In Sync with Today's Industrial System Clocks

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***Abstract*—Synchronization is essential for correct and consistent operation of automation systems. Synchronized devices accurately time-stamp the events and enable timely communication of messages over a communication network. In absence of a common time base, critical functions of automation systems cannot be carried out in a safe fashion. Unsynchronized systems may lead to malfunctions such as false alarms, wrong decisions and erroneous outcomes resulting into serious showstopper for plant operations.**

Despite technical advances in synchronization, industrial automation systems have lagged compared to telecommunication and financial services in utilization of latest synchronization technology. Thus, there is a need to investigate the adoption of synchronization in industrial networks, its current state and implementation problems. We carried out an extensive literature search in a structured way to study the evolution of synchronization in automation systems. We also investigated today's industrial automation systems and their network topologies to get insight into the synchronization techniques and mechanisms being used. As an outcome of study, the paper highlights the challenges related to synchronization in existing automation networks that need to be addressed in the immediate and short-term future.

***Keywords*—Synchronization, NTP, SNTP, PTP, IEEE 1588, IEEE C37.238, IEEE 802.1AS, Heterogeneous communication, Last-mile connectivity, Secured synchronization, Industrial automation, Factory Automation, Substation Automation, Building Automation, Industrial networks**

I. INTRODUCTION

Industrial automation systems have come a long way covering a range of automation controls such as from PLCs (Programmable Logic Controllers) to SCADA (Supervisory Control and Data Acquisition). Power generation/transmission/distribution, transportation and water distribution are some of the examples that show the critical importance of such networks. These systems manage everything from the smallest unit, e.g., nut-bolt production to the biggest units, e.g., locomotive production [1]. Automated systems monitor and control industrial operations that include field devices, control devices, number of computer systems operating at various levels and industrial networks that connect them all. Synchronizing the devices and sub-systems is paramount in achieving the goal of automation systems, i.e., monitoring, protecting and controlling primary equipment. Industrial networks synchronize several devices to specific precision using techniques primarily based on GPS (Global Positioning System), PTP (Precision time Protocol) [2] or NTP (Network Time Protocol) [3].

GPS is a satellite based system that provides timing information to receivers on the earth. GPS can achieve a synchronization accuracy of the order of sub microseconds. PTP is a network packet-based synchronization method that uses hardware time-stamps to compute delays. PTP can offer a sub-microsecond level synchronization accuracy but it requires Ethernet and hardware support to achieve that. NTP is another network packet-based synchronization technique that uses software time-stamps to compute delays. NTP is easy to implement, deploy and cost-effective compared to GPS and PTP but with the synchronization accuracy in the range of tens to thousands of milliseconds.

Varying synchronization requirements for monitoring and control applications, need of more precise clocks, no connection to real-world clocks, harsh industrial environments, and non-deterministic industrial networks all pose challenges for synchronizing industrial devices. Although there are technical advances in the synchronization area, their adoption in industrial networks is slower compared to the telecommunication or financial areas [4].

So far, there is a limited research effort in identifying the challenges related to synchronization systems in industrial automation. There are works looking into present challenges in industrial networks and investigating problems such as assessing feasibility of using wireless networks for synchronization [5], improving fault tolerance [6] and achieving synchronization in heterogeneous networks [7]. The available research provides limited insight into the on-field synchronization-related problems being faced by present industrial networks. To get a deeper understanding of the practical aspects of synchronization, a structured literature review was conducted. The review considered the entire eco-system of industrial automation systems, networks and applications, in order to understand the real need of synchronization, and existing synchronization solutions. The objective of the study was to come up with current synchronization-specific issues being faced by automation industries.

The contributions of this paper are as follows:
(1) It covers the evolution journey of synchronization in industrial automation systems as mapped to evolution of industrial automation systems. Given that industrial automation is a well-known research area, the connection between clock synchronization and industrial automation systems enables a better understanding of the processes behind the evolution of the former, and points out a way to predict its future directions.
(2) It brings out key synchronization-related issues that stand out in existing industrial network deployments. The

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identification of these practical issues is important as they need to be addressed soon in order for industrial network systems to work efficiently.

The holistic review approach of considering the entire ecosystem of automation systems in a structured way to identify the need, the solutions and then the challenges pertaining to synchronization, is an important aspect of this paper. Given the limited literature on synchronization and its low adoption in industrial automation systems, this approach provides a good insight into the journey, the present state and challenges of synchronization systems in industrial networks.

