Intelligent and Low Overhead Network Synchronization for Large-Scale Industrial IoT Systems in the 6G Era

Xianbin Wang, Pengyi Jia, Xuemin (Sherman) Shen, and H. Vincent Poor

Abstract

Holistic temporal coherence among distributed industrial infrastructures enabled by accurate network synchronization is essential for achieving tight orchestration of large-scale Industrial Internet of Things (IIoT) systems. However, the low efficiency and situation agnosticism of conventional synchronization techniques using an inflexible "observing-and-calibrating" approach for clock offset correction are inevitably hindering the performance of many IIoT applications with increasing scale and heterogeneity. In this article, we provide an in-depth analysis of the challenges associated with conventional synchronization schemes over large-scale IIoT systems and then present three promising research directions for achieving intelligent and low overhead IIoT synchronization. Particularly, we first propose a new model-based network synchronization scheme that can proactively enable low overhead clock calibration by leveraging the inherent characteristics of heterogeneous clocks to avoid frequent timestamp exchange. We then design an intelligent device clustering mechanism with a specifically designed synchronization strategy for each group of IIoT devices by jointly exploiting their distinctive synchronization requirements and multi-dimensional device attributes. To leverage the unique characteristics of each oscillator, we analyze historical timestamps to reject unreliable timestamps and identify unreliable devices. Finally, we envision an edge-cloud collaborative network synchronization paradigm to implement the proposed schemes and demonstrate their efficacy in large-scale IIoT systems.

Introduction

The rapid convergence of communication technologies, intelligent computing, and vertical industrial applications is empowering the fourth industrial revolution and many new IIoT applications [1]. By enabling ubiquitous connectivity, seamless interactions, and distributed intelligent collaborations in IIoT systems, the 5G and the envisioned 6G networks are becoming the most critical foundation of the ongoing industrial transformation.

With the increasing complexity, distributed nature, and heterogeneity among IIoT facilities, accurate system-wide synchronization becomes essential for large-scale orchestration and coherent task coordination. Figure 1 shows the typical architecture of a large-scale IIoT system, where the heterogeneous IIoT elements within each subsystem will collaborate seamlessly to support diverse applications. Here, efficient inter-subsystem interaction among subsystems is critical to accomplish increasingly complicated industrial tasks, which require system-wide coordination among all involved facilities during a specific industrial process. However, given the stringent requirements of industrial machines from their designated tasks and deterministic control processes, time-engineered industrial applications cannot be achieved effectively without a system-wide temporal consensus [2]. Therefore, accurate network synchronization, which is critical to precisely align time across distributed connected devices over the Internet, is becoming a baseline technology for enabling various collaborations in large-scale IIoT systems.

Specifically, the extensive technological advancements during the last few decades have dramatically boosted the precision of machine processing and the resolution of the associated data, leading to increasingly stringent requirements on synchronization accuracy in a wide variety of IIoT applications. For instance, centimeter-level positioning in advanced manufacturing systems (AMS) is necessary to efficiently support automated object tracking [3], which hinges on the extremely accurate alignment of the temporal data generated at distributed IIoT devices. In achieving this positioning accuracy, sub-microsecond time synchronization among the involved devices is essential to accurately track critical facilities and avoid potential manufacturing malfunctions.

Furthermore, considering the heterogeneity of IIoT systems in terms of their hardware/software/communication capabilities and clock precision, distributed devices with diverse synchronization requirements will have to interact efficiently through sophisticated IIoT networks. The existing situation-agnostic synchronization mechanisms experience many challenges due to device heterogeneity and diverse synchronization requirements. As a result, efficient system-wide

Digital Object Identifier: 10.1109/MNET.107.2100631

Xianbin Wang (corresponding author) and Pengyi Jia are with Western University, Canada; Xuemin (Sherman) Shen is with University of Waterloo, Canada; H. Vincent Poor is with Princeton University, USA.

