Guest Editorial: AI-Enabled Software-Defined Industrial Networks: Architectures, Algorithms, and Applications

With the development of intelligent manufacturing, new manufacturing modes such as personalized customization and networked collaboration have been widely developed. These new manufacturing modes require frequent data exchanges between manufacturing machines and industrial information systems through the networks, and dynamically change according to the variations of orders, business, and environments, which cannot be supported in traditional manufacturing modes that focus on local and fixed processes. The current industrial network architecture cannot meet the needs of the aforementioned upcoming manufacturing mode. For example, there are many industrial network protocols, forming a complex industrial heterogeneous network, which seriously affects the interconnections between the underlying devices and the upper layer application systems. In addition, the layering information technology (IT) networks and the operation technology (OT) networks in the factory have hindered the developments of the industrial networks and intelligent manufacturing. There is an urgent need to build a flat, efficient, and flexible industrial network to support the new manufacturing modes.

Fully interconnected, flat, and flexible industrial networks will be the development trends of intelligent manufacturing, and designing new communication protocols to replace the traditional heterogeneous network protocols maybe a feasible solution. In the application layer, a data communication protocol independent of manufacturers and platforms (e.g., OPC UA) can be used to support data exchanges among different operating systems or devices from distinct manufacturers, and achieve the fusion of heterogeneous industrial networks. However, the application layer protocols can only be used in the management and configuration process, but cannot guarantee real-time performance, which prohibits them from directly participating in automatic control.

Software-defined networking (SDN) improves the controllability of the network by the separation of the data plane and the control plane. Without introducing new link layer protocols, SDN can be compatible with existing industrial communication protocols, and flexible to modify and reconstruct the network based on various quality of service (QoS) requirements. Artificial intelligence (AI) has learning abilities and can provide better network management and traffic optimization without any expert knowledge. AI can be used to detect vulnerabilities or anomalies in an automated way on the environment resulted from the convergence of OT and IT. SDN with AI assistance through different condition is utilized and uses network management, decision-making, fault detection, path planning, and routing schemes in several scenarios such as enterprise network and campus network. Thus, the combination of AI and SDN has considerable application potential for industrial networks enhancement, whereas implementing SDN in industrial networks still faces some fundamental issues, including the integration of heterogeneous network protocols, unified access control, interconnection with industrial wireless networks, real-time transmission scheduling, etc.

In this special issue, authors from both academia and industry were invited to submit papers presenting new research related to the theory or practice of software-defined industrial networks (SDINs), including algorithms, modeling, technologies, and applications. After a rigorous review process, ten papers have been selected to be published in this special issue.

To ensure the continuity and robustness of Industrial Internet of Things (IIoT) communications in the case of damaged infrastructure communication facilities postdisaster, the industrial IoT can be connected with satellite networks in emergencies. Zong *et al.* [A1] in "End-to-End Transmission Control for Cross-Regional Industrial Internet of Things in Industry 5.0" present a cross-regional, end-to-end, transmission control scheme for satellite-supported, multihop industrial IoT. They propose a scheme that adjusts the window of data transmission from two phases, slow start and congestion avoidance, to accommodate the low-transmission performance caused by a long delay and high bit error rate in converged networks. The window of data transmission is also adjusted to increase the amount of data transmission for the slow start to fill the high bandwidth delay product of the converged network while adjusting the threshold of data transmission based on feedback information to distinguish different data losses during congestion avoidance. The feasibility of the heterogeneous network transmission model is experimentally verified. The results show that the scheme can achieve good performance in heterogeneous networks of industrial IoT and satellite networks.

The ResNets-based intrusion detection system (IDS) has a long detecting interval in SDIN since the multibranch

Date of current version February 18, 2022.
Digital Object Identifier 10.1109/TII.2022.3142146

architecture has memory access overhead. To address this problem, Zhu *et al.* [A2] in "Juggler-ResNet: A Flexible and High-Speed ResNet Optimization Method for Intrusion Detection System in Software-Defined Industrial Networks" propose Juggler-ResNet with a fusible residual structure that preserves the feature extraction ability of the residual structure and enables equivalent transformation to linear topology to support low latency inference service in the industrial application. First, they propose a fusible multibranch residual structure to avoid gradient vanishing problems in the training phase. Then, they convert it to liner topology by using a set of equivalent fusion operators. Finally, the liner-topology model is deployed to accelerate inference speed. Their experimental results on CIFAR-10 and CIFAR-100 show that fusible residual structure can achieve 2.08–4.3$\times$ acceleration with the state-of-the-art level accuracy performance.

