Ultra-Reliable Communications for Industrial Internet of Things: Design Considerations and Channel Modeling

Jingya Yang, Bo Ai, Ilsun You, Muhammad Imran, Longhe Wang, Ke Guan, Danping He, Zhangdui Zhong, and Wilhelm Keusgen

Abstract

Factory automation is the next industrial revolution. 5G and IIoT are enabling smart factories to seamlessly create a network of wirelessly connected machines and people that can instantaneously collect, analyze, and distribute real-time data. A 5G-enabled communication network for IIOT will boost overall efficiency, launching a new era of market opportunities and economic growth. This article presents the 5G-enabled system architecture and ultra-reliable use cases in smart factories associated with automated warehouses. In particular, for URLLC-based cases, key techniques and their corresponding solutions, including diversity for high reliability, short packets for low latency, and on-the-fly channel estimation and decoding for fast receiver processing, are discussed. Then the channel modeling requirements concerning technologies and systems are also identified in industrial scenarios. Ray tracing channel simulation can meet such requirements well, and based on that, the channel characteristic analysis is presented at 28 and 60 GHz for licensed and unlicensed band frequencies to exploit the available degrees of freedom in the channels.

Introduction

Factory automation merges operational, information, and communication technologies with cyber-physical systems. Industrial companies are betting on the fifth generation (5G) wireless system and the Industrial Internet of Things (IIoT) service to realize it. One of the main differences between 5G and previous generations of cellular networks lies in 5G's strong focus on massive machine-type communication (mMTC) and ultra-reliable low-latency communication (URLLC) for machine connectivity. The capabilities of 5G thus extend far beyond enhanced mobile broadband (eMBB). The three 5G communication types come into the IIOT service, which can truly bring together brilliant machines, advanced analytics, and people at work to deliver valuable new insights like never before. These insights can then help drive smarter, faster business decisions for industrial companies.

Among the three communication types, URLLC is the most innovative one, and it will be vital for mission-critical communications in future automation. In the first phase of 5G specifications, its capacity is specified to achieve latency of 1 ms with reliability of 99.999 percent [1]. Important transmission schemes for URLLC include diversity techniques, short packets within a short transmission time interval (TTI) [2], and so on. Focusing on industrial ultra-reliable communications, the various use cases with different latency limitations are presented in this article to increase universality.

Physical layer channel modeling is critical for design and performance evaluation of ultra-reliable communications. For the channels, we briefly survey the literature and present some examples of work; our survey is necessarily brief, and we invite the interested reader to consult the references within each of the citations. In [3] the authors conducted narrowband channel measurements in various industrial scenarios at 900, 2400, and 5200 MHz, and studied the physical model explaining the dependency on industrial topography of the fading parameters. Reference [4] provides experimental results for industrial wideband channels, including the power delay profile (PDP) and delay spread. This work emphasizes that the abundance of metallic scatterers present in the industrial environment causes dense multipath scattering. Similar results obtained from different industrial environments are presented in [5]. It can be seen that the special topology and dense metallic scatterers are significant differences between industrial, office, and residential propagation environments [6].

The channels in [3–5] focus on long-range industrial radio; for short-range radio, [7–9] present the channels for ultra-reliable MTC in automation systems. In [7], a time-varying channel between a robot arm and its controller entity is studied during the repeated pick-and-place process at 2.25 GHz. The temporal evolution of rich multipath components (MPCs) and repeated channel response pattern are observed. Such channel characteristics are shown in [8] from similar measurement at 5.8 GHz. Reference [9] provides a statistical analysis of channel delays during the robot arm movement at 5.8 GHz. These ultra-reliable channel results are mainly about the temporal evolution of MPCs in the delay domain,

Jingya Yang, Bo Ai, Longhe Wang, Ke Guan, Danping He, and Zhangdui Zhong are with Beijing Jiaotong University and Beijing Engineering Research Center of High-Speed Railway Broadband Mobile Communications; Ilsun You (corresponding author) is with Soonchunhyang University; Muhammad Imran is with King Saud University; Wilhelm Keusgen is with Fraunhofer HHI.