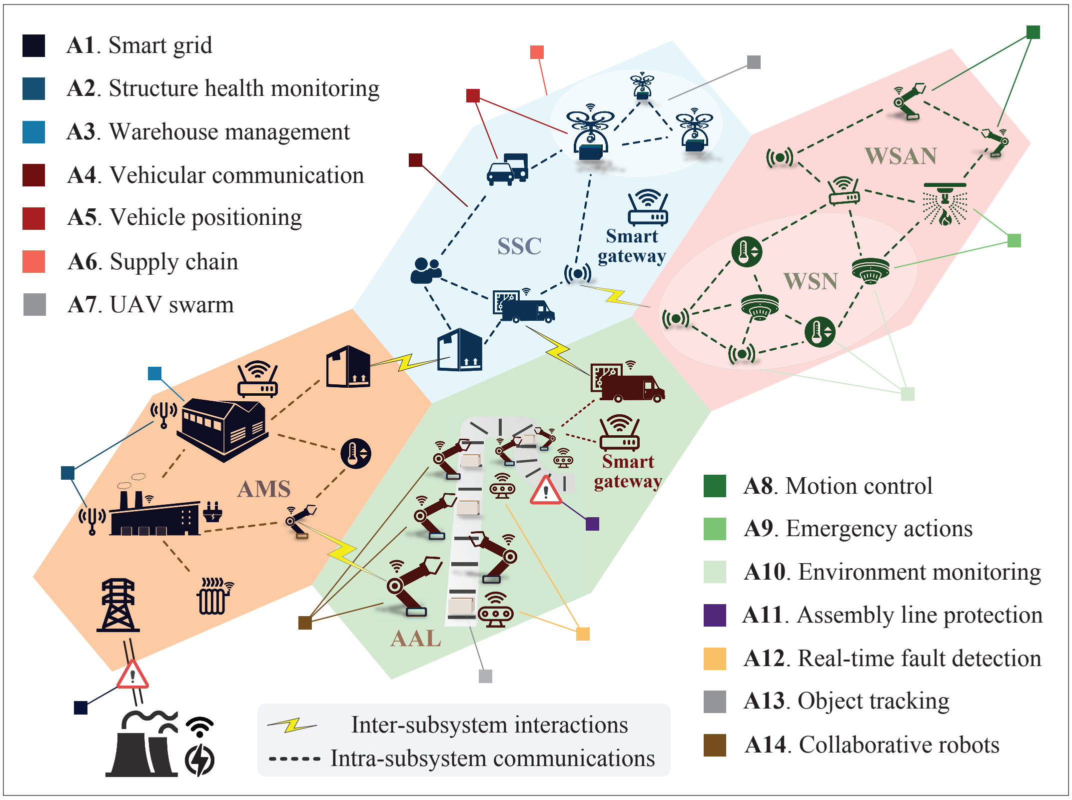

FIGURE 1. An elaborated structure of a large-scale IIoT system with various sub-systems. A wide variety of industrial applications are enabled by the seamless interconnection and collaboration among the heterogeneous IIoT devices and infrastructures.

synchronization will be increasingly essential with growing network scales and will be indispensable in bridging the gap among different local networks to improve the efficiency of orchestration and interoperability.

However, conventional accurate synchronization techniques (e.g., Precision Time Protocol) exclusively rely on the frequent exchange of timestamps among the involved entities over the Internet to achieve the "observing-and-calibrating" based synchronization approach. This situation-agnostic and inefficient way of eliminating time offsets severely degrades the performance of critical industrial applications due to overwhelming resource consumption and its lack of flexibility and intelligence. The frequent synchronization-related packet exchange will excessively consume the limited network resources that could be otherwise used for supporting industrial applications, leading to the deteriorated and even unattainable collaboration among IIoT devices [4]. Moreover, adopting conventional inflexible synchronization methods without understanding the industrial circumstances will lead to additional challenges, manifesting as an increasing synchronization frequency and uncontrollable synchronization error. Therefore, these challenges necessitate novel industry-oriented synchronization strategies with improved efficiency and situation-awareness to accommodate the stringent synchronization requirements in challenging industrial environments.

In this article, we first analyze the main challenges that the traditional clock synchronization protocols encountered in large-scale IIoT systems. In tackling these challenges, three promising solutions are presented as potential research directions. Specifically, we propose a proactive synchronization mechanism by accurately modeling heterogeneous clocks with a thorough characterization of each device. Clock offsets are predictively eliminated so that explicit and frequent timestamp exchange for synchronization is significantly reduced compared to the traditional "observing-and-calibrating" approach. Furthermore, the real-time situation and the intrinsic features of each local industrial device are further utilized to support intelligent device clustering for efficient synchronization, aiming at minimizing the network overhead while enhancing the situation-awareness during synchronization. Finally, historical timestamps are analyzed for each clock to reject unreliable timestamps and devices, which improves the reliability of the holistic synchronization design. The envisioned edge-cloud collaborative synchronization paradigm demonstrates that the proposed strategies are effective in compensating for the inherent deficiencies of traditional clock synchronization methodologies.

Challenges for Accurate Clock Synchronization in IIoT Systems

With the growing scale and intrinsic heterogeneity of IIoT systems, several major technical challenges are hindering the performance of large-scale network synchronization, as demonstrated in Fig. 2. In this section, three critical challenges of conventional clock synchronization techniques are identified below.

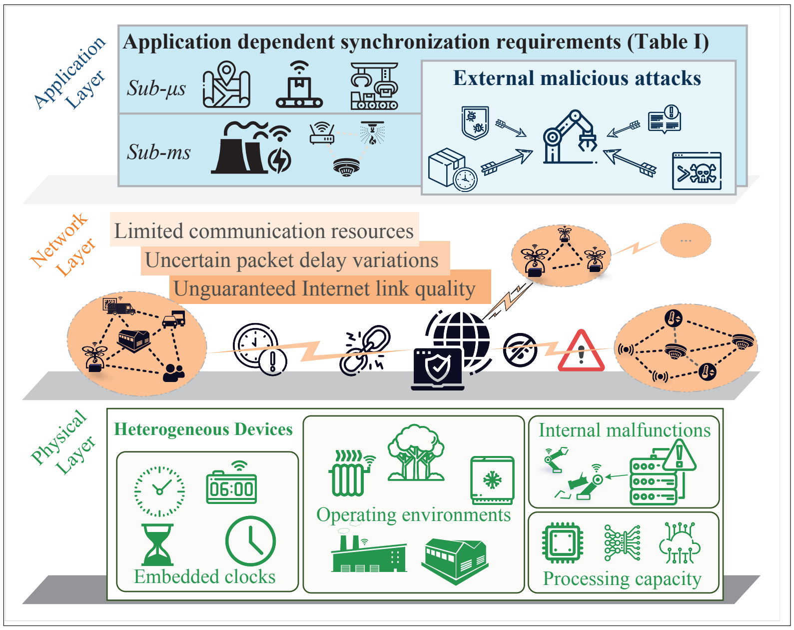

FIGURE 2. The challenges encountered by traditional clock synchronization techniques in large-scale IIoT systems with three hierarchical layers.

Functionality	Synchronization Accuracy	Applications in Fig. 1
Industrial automation	Sub-microsecond	A8
Localization and tracking	Sub-microsecond	A4, A13
Multi-agent cooperation	Microsecond	A7, A14
	Tens of microseconds	A5
Data fusion	Tens of microseconds	A9, A12
	Sub-millisecond	A10
Fault protection	Sub-millisecond	A1, A11
Remote monitoring	Millisecond	A2
Smart logistics	Flexible	A3, A6

TABLE 1. Application-dependent synchronization requirements in large-scale IIoT systems.

