforementioned applications. For high mobility as well as stationary (slowly moving) users, a system operating in the mmWave band is predicted to offer multi-Gbps data speed, which is sufficient for real-time transfer of sensor data, control signals, and high-resolution video streams between several endpoints in an industrial wireless network. Therefore, due to high spectral congestion and limited bandwidth at sub-6 GHz ISM bands, it is need of the hour to build 60 GHz mmWave communication and sensing systems, so that URLLC could soar to its full potential in Industry 4.0 and beyond.

B. Contribution

In this paper, we present an overview of the major shortcomings of existing industrial wireless communication at sub-6 GHz bands and address the potential role of mmWave communication to ensure URLLC in smart industries. We proposed and designed a new antenna system that covers the complete 60 GHz band providing a bandwidth of 9 GHz (from 57 GHz to 66 GHz) and covers applications of various 60 GHz protocols such as WiGig IEEE802.11ay, IEEE802.11ad, IEEE802.15.3c, ECMA-387 and WirelessHD. The proposed antenna system shows excellent performance in terms of high gain, radiation efficiency and stable beam coverage over the whole operating band. It covers four channels of IEEE802.11ad and IEEE802.11ay protocols with high gain and efficiency. Moreover, the beamforming performance of the array design shows a peak gain of 16.1 dBi which provides good immunity against path loss and attenuation at the 60 GHz band. The proposed antenna system is quite small (10 mm × 9 mm, fabricated sample shown in the inset of Fig. 7) enabling its conformability with industrial terminals and sensor nodes, and can be easily integrated with various components of industrial automation and sensor systems. Moreover, it finds its applications in miniature radios and industrial IoT sensor networks which can be installed in motor bearings, robotic arms, spinning engines, oil pumps, and other inaccessible locations in factory automation settings.

II. Overview Of Industrial Revolutions

Industrial history is quite old and the first industrial revolution started in the late 18th century with the utilization of steam, water and fossil fuels [20]. After the advent of electricity, the second industrial revolution started in the late 19th century and the concept of assembly line production began [21]. After that in the last quarter of the 20th century, as the semiconductor electronics domain made profound growth, the third industrial revolution era started which employed logic controls and robotics to bring product modernization [22]. With the rapid development of the internet, IoT, smart communication and manufacturing advancements, today we are living in the fourth industrial revolution era, known as Industry 4.0. An industrial revolution journey is illustrated in Fig. 1.

The industry 4.0 paradigm is based on completely automated and digitalized smart factories for improved production and personalised user experience [23]. Cloud computing, big data, Industrial Internet of Things (IIoT), digital twins, artificial intelligence, additive manufacturing, advanced robotics and cyber-physical system are the major key enabling technologies associated with Industry 4.0 [24]. As a result of the automated and digitalized philosophy of Industry 4.0, worldwide unemployment is supposed to be increased due to the lack of human creativity involved in the industrial regime. Therefore, a new industrial revolution known as Industry 5.0 is under conception whose philosophy is based on the involvement of human creativity back in the industry to develop a co-bot human-machine type interactive environment [25]. Yet to the surprise of readers, this is not the end and researchers have put the

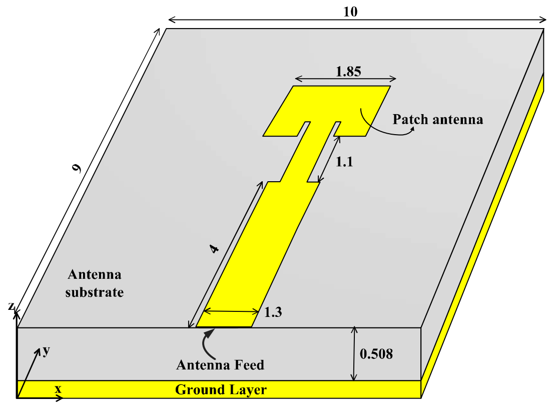

Fig. 3. Prototype of the optimized proposed antenna design covering IEEE802.11ad/ay, IEEE802.15.3c and WirelessHD protocols for mmWave industrial IoT and communication (dimensions in mm).

