Tactile Internet

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I. INTRODUCTION

Mobile communication continues to play an important role in the modern economy, including consumer, health, education, logistics, and other major industries. At the same time, the current Internet has created a key infrastructure component for our modern world, having an impact on almost every aspect of our daily lives. The Internet democratized access to information and has enabled emerging economies to participate in the modern global economy. We are now approaching the next big wave of the Internet innovation: the Tactile Internet. The widely used term "Tactile Internet" was coined and defined by the IEEE P1918.1 as: "A network or network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in perceived real time by humans or machines."

The papers in this special issue provide insight into the most relevant aspects of the Tactile Internet.

With the recent technological advancements, the stage is being set for the emergence of the Tactile Internet in which physical remote interaction with real and virtual objects (or systems) is realized in perceived real time. The emergence of the Tactile Internet is believed to be a true paradigm shift in which a sufficiently responsive, reliable, and intelligent networking paradigm enables delivery of physical, tactile experiences remotely. In contrast to the prior Internets, which only enabled the content delivery, the Tactile Internet will allow for skillset delivery and, therefore, pave way for an "*Internet of Skills*."

The Tactile Internet aims to enhance the collaboration and interaction between humans and machines (or systems) in real, virtual, and remote environments. Thus, going far beyond the current state of the art, the Tactile Internet democratizes the access to skills and expertise in the same way as the current Internet has enabled the access to information. This requires a multidisciplinary approach to: 1) advance the understanding of human perception; 2) develop fast, bendable, adaptive, and reconfigurable electronics; 3) create intelligent, resilient, secure, and real-time communication networks; and 4) design adaptive mechanisms as well as the interface solutions for machines and humans to predict and augment each other's actions. Hence, the Tactile Internet opens a totally new era of research to enable human-in-the-loop and machine-in-the-loop use cases. The use cases of the Tactile Internet imply massive requirements in terms of throughput, latency, and resilience. The challenge is to design a Tactile Internet infrastructure that supports such resilient communication systems that are robust enough for novel control algorithms, as well as control algorithms that give enough leeway for imperfections in wireless communication such as packet errors and jitter in latency.

It is known that the fifth generation (5G) of mobile communications will not only support the evolution of traditional mobile communication services, such as personal mobile multimedia communication or personal mobile broadband services but also address novel use cases such as massive machine-type communication and ultrareliable low-latency communication (URLLC). Therefore, 5G is considered to become an important enabler of the Tactile Internet as it will need to deliver the required latency, reliability, and edge connectivity. Because the Tactile Internet will be servicing really critical aspects of society, it will need to be ultrareliable in the order of seconds of downtime per year; support very low latency and short end-to-end delays in the order of milliseconds;

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and have sufficient capacity to allow large numbers of devices to communicate with each other simultaneously and autonomously. It will need to be able to interconnect with the traditional wired Internet, the mobile Internet, and the Internet of Things, thereby forming an Internet of entirely new dimensions and capabilities.

To achieve the stringent latency and reliability requirements of Tactile Internet applications, significant changes to incumbent as well as emerging communications systems need to be invoked. Since reliability and latency may result from many factors, several new techniques in different areas need to be investigated. Notably, a novel architecture to enable real-time control and achieve ultraresponsiveness has to be introduced. The physical remote interaction requires codecs for the haptic communication of humans, and equivalently for machines. Moreover, novel physical layer solutions together with resource management techniques need to be developed. Although some of these challenges can be met by emerging 5G communications systems, other challenges require technological breakthroughs. In this regard, this special issue explores recent developments and new enabling technologies for the Tactile Internet. New approaches to enable remote control in real time are presented alongside potentially revolutionary new system design and technologies such as the wireless edge, physical layer solutions, and resource management algorithms. In addition, solutions for Tactile Internet applications for the cases of human-in-the-loop and machine-in-the-loop are part of the special issue.

II. OVERVIEW OF THE SPECIAL ISSUE

This special issue covers the recent and most relevant aspects of the Tactile Internet: architecture, functional entities, wireless edge solutions, relation to 5G communication systems, physical and medium access control layer solutions, machine-in-the-loop use cases, and human-in-the-loop use cases. The special issue consists of 13 invited papers. These articles present different aspects of the Tactile Internet including foundations for the architecture design and theoretic solutions to achieve stringent Tactile Internet requirements, new techniques for overcoming the limitations of legacy solutions, different types of applications, and advanced mobile edge technology solutions. A brief description of the articles published in this special issue is as follows.

In "The IEEE 1918.1 'Tactile Internet' Standards Working Group and its standards" by Holland *et al.*, a summary of the IEEE P1918.1 working group's standardization results is given.

The article "Low-latency networking: Where latency lurks and how to tame it" by Jiang *et al.* presents a holistic analysis and classification of the main design principles and enabling technologies for the deployment of low-latency wireless networks.

In "5G-based systems design for Tactile Internet" by Li *et al.*, physical and medium access control layer perspective and the system design solutions for URLLCs in new radio and long-term evolution are presented together with a case study of factory automation as a 5G-based Tactile Internet application.

Sachs *et al.* provide an overview of Tactile Internet services and haptic interactions and communications in "Adaptive 5G low-latency communication for Tactile Internet services."

In "Softwarization and network coding in the mobile edge cloud for the Tactile Internet" by Cabrera *et al.*, software-defined networks and network function virtualization importance to 5G networks and Tactile Internet applications is provided. The authors present a holistic testbed, a fundamental step toward creating an infrastructure for 5G systems and Tactile Internet applications.

In "Leveraging Tactile Internet cognizance and operation via IoT and edge technologies" by Oteafy and Hassanein, novel techniques for Cloudlet-based cyber foraging (i.e., edge computing) are presented to project how Tactile Internet interactions could benefit from IoT contextualization.