Low Efficiency of the "Observing-and-Calibrating" Based Synchronization

During the conventional synchronization process, the embedded clock of each IIoT facility driven by its crystal oscillator will continuously generate a series of timestamps, which will accumulatively deviate from the standard time with its own drifting rate, thereby inevitably leading to the frequent clock calibration for maintaining synchronization. Conventional clock synchronization techniques fulfill the offset correction by frequent timestamp exchange between each target device and the time reference to ensure the synchronization accuracy, instead of understanding the reason behind the growing clock offset over time due to accumulated clock drifting. This kind of situation-agnostic *offset-driven* scheme is achieved by passively responding to each observed clock offset, while the frequent clock calibration processes cannot be avoided. Consequently, the effectiveness of each timestamp exchanged in terms of the achievable clock accuracy is strictly constrained by the clock offset observation frequency and resolution. Severe difficulties will be caused during network synchronization due to the lack of proactive calibration mechanisms, mainly manifesting as the significantly reduced *synchronization efficiency* (i.e., the achievable synchronization accuracy over resource consumption) in large-scale IIoT systems.

Moreover, the observation of clock inaccuracy relies heavily on the explicit interactions and timestamps exchange among the involved IIoT facilities. Without an in-depth understanding of the intrinsic characteristics of the distributed clocks, the unknown and diversely accumulated clock offsets throughout the system cannot be predicted by the conventional clock synchronization techniques, leading to the difficulties of selecting an opportune time for repeating the clock calibration process. The simultaneous but unoptimized system-wide timestamp exchange will cause inappropriate synchronization frequency for each industrial facility. Corresponding challenges may include the overwhelming occupation of the limited network resources in terms of excessive clock calibration and the misaligned local data generation due to insufficient time synchronization [5]. Additionally, the time-consuming system-wide interactions during clock offset estimation will occupy an increasing amount of limited communication resources in large-scale IIoT systems, while the available resources for other critical industrial applications will be further reduced.

Unpredictable Synchronization Accuracy in Sophisticated IIoT Systems

The increasing complexity of large-scale IIoT systems poses more challenges in provisioning timely and reliable timestamps during synchronization due to the highly complicated end-to-end communication process and the unguaranteed timestamp delivery [6]. On the one hand, although conventional point-to-point clock calibration techniques can theoretically achieve high accurate time synchronization (e.g., microsecond level for PTP [7]), they are still very challenging to overcome several realistic challenges and meet the stringent synchronization requirements of industrial applications. As a result of the expeditious development of ICT technologies, large-scale IIoT systems generally comprise a wide variety of communication protocols, leading to the necessity of cross-standard interactions among the distributed industrial facilities. The best-effort service provided by Internet-based communications and random-access protocol used in wireless networks will induce unguaranteed communication outcomes in large-scale systems, including the stochastic packet dropouts, increased access contentions, and dynamic routing of mesh networks [8]. These critical issues will severely degrade the timeliness of the timestamps exchanged. Meanwhile, the increasing backhauls and multiple handshakes incurred by end-to-end timestamp sharing in the cross-network interconnections will accumulate excessively long and unpredictable latency, which will further deteriorate the timeliness and usefulness of the timestamps during the synchronization process.

On the other hand, the security threats at the vulnerable industrial facilities incurred by the ubiquitous and collaborative interconnections in large-scale IIoT systems will influence the reliable provisioning of accurate timestamps for clock calibration, which becomes a critical consideration during synchronization design [9]. The timestamps generated by the master clock and relayed by adjacent network nodes could become suspicious due to the susceptibility of resource-constrained IIoT devices to external interference and malicious attacks, such as spoofing, replaying, and faulty data injection [10]. The involvement of unreliable timestamps and suspect reference nodes will lead to uncontrollable and catastrophic results subsequent to the synchronization, including unattainable collaborations for time-sensitive applications and the potential shutdown of industrial factories.

Heterogeneous Synchronization Requirements and Clock Qualities in Large-Scale IIoT Systems

A wide variety of industrial applications involving intelligent machines and infrastructures forms the backbone of large-scale IIoT systems. The highly complicated and heterogeneous features of IIoT systems will further degrade the synchronization performance from several perspectives.

The diverse industrial applications, which are enabled by the timely intra-subsystem interactions among the distributed constituents, pose different expectations on the synchronization accuracy, as summarized in Table 1. This synchronization demand will vary extensively from sub-microsecond in critical applications (e.g., industrial automation) to a few milliseconds for less time-sensitive scenarios (e.g., remote environment monitoring). Designing a unified synchronization strategy for different industrial applications throughout large-scale IIoT systems will inevitably degrade the overall synchronization efficiency. Moreover, due to the heterogeneous quality of the integrated crystal oscillator at each IIoT device in terms of the initial manufacturing and the stability under environmental variations, the distributed clocks will vary at different rates compared to the reference time. For example, the Simple Packaged Crystal Oscillators (SPXO) densely deployed in IIoT systems will drift hundreds of times faster than Oven Controlled Crystal Oscillators (OCXO) due to their low cost and lacking appropriate techniques for eliminating temperature impacts [11]. Furthermore, the diverse and dynamic industrial operating environments in large-scale IIoT systems will further deteriorate the clock inconsistency throughout the system. As we previously studied [4], clocks in complicated circumstances are more susceptible to drift due to the temperature variation, which may be more challenging for devices assigned multiple collaborative applications in dynamic environments, such as vehicular ad-hoc networks [12].

However, the conventional inflexible, unchanging, and application-agnostic synchronization strategies always ignore these heterogeneous characteristics inherent to the distributed IIoT facilities. The unoptimized priority assignment and random resource allocation during frequent synchronization requests/responses at each IIoT device will degrade the synchronization efficiency and cause significant resource-wasting, which becomes one of the technical bottlenecks in accomplishing effective synchronization in large-scale IIoT systems with extensive heterogeneities.