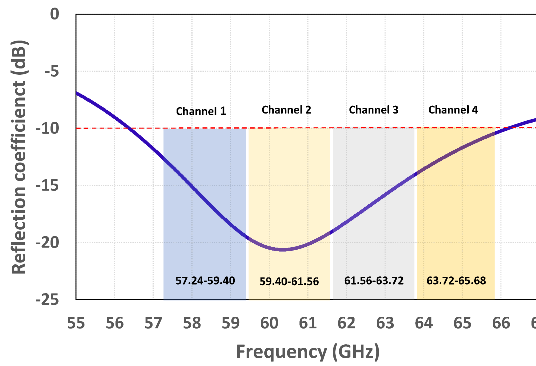

Fig. 4. Achieved bandwidth covering four channels. The reflection coefficient is below -10dB from 56.5 GHz to 66 GHz.

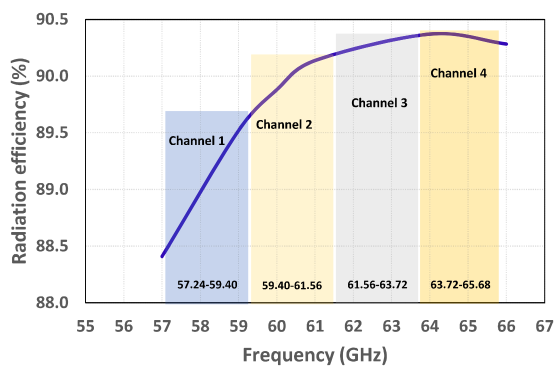

Fig. 5. Radiation efficiency in the whole band is greater than 88.5% in channels 1 and 2, while greater than 90% in channels 3 and 4.

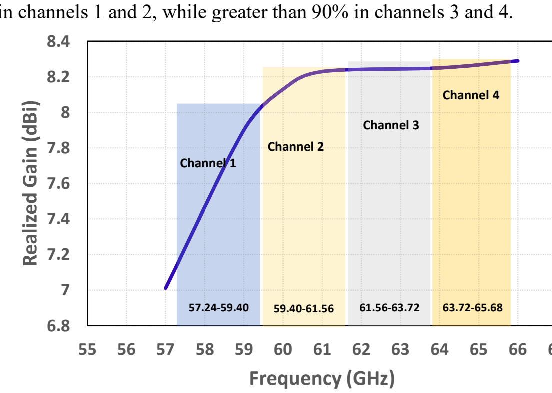

Fig. 6. Realized gain of single antenna element over the bandwidth of 9 GHz.

conceptualization of Industry 6.0 [26], which seems beyond the scope of this paper's discussion due to brevity. However, Industry 4.0 is still under adaptation and not fully conceived yet. Nevertheless, the research output in wireless communication and industrial network performance is equally applicable to these modern industrial generations which we collectively term here as *Industry 4.0 and beyond*.

III. Proposed Antenna System Performance And Results

With the motivation to enable mmWave industrial IoT and communication network, we designed and elucidated the performance of a new patch antenna at 60 GHz band. The proposed antenna is fully optimized in a 3D electromagnetic solver to cover full 9 GHz of bandwidth from 57 to 66 GHz. The permittivity of the substrate is 2.2 with a thickness of 0.508 mm. The prototype is shown in Fig. 3. The achieved bandwidth with reflection coefficient is shown in Fig. 4. The bandwidth of an antenna system is measured by -10 dB reference of reflection coefficient, which means the antenna system is 90% radiating the RF signal and only 10% signal is lost in it (due to impedance mismatch or practical conductor and dielectric losses). The VSWR of the designed antenna is much less than 2 overall the achieved bandwidth. The -10 dB reference line is shown in the red dotted line in Fig. 4. The antenna system covers four complete channels of IEEE802.11ad and 802.11ay protocols. In IEEE802.11ad, each wireless channel has to cover a bandwidth of at least 2.16 GHz [16]. Whereas IEEE802.11ay protocol supports channel bonding and aggregation and can support the combined bandwidth of 8.64 GHz by combining four such channels. In this view, our proposed antenna system covers channel 1 (57.24-59.40 GHz), channel 2 (59.40-61.56 GHz), channel 3 (61.56-63.72 GHz), and channel 4 (63.72-65.88 GHz), each with 2.16 GHz of bandwidth. The proposed antenna also covers channel 9 (57.24-61.56 GHz), channel 10 (59.40-63.72 GHz) and channel 11 (61.56-65.68 GHz), each of which can provide 4.32 GHz of bandwidth when used in channel bonding configuration under IEEE802.11ay protocol.

