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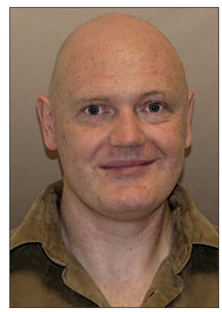
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The Internet of Time-Critical Things: Advances and Challenges in Computing and Communications

Time is a precious and critical resource to computers, sensors, actuators, and most Internet of Things (IoT) systems and applications. Precise time and timeliness in task execution and data communication are fundamental requirements for emerging IoT applications and new experiences enabled by advances in distributed computing, from cloud to edge. Industry 4.0, mobile and collaborative robots, autonomous systems, immersive and interactive human-cyber experiences are only a few examples of the Internet of Time-Critical Things where precise time, computing, and communication with bounded latencies and high reliability are strictly required. Furthermore, these applications might not only be time-critical but also safety-critical as they often involve interactions between humans and machines. Such stringent time and safety requirements bring new practical challenges, as well as new opportunities to revolutionize the traditional design, deployment and management of computing and communication infrastructures. New concepts in software-defined systems and networks, cloud/edge computing, AI-driven resource orchestration, Time-Sensitive Networking (TSN) and advances in wireless communications (Wi-Fi 6/7, 5G and beyond) are emerging as potential building blocks to enable the transformation of computing and communications infrastructure to enable time-critical applications.

This Special Issue (SI) brings a comprehensive view of the time-critical IOT applications, their requirements and challenges in designing, deploying, and measuring performance of computing and communication infrastructures. The articles cover practical challenges in cloud and edge computing and connectivity for realistic applications, especially related to meeting strict performance targets in computing and wireless systems. The SI also covers measurement methodologies and case studies evaluating the performance of real IOT systems.

In "IoT Edge Caching: Taxonomy, Use Cases and Perspectives," edge computing and caching concepts are explored jointly to reduce latency and increase efficiency. An extensive review of the state-of-the-art in Edge Caching approaches is provided along with use cases in various domains, from Industry 4.0 to smart grids, agriculture, and vehicular applications. An evaluation of a real Structural Health Monitoring system provides insights into the benefits of edge caching and associated tradeoffs.

In "Joint Scheduling and Coding for Reliable, Latency-Bounded Transmission over Parallel Wireless Links," the authors dive into the wireless communication challenges for enabling immersive experiences, such as remote robot control, using Virtual Reality (VR). The article advocates for a joint design of packet-level coding and resource scheduling leveraging parallel wireless links and evaluates the concept considering a combination of sub-6GHz and mmWave links.

"Towards Factory-Scale Edge Robotic Systems: Challenges and Research Directions" presents a system level vision of a robotic system where computing is offloaded to the edge enabled by high performance wireless communication systems. The article also proposes a new approach to co-design computing, communications, and control components in the system to meet time-sensitive robotic task requirements with higher efficiency and lower power consumption.

In “Low-Latency Anomaly Detection on the Edge-Cloud Continuum for Industry 4.0 Applications: the SEAWALL Case Study,” the authors describe the design, implementation, and evaluation of an edge-cloud computing platform for IOT system monitoring and fault detection algorithms. The article evaluates the latency tradeoffs of cloud vs edge computing in a real testbed considering various workload orchestration policies.

“Unobtrusive, Accurate, and Live Measurements of Network Latency and Reliability for Time-Critical Internet of Things” addresses the challenges related to measuring stringent communication performance with high accuracy, which is critical for many IOT systems. The article proposes a new methodology to measure latency and reliability in wireless networks and evaluates the approach in a testbed with Wi-Fi 6 and 5G devices.

Last, but not least, “Time-Critical IoT Applications Enabled by Wi-Fi 6 and Beyond” covers the emerging time-critical use cases and their requirements and discusses the latest Wi-Fi 6 and TSN capabilities. The article provides a practical perspective on how Wi-Fi capabilities can be leveraged to enable industrial control, remote rendering for extended reality and cooperative simultaneous localization and mapping for mobile robots. The article also discusses next generation Wi-Fi enhancements, such as Multi-Link Operation in Wi-Fi 7 and how they contribute to achieve low latency and high reliability.

Although time-critical performance has long been a focus within the industrial control and automation space, more and more applications, across different markets, will depend on computing and communication with strict performance guarantees. This SI not only provides a broad coverage of the current state of the art, but also addresses open research challenges from different perspectives across industry and academia. The six articles have been selected through a thorough peer-review process and we would like to thank the authors, reviewers, and editorial team for their contribution to make this special issue possible.

Biographies

Dave Cavalcanti [SM] (dave.cavalcanti@intel.com) is Principal Engineer at Intel Corporation where he develops next generation wireless connectivity and distributed computing technologies to enable time-sensitive systems and applications. He received his Ph.D. in computer science and engineering in 2006 from the University of Cincinnati. He is the recipient of best demo award at IEEE Infocom 2018, and best paper awards at IEEE WFCS’21, INDIN’21, and WFCS’22. He serves as the chair for the Wireless TSN working group in the Avnu Alliance, an industry group facilitating an ecosystem of interoperable deterministic networking across Ethernet, Wi-Fi and 5G technologies. He is Senior Member of the IEEE and has served as Chair of the IEEE Technical Committee on Simulation, and as guest editor for the *IEEE Computer Magazine*, *IEEE Communications Magazine*, and *IEEE Wireless Communications*.