> Accurate synchronization over large-scale networks is extremely challenging due to the inherent inefficiency and situation agnosticism in traditional observing-and-calibrating synchronization techniques. The growing scale, intrinsic heterogeneity, and uncertain service provisioning of 6G IIoT systems further exacerbate this difficulty.

Large-Scale Synchronization in 6G Era: An Industrial Perspective

In this section, three promising research directions are proposed to demonstrate the design of large-scale synchronization schemes in tackling the existing challenges in 6G era IIoT systems.

Proactive Model-Driven Large-Scale Synchronization for Overhead Reduction

One of the main objectives in 6G-enabled IIoT systems is to achieve digital virtualization of the physical infrastructures for effective monitoring and control in an efficient and predictive manner. However, conventional synchronization techniques typically achieve clock calibration by directly adopting immutable empirical clock models during offset estimation, which will inevitably induce accumulated errors due to the modeling inaccuracy, especially for network synchronization with massive IIoT devices and multi-hop timestamp delivery. Meanwhile, the offset estimation process will consume an excessive amount of network resources, which will become eventually intolerable for large-scale IIoT systems.

To address these deficiencies while digitally virtualizing physical facilities, we propose low overhead model-based clock synchronization by comprehensively characterizing the features of heterogeneous clocks during synchronization in industrial environments to avoid using frequent observation-based offset estimation. The crystal oscillator enclosed at each IIoT device is uniquely affected by its intrinsic characteristics, among which the issues that remained unsolved in low-cost IIoT devices are temperature sensitivity, manufacturing defect, and aging issues. Moreover, the extreme and dynamic temperatures inherent to inhospitable operating environments in distributed industrial systems will further exacerbate the instability of the crystal oscillator. Based on these observations, it would be critical to gather all available local information at each IIoT device during the clock modeling phase. The collected inherent attributes, including the sequentially generated timestamps and the correlated environmental factors, can help to investigate the intrinsic features of each clock thoroughly. By virtue of the regression analysis assisted by model-based methods and machine learning techniques, the informative attributes of the distributed devices can be transferred into useful clock models to guide the subsequent time synchronization.

The establishment of comprehensive digital clock models (referred to as digital twin in [4]) can be advantageous in enhancing the efficiency of synchronization from two aspects. The intelligently formed clock models can be utilized to predict the real-time behavior of each clock, which can assist in estimating the expected clock offsets throughout the entire system. Proactive synchronization can be, thereby achieved by *predictively* eliminat-

Accurate modeling of clock intrinsic features and its situation-aware utilization, in conjunction with an in-depth understanding of operating environments and application requirements, constitute the foundation for intelligent, distributed, and low-overhead network synchronization mechanisms tailored to specific needs of 6G IIoT systems.

ing the distributed clock offsets to alleviate the necessary explicit interactions during clock calibration and dramatically reduce the incurred network overhead. Furthermore, the improved understanding of the intrinsic clock characteristics at distinctive IIoT devices is indispensable in achieving the situation-awareness during synchronization. For large-scale heterogeneous IIoT systems, this superior comprehension can enable more efficient synchronization mechanisms in terms of the optimized synchronization-related network resources allocation and appropriate scheduling among complicated industrial processes.

Device Clustering Enabled Distributed Parallel and Efficient Synchronization

Another main reason behind inefficient synchronization lies in the routine and unchanging way of timestamp exchange without considering the heterogeneity within the large-scale IIoT systems in terms of the application-specific synchronization requirements and the diverse clock characteristics. Additionally, lacking holistic coordination among concurrent calibration processes in large-scale IIoT systems will further aggravate the efficiency of the overall network synchronization.

Therefore, we propose to intelligently adjust synchronization frequencies for distributed IIoT devices by jointly exploiting their multi-dimensional intrinsic attributes. Typical synchronization-related attributes of an IIoT device include the initial clock offset, clock skew, timestamps generation frequency, applications to support, potential collaboration partners, operating environment, etc. By remotely extracting relevant attributes from a device to be synchronized, comprehensive analysis can be conducted at platforms with massive processing capacity (e.g., edge/cloud servers). Proper machine learning techniques can even be adopted to enhance the analysis accuracy while considering multi-dimensional device attributes. By exploiting the extracted device characteristics, more device-specific decisions can be timely generated to guide the overall system-wide synchronization. Specifically, devices with highly prioritized attributes (e.g., sub-microsecond accuracy requirement, unstable crystal oscillator, and inhospitable operating environments) should be assigned much higher synchronization frequency, while other IIoT devices can be synchronized less frequently to reduce the overall synchronization overhead. Meanwhile, network resources can be preferentially allocated to industrial devices with more stringent and emergent synchronization requirements, which will be beneficial in enhancing holistic synchronization performance. Consequently, by accurately understanding the multi-dimensional device attributes, device-specific synchronization strategy and orchestrated message exchange can be achieved for each IIoT device to enhance the overall efficiency of network synchronization.

Timestamp Reliability Enhancement via Communication Process Control and Packet Analysis

The reliable provisioning of timestamps during synchronization is severely hindered by various uncertain factors induced by the intermediate communication within an end-to-end process, including varying channel conditions, packet delay variations (PDV), and external malicious attacks. Different process controlling and packet filtering approaches can be adopted to address these issues.

The network uncertainties during packet exchange will degrade the timeliness of the associated timestamps, leading to uncontrollable synchronization performance. However, this kind of effect can be mitigated or eliminated by designing dedicated communication protocols for time synchronization. For example, an entirely controlled communication channel is designed in [8] by reserving intermediate nodes for synchronization data relaying, which can minimize the redundant processing during timestamps transmission. Meanwhile, a prioritized data transfer protocol [13] is designed to alleviate the effect of communication randomness by assigning higher priority to synchronization-related data and guarantee corresponding channel access. These methodologies are effective in proactively reducing the influence of network uncertainties prior to synchronization in dedicated communication environments.