The current Industrial Internet has many drawbacks in terms of network systems, such as low network expansion, inconvenient troubleshooting, and low data transmission efficiency. Wang *et al.* [A3] in "SMA: SRv6 Based Multi-Domain Integrated Architecture for Industrial Internet" propose a novel SRv6-based multidomain integrated architecture for industrial Internet (SMA). They deploy multilayer controllers in SMA and replace the SDN controller by SMA nodes, which realize the high network scalability and efficient data transmission of the Industrial Internet. The faulty node in the SMA can be quickly and accurately identified through the periodic detection actively sent by the controller node in the domain and the passive feedback of the SMA nodes, and the generated SMA Nodes Trusted Set can be used for forwarding path generation. They propose a Bellman–Ford algorithm with a hop count constraint based on the total number of SNTS nodes, which effectively avoids long-path forwarding and improves network resource utilization. Through theoretical analysis, the safety and scalability of SMA have been fully verified. The simulation results show that SMA is superior to the existing Industrial Internet network structure in terms of troubleshooting efficiency of faulty nodes, network throughput, and data communication overhead.

The traditional spectrum access schemes are difficult to adapt to the various communication environments for the Cognitive Industrial Internet of Things (CIIoT). Liu *et al.* [A4] in "Reinforcement Learning Based Dynamic Spectrum Access for Software-Defined Cognitive Industrial Internet of Things" propose Q-learning-based dynamic spectrum access to intelligently utilize the spectrum resources in three access scenarios: orthogonal multiple access, underlay spectrum access, and nonorthogonal multiple access (NOMA). The simulation results have shown the advantages of the Q-learning-based NOMA scheme in terms of guaranteeing the throughput of the CIIoT nodes and decreasing the interference to the primary users.

SDIN suffers from low traffic scheduling efficiency caused by large and imbalanced flows, known as the heavy hitters problem. Liu *et al.* [A5] in "Imitation-Learning Based Heavy-Hitter Scheduling Scheme in Software Defined Industrial Networks" propose a novel imitation learning-based flow scheduling (ILFS) method. They utilize P4-based in-band network telemetry technology to collect fine-grained, real-time traffic data from SDIN's data plane. In the control plane, they integrate the generative adversarial imitation learning model with a soft actor critic to preserve the experiences of flow, thereby better scheduling large flows. The experiment results indicate that ILFS successfully controls the link bandwidth utilization between 10% and 80% and significantly improves the average network throughput and link utilization rate.

Toward energy-efficient and secure data transmission in AI-enabled SDINs, Fang *et al.* [A6] in "Towards Energy-Efficient and Secure Data Transmission in AI-Enabled Software Defined Industrial Networks" presents a metric called ECPUB, which means energy cost of transmitting per useful bit, to evaluate energy efficiency. They also propose an energy-efficiency-based secure multipath routing scheme (E2SMR) by adopting the ECPUB and (t, n) threshold secret sharing scheme, for enhancing the security under the premise of guaranteeing energy efficiency. Extensive simulation results show that ECPUB can evaluate the energy efficiency and facilitate the balance of network load, whereas E2SMR can prolong the lifetime of the network and simultaneously ensure the network functionality securely.

The security of the distributed control plane is rarely considered in SDIN. Wang *et al.* [A7] in "Deep Reinforcement Learning for Securing Software Defined Industrial Networks with Distributed Control Plane" study attacks against SDIN with distributed control plane, demonstrate their propagation across multiple controllers, and analyze their impacts. They propose an attack mitigation scheme based on deep reinforcement learning to adaptively prevent the spread of attacks. The scheme has the ability of learning from the environment and flexibly adjusting the switch takeover decisions to isolate the attack source, so as to tolerate attacks and enhance the resilience of SDIN.