Digital Object Identifier: 10.1109/MNET.2019.1800455

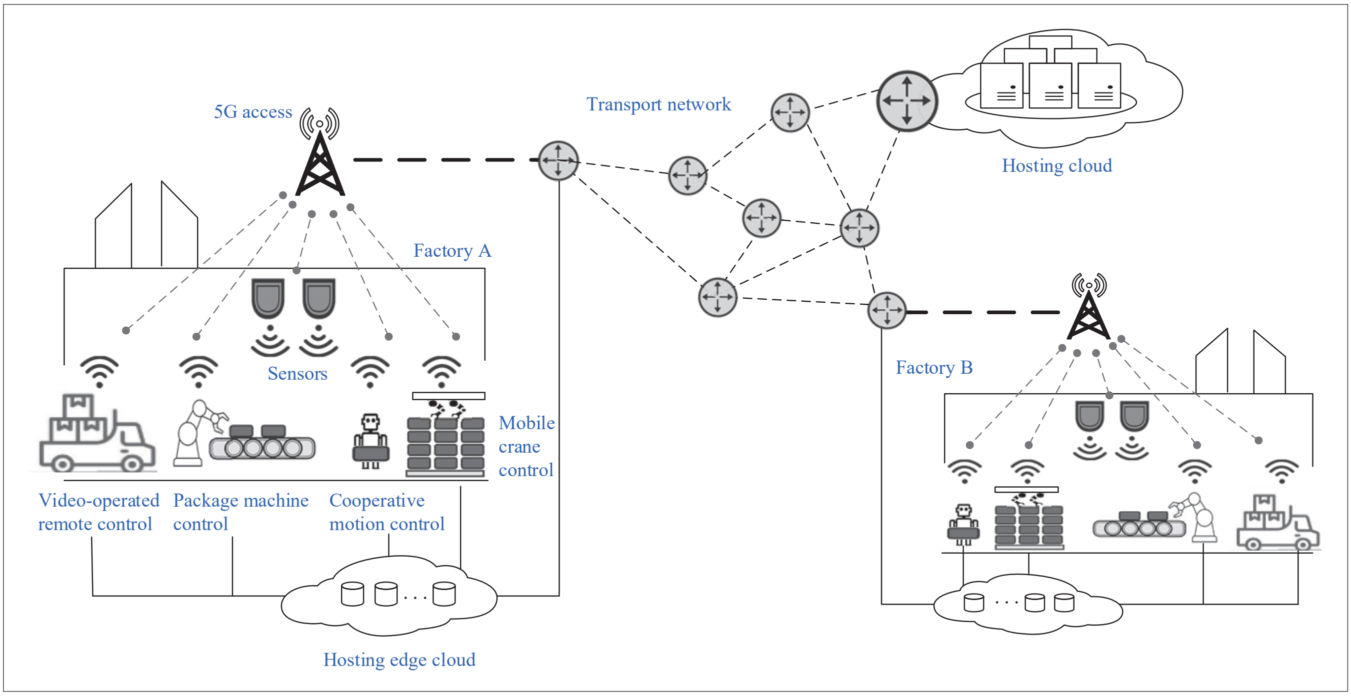

FIGURE 1. A basic 5G-enabled system architecture.

neglecting the space domain, and all in the sub-6 GHz frequency band. The authors of [10] employ a ray-tracing (RT) approach, and model light and heavy industrial environments to obtain the channel at 28 and 60 GHz. The path loss, temporal fading, and delay spread are discussed. However, the time-varying and space characteristics also need to be considered, which is important for reliable transmission scheme design.

In this article, the 5G-enabled system architecture is proposed for IIoT services in an automated warehouse scenario. This paves the way for numerous use cases (e.g., sensor monitoring, cooperative motion control, and video-operated remote control). In ultra-reliable use cases in particular, 5G has a significant impact through enhanced transmission schemes aiding in communication system design. For contending transmission scheme evaluation, we present the accurate RT channel models at two candidate millimeter-wave (mmWave) frequencies of 28 and 60 GHz for licensed and unlicensedband communication, respectively. Note that a 3D model scenario is constructed according to typical warehouse sizes, topology, and radio environmental characteristics. Herein, the time evolution of the delay and Doppler power spectra over automation processes are presented; the effects of these channels on different transmission schemes are shown through the analysis in delay and space domains.

The remainder of this article is organized as follows. First, we propose the 5G-enabled system architecture in smart factories, and present the ultra-reliable use cases and critical schemes focused on the URLLC-based cases to challenge the design difficulties. Then we study the channel model requirements in the industrial scenario. Based on the RT channel modeling, an analysis of the required channel characteristics is provided at 28 and 60 GHz. Finally, concluding remarks are presented.

5G-Enabled Communication System for IIOT

System Architecture

A basic 5G-enabled system architecture is shown in Fig. 1. The main components of the system are access, transport, management, cloud, and applications. The access provides radio connectivity between the devices and the 5G access nodes. The transport network is interconnected via backbone nodes that carry information from the access nodes to the hosting cloud, in which most of the industrial information is stored and processed, and the 5G-enabled network is managed. The hosting edge clouds have powerful information processing capabilities, and the data from nearby devices can be handled effectively. Applications, including data storage and sharing, order entry, inventory management, customer relationship management, and financial accounting features, can run in cloud environments. Note that the 5G network enables both communications within the factory and with other factories.

5G is built on multiple network slices to meet different requirements flexibly. As presented in Fig. 1, the ultra-reliable use cases associated with automated warehouses are illustrated in smart factories. The application areas range from logistics for supply to inventory management. Making full use of the robot gripper may break the technical limits of today's warehouse systems. In Fig. 1, robot grippers appear in multiple use cases, for example, package motion control, cooperative motion control, and mobile crane control. It can automate the process between picking and packaging. However, the control of grippers appears to be the most challenging and demanding due to its responsibility for picking items up or dropping them back down again in a well-defined manner. To make the motion quicker and more reliable, URLLC links are necessary.

Use case	Reliability	Latency	Typical device number	Typical payload size	Typical service area
Package machine control	> 99.9999 %	< 1 ms	50	40 bytes	10 m × 5 m × 3 m
Cooperative motion control	> 99.9999 %	1 ms	100	40 – 250 bytes	< 1 km^2
Mobile crane control	> 99.9999 %	12 ms	2	40 – 250 bytes	40 m × 60 m
Video-operated remote control	> 99.9999 %	10 – 100 ms	100	15 – 150 kbytes	< 1 km^2

TABLE 1. Considered use cases and their requirements.

The detailed performance requirements of the considered use cases are provided in Table 1, and the specifications are from [11]. As can be seen, some cases' associated control information has the highest requirements concerning reliability and latency, often characterized by small payload sizes. In cooperative motion control and video-operated remote control, their reliability requirements, the size of typical service areas, and the number of connected devices are almost the same. Due to the difference in the transmission content, the latency bounds vary greatly. The channel modeling for the two use cases is studied to enable their technical designs and system evaluation.