Furthermore, the unreliable timestamps due to the vulnerability of resource-constrained IIoT devices in terms of inner malfunctions and external malicious attacks can be further filtered by timely packet analysis of historical information. In our previous work [14], an autoregressive model-based filtering mechanism is designed to detect unreliable timestamps and malicious devices according to the varying rate of skew (VRS) calculated at each local IIoT device. With increasingly massive timestamps involved in large-scale IIoT systems, other machine learning techniques (e.g., principal component analysis) can be considered to enhance the detection accuracy and efficiency during synchronization.

Intelligent and Low Overhead Synchronization by Edge-Cloud-Collaboration

As an elaboration of the three strategies above, the proposed intelligent and low overhead synchronization scheme is demonstrated in Fig. 3, which consists of three successive phases enabled by edge-cloud collaboration. Initially, support vector machine (SVM)-based heterogeneous clock modeling is achieved by thoroughly analyzing the uploaded timestamps, where a proactive synchronization scheme is established. Moreover, according to the obtained clock characteristics and other critical attributes extracted from the synchronization-related information at each IIoT device, an efficient synchronization scheme is further designed with cluster-wise network orchestration. Finally, historical timestamps are effectively analyzed with the help of principal component analysis (PCA) at the cloud server, aiming at improving the reliability of the timestamps provisioned throughout the system.

Phase I: Timestamps Analysis and Comprehensive Clock Modeling

Aiming to thoroughly investigate the characteristics of each clock in diverse operating environments, local timestamps of each clock together with its operating temperatures are continuously collected by the nearby edge devices. Since the oscillation frequency approximately follows a quadratic relationship with the operating temperature, an SVM-based algorithm is designed at the edge device to fully investigate the intrinsic characteristics of the local IIoT devices. Specifically, the timestamps of each local device and the edge device are firstly compared to obtain the local clock offset. Then, the clock offsets and the corresponding operating temperature will serve as the inputs of the SVM algorithm, aiming at exploiting comprehensive modeling of each clock. The critical clock parameters, including temperature sensitivity factor, ideal operating temperature, and initial clock skew can be thoroughly estimated, which can be further used to build the learning model. The SVM model is further transmitted back to each local device for conducting skew compensation and predictive synchronization. Moreover, the obtained clock models will be stored in the cloud server to provide modeling credibility, which will be responsible for initializing remodeling if the newly collected timestamps violate the current trained parameters. By adopting model-based predictive skew/offset calibration at each local IIoT device, the effect of network uncertainty can be alleviated, and the overhead incurred will be significantly reduced.

Phase II: Intelligent Device Clustering and Optimized Synchronization

Due to modeling inaccuracy and the variations of the inherent characteristics at each IIoT device, periodic clock calibrations are indispensable in ensuring the accuracy of synchronization for critical collaborative applications. Local information of each IIoT device, including the sequentially generated timestamps, the associated collaborative applications, and local operating temperature, will be uploaded to the cloud server for critical information extraction. The temperature-sensitivity factor (i.e., clock quality) can be estimated from the sequential timestamps, while the application-dependent time-sensitivity indicates the synchronization requirement for specific applications. All attributes extracted will be jointly processed to determine the synchronization necessity (i.e., the weighted sum of the collected attributes) of each device. Based on the synchronization necessity of each device, an adaptive threshold-based k-means clustering algorithm [14] is conducted in the cloud center to organize all involved devices into several clusters, where the number of clusters can be adjusted based on the predefined threshold during clustering. An edge device will be allocated to each group as the cluster head responsible for disseminating time reference. Each group of devices will be assigned a unique and optimized synchronization frequency according to their synchronization necessity, which will be beneficial in reducing the network overhead and avoiding excessive resource contention during synchronization. Therefore, a distributed and optimized synchronization scheme is finally fulfilled with cluster-wise clock calibration for the heterogeneous IIoT devices in terms of their clock inconsistency, environmental circumstances, and application-specific requirements.

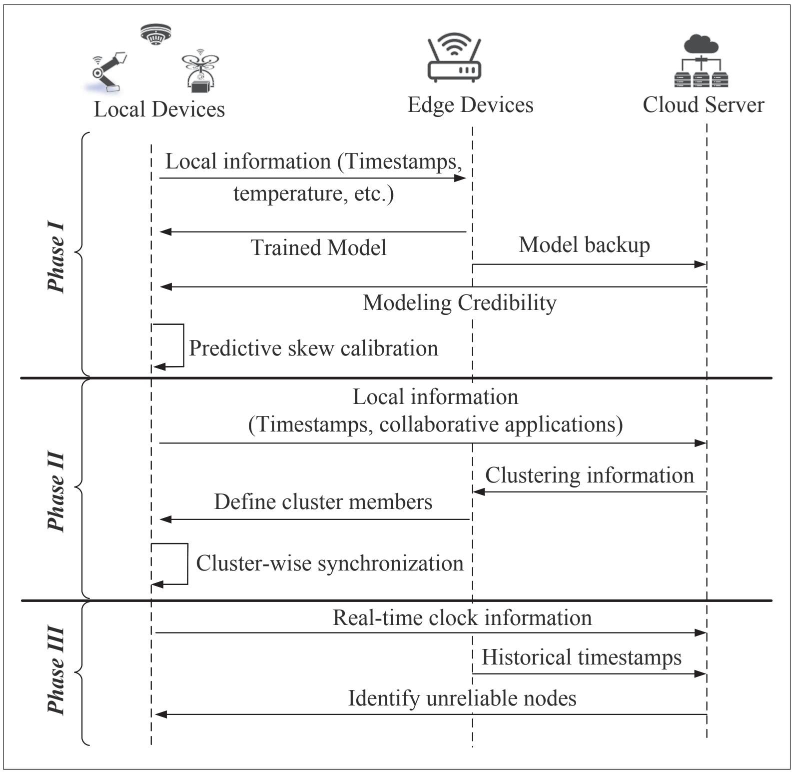

FIGURE 3. The holistic overview of the proposed synchronization scheme with the assistant of edge-cloud collaborations. Three phases in terms of comprehensive modeling, intelligent device clustering, and unreliable node rejection are achieved successively.