Carlos Kamienski is a Full Professor of Computer Science at the Federal University of ABC (UFABC, Brazil). Currently, he leads the NUVEM Strategic Research Unit comprising faculty members and students working in five broad research lines, namely smart societies, virtual sensations, connected mobility, extreme computing, and integrated universes. He was the Brazilian coordinator of SWAMP (swamp-project.org), an EU-Brazil collaborative research project that developed IoT-based methods and approaches for smart water management in precision irrigation. His current research interests include Internet of Things, smart agriculture, smart cities, fog computing, network softwarization, and Future Internet.

Kaushik Chowdhury is Professor in the Electrical and Computer Engineering Department at Northeastern University, Boston, USA. He is the winner of the U.S. Presidential Early Career Award for Scientists and Engineers (PECASE) in 2017, the Defense Advanced Research Projects Agency Young Faculty Award in 2017, the Office of Naval Research Director of Research Early Career Award in 2016, and the National Science Foundation (NSF) CAREER award in 2015. He is the recipient of best paper awards at IEEE GLOBECOM’19, DySPAN’19, INFOCOM’17, ICC’13, ’12, ’09, and ICNC’13. He serves as area editor for *IEEE Trans. on Mobile Computing*, *Elsevier Computer Networks Journal*, *IEEE Trans. on Networking*, and *IEEE Trans. on Wireless Communications*. He has served in several leadership roles, including Chair of the IEEE Technical Committee on Simulation, and as Technical Program Chair for IEEE INFOCOM 2021, IEEE CCNC 2021, IEEE DySPAN 2021, and ACM MobiHoc 2022. His research interests are in applied machine learning for wireless communications and networks, networked robotics, and self-powered Internet of Things.

Vivek Jain [SM] is Lead Expert at Bosch Research where he leads research on ML/AI models for wireless, RF localization and sensing, intelligent connectivity, cooperative wireless networks, and lightweight implementation. He received his Ph.D. in computer science and engineering in 2007 from University of Cincinnati and Bachelors degree in electronics and communication engineering in 2002 from Indian Institute of Technology Roorkee. He joined Bosch in 2006 and brings in extensive domain knowledge and research experience in automotive, industrial, building and residential networking applications. He has created and led several innovations at Bosch including the Perfectly Keyless product for which he received the Robert Bosch Innovation Award in 2019. He has served as reviewer/TPC for more than 30 diverse International journals and conferences. He has also served as Judge for CES 2022 Innovation Awards and “Create the Future” design contest by SAE Media Group in 2020- 2022.

Stefano Vitturi [SM] is a Director of Research with the Institute of Electronics and Computer and Telecommunications of the National Research Council of Italy (CNR–IEIIT) and an adjunct professor at the University of Padova (Italy). He received the Laurea degree in Electronics Engineering from the University of Padova, in 1984. From 1985 to 2001 he worked at the control and data acquisition system of RFX, a nuclear fusion experiment built within the framework of the European fusion research program, where he was the head of the Automation and Informatics group. In 2003, he founded the CNR–IEIIT Padova territorial site of which he is currently the head. His current research interests include industrial automation systems and industrial communication networks, with particular attention to the design and implementation of real–time protocols. He has co-authored more than 150 publications, including journal papers, book chapters and conference papers. He has served as Program co-chair and Track co-chair in several IEEE IES conferences like INDIN, ETFA and WFCS.

Malcolm Smith is a Sr. technical advisor to the Cisco CTO wireless responsible for Enterprise Wi-Fi innovation & strategy including University research, standards and industry partnerships. He leads the research for Wi-Fi 6/7/8 with a focus on deterministic Wi-Fi technology and methods. He currently leads the Industrial IOT work-group at the WBA (Wireless Broadband Alliance) and co-chairs the XR MSTG at the WFA (Wi-Fi Alliance) and contributes regularly to IEEE P802.11be. Finally, Malcolm has 100+ patents in the wireless/mobility space.

Andreas Willig [SM] is currently a Professor in the Department of Computer Science and Software Engineering at the University of Canterbury, Christchurch, New Zealand. He obtained the Dr.-Ing. degree in electrical engineering from the Technical University Berlin (Germany) in 2002, and the diploma degree in computer science from the University of Bremen (Germany) in 1994. From 2004 to 2010 he was with the Telecommunication Networks Group (TKN) at the Technical University of Berlin as a postdoctoral researcher, and in 2010 he joined the University of Canterbury as a faculty member. His research interests include wireless networks, ad-hoc and sensor networks/Internet of Things, drone networks, field bus and real-time systems, all with specific focus on protocol design and performance aspects. He has co-authored a well-received textbook on wireless sensor networks, and is author or co-author of more than a 100 book chapters and papers in peer-reviewed conferences and journals. He is recipient or co-recipient of five best paper awards. Furthermore, he has served as regular or guest editor for the *IEEE Transactions on Industrial Informatics*, Elsevier Computer Communications and MDPI Sensors.