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Design and Analysis of Communication Interfaces for Industry 4.0: Guest Editorial

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I. Introduction

A. Motivation

THIS special issue (SI) aims to present recent advances in the design and analysis of communication interfaces for Industry 4.0. The Industry 4.0 paradigm aims to integrate advanced manufacturing techniques with Industrial Internet-of-Things (IIoT) to create an agile digital manufacturing ecosystem. The main goal is to instrument production processes by embedding sensors, actuators and other control devices which autonomously communicate with each other throughout the value-chain [1].

The information collected from the IIoT devices can be utilized to create digital replicas of the physical processes, machines and operating conditions. These digital replicas are more commonly known as **digital twins**. A digital twin of a physical entity can be placed in a virtual production environment, allowing prediction of the future state of system given the current trajectory of evolution, which is based on the sensed data. This allows for proactive optimization of the production processes and reduction in the downtime for the equipment. In summary, the key benefits [2] of digital twinning include: i) reduction in down-time through proactive repairs and agile reconfiguration of manufacturing cells; ii) reduction in ramp-up time for new manufacturing processes; iii) decrease in cycle-time through online optimization.

Besides digital twining, other key enablers for Industry 4.0 include collaborative robotics (also known as **cobotics**) and **telerobotics**. The former is mainly focused on robot-robot and human-robot collaborative assembly on a production line, while the latter is geared towards amplification of human capacity (e.g. force or scale of operation) or operation in hard to access areas. Recently, the **cloud robotics** [3] paradigm whereby the brain of the robotic system can be implemented in the cloud has gained significant popularity and is envisioned as a key proponent of both cobotics and telerobotic systems.

The abovementioned applications vary significantly in terms of the requirements of connectivity [4] ranging from low data rate, reliable connections for IIoT sensor readings to high bandwidth, low-latency connections for immersive virtual/augmented reality (VR/AR) digital twins. While 5G wireless technologies are seen as a key enabler for realizing ultra-reliable low-latency communication (URLLC), the current Release 15 which is commercially being deployed does not include such features. In summary, an extensive mapping [5] of the desired features for these Industry 4.0 applications leads to three key requirements for the communication networks, i.e., reliability, resilience, and security.

B. Overview of Research Challenges

➲ Reliability: The URLLC has been envisioned as a key feature for critical and industrial automation IoT [6]. Current approaches for provisioning the URLLC include:

- Grant-free uplink access [7]-[8]: which reduces latency for the IIoT devices by providing pre-configured wireless resources for uplink transmission. This is achieved by scrapping the requirement of obtaining uplink-scheduling requests and access-grant cycles [9].
- Non-orthogonal multiple access (NOMA)[8],[10]: aims to reduce latency by allowing multiple devices to share the same wireless resources simultaneously. The transmissions can be demultiplexed by employing advanced signal processing techniques on the IIoT gateway.
- Diversity techniques: which exploit multiple antennas [9] to harness the diversity gain which can improve transmission reliability. Recent advances in Massive multiple-input and multiple-output (MIMO) [11] systems promise significant diversity and multiplexing gains which can be harnessed for provisioning URLLC. Other forms of diversity for URLLC includes interface diversity, i.e. exploitation of multiple wireless interfaces [12].

In this SI, we have received contributions that tackle the optimization of both NOMA and Massive MIMO based techniques for URLLC. A summary of these contributions is presented in Section II.

➲ Resilience: It is well established that a significant reduction in latency and improvement in reliability for IIoT applications can be attained by pushing intelligence out to the edge controllers [5]. The implementation of the edge controller requires: a. delivery of fresh information from sensors and end-devices to the edge controller; and, b. proactive caching of tasks/content on the edge-controller which need to be delivered

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to the end-devices from the cloud. Recently, a new metric called age-of-information (AoI) [13] has been introduced to quantify freshness of information specifically for real-time status updates. Interestingly, the transmission policies which optimize AoI are not necessarily the same as those which minimize latency. Consequently, the quantification of AoI for IIoT networks and its minimization has attracted a lot of attention from the research community [13]-[14]. Proactive caching of control tasks [15] or the contents [16] in the downlink at the IIoT gateways can introduce network-level resilience in the event of connectivity outages between the cloud and the gateway. Distributed storage of data across the edge-cloud continuum in a manner such that latency requirements for requesting end-nodes can be met can also improve resilience in IIoT networks.