Phase III: PCA-Assisted Timestamp Uncertainty Control and Reliability Enhancement

To further enhance the reliability during synchronization and alleviate the effect of uncertainty issues, PCA is adopted to filter suspect timestamps based on offline training using historically delivered timestamps. Specifically, due to the uniqueness of the clock skew at each local clock, which can be treated as identification during timestamp exchange, any timestamps violating the expected trend will be regarded as untrustworthy, thereby the associated devices will be suspicious. In the proposed scheme, historical timestamps will be initially uploaded to the cloud center, based on which a PCA model can be established during the training process. After successful training, the cloud center will collect real-time clock information from the distributed IIoT devices. Due to the sensitivity of the PCA model to the abnormality within the newly arrived data, any anomalous timestamps and malicious devices can be effectively identified and rejected. With the PCA-assisted uncertainty control, the overall synchronization performance can be improved in terms of reliable timestamps provisioning during clock calibrations.

Performance Evaluation

In this section, numerical simulations are carried out to evaluate the proposed synchronization scheme in terms of clock modeling accuracy and network

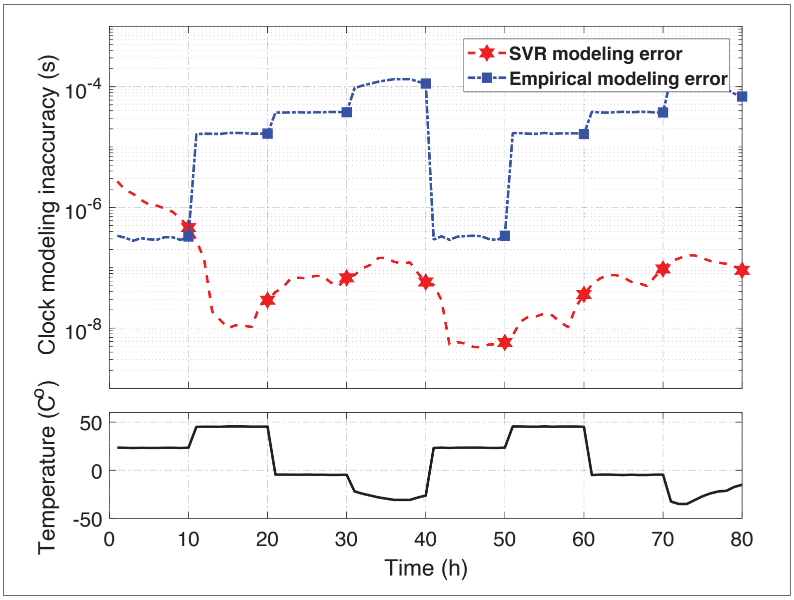

FIGURE 4. The modeling accuracy with the help of the SVM algorithm is significantly enhanced compared to the empirical model used in traditional clock synchronization methods. With fluctuating and inhospitable operating environments, sub-microsecond modeling errors are always attainable by utilizing the proposed SVM-based scheme.

overhead reduction during system-wide synchronization. As two critical enablers for situation-aware synchronization, the results of SVM-based clock modeling and adaptive threshold-based k-means clustering are demonstrated, respectively.

An application scenario is demonstrated in Fig. 4, where an unmanned vehicle will periodically move within different IIoT environments (e.g., manufacturing space and storage) with diverse operating temperatures. Some of the temperatures will be inhospitable compared to office spaces, possibly reaching –40°C and 40°C, or even harsher in some specific circumstances. Such an extreme and dramatic temperature variation will pose a significant impact on the oscillation frequency, causing unstable clock skew that cannot be captured by empirical models utilized in traditional synchronization schemes. It can be observed from Fig. 4 that the empirical clock model will deviate from the real clock with the change of temperature, especially when the operating environment dramatically varies from its ideal operating temperature (i.e., around 25°C). By contrast, after gathering and analyzing sufficient timestamps at edge devices, the training inaccuracy of the SVM-based method is almost eliminated. With the variation of the external environment, some minor fluctuations are inevitable, but the overall modeling accuracy is significantly enhanced as compared to the empirical situation. Moreover, the cloud center will take the responsibility to monitor the modeling error and make the decision on triggering new training processes. The comprehensive clock models established are insightful in enhancing synchronization performance. The real-time skew/offset estimation of local IIoT devices can help achieve proactive clock calibration, while the estimated clock characteristics can be further utilized as a unique attribute of the local device, which can be used in the subsequent phases.

Furthermore, intelligent clustering can be achieved prior to synchronization aiming at organizing the distributed devices in a large-scale system to improve the efficiency during timestamps exchange. More specifically, multi-dimensional attributes at each local IIoT device, including application-specific synchronization requirement (*SR*), environmental harshness causing temperature deviation from the ideal circumstance (T_d), and temperature sensitivity factor (η), are collected and estimated by the cloud center, which will be responsible for jointly analyzing the synchronization necessity of each device. All IIoT devices in the system are clustered into a few groups based on their synchronization necessity with the assistance of k-means algorithms. The clustering result is demonstrated in Fig. 5a, where all devices are efficiently organized into four clusters based on their synchronization necessity. According to the uniquely assigned synchronization frequency, clock calibration processes are periodically conducted for each cluster, with the time reference disseminated from the associated edge devices. It is straightforward to observe that the network resources consumed to guarantee the application requirement will be dramatically reduced, especially in clusters with lower synchronization necessities. This improvement will lead to a significant reduction of the overall network overhead throughout the large-scale IIoT systems. Moreover, the performance of the proposed scheme in terms of synchronization efficiency enhancement is shown in Fig. 5b, where the synchronization efficiency for two schemes is normalized into the same range for better comparison. It can be observed that the normalized synchronization efficiency of the cluster-wise mechanism will be much higher than the conventional methods so that more network resources can be saved in larger-scale IIoT systems.