The achieved radiation efficiency is above 88.5% throughout the band as shown in Fig. 5. The maximum realized gain of the single antenna element is 8.2 dBi around 62 GHz, as shown in Fig. 6. Furthermore, a major issue in mmWave communication is path loss and signal attenuation, especially in rich scattered and harsh industrial environment [27], therefore we presented beamforming gain of the proposed antenna as well to combat path loss. As per Friis equation, the average received power in LOS scenario depends on the antenna gain as:

$$Pr = \frac{P_t G_t(\theta,\Phi) G_r(\theta,\Phi) \lambda^2}{4\pi d^2} \quad (1)$$

where Pt is the transmitted power, Pr is the received power, Gt and Gr are the antenna gains as a function of elevation and azimuth directions, λ is free space wavelength and d is the distance between the Tx and Rx.

A linear array of 8 element is designed at λ/2 element spacing (Fig. 9), which revealed high beamforming gain of 16.1 dBi at 64 GHz (Fig. 8). The half-power beamwidth is 11° which shows high directionality of the array. Such array beamforming gain is a desirable feature at 60 GHz band because mmWave channel measurements of industrial radio environment have shown high path losses [27], [28], which require beamforming array gain at the PHY level. The antenna size in array configuration is 1 cm × 2.25 cm which is still very compact. The coverage performance of the proposed antenna system is quite stable over the whole frequency band which is shown in Fig. 7 and Fig. 8.

The proposed 60 GHz antenna is low cost, easy to develop and integrateable with RF frontend and circuitry to make a compact IoT and communication network at 60 GHz mmWave ISM band.

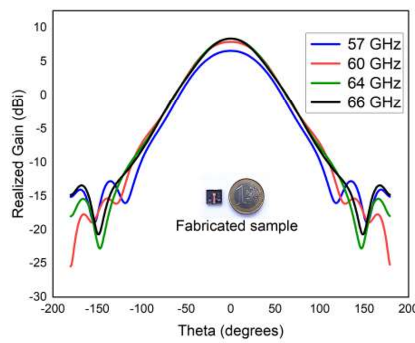

Fig. 7. 2D (realized gain) coverage of the proposed single antenna in elevation plane (x-z plane).

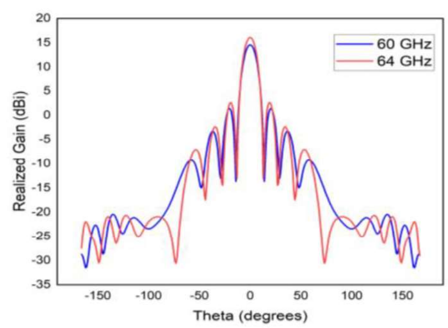

Fig. 8. 2D realized beamforming gain coverage of the proposed 8 elements linear array (x-z plane).

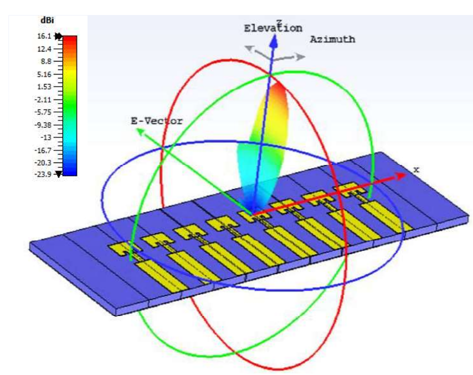

Fig. 9. Highly directional beam showing high beamforming array gain of 8 elements antenna array at 60 GHz band.