In addition to prefetching the control tasks via caching, the overall performance of IIoT networks can be optimized via the joint design of the controller implementation and communication protocols on the edge. Notice that the overall requirement of resilience and reliability is not only in terms of data communication but also for the localization services. High precision localization of end-effectors and actuators is also key for enabling cobotics and telerobotics applications. The localization techniques must be able to dynamically reconfigure within the dynamics of a harsh propagation environment.

In this SI, we have received contributions that tackle these aforementioned research issues. A summary of these contributions can be found in Section II.

➲ Security: For applications such as digital twining, cobotics and telerobotics many hardware and software sub-systems provided by various manufacturers need to be integrated through a connectivity fabric. Consequently, end-to-end security and privacy of data is of prime importance. In particular, at the device level, robust authentication mechanisms are required. At the network level anomalies in data and traffic both need to be detected. The former can be accomplished using either classical key-based authentication mechanisms or more recently introduced distributed-ledger based techniques, while the latter can be accomplished using machine learning and time-series analysis techniques.

The data generated by sensors is pre-processed to preserve privacy. Differential privacy-based [17] techniques allow privacy preservation for individual entities while providing the capability to analyze overall dynamics. These techniques have been rapidly applied to consumer IoT. However, applications in the area of IIoT is still nascent.

In this SI, we have three contributions that address the security and privacy issues for IIoT networks. A summary of these contributions is presented in Section II.

C. Organization

The aim of this SI is to provide a platform for reporting recent advances that tackle the aforementioned design issues for enabling Industry 4.0 applications. With this goal, a Call for Papers for the Special Issue (SI) on the Design and Analysis of Communication Interfaces for Industry 4.0, IEEE Journal on Selected Areas in Communications, was published in March, 2019. The SI attracted 40 high quality submissions from around the world. All papers received at least three reviews and the accepted papers went through at least one revision round. We eventually accepted 13 technical papers covering the important aspects which address reliability, resilience and security issues for IIoT networks. These papers have been classified into six sub-themes and a summary of contributions in each sub-themes is presented in Section II.

II. Summary of Accepted Papers

A. Resource Allocation & Connectivity Optimization for IIoT

The paper, "Online Task Scheduling and Resource Allocation for Intelligent NOMA-Based Industrial Internet of Thing" by Kunlun Wang et al. investigates the possibility of combining fog-computing with non-orthogonal multiple access (NOMA) for IIoT applications. In particular, fog-computing nodes can provide on-demand compute and storage resources for various delay sensitive IIoT applications. However, when such nodes are accessed via multiple end-devices over wireless medium, significant latency may be introduced through multiple access scheme. The authors proposed exploitation of NOMA to minimize this additional latency. The proposed framework is geared towards both improvements in spectral and energy efficiencies while considering implications on overall latency. The authors formulate a joint task scheduling and subcarrier allocation problem, with an objective to minimize the total cost in terms of the delay and energy consumption, while taking into account the practical communication and computation constraints. This translates into a combinatorial optimization problem which is quite difficult to solve for the optimal solution. To that end, authors tackle task scheduling and subcarrier allocation problems through an online learning mechanism. The authors demonstrate that the proposed algorithms can significantly reduce both latency and the energy consumption for IIoT applications.

The paper "Joint Pilot and Payload Power Allocation for Massive-MIMO-enabled URLLC IIoT Networks" by Hong Ren et al. advocates adaptation of massive multiple-input and multiple-output (MIMO) base-stations to enable URLLC in IIoT networks. The authors demonstrate feasibility of deterministic communications due to channel hardening effects in Massive MIMO systems. It is shown that in order to reduce the latency, finite block length coding needs to be employed by the robots, sensors and actuators in the uplink. Consequently, traditional resource allocation methods for Massive MIMO transmission which are typically designed for capacity achieving infinite block length codes are no longer optimal. The authors develop analytical lower bound on the achievable uplink data rate for massive MIMO system with imperfect channel state information (CSI) for both maximum-ratio combining (MRC) and zero-forcing (ZF) receivers. Based on the analytical framework, the authors develop low-complexity algorithms which maximizes the data rate through joint optimization of the pilot and payload transmission power for both MRC and ZF receivers. The authors demonstrate that the proposed algorithm converges rapidly and provides performance gains over existing state-of-the-art algorithms.