Key Technologies for URLLC-Based Service

For a data packet, such requirements can be expressed as during *L* seconds, transfer of data packets that have at most *B* bytes with a delay lower than *D* seconds in 99.9999 percent of the attempts [12]. The expression creates a simple criterion to see whether the system meets the requirement or not. However, this criterion is rigid. To achieve the criterion, one needs to reconsider the key technologies for URLLC.

Diversity/Redundancy for High Reliability: Diversity is a common technique for combating fading and avoiding error bursts. It may exploit the multipath components (MPCs) in different dimensions, resulting in diversity gains, often measured in decibels. Diversity can be provided by different means including microscopic diversity and macroscopic diversity.

For URLLC, microscopic diversity can be operated over space or frequency to combat deep fade. Due to the great low-latency requirement, the time diversity cannot be exploited. Multiple-input multiple-output (MIMO) schemes provide space availability, and increasing the number of antennas results in higher space diversity gain. In a smart factory, [13] presents the feasibility of achieving diversity orders beyond 10 through multiple antennas at both the base station and the device. When the use of a bandwidth greater than the coherence bandwidth of the frequency-selective channel, frequency diversity can be extracted; that is, transmission data modulated on sub-carriers in the frequency domain as each experiences independently flat fading.

Macroscopic diversity allows revivers to communicate with multiple access nodes simultaneously to create multi-connectivity. The multiple replicas of the information are obtained at the receiver, and more reliable detection can be achieved. It is an effective way to tackle shadow fading in industrial scenarios. Multi-connectivity can also be used to enhance mobile communications for URLLC. The correlation between multiple links may decrease diversity gains.

Short Packets for Low Latency: The use cases in Table 1 have different requirements for latency. The package machine control requires end-to-end latency within 1 ms. Its data messages are typically short control messages that are transmitted in the resource blocks with 40 bytes. Short TTI on the order of 100 ms may be needed for such control [14]. In the LTE system, 1 ms TTI and 8 ms waiting time at every retransmission are specified, which results in an end-to-end latency of 20–40 ms. Such specification can support the video-operated remote control in Table 1. The relaxed latency is not a design criterion for the most ultra-reliable use cases.

The continuous-time signal for payload with approximate duration *T* and given bandwidth W can be described by $n \approx TW$ complex parameters [12]. Referring to *n* as the packet size is natural. It is found that short packets will be a need for the short TTI or latency limit. Moreover, a TTI is the atomic time unit in which access to the radio channel is enabled. An arriving packet has to wait until the next access opportunity before starting the transmission. Short TTI can further reduce the delay. For the requirement of low latency, the short packet within a short TTI is desirable, which can somewhat ensure the given level of reliability. However, to gain more from coding, a packet must, in general, be long. The trade-off between the two contradicting requirements determines the packet size.

Fast Receiver Processing: Another important design option for URLLC is to enable fast receiver processing, that is, when receiving the first symbols in a TTI, the receiver can perform channel estimation and then start decoding. The fast channel estimation requires the reference signal to arrive first. The reference signal can be placed at the beginning of a TTI and not be spread over the TTI. In general, the channel is not rapidly time-varying in the industrial scenario due to the low-speed mobility. Therefore, in a short TTI, the channel is quasi-stationary, and the channel estimation at the starting time is sufficient. The prior knowledge of the channel can be stored in a mesh-grid database to enable the channel estimation quickly.

The channel coding has an impact on the receiver processing delay. In Third Generation Partnership Project (3GPP) Release 15, turbo codes or low-density parity check (LDPC) codes are used for data channels, and convolutional or polar codes for control channels. Iterative codes, for instance, turbo codes and LDPC codes, may have an error floor, which makes it hard to reach very low packet error rates (e.g., 10^{-9}) [1]. For iterative decoding, since an entire data block needs to be received, a processing delay is inevitable. Therefore, for use cases with low-latency requirements, the application of turbo or LDPC codes are limited. For the short control signaling requiring very high reliability, convolutional codes have benefits over iterative codes, as they do not have the error floor and can start decoding when the data are being received. Compared to polar codes, the encoding and decoding for convolutional codes have lower complexity. As a result, convolutional coding enables fast and simple receiver processing. Further improvements in channel coding are expected to be introduced to satisfy the requirements of wireless communication in factory automation.

Industrial Channel Modeling Requirements

Industrial channel models are crucial for design and comparing the performance of various technology proposals and for assessment of the overall performance of the industrial ultra-reliable communication system. Considering the ultra-reliable use cases and key technologies in smart factories, the fundamental requirements are as follows.

Extreme frequency ranges: The industrial ultra-reliable wireless communication is interested in deployments in both the sub-6 GHz and mmWave bands [11]. The channel models need to cover the full range.

Ultra-wide bandwidths: Due to greater bandwidths available in the high-frequency regime, ultra-reliable communication systems can provide bandwidths of 500 MHz and above. This means that the modeled channel can hold high delay resolution (e.g., 1 ns).

Support the massive MIMO antenna array: The massive MIMO antenna array usually comes with mmWave and beamforming. Because of its small wavelength, the use of mmWave provides possibilities to realize massive MIMO in available space. However, the physical size of the array is relatively large with respect to its wavelength, so spherical wavefronts can be assumed to characterize near field effects that result in variations on the antenna array. For highly directive beamforming or large antenna arrays, the channel models provide high angular resolution. In addition, elevation extension has to be added for supporting 3D channel models for the planar or cylindrical array.