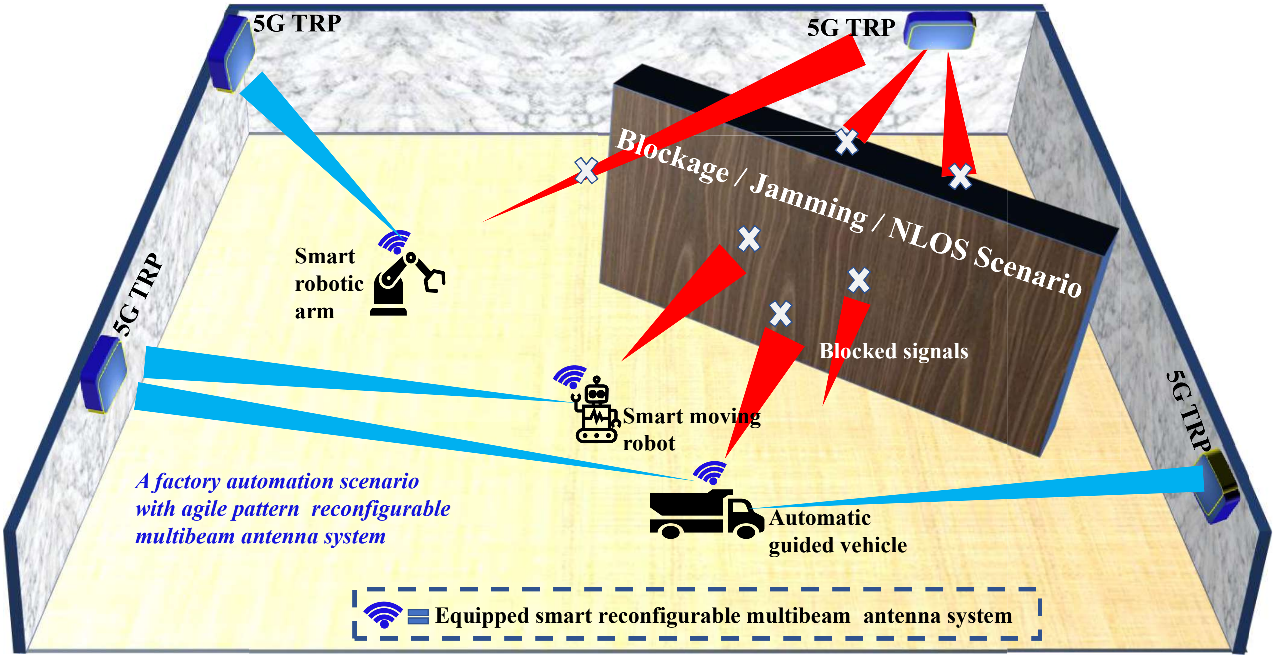

Fig. 10. A conceptual illustration of a smart factory floor where smart users such as automatic guided robots and automatic guided vehicles etc are equipped with smart reconfigurable multi-beam antennas. If the LOS link is blocked due to some jammer or moving object, the robots or any entity can still be connected with other access points to ensure seamless connectivity. This will ensure high reliability and save the industrial network from unnecessary blockages and latency. Moreover, narrow beam directional communication shows inherent interference mitigation at the mmWave band with extremely high throughput.

IV. Conclusion And Future Work

In this paper, we addressed physical layer (PHY) requirements of modern industrial communication (factory automation) in the viewpoint of Industry 4.0 and Industry 5.0. The key performance indicators of industrial communication depict the requirement of low latency up to a microsecond level, bit error rate of 10^{-9} and reliable agile industrial communication to perform automated tasks seamlessly. In this view, 60 GHz mmWave ISM band carries a huge potential for ultra-reliable and low latency industrial applications.