In "Ultrareliable and low-latency communication techniques for Tactile Internet services" by Kim *et al.*, novel physical layer solutions for spectrally efficient URLLC are introduced.

In "Multiconnectivity in multicellular, multiuser systems: A matching-based approach," Simsek *et al.* discuss the feasibility of multiconnectivity approached to achieve reliability requirements of URLLC. A matching-theory-based algorithm together with a novel scheduler is proposed to achieve these requirements.

In "The Tactile Internet for industries: A review" by Aijaz and Sooriyabandara, technology landscape for the Tactile Internet to enable high-performance industrial wireless communication is presented.

In "Cooperative driving and the Tactile Internet" by Dressler *et al.*, opportunities of Tactile Internet concepts that integrate interdisciplinary approaches from control theory, mechanical engineering, and communication protocol design are presented.

In "Haptic codecs for the Tactile Internet," Steinbach *et al.* present the fundamentals and state of the art in haptic codec design for the Tactile Internet.

In "Tactile Robots as a central embodiment of the Tactile Internet" by Haddadin *et al.*, the concept of the Tactile Robot connected with human operators via smart wearables as an essential multimodal embodiment of the coming Tactile Internet is discussed. ■

ABOUT THE GUEST EDITORS

Meryem Simsek received the Dipl.-Ing. degree in electrical engineering and information technology and the Ph.D. degree with a focus on learning-based techniques for intercell interference coordination in long term evolution-advanced heterogeneous networks from the University of Duisburg-Essen, Duisburg, Germany, in 2008 and 2013, respectively.

Since 2014, she has been a Research Group Leader with Technical University Dresden, Dresden, Germany. Since 2016, she has been a Visiting Scientist with the University of California, Berkeley, Berkeley, CA, USA. She is currently a Senior Research Scientist with the International Computer Science Institute, Berkeley. She was the first electrical engineering student to graduate before the regular duration of study and the best Diplom-graduate in electrical engineering at the University of Duisburg-Essen in 2008. She has authored more than 60 publications. Her current research interests include end-to-end modeling and optimization of emerging wireless systems, heterogeneous wireless networks, achieving high reliability and low latency in 5G networks, machine learning-based resource management, developing novel tools for wireless network management, wireless edge automation, and autonomous wireless networks.

Dr. Simsek was a recipient of fellowships from the German Physical Society (2004–2005), the German National Academic Foundation (2004–2008), which is only granted to the outstanding 0.5% students in Germany, and the IEEE Communications Society Fred W. Ellersick Prize 2015 for her *IEEE Communications Magazine* paper “When cellular meets WiFi in wireless small cell networks.” She was the Chair of the IEEE Tactile Internet Technical Committee. She serves as the Secretary for the IEEE P1918.1 Standardization Working Group, which she co-initiated. She holds the honorary positions of the Industry and Student Activities Coordinator in the IEEE Women in Communications Engineering Committee and the Vice-Chair of the IEEE ComSoc Mobile Communication Networks Standards Committee.

Gerhard P. Fettweis (Fellow, IEEE) received the Ph.D. degree, under the supervision of H. Meyr, from RWTH Aachen University, Aachen, Germany, in 1990.

After one year at IBM Research in San Jose, CA, USA, he moved to TCSI Inc., Berkeley, CA, USA. Since 1994, he has been the Vodafone Chair Professor with Technical University Dresden, Dresden, Germany, where he has been the Head of the Barkhausen Institute since 2018. He coordinates the 5G Lab Germany, and two German Science Foundation (DFG) centers at TU Dresden, Center for Advanced Electronics Dresden and highly adaptive energy-efficient computing. His current research interests include wireless transmission and chip design for wireless/IoT platforms, with 20 companies from Asia, Europe, and the U.S. sponsoring his research.

Dr. Fettweis is a member of the German Academy of Sciences (Leopoldina) and the German Academy of Engineering (acatech). He was a recipient of multiple IEEE recognitions and the VDE ring of honor. He served as the General Chair of VTC Spring 2013 and DATE 2014. He is the Co-Chair of the IEEE 5G Initiative. He served as a TPC Chair for ICC 2009 and TTM 2012.

Chih-Lin I received the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, USA.

She is currently the China Mobile Chief Scientist of wireless technologies with the China Mobile Research Institute, where she is involved in advanced wireless communication research and development efforts. She established the Green Communications Research Center of China Mobile, where she leads major initiatives including 5G key technologies research and development; high-energy efficiency system architecture, technologies, and devices; green energy; cloud radio access network; and soft base station. She was involved in wireless communication area. She was with various world-class companies and research institutes, including the Wireless Communication Fundamental Research Department, AT&T Bell Labs, USA; Headquarter of AT&T as the Director of Wireless Communications Infrastructure and Access Technology; the Industrial Technology Research Institute, Taiwan, as the Director of wireless communication technology; and the Hong Kong Applied Science and Technology Research Institute, Hong Kong, as the Vice President and the Founding GD of communications technology domain.

Dr. I was a recipient of the IEEE TRANSACTIONS ON COMMUNICATIONS Stephen Rice Best Paper Award and, CCCP “National 1000 talent” Program. She was an Elected Board Member of the IEEE ComSoc, the Chair of ComSoc Meeting and Conference Board, and the Founding Chair of the IEEE WCNC Steering Committee. She is currently the Chair of FuTURE Forum 5G SIG, an Executive Board Member of GreenTouch, a Network Operator Council Member of ETSI network function virtualizations, a Steering Board Member of Wireless World Research Forum, and an Adjunct Professor of the Beijing University of Posts and Telecommunications.