Spatial consistency: The ultra-reliable communication system will consist of various link types, such as machine-to-machine (M2M), cellular communication links, and future moving base stations as well as multi-connectivity. These links will coexist in the same propagation environment. Moreover, when the transmitter and/or receiver moves or turns, the channel will evolve smoothly as it is. All these features set the spatial consistency to channel modeling.

Industrial Channel Modeling and Characteristic Analysis

The channel characteristic for the two use cases, that is, video-operated remote control and cooperative motion control, are analyzed at the candidate mmWave frequencies of 28 and 60 GHz for licensed and unlicensed band communication, respectively. We construct the 3D automated warehouse scenario in a smart factory as the radio propagation environment in which the mobile robots travel between zones to find the objects required and pick them by use of beefy mobile manipulators. The automate logistics are a cost-efficient solution to running the automated warehouse, which may lead to substantial improvements and optimizations in smart factories. Due to the multi-dimensional and fine-grained channel modeling requirements, the cloud-based ray tracing (CloudRT) simulator is used to obtain comprehensive and accurate channel characteristics.

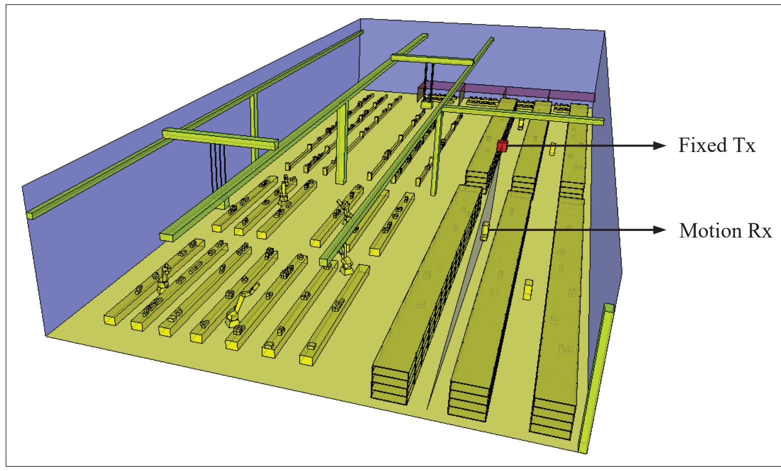

FIGURE 2. 3D automated warehouse scenario.

Automated Warehouse Scenario

The automated warehouse shown in Fig. 2 stems from existing inventory facilities of discrete smart factories. As a standard unique facility environment does not exist, a model scenario is presented that depicts typical sizes, topology, and radio environmental characteristics. Typical for industrial automated warehouse scenarios are:

- The main structure of the warehouse can be considered to be built of concrete walls and ceiling. The columns are placed 10–20 m apart to support the ceiling.
- The space of 1–5 m below the warehouse's ceiling is occupied with metallic objects, including long narrow metallic shelves with gangways between them, mobile cranes, lighting, and so on. Radio equipment cannot hold gangways to allow access to the top level of all shelves.
- Alleys between layered shelves, where the space up to a height of some 4 m above ground, must stay clear of any fixed mounted object (e.g., antennas) to make way for mobile robots. The robots in the alleys are metallic, moving slowly, and of medium size.
- The layered shelves are usually made of metal, on which storage boxes can be designed by different materials for different types of items.

The mobile robots are designed with a zippy mobile base and beefy mobile manipulator. Since one of the big challenges in logistics is the traversal of the warehouse, a robot to zip around the warehouse can get stuff done. A robot with robust autonomous navigation can move as fast as a person or faster. Coordination is a common issue in cooperative motion control. Cooperat-

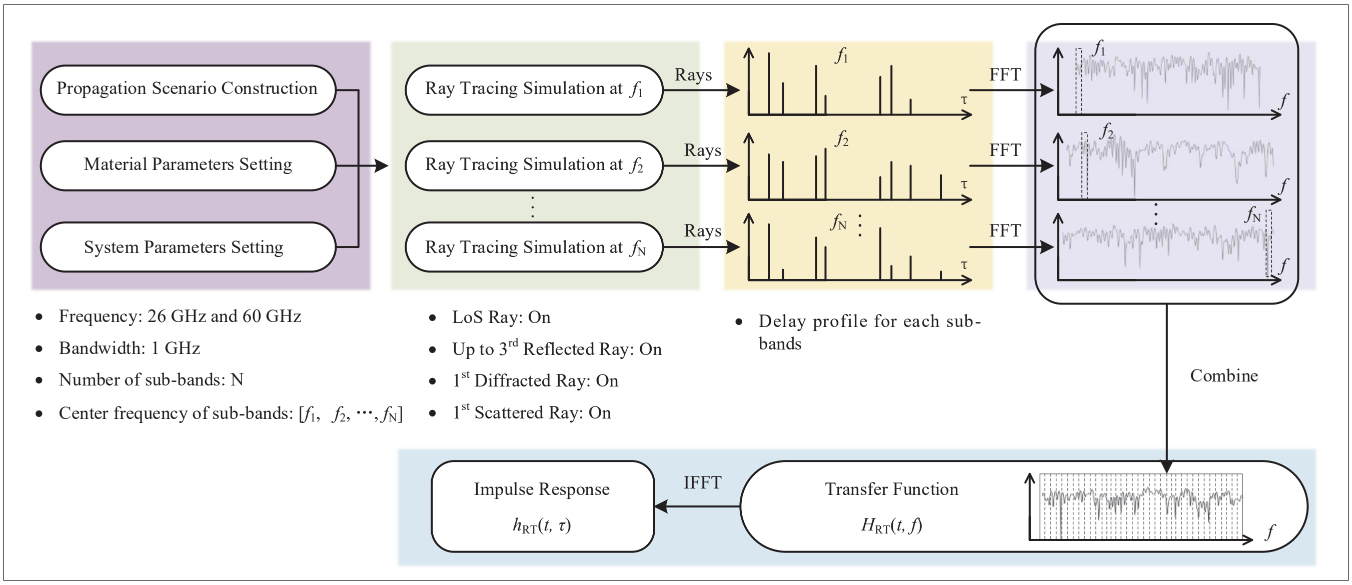

FIGURE 3. The flow chart illustrating the RT procedure to obtain the channel characteristics.