The SDIN architecture is vulnerable to network attacks, which may degrade manufacturing productivity, and even cause accidents. Hu *et al.* [A8] in "A Deep One-class Intrusion Detection Scheme in Software-Defined Industrial Networks" propose a deep-learning-based one-class intrusion detection scheme (DO-IDS) to improve the security of industrial networks. First, DO-IDS periodically extracts the flow statistics of the industrial network traffic to generate network status features. Then, it utilizes a deep-learning-based dimension reduction approach to filter redundant features. In addition, a deep-learning-based one-class detector is designed to calculate the abnormal scores of the network status features. Finally, they conduct extensive simulations, which demonstrates that DO-IDS can detect abnormal traffic with enhanced accuracy and high efficiency.

The IIoT enables intelligent manufacturing through the interconnection and interaction of industrial production elements. Ji *et al.* [A9] in "Dynamic Network Slicing Orchestration for Remote Adaptation and Configuration in Industrial IoT" propose a network slicing orchestration system for remote adaptation and configuration in smart factories. To optimize network resource allocation and adapt to the dynamic network environments, they propose two heuristic algorithms with the assistance of

AI and the theoretical analysis of the network slicing system. The experiment results show the effectiveness and efficiency of the proposed algorithms when multiple network services are concurrently running in the IIoT.

With the growth of the number of IoT devices and the emergence of new applications, satisfying distinct QoS in the same physical network becomes more challenging. Mai *et al.* [A10] in "Transfer Reinforcement Learning aided Distributed Network Slicing Optimization in Industrial IoT" design a network slicing architecture over the SDN-based long-range wide area network (LoRaWAN) to meet the distinct QoS in industrial IoT. They proposed a deep deterministic policy gradient (DDPG) based slice optimization algorithm, which enables LoRa gateways to intelligently configure slice parameters to improve the slice performance. To accelerate the training process across multiple LoRa gateways, they leverage the transfer learning framework and design a transfer learning based multi agent DDPG algorithm.

In closing, we would like to thank all the people who have made significant contributions to this special issue, including the contributing authors, the anonymous reviewers, and the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS publication staff. We believe that the research results presented in this special issue will stimulate further research and development ideas in SDIN.

GUANGJIE HAN, *Guest Editor*
Hohai University
Changzhou 213022, China
hanguangjie@gmail.com

ADNAN M. ABU-MAHFOUZ, *Guest Editor*
NextGen Enterprises and Institutions
Council for Scientific and Industrial Research
Pretoria 0184, South Africa
a.abumahfouz@ieee.org

JOEL J. P. C. RODRIGUES, *Guest Editor*
Senac Faculty of Ceará
60160-194 Fortaleza-CE, Brazil
Instituto de Telecomunicações
6201-001 Covilhã, Portugal
joeljr@ieee.org

XIANBIN WANG, *Guest Editor*
Department of Electrical and Computer Engineering
The University of Western Ontario
London, ON N6A 5B9, Canada
xianbin.wang@uwo.ca

APPENDIX
RELATED WORKS

[A1] L. Zong, F. H. Memon, X. Li, H. Wang, and K. Dev, "End to end transmission control for cross regional industrial Internet of Things in industrial 5.0," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3133885.

[A2] Z. Zhu *et al.*, "Juggler-ResNet: A flexible and high-speed ResNet optimization method for intrusion detection system in software-defined industrial networks," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3121783.

[A3] L. Wang, F. Wen, K. Cheng, X. Feng, and H. Shen-Tu, "SMA: SRv6 based multi-domain integrated architecture for industrial Internet," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3131737.

[A4] X. Liu, C. Sun, W. Yu, and M. Zhou, "Reinforcement learning based dynamic spectrum access for software-defined cognitive industrial Internet of Things," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3113949.

[A5] Y. Liu, Q. Wu, J. Niu, X. Li, and Z. Song, "Imitation-learning based heavy-hitter scheduling scheme in software defined industrial networks," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3130279.