The paper, “Joint Optimization in Cached-Enabled Heterogeneous Network for Efficient Industrial IoT” by Jiachen Yang et al. presents a framework for optimization of content placement in cache-enabled HetNets deployed in an Industrial setup. The proposed framework explicitly incorporates spatial dynamics of the deployment using the cluster Poisson point processes. The probability that content is not found in the cache of the serving base-station is employed as a key performance indicator (KPI). Considering this KPI, authors investigate optimal placement of content and activation of base-stations across different tiers. The authors demonstrate that joint activation and content placement optimization problem for the considered IIoT networks can be cast as a convex optimization problem which and solved to obtain exact analytical results. Based on the analysis of the exact optimal solution, a sub-optimal algorithm with much lower implementation complexity is proposed. The proposed framework is employed to demonstrate that the joint optimization of placement and activation of the BS yields significant gains, in contrast to traditional mechanisms which solely focus on optimization of content placement.

The paper, “Reachability Analysis of Networked Finite State Machine with Communication Losses: A Switched Perspective” by Zhipeng Zhang et al. focuses on representation of IIoT nodes as networked finite state machines (FSMs). These networked FSMs often connected through communication interfaces which may have limited bandwidth and can frequently encounter packet losses. In such networks both controllability [18] and reachability [19] are important to analyze. The authors present a mathematical framework to investigate reachability of such networks under communication losses and delays. Reachability analysis is of importance for various applications including blocking detection, safety analysis and communication system design for IIoT networks.

B. Transmission Scheduling and Multiple Access for IIoT

The paper, “Minimizing Age of Information with Power Constraints: Multi-User Opportunistic Scheduling in Multi-State Time-Varying Channels” by Haoyue Tang et al. is geared towards development of a medium access strategy which can guarantee delivery of fresh information from IIoT end-nodes to a central controller. In order to quantify the freshness of information, AoI is used as a primary metric. The authors characterize the performance of the considered IIoT deployment in terms of AoI and subsequently investigate a scheduling algorithm for its achievability. This is particularly challenging for time-varying channels. First, to tackle this problem, the authors decouple the multi-sensor scheduling problem into a node level constrained Markov decision process (CMDP). Second, the authors demonstrate that at the node-level optimal policy exhibits threshold structure, consequently the the network level optimal scheduling problem can be solved by employing linear programming. The proposed solution opportunistically exploits channel state to minimize the AoI for time-varying channels where IIoT nodes are power constrained. The paper, “Decentralized State-Driven Multiple Access and Information Fusion of Mission-Critical IoT Sensors for 5G Wireless Networks” by Vincent K. N. Lau considers a mission-critical control system, where an unstable dynamic plant is monitored by multiple distributed IoT sensors over a wireless communication network with shared common spectrum. Kalman filtering is employed in such a setup for tracking and estimating the state of the plant. To reduce the complexity of Kalman filtering, the authors consider a constant gain filter at the remote controller. The authors propose decentralized dynamic scheduling and information fusion of the IoT sensors to stabilize the unstable dynamic plant. The proposed scheme has a state-driven multiple access structure, where a large state estimation MSE (high transmission urgency) and good wireless channel conditions (good transmission opportunities) promote the active mode of the sensors. Using Lyapunov techniques, the authors provide a closed-form sufficient condition for stability and closed-form characterizations of the trade-off between a state estimation MSE and the average power consumption of the sensors. The authors also propose design guidelines for the constant filter gain based on minimizing the state estimation MSE. It is demonstrated that the proposed techniques provide significant gains in comparison to the state-of-the-art.

C. Co-design of Control and Communications for IIoT

The paper, “Reinforcement Learning-Based Control and Networking Co-design for Industrial Internet of Things” by Hansong Xu et al. addresses the challenge of synthesizing control, networking and computing into a single fabric to implement a cyber-physical system (CPS). The authors leverage reinforcement learning (RL) techniques to automatically configure the control and networking systems in a dynamic industrial environment. Essentially the proposed framework enables co-design of communication and controls for IIoT network. The authors design three new policies based on the characteristics of industrial systems to facilitate rapid convergence for the RL. The proposed RL based co-design approach is integrated and implemented on a CPS simulator for extensive experimental investigation. The presented experimental results demonstrate that the proposed approach can effectively and quickly reconfigure the control and networking systems automatically in a dynamic industrial environment.

D. Localization and Positioning for IIoT

The paper, “Adaptive positioning system based on multiple wireless interfaces for Industrial IoT in harsh manufacturing environments” by Jordy Mongay Batalla et al. investigates localization and positioning services for IIoT networks in harsh propagation environments. The contribution fills in the existing gap between static approaches and dynamic indoor positioning systems, by presenting a solution for adapting the system to changing conditions of the environment. The proposed solution employs a feedback loop based on ML. The ML based fingerprinting of the environment enables rapid and dynamic adaptation of the localization services providing significant gains as compared to the state-of-the-art algorithms.