ing between the arm and the telescoping spine, the robot has a grasping range all the way from the floor up to just under 3 m, which can cover approximately the same manipulation range as a human. The gripper is modular with a standard interface and includes a radio connection so that the information can be received from the camera for up-close vision or any other sensor. Such information is processed to provide accurate motion control. In reality, motion control and sensor architecture issues both affect the efficiency of cooperative motion control.

This model scenario, shown in Fig. 2, is a hall of 180 m × 80 m with a height of 20 m — no additional separating walls are included. It can be divided into an elevated cargo transfer area and a ground logistics distribution area. Figure 2 depicts the essential elements in the two areas, including mobile crane, mobile robots, robotic arm, assembly lines, conveyor belts, layered shelves, and so on. The use cases listed in Table 1 can be implemented in the model scenario because its topology reflects the various production plants. In this article, the channel analysis concentrates on two use cases, that is, video-operated remote control and cooperative motion control. The mobile robots travel in different alleys to find the required objects. When the robots are moving, the video-operated remote control supports the autonomous navigation to detect any collisions and stop immediately. After the mobile robots come to the layered shelves with the required item, the mobile robot is under cooperative motion control to detect items, pick them up, or drop them back down. Note that the robots can perform using very similar movement patterns under motion control, which makes the robots themselves quicker and more reliable.

RT Simulation

It is a challenge to provide adequate industrial ultra-reliable channel modeling in terms of a particular radio environment, accurate propagation characteristics, and low computational complexity. The simple modeling approach would be to extend present geometry-based stochastic modelings such as International Telecommunication Union (ITU) IMT-Advanced and 3GPP spatial models. However, these models are empirical and proposed from extensive measurements to assess their various channel parameters. Since highly resolved directional characteristics must be spatially consistent for mobility or coexisting multiple links, the required number of degrees of freedom for industrial channel modeling is very high. It is not currently possible to accurately model all of these parameters by measurements.

An obvious solution to provide industrial channel modeling in a feasible way and still meet the channel requirements in industrial scenarios is to use RT. The main advantage is that RT simulation is inherently spatially consistent and that only a few of the material parameters need to be calibrated by measurements. However, the computational complexity is the main concern of users. Aiming at 5G and beyond wireless communications, our team and Technische Universität Braunschweig jointly developed the high-performance computing (HPC) CloudRT [15]. The simulation speed is improved significantly, which is critical for channel analysis in large-scale complex communication scenarios. The HPC CloudRT is publicly available at http://www.raytracer.cloud/.

The implementation of cloudRT is shown in Fig. 3. The propagation environment is given in Fig. 2, and it is constructed by SketchUp software. The essential elements in the real automated warehouse are modeled, including the storage boxes, layered shelves, metallic shelves, walls, ceiling, columns, mobile robots, and so on. The materials, such as concrete, brick, wood, plastic, and metal, are assigned to the elements. The complex permittivity of the materials can be obtained by visiting the URL above. We consider two frequencies of 28 and 60 GHz for licensed and unlicensed band communication. The reason for the choice is that on the mmWave band the wideband connect is natural for use by video operation, and due to the poor penetration and high path loss, the interference can be greatly suppressed by dedicated

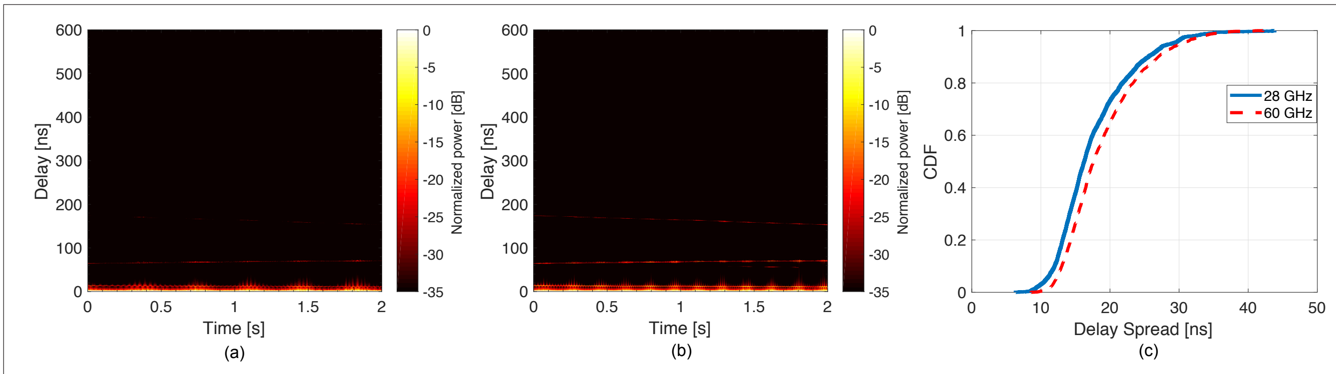

FIGURE 4. Channel characteristics in the delay domain: a) power delay profile evolution at 28 GH; b) power delay profile evolution at 60 GHz; c) RMS delay spread comparison.

antenna design [10]. For the service area of 1 km^2, if a line-of-sight (LoS) path or strongly reflected path is available, reliable communication can be enabled. Therefore, transmitters (Txs) are deployed at the center of the warehouse, and the intervals between them are the same as the distance between two adjacent alleys. The height of a Tx is 7 m, and the beam from the Tx can scan the alley. The receiver (Rx) is installed on the mobile robots at a height of 2.1 m. The actual positions of Tx and Rx are also given in Fig. 2. The robots travel in the alley, and the speed is 2 m/s, which is consistent with human walking speed.