Conclusion and Future Work

In this article, we have investigated three main technical challenges of conventional clock synchronization methodologies in terms of the inefficient timestamps exchanging mechanisms, network uncertainty-induced inaccuracy, and the heterogeneity inherent to the complicated IIoT systems. Specifically, a proactive time synchronization scheme has been designed to enhance the timeliness and efficiency during timestamps exchange based on comprehensive clock modeling in edge devices. To further reduce the overall network overhead, a distributed and optimized cluster-wise clock calibration mechanism has been proposed by adopting intelligent clustering algorithms in the cloud server according to the intrinsic features of each IIoT entity. Additionally, uncertainties induced by communication processes have been effectively alleviated by removing uncontrollable issues from the synchronization through designing dedicated communication protocols and adopting anomaly detection schemes based on the historical timestamps. In a nutshell, the proposed edge-cloud collaborative design can holistically enhance efficiency, situation-awareness, and reliability during large-scale synchronization.

System-wide synchronization has become increasingly important in the era of Industrial 4.0, with the extensive development of communication technologies and vertical industry applica-

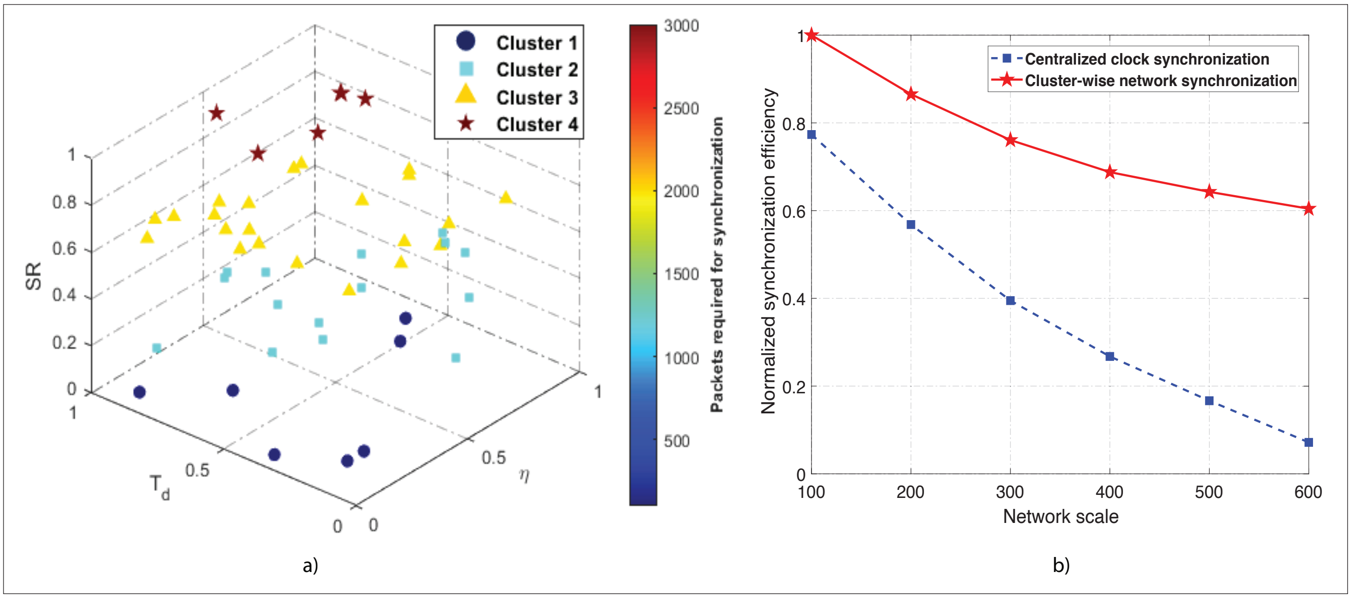

FIGURE 5. The synchronization performance using cluster-wise distributed clock calibration: a) the distributed industrial devices in a large-scale IIoT system are accurately organized into four clusters according to their synchronization necessities defined by analyzing the three normalized attributes; b) synchronization efficiency is significantly enhanced for cluster-wise synchronization due to the improved understanding of the heterogeneous IIoT devices.

tions. Some promising future research directions on synchronization and its subsequent utilization are summarized as follows: On the one hand, resource-constrained devices are densely deployed in large-scale IIoT systems for ubiquitous sensing and seamless interconnections. The temporal consistency of the sensed data is necessary for the subsequent data analytics, but some of the devices may lack power or opportunity to exchange timestamps for accurate clock calibration. Therefore, novel synchronization schemes should be designed without posing burdens on the end devices. Specifically, model-based synchronization for distributed data alignment without calibrating the local clocks can be achieved as a follow-up to the proposed comprehensive clock modeling in this article. With a thorough understanding of the distributed clocks throughout the system, the edge/cloud server can effectively improve the temporal consistency and achieve accurate synchronization before conducting data processing. On the other hand, accurate synchronization plays a critical role in a wide variety of research fields, for instance, simultaneous localization and mapping (SLAM) in multi-agent systems [15]. Accurately sampled and timestamped data packets are essential in supporting seamless coordination among distributed facilities, while the temporal misalignments within the involved robots will inevitably induce localization and mapping errors during data processing. With accurately synchronized agents throughout the large-scale systems, distributed data packets delivered can be effectively fused for constructing the entire map. Moreover, with accurate temporal alignment and improved consistency among distributed agents, their local timelines can be utilized as common references to track the distributed events. Therefore, a more informative map construction with dynamically updated location and event knowledge can be achieved to support holistic situation-awareness in long-term system analysis.