[A6] W. Fang, C. Zhu, R. Yu, K. Wang, and W. Zhang, "Towards energy-efficient and secure data transmission in ai-enabled software defined industrial networks," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3122370.

[A7] J. Wang, J. Liu, H. Guo, and B. Mao, "Deep reinforcement learning for securing software defined industrial networks with distributed control plane," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3128581.

[A8] B. Hu *et al.*, "A deep one-class intrusion detection scheme in software-defined industrial networks," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3133300.

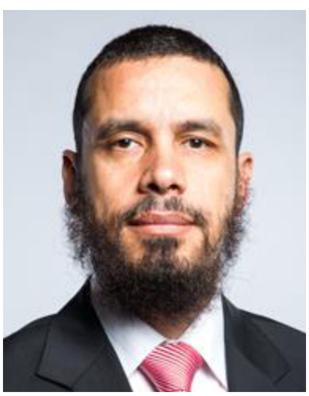
[A9] L. Ji, S. He, W. Wu, C. Gu, J. Bi, and Z. Shi, "Dynamic network slicing orchestration for remote adaptation and configuration in industrial IoT," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3131355.

[A10] T. Mai, H. Yao, N. Zhang, W. He, D. Guo, and M. Guizani, "Transfer reinforcement learning aided distributed network slicing resource optimization in industrial IoT," *IEEE Trans. Ind. Informat.*, to be published, doi: 10.1109/TII.2021.3132136.

Guangjie Han (Senior Member, IEEE) received the Ph.D. degree in computer science from Northeastern University, Shenyang, China, in 2004.

In February 2008, he finished his work as a Postdoctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From October 2010 to October 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. From January 2017 to February 2017, he was a Visiting Professor with City University of Hong Kong, Hong Kong. From July 2017 to July 2020, he was a Distinguished Professor with Dalian University of Technology, Dalian, China. He is currently a Professor with the Department of Internet of Things Engineering, Hohai University, Changzhou, China. His research interests include Internet of Things, Industrial Internet, machine learning and artificial intelligence, mobile computing, and security and privacy.

Dr. Han has more than 400 peer-reviewed journal and conference papers, in addition to 160 granted and pending patents. Currently, his H-index is 51 and i10-index is 193 in Google Citation (Google Scholar). Total citation count of his papers raises above 10 000+ times. He is a Fellow of the U.K. Institution of Engineering and Technology. He has served on the editorial boards of up to ten international journals, including the IEEE NETWORK, IEEE SYSTEMS, IEEE/CCA JOURNAL OF AUTOMATICA SINICA, IEEE ACCESS, *Telecommunication Systems*, etc. He has guest edited a number of special issues in IEEE journals and magazines, including the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE COMMUNICATIONS, IEEE WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, *Computer Networks*, etc. He has also served as a Chair of organizing and technical committees in many international conferences. He was the recipient of the 2020 IEEE Systems Journal Annual Best Paper Award and the 2017–2019 IEEE Access Outstanding Associate Editor Award.



Adnan M. Abu-Mahfouz (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in computer engineering from the University of Pretoria, Pretoria, South Africa, in 2005 and 2011, respectively.

He is currently a Chief Researcher and Center Manager of the Emerging Digital Technologies for 4IR research center with the Council for Scientific and Industrial Research, an Extraordinary Professor with the University of Pretoria, the Professor Extraordinaire with Tshwane University of Technology, Pretoria, and a Visiting Professor with the University of Johannesburg, Johannesburg, South Africa. His research interests include wireless sensor and actuator network, low power wide area networks, software defined wireless sensor network, cognitive radio, network security, network management, and sensor/actuator node development.

Dr. Abu-Mahfouz is a Specialty Chief Editor for IoT Communication and Networking Protocols, a specialty section of Frontiers in Internet of Things, an Associate Editor for the IEEE ACCESS, IEEE INTERNET OF THINGS, and IEEE TRANSACTION ON INDUSTRIAL INFORMATICS, and a member of many IEEE Technical Communities. He participated in the formulation of many large and multidisciplinary R&D successful proposals (as Principal Investigator or main author/contributor). He is the founder of the Smart Networks collaboration initiative that aims to develop efficient and secure networks for the future smart systems, such as smart cities, smart grid, and smart water grid.