For RT simulation, the omnidirectional antenna is installed at both the Tx and Rx to explore the full degrees of freedom in the propagation channels. The setting for propagation mechanisms is given in Fig. 3. Then, by using the RT to obtain rays at equal-interval frequency points, we calculate the transfer function $H_{RT}(t, f)$ according to the sub-band division method. Finally, this function can be inverse Fourier transformed into the time domain to get the impulse response $h_{RT}(t, t)$.

Channel Characteristic Analysis

For ultra-reliable wireless communications, diversity is a critical technology. The channel analysis here aims to find the possible degrees of freedom in the automated warehouse propagation environment. Generally, the URLLC-based communications (e..g., the radio link for cooperation motion control) explore the degrees of freedom over delay/frequency and space dimensions. In video-operated remote control, the relaxed latency limit offers the chance to further explore the time/Doppler dimension.

Regarding mobility, the impulse responses (IRs) are generated during the movement of the robots. The robot moves away from the Tx, and the moving distance is set as 4 m. Since we focus on the fading that increases the risk of temporary outage and packet losses, there is no need to choose an extensive distance range of movement. To observe the Doppler characteristics of the channel, the snapshot repetition time is set as 0.5 ms, which is 1 mm sampling in the distance that is much smaller than half of the considered mmWave wavelength. Due to the 1 GHz bandwidth, the delay resolution is very small at 1 ns. When the robot stops at the location of the object that it is looking for, it executes the pick-and-place process with repetitions. Since the Rx is mounted on the top of the robot, the dominant multipath structure does not change much during the arm movement to grasp an object. Hence, the channel for cooperative motion control can be obtained from individual snapshots. The temporal evolution of the channel characteristics is estimated in the delay and space domains, respectively. Note that the arrival angle can be illustrated by the Doppler shift of MPCs.

In Figs. 4a and 4b, the fine delay resolution makes the MPC easy to distinguish. Apparently, the number of dominant MPCs at 60 GHz is bigger than that at 28 GHz, which is also demonstrated in Fig. 4c as the large delay spread at 60 GHz. The empirical distribution of delay spread is consistent with the one presented in [10], which analyzes a similar warehouse scenario at the same frequencies. At 60 GHz, the reflected rays with high power increase compared to the ones at 28 GHz due to the smaller wavelength. The wideband channel has natural frequency selectivity. Considering the maximum delay spread of 40 ns, the coherence bandwidth is about 5 MHz. The subcarriers that are separated by more than the coherence bandwidth fade more or less independently, and hence frequency diversity is present. Ideally, the frequency diversity order can achieve 200 in the warehouse scenario.

The time-varying Doppler spectra are shown in Figs. 5a and 4b for 28 GHz and 60 GHz, respectively. Comparing the two spectra, the dominant MPCs at 60 GHz are clearer, and their temporal evolution can be tracked. It is convenient for the beamforming to follow such dominant MPCs. The effective space diversity can be achieved. The source for generating dominant MPCs is the metal layered shelves, which are the main reflectors when robots are moving in the alley. The radio propagation environment is semi-closed, and the densely arranged boxes on shelves scatter rich rays, as shown in Fig. 5a However, as reliable communication depends on strong paths, the diffuse paths with low power will present deep fades, and the transmission data will likely suffer from errors. Figure 5c shows the space correlation at the Rx. The analysis is based on a moving virtual antenna array, and then virtual multiple-input single-output (MISO) channel data are derived from single-antenna simulation. As can be seen, the space correlation at 60 GHz is smaller than that at 28 GHz. For the given correlation level 0.5, the decorrelation distances are 2.6 λ_{28} (28

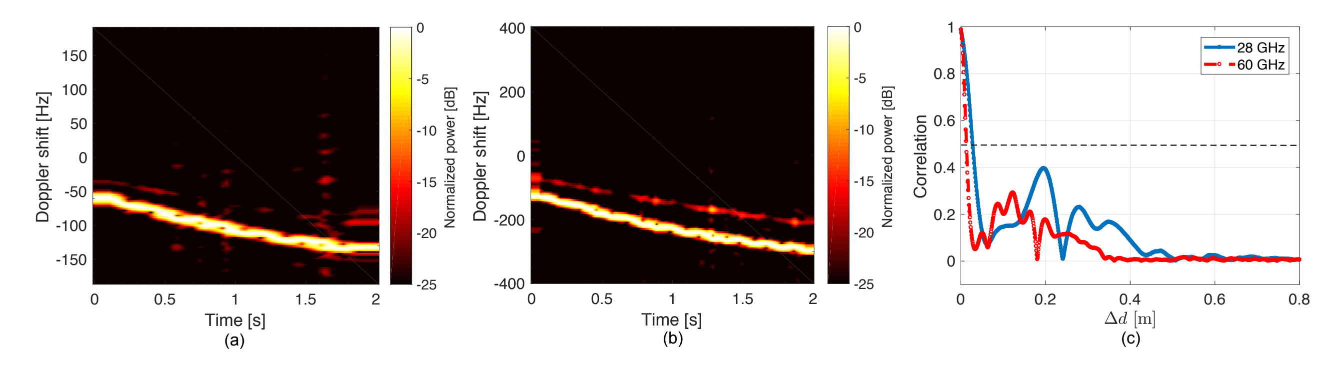

FIGURE 5. Channel characteristics in space domain: a) Doppler spectrum evolution at 28 GHz; b) Doppler spectrum evolution at 60 GHz; c) Space correlation comparison.