We proposed and designed a novel antenna system to achieve the entire 9 GHz bandwidth of 60 GHz band to support the PHY performance of industrial communication. The high gain of a single antenna element was 8.25 dBi, whereas the beamforming gain with only eight such linear elements reached to 16.1 dBi, which shows high directionality at the 60 GHz band to mitigate path loss and attenuation.

Moreover, the average radiation efficiency of the proposed antenna system in the acquired bandwidth is about 90% with highly stable radiation coverage performance in the whole band. The proposed antenna design system is a building block to develop multi-beam beamforming antenna system which can support PHY URLLC at 60 GHz ISM band in modern factory automation scenarios such as time-sensitive networking (TSN), IIoT, and quality multi-point communication to ensure URLLC in modern industrial settings.

One of the most crucial PHY performance indicators in smart manufacturing and factory automation is reliability. At PHY, quality multi-point communication can be employed to ensure URLLC, for which a smart reconfigurable antenna system is required. One user device simultaneously communicates with multiple 5G transmission-reception access points (TRP) to create a redundancy of beams. Once any one of the radio links is discontinued due to random motion of any object on the factory floor or due to some reflecting objects, the smart multi-beam antenna system on the user end (either robot, automatic guided vehicle, etc) can still be connected to other TRPs to ensure seamless connectivity. This ultimately ensures reliable communication in Industry 4.0 and beyond networks. A conceptual depiction of this concept has been shown in Fig. 10. Such smart reconfigurable multi-beam antenna systems can serve as an enabling technology to provide URLLC in IIoT as well as industrial communication and control.

References

[1] W. Hong et al., "The Role of Millimeter-Wave Technologies in 5G/6G Wireless Communications," IEEE J. Microwaves, vol. 1, no. 1, pp. 101–122, 2021, doi: 10.1109/jmw.2020.3035541.

[2] W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," IEEE Netw., vol. 34, no. 3, pp. 134–142, 2020, doi: 10.1109/MNET.001.1900287.

[3] C. Pielli, T. Ropitault, and M. Zorzi, The potential of mmWaves in smart industry: Manufacturing at 60 GHz, vol. 11104 LNCS. Springer International Publishing, 2018.

[4] M. Cheffena, "Industrial wireless communications over the millimeter wave spectrum: opportunities and challenges," IEEE Commun. Mag., vol. 54, no. 9, pp. 66–72, 2016.

[5] Qualcomm, "Global update on spectrum for 4G & 5G," Qualcomm Inc., San Diego, CA, White Pap., no. December, pp. 1–21, 2020, [Online].Available:https://www.qualcomm.com/media/documents/files/spectrum-for-4g-and-5g.pdf.

[6] T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao, and J. I. Tamir, "Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor Urban cellular communications," IEEE Trans. Antennas Propag., vol. 61, no. 4, pp. 1850–1859, 2013, doi: 10.1109/TAP.2012.2235056.

[7] S. Kutty and D. Sen, "Beamforming for Millimeter Wave Communications: An Inclusive Survey," IEEE Commun. Surv. Tutorials, vol. 18, no. 2, pp. 949–973, 2016, doi: 10.1109/COMST.2015.2504600.

[8] B. Holfeld et al., "Wireless communication for factory automation: An opportunity for LTE and 5G systems," IEEE Commun. Mag., vol. 54, no. 6, pp. 36–43, 2016.

[9] Q. Wang and J. Jiang, "Comparative examination on architecture and protocol of industrial wireless sensor network standards," IEEE Commun. Surv. \& Tutorials, vol. 18, no. 3, pp. 2197–2219, 2016.

[10] R. Candell and M. Kashef, "Industrial wireless: Problem space, success considerations, technologies, and future direction," in 2017 Resilience Week (RWS), 2017, pp. 133–139.

[11] Y. Niu, Y. Li, D. Jin, L. Su, and A. V Vasilakos, "A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges," Wirel. networks, vol. 21, no. 8, pp. 2657–2676, 2015.