The paper is structured as follows. Section II covers the technology progress of synchronization as against the typical evolution milestones of industrial automation systems. Section III studies the synchronization related applications in typical automation systems, namely - process, building, substation and factory. Section IV includes the major synchronization challenges being faced by industrial networks.

II. Evolution of Synchronization in Industrial Automation Systems

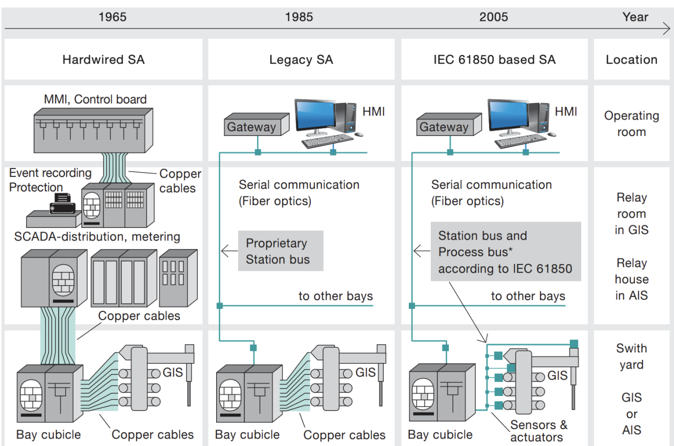

Fig. 1. Evolution of substation automation systems (Source:[9])

Industrial automation systems need a reliable timing reference for correct time-stamping of events, right sequencing of operations and deterministic message delivery. A synchronization mechanism fulfills this need using various means and techniques that have evolved over time. The evolution journey of synchronization specifically in industrial networks is closely associated with the evolution journey of industrial automation systems.

In our work, we chose to trace the evolution of synchronization by looking at the evolution of one of the industrial automation systems - Substation Automation System (SAS).

A typical modern SAS, shown in year 2005 in the timeline of Fig. 1, has a hierarchical structure with levels known as – station, bay and process levels [8]. A process interface called process bus, separates process level represented by primary equipment like current/voltage transformers, from the bay level (bay cubicle). The station level of a SAS includes Operator Work Station with HMI (Human Machine Interface) and a gateway to Network Control Center. Network Control Center hosts central Energy Management System (EMS) and/or Supervisory Control and Data Acquisition (SCADA) systems to regulate the power generation and distribution to consumers.

SAS has a long evolution journey [9] that includes milestones as described below. Fig. 2 shows progress updates of the synchronization technology over a timeline that also maps to the SAS milestones:

• Hardwired SAS (around 1965): Each substation device hosted only one monitoring or protection/control function. The communication within the bay level and between the bay level and the station level was established using copper wires [8].

Due to hardwired copper connections, sequencing of operations was easy to achieve. Time stamping of events was not warranted due to a low number of signals and the deterministic nature of events. Thus the need of a separate synchronization mechanism did not arise.

• Legacy SAS (around 1995): The legacy SAS was connected to a proprietary station bus. The hardwired copper links between bay and station were replaced by digital communication links or a bus. However, the network traffic was increased due to more number of devices sharing the links or buses. This affected the desired sequencing of substation events.

During the 1960's through 1980's, direct synchronization techniques such as GPS and Inter-range Instrumentation Group (IRIG) [10] were invented and became practically realizable to implement in industrial products. The 1990's decade saw the invention and rise of the network synchronization technique, NTP. To overcome the non-deterministic sequencing of events, the direct synchronization techniques such as GPS and network based synchronization techniques such as NTP were introduced in industrial automation systems. The use of GPS was limited for mission critical functions. Industrial automation systems started using NTP as a prominent synchronization technique due to low-cost, ease of of installation and deployment.

• IEC 61850 SAS with a station bus (around 2005): The IEC 61850 family of substation communication systems standards were introduced in early 2000's. All complaint SASs started implementing station bus according to the IEC 61850 standard.

The wider acceptance of a station bus by SAS owners through IEC standardization facilitated the use of GPS for critical functions, and NTP for most of the other functions for synchronization purposes. During this time, NTP also came up with new versions with better synchronization accuracy as shown in Fig. 2.

• IEC 61850 SAS with station and process bus (around 2015): The IEC 61850 based SAS implemented process and station bus according to the IEC 61850 standard. Increased digital buses in SAS resulted in an increased number of devices on network.

The use of NTP for synchronization continued with newer releases of NTP with improved synchronization features.