Acknowledgment

This work was supported in part by the NSERC Discovery Program under Grant RGPIN2018-06254, in part by the NSERC Idea to Innovation Program under Grant I2IPJ 538563-19, in part by the Canada Research Chair Program, and in part by the U.S. National Science Foundation under Grant CNS-2128448.

References

[1]. M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," *IEEE Ind. Electron. Mag.*, vol. 11, no. 1, 2017, pp. 17–27.
[2]. ITU-T FG-NET-2030, "2030-A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond," 2019.
[3]. R. Luo *et al.*, "High-Reliability Sub-Nanosecond Network Time Synchronization Method Enabled by Double-Frequency Distributed Time Synchronization," *IEEE J. Opt. Commun. Netw.*, vol. 11, no. 1, 2019, pp. A40–51.
[4]. P. Jia, X. Wang, and X. Shen, "Digital-Twin-Enabled Intelligent Distributed Clock Synchronization in Industrial IoT Systems," *IEEE Internet Things J.*, vol. 8, no. 6, 2021, pp. 4548–59.
[5]. M. Rizzi et al., "Synchronization Uncertainty Versus Power Efficiency in LoRaWAN Networks," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 4, 2019, pp. 1101–11.
[6]. P. Dass, S. Misra, and C. Roy, "T-Safe: Trustworthy Service Provisioning for IoT-Based Intelligent Transport Systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, 2020, pp. 9509–17.
[7]. A. Mahmood *et al.*, "Clock Synchronization Over IEEE 802.11, a Survey of Methodologies and Protocols," *IEEE Trans. Ind. Inf.*, vol. 13, no. 2, Apr. 2017, pp. 907–22.
[8]. X. Wang, "System, Method, and Apparatus for End-to-End Synchronization, Adaptive Link Resource Reservation and Data Tunnelling," U.S. Patent No. 10,856,243, 2020.
[9]. L. Narula and T. E. Humphreys, "Requirements for Secure Clock Synchronization," *IEEE J. Sel. Topics in Signal Process.*, vol. 12, no. 4, 2018, pp. 749–62.
[10]. K. R. Choo, S. Gritzalis, and J. H. Park, "Cryptographic Solutions for Industrial Internet-of-Things: Research Challenges and Opportunities," *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, 2018, pp. 3567–69.
[11]. Y. Geng *et al.*, "Exploiting a Natural Network Effect for Scalable, Fine-Grained Clock Synchronization," *Proc. 15th USENIX Symp. Netw. Syst. Des. Implement.*, Renton, WA, USA, 2018, pp. 81–94.
[12]. L. Zhao *et al.*, "A Novel Prediction-Based Temporal Graph

Routing Algorithm for Software-Defined Vehicular Networks," *IEEE Trans. Intelligent Transportation Systems*, vol. 23, no. 8, Aug. 2022, pp. 13,275–90.
[13]. S. Bhandari and X. Wang, "Prioritized Clock Synchronization for Event Critical Applications in Wireless IoT Networks," *IEEE Sensors J.*, vol. 19, no. 16, Aug. 2019, pp. 7120–28.
[14]. P. Jia *et al.*, "Distributed Clock Synchronization Based on Intelligent Clustering in Local Area Industrial IoT Systems," *IEEE Trans. Ind. Informat.*, vol. 16, no. 6, 2020, pp. 3697–3707.
[15]. Q. Shi *et al.*, "BLAS: Broadcast Relative Localization and Clock Synchronization for Dynamic Dense Multiagent Systems," *IEEE Trans. Aerospace and Electronic Systems*, vol. 56, no. 5, Oct. 2020, pp. 3822–39.

Biographies

Xianbin Wang [S'98, M'99, SM'06, F'17] (xianbin.wang@uwo.ca) is a Professor and Tier 1 Canada Research Chair at Western University. His current research interests include 5G and beyond, intelligent wireless communications, Internet of Things, and communications security. He has over 500 peer reviewed journal and conference papers. He is a Fellow of CAE, EIC, and IEEE. He currently serves/has served as an Editor-in-Chief and Editor/Associate Editor for over 10 journals. He was the Chair of the ComSoc SPCC Technical Committee and is serving as the Central Area Chair of IEEE Canada.

Pengyi Jia [S'17, M'21] (pjia7@uwo.ca) received his Ph.D. in the Department of Electrical and Computer Engineering, Western University, London, ON, Canada, in 2021. His research interests include network-wide time synchronization, intelligent coordination of large-scale Internet of Things systems, and digital twin-enabled network optimization.

Xuemin (Sherman) Shen [M'97, SM'02, F'09] (sshen@uwaterloo.ca) is currently a University Professor with the Department of Electrical and Computer Engineering, University of Waterloo. His research focuses on network resource management, wireless network security, social networks, 5G and beyond, and vehicular ad hoc networks. He is a Canadian Academy of Engineering Fellow, a Royal Society of Canada Fellow, and a Chinese Academy of Engineering Foreign Fellow. He received the R.A. Fessenden Award in 2019 from IEEE, Canada; the James Evans Avant Garde Award in 2018 from the IEEE Vehicular Technology Society; and the Joseph LoCicero Award in 2015 and Education Award in 2017 from the IEEE Communications Society.

H. Vincent Poor [S'72, M'77, SM'82, F'87] (poor@princeton.edu) is the Michael Henry Strater University Professor at Princeton University. His interests include information theory, machine learning, networks science, and their applications in wireless networks, energy systems, and related fields. He is a member of the U.S. National Academy of Engineering and the U.S. National Academy of Sciences, and a foreign member of the Chinese Academy of Sciences and the Royal Society. He received the Marconi, Armstrong, Hertz, and Ellersick Awards from the IEEE Communications Society in 2007, 2009, 2018, and 2020, respectively, and the IEEE Alexander Graham Bell Medal in 2017.