mm) and 1.2 λ_{60} (11 mm) for 28 GHz and 60 GHz, respectively. In the case of limited installation space for MIMO antennas, the 60 GHz band is a better choice. Due to the small decorrelation distances, the antenna diversity can be enabled on the robots for high diversity order.

Conclusion

IIoT unites communications and automation to offer increased flexibility and efficiency. In this article, for IIOT, we present a typical 5G system architecture in smart factories enabling process automation for warehouses, and pay close attention to the ultra-reliable use cases. The key technologies, including diversity, short packet transmission, and fast receiver processing, are discussed for 3GPP future-standardized URLLC. We further clarify the channel modeling requirements for the industrial ultra-reliable use cases and technologies. To satisfy such requirements, we develop the RT simulation in an automated warehouse scenario as an example. Considering the performance requirements in two critical use cases, that is, video-operated remote control and cooperative motion control, we choose the licensed band 28 GHz and unlicensed band 60 GHz for communication. Based on the RT simulation, the channel characteristics are compared between the two frequencies in terms of the time, delay, and space domains. Due to the shorter wavelength of 60 GHz, the reflected MPCs with high power increase, and then the strong paths supporting reliable radio links are enhanced. The diversity in frequency and space dimensions are also demonstrated, in which the 60 GHz channel achieves higher diversity orders, and effective combining at the end user is possible. A future industrial ultra-reliable communication scheme will fully exploit the available degrees of freedom in the channels to fill stringent requirements.

Acknowledgments

This work was supported by the National Key R&D Program of China under Grant 2016YFE0200900 and the Soonchunhyang University Research Fund.

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Biographies

JINGYA YANG received her B.Eng. and M.Eng. degrees in communication and information systems from Zhengzhou University in 2010 and Beijing Jiaotong University (BJTU) in 2013, respectively. She is currently a Ph.D. candidate in the School of Electronic and Information Engineering, BJTU. Her current research interests include time-varying channel modeling, high-speed train wireless propagation characterization and modeling, and LTE-R system evaluation based on realistic channels.

BO AI received his Master's degree and Ph. D. degree from Xidian University, China. He graduated from Tsinghua University with the honor of Excellent Postdoctoral Research Fellow at Tsinghua University in 2007. He was a visiting professor in the Electrical Engineering Department, Stanford University in 2015. He is now working at BJTU as a full professor and Ph. D. candidate advisor. He has authored/co-authored 8 books and published over 300 academic research papers in his research area. He holds 26 invention patents. He has been the research team leader for 26 national projects and has won some important scientific research prizes. He has been notified by the Council of Canadian Academies (CCA) that, based on the Scopus database, he has been listed as one of the Top 1 percent of authors in his field all over the world. His interests include the research and applications of channel measurement and channel modeling, and dedicated mobile communications for rail traffic systems. He is a n IET Fellow and an IEEE VTS Distinguished Lecturer. He has been a Co-Chair or a Session/Track Chair for many international conferences. He is an Editor of *IEEE Transactions on Consumer Electronics* and an Editorial Committee member of the *Wireless Personal Communications* journal. He has been the Lead Guest Editor for Special Issues of *IEEE Transactions on Vehicular Technology*, *IEEE Antennas and Propagations Letters*, and the *International Journal on Antennas and Propagation*. He has received many awards such as Outstanding Youth Foundation from the National Natural Science Foundation of China, the Qiushi Outstanding Youth Award by the Hong Kong Qiushi Foundation, New Century Talents by the Chinese Ministry of Education, the Zhan Tianyou Railway Science and Technology Award of the Chinese Ministry of Railways, and the Science and Technology New Star of the Beijing Municipal Science and Technology Commission.

ILSUN YOU [SM] received his M.S. and Ph.D. degrees in computer science from Dankook University, Seoul, Korea, in 1997 and 2002, respectively. He received a second PhD degree from Kyushu University, Japan, in 2012. From 1997 to 2004, he was at THINmultimedia Inc., Internet Security Co., Ltd., and Hanjo Engineering Co., Ltd. as a research engineer. Currently, he is an associate professor in the Department of Information Security Engineering, Soonchunhyang University. He has served or is currently serving as a main organizer of international conferences and workshops inncluding MIST, MobiWorld, MobiSec, and so forth. He is the EiC of the *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications*. He is on the Editorial Boards of *Information Sciences*, the *Journal of Network and Computer Applications*, *IEEE Access*, *Intelligent Automation & Soft Computing*, the *International Journal of Ad Hoc and Ubiquitous Computing*, *Computing and Informatics*, and the *Journal of High Speed Networks*. In particular, he has focused on 4/5G security, security for wireless networks and mobile Internet, IoT security, and so forth while publishing more than 180 papers in these areas. He is a Fellow of the IET.