E. Edge & Cloud Computing for IIoT

The paper, “Distributed Data Access in Industrial Edge Networks” by Theofanis P. Raptis et al. addresses the issue of distributed data storage in wireless industrial edge networks. The authors argue that the current data management approaches which rely on centralized storage will not be scalable for Industry 4.0 applications, while distributed solutions are increasingly being explored. To that end, the authors investigate the problem of distributed data access in multi-hop wireless industrial edge deployments, whereby a set of consumer nodes needs to access data stored in a set of data cache nodes, satisfying the industrial data access delay requirements and at the same time maximizing the network lifetime. The authors proved that the exact solution of the problem is computationally intractable and develop a low complexity sub-optimal algorithm to tackle this issue. Furthermore, the authors provide validation for the proposed algorithm by experimental evaluation on an open testbed with real devices. These experimental results are further expanded through computer simulations. The authors demonstrate that the adoption of the proposed algorithm leads to significant lifetime prolongation and energy efficiency gains.

The paper, "An Energy-Efficient Networking Approach in Cloud Services for IIoT Networks" by Dingde Jiang et al. investigates the problem of the energy-efficient networking in cloud services with geographically distributed data centres for industrial IIoT networks. The networking dynamics are particularly challenging when considering variability in demand, energy consumption, link utilization, bandwidth, and delay. To solve these issues, the authors propose a multi-constraint optimization model. An intelligent heuristic algorithm is presented to solve this model for dynamic request demands between different data centres and between data centres and IoT devices. The authors demonstrate that significant energy efficiency gains can be harnessed by adopting their proposed algorithm.

F. Security & Privacy of IIoT Networks

The paper, "Blockchain-Assisted Secure Device Authentication for Cross-Domain Industrial IoT" by Meng Sheng et al. explores a distributed-ledger based authentication techniques for multi-party cross-domain IIoT networks. Typically, manufacturing processes usually involve hardware and software subsystems that belong to different administrative IoT domains. Devices from different domains collaboratively perform the overall tasks. Mutual authentication of these devices before initiating collaboration is essential. While such authentication can be accomplished by employing traditional key-based approaches, the solution entails costs in terms of heavy key management overhead or having to rely on a trusted third party. To that end, authors present an efficient blockchain-assisted secure device authentication mechanism for cross-domain industrial IoT. Specifically, consortium blockchain is introduced to construct trust among different domains. Identity-based signature (IBS) is exploited during the authentication process. To preserve the privacy of devices, they design an identity management mechanism, which can realize that devices being authenticated remain anonymous.

The paper, "iFinger: Intrusion Detection in Industrial Control Systems via Register-based Fingerprinting" by Kai Yang et al. proposes a novel intrusion detection approach to mitigate attacks on the industrial control systems. The authors leverage the fact that devices register states and access sequences can be used to generate unique device fingerprints. These fingerprints can then be employed by active and passive detection mechanism. The authors demonstrate efficacy of the register-based approach in real-world experiments, presenting a prototype that automatically generates ICS control device fingerprints and detects malicious attacks. Results show that the proposed approach achieves 97.1% F1 score in device identification.

Finally, the paper, "Privacy-Preserved Data Sharing towards Multiple Parties in Industrial IoTs" by Xu Zheng et al. investigate privacy preservation techniques for data sharing between multiple parties in IIoT networks. The proposed mechanism is formulated on the basis of the well-known differential privacy framework. The authors have also provided validation of the proposed methods on openly available real datasets.

III. Conclusion & Acknowledgment

We would like to thank all the authors who submitted their valuable contributions to this special issue. These contributions address key challenges for the design and analysis of communication interfaces for Industry 4.0 applications. We would also like to thank the reviewers who provided thorough and timely reviews, hence contributing to the success of this special issue. A special thanks to Raouf Boutaba, IEEE JSAC Editor-in-Chief, Philip Whiting, IEEE JSAC Senior Editor, Chang Wen Chen, IEEE JSAC Senior Editor and Janine Bruttin, Executive Editor, for their support in the preparation of this special issue and the continuous assistance in the various phases of the special-issue review and paper acceptance. Finally, we would like to thank fantastic support from IEEE editorial support and production team, especially Lauren Beride and Michael Hellrigel.

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