Joel J. P. C. Rodrigues (Fellow, IEEE) received the B.Sc. in computer science and engineering from the University of Coimbra, Coimbra, Portugal, in 1995, and the M.Sc. degree in management and the Ph.D. degree in computer science and engineering from the University of Beira Interior, Covilhã, Portugal, in 2002 and 2006, respectively.

He is with the Senac Faculty of Ceará, Brazil; the Head of Research, Development, and Innovation; and a Senior Researcher with the Instituto de Telecomunicações, Covilhã, Portugal. He received the Academic Title of Aggregated Professor from the University of Beira Interior, Portugal in 2015, the Habilitation in Computer Science and Engineering with the University Mulhouse Haute-Alsace in 2014, France. He is an Highly Cited Researcher, the Leader of the Next Generation Networks and Applications Research Group (CNPq), an IEEE Distinguished Lecturer, Member Representative of the IEEE Communications Society on the IEEE Biometrics Council, and the President of the scientific council at ParkUrbis—Covilhã Science and Technology Park, Tortosendo, Portugal. He was the Director for Conference Development - IEEE ComSoc Board of Governors, Technical Activities Committee Chair of the IEEE ComSoc Latin America Region Board, a Past Chair of the IEEE ComSoc Technical Committee (TC) on eHealth and the TC on Communications Software, a Steering Committee Member of the IEEE Life Sciences Technical Community and Publications Co-Chair.

Prof. Rodrigues is the Editor-in-Chief for the International Journal of E-Health and Medical Communications and Editorial Board Member of several high-reputed journals (mainly from IEEE). He has been a General Chair and TPC Chair of many international conferences, including IEEE International Conference on Communications, IEEE Global Communications Conference, IEEE International Conference on e-Health Networking, Application and Services, and IEEE Latin-American Conference on Communications. He has authored or coauthored about 1000 papers in refereed international journals and conferences, three books, two patents, and one ITU-T Recommendation. He was the recipient of several Outstanding Leadership and Outstanding Service Awards by IEEE Communications Society and several best papers awards. He is a Member of the Internet Society, a Senior Member ACM, and a Fellow of AAIA.

Xianbin Wang (Fellow, IEEE) received the Ph.D. degree in electrical and computer engineering from the National University of Singapore, Singapore, in 2001.

He is currently a Professor and Tier-1 Canada Research Chair with Western University, London, ON, Canada. Prior to joining Western University, he was with Communications Research Centre Canada as a Research Scientist/Senior Research Scientist from July 2002 to December 2007. From January 2001 to July 2002, he was a System Designer with STMicroelectronics, Geneva, Switzerland. His research interests include 5G/6G technologies, Internet of Things, communications security, machine learning, and intelligent communications.

Dr. Wang has more than 450 highly cited journal and conference papers, in addition to 30 granted and pending patents and several standard contributions. He is a Fellow of Canadian Academy of Engineering, a Fellow of Engineering Institute of Canada, and an IEEE Distinguished Lecturer. He was the recipient of many awards and recognitions, including Canada Research Chair, CRC President's Excellence Award, Canadian Federal Government Public Service Award, Ontario Early Researcher Award, and six IEEE best paper awards. He currently serves/has served as an Editor-in-Chief, Associate Editor-in-Chief, Editor/Associate Editor for more than ten journals. He was involved in many IEEE conferences including IEEE Global Communications Conference, IEEE International Conference on Communications, Vehicular Technology Conference, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, IEEE Wireless Communications and Networking Conference, IEEE Canadian Conference of Electrical and Computer Engineering, and Canadian Workshop on Information Theory, in different roles such as General Chair, Symposium Chair, Tutorial Instructor, Track Chair, Session Chair, TPC Co-Chair, and Keynote Speaker. He has been nominated as an IEEE Distinguished Lecturer several times during the last ten years. He is currently the Chair of IEEE London Section and the Chair of ComSoc Signal Processing and Computing for Communications Technical Committee.