MUHAMMAD IMRAN received his M.C.S. degree in computer science from the National University of Modern Languages, Pakistan, in 2005, his M.S. degree with majors in communication and networks from Federal Urdu University of Arts, Science and Technology, Pakistan, in 2007, and his Ph.D. degree in information technology from the Universiti Teknologi PETRONAS, Malaysia in 2011. Currently, he is working as an associate professor in the College of Applied Computer Science, King Saud University (KSU). His research interests include the Internet of Things, big data analytics, intelligent transportation systems, cloud and edge computing, and security and privacy. His research is financially supported by several grants, and he has completed a number of international collaborative research projects with reputable universities. He has published more than 150 research articles in top international conferences and journals. The European Alliance for Innovation has appointed him a Co-Editor-in-Chief of *EAI Transactions on Pervasive Health and Technology*. He also serves as an Associate Editor for reputable international journals such as *IEEE Communications Magazine*, *Future Generation Computer Systems*, *IEEE Access*, the *Wireless Communication and Mobile Computing Journal*, the *Ad Hoc and Sensor Wireless Networks Journal*, *IET Wireless Sensor Systems*, and the *International Journal of Autonomous and Adaptive Communication Systems*. He has served/is serving as a Guest Editor for more than a dozen Special Issues of top international journals. He has been involved in more than 75 conferences and workshops in various capacities such as Chair, Co-Chair, and Technical Program Committee member.

LONGHE WANG is currently pursuing a Ph.D. degree with the State Key Laboratory of Rail Traffic Control and Safety, BJTU, China. His research interests include ray-tracing acceleration algorithms based on high-performance computing techniques, large-scale coverage prediction, and mmWave channel modeling.

KE GUAN received his B.E. and Ph.D. degrees from BJTU in 2006 and 2014, respectively. He is an associate professor in the State Key Laboratory of Rail Traffic Control and Safety and the School of Electronic and Information Engineering, BJTU. In 2015, he was awarded a Humboldt Research Fellowship for Postdoctoral Researchers. He was the recipient of a 2014 International Union of Radio Science Young Scientist Award. His papers have received six Best Paper Awards. In 2009, he was a visiting scholar in Universidad Politécnica de Madrid, Spain. From 2011 to 2013, he has been a research scholar at the Institut für Nachrichtentechnik (IfN) at Technische Universität Braunschweig, Germany. From September 2013 to January 2014, he was invited to conduct joint research with Universidad Politécnica de Madrid. He received the Huawei Excellent Student Award of China in 2013 and the First National Scholarship for Ph. D Candidates in 2012. His current research interests are in the field of measurement and modeling of wireless propagation channels, high-speed railway communications, vehicle-to-X channel characterization, and indoor channel characterization for high-speed short-range systems including future terahertz communication systems. He has authored/co-authored 2 books and one book chapter, more than 160 journal and conference papers, and one patent. He is the pole leader of EURNEX (European Railway Research Network of Excellence). He is an Editor of *IEEE Access* and a Guest Editor of *IEEE Transactions on Vehicular Technology*. He served as a Publicity Chair for PIMRC 2016, a Publicity Co-Chair for ITST 2018, a Track Co-Chair for EuCNC, the Session Convener of EuCAP 2015, 2016, 2017, and 2018, and a TPC member for many IEEE conferences, such as GLOBECOM, ICC, and VTC. He has been a member of the IC1004 and CA15104 initiatives.

DANPING HE received her B.E. degree from Huazhong University of Science and Technology in 2008, her M.Sc. degree from the Universite Catholique de Louvain and Politecnico di Torino in 2010, and her Ph.D. degree from Universidad Politécnica de Madrid in 2014. In 2012, she was a visiting scholar at Institut national de recherche en informatique et en automatique, France. She worked at Huawei Technologies from 2014 to 2015 as a research engineer, and she is currently conducting postdoctoral research in the State Key Laboratory of Rail Traffic Control and Safety, BJTU. She has authored/co-authored more than 30 papers, 3 patents, and 1 IEEE standard. Her papers have received four Best Paper Awards. Her current research interests include radio propagation and channel modeling, ray tracing simulator development, and wireless communication algorithm design.

ZHANGDUI ZHONG received his B.E. and M.S. degrees from BJTU in 1983 and 1988, respectively. He is a professor and advisor of Ph.D. candidates with BJTU. He is currently a director of the School of Computer and Information Technology and a chief scientist of the State Key Laboratory of Rail Traffic Control and Safety, BJTU. He is also a director of the Innovative Research Team of the Ministry of Education, Beijing, and a chief scientist of the Ministry of Railways, Beijing. He is an Executive Council Member of the Radio Association of China and a Deputy Director of the Radio Association, Beijing. His interests include wireless communications for railways, control theory and techniques for railways, and GSM-R systems. His research has been widely used in railway engineering, such as the Qinghai-Xizang railway, Datong-Qinhuangdao Heavy Haul railway, and many high-speed railway lines in China. He has authored or coauthored seven books, five invention patents, and over 200 scientific research papers in his research area.

WILHELM KEUSGEN received his Dipl.-Ing. (M.S.E.E.) and Dr.-Ing. (Ph.D.E.E.) degrees from RWTH Aachen University, Germany, in 1999 and 2005, respectively. From 1999 to 2004, he was with the Institute of High Frequency Technology, RWTH Aachen University. Since 2004, he has been heading a research group for millimeter waves and advanced transceiver technologies, Fraunhofer Heinrich Hertz Institute, Berlin, Germany. Since 2007, he has also had a lectureship at the Technical University of Berlin, Germany. His main research interests include millimeter-wave communications for 5G, measurement and modeling of wireless propagation channels, multiple antenna systems, and compensation of transceiver impairments.