[12] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," Proc. IEEE, vol. 99, no. 8, pp. 1390–1436, 2011, doi: 10.1109/JPROC.2011.2143650.

[13] A. Jabbar et al., "Millimeter-Wave Smart Antenna Solutions for URLLC in Industry 4.0 and Beyond," 2022.

[14] S. Saponara, F. Giannetti, B. Neri, and G. Anastasi, "Exploiting mm-wave communications to boost the performance of industrial wireless networks," IEEE Trans. Ind. Informatics, vol. 13, no. 3, pp. 1460–1470, 2017.

[15] Y. Ghasempour, C. R. C. M. Da Silva, C. Cordeiro, and E. W. Knightly, "IEEE 802.11ay: Next-Generation 60 GHz Communication for 100 Gb/s Wi-Fi," IEEE Commun. Mag., vol. 55, no. 12, pp. 186–192, 2017, doi: 10.1109/MCOM.2017.1700393.

[16] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and I. N. P. Aper, "IEEE 80211ad : Directional 60 GHz Communication for," no. December, pp. 132–141, 2014.

[17] S. Lagen et al., "New Radio Beam-Based Access to Unlicensed Spectrum: Design Challenges and Solutions," IEEE Commun. Surv. Tutorials, vol. 22, no. 1, pp. 8–37, 2020, doi: 10.1109/COMST.2019.2949145.

[18] N. Patriciello, S. Lagén, B. Bojović, and L. Giupponi, "NR-U and IEEE 802.11 technologies coexistence in unlicensed mmWave spectrum: Models and evaluation," IEEE access, vol. 8, pp. 71254–71271, 2020.

[19] N. Patriciello et al., "NR-U and WiGig coexistence in 60 GHz bands," arXiv Prepr. arXiv2001.04779, 2020.

[20] S. E. Company, "Journal of Industrial Strategic Management," vol. 2, no. 3, pp. 5–20, 2021.

[21] Y. Yin, K. E. Stecke, and D. Li, "The evolution of production systems from Industry 2.0 through Industry 4.0," Int. J. Prod. Res., vol. 56, no. 1–2, pp. 848–861, 2018.

[22] D. A. Zakoldaev, A. V. Shukalov, and I. O. Zharinov, "From Industry 3.0 to Industry 4.0: Production modernization and creation of innovative digital companies," IOP Conf. Ser. Mater. Sci. Eng., vol. 560, no. 1, pp. 0–6, 2019, doi: 10.1088/1757-899X/560/1/012206.

[23] B. Meindl, N. F. Ayala, J. Mendonça, and A. G. Frank, "The four smarts of Industry 4.0: Evolution of ten years of research and future perspectives," Technol. Forecast. Soc. Change, vol. 168, no. March, 2021, doi: 10.1016/j.techfore.2021.120784.

[24] P. K. Malik et al., "Industrial Internet of Things and its Applications in Industry 4.0: State of The Art," Comput. Commun., vol. 166, no. October 2020, pp. 125–139, 2021, doi: 10.1016/j.comcom.2020.11.016.

[25] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and Industry 5.0—Inception, conception and perception," J. Manuf. Syst., vol. 61, pp. 530–535, 2021.

[26] A. S. Duggal et al., "A sequential roadmap to Industry 6.0: Exploring future manufacturing trends," IET Commun., vol. 16, no. 5, pp. 521–531, 2022, doi: 10.1049/cmu2.12284.

[27] M. Cheffena, "Industrial indoor multIPath propagation - A physical-statistical approach," IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC, vol. 2014-June, pp. 68–72, 2014, doi: 10.1109/PIMRC.2014.7136134.

[28] C. Cano, G. H. Sim, A. Asadi, and X. Vilajosana, "A Channel Measurement Campaign for mmWave Communication in Industrial Settings," IEEE Trans. Wirel. Commun., vol. 20, no. 1, pp. 299–315, 2021, doi: 10.1109/TWC.2020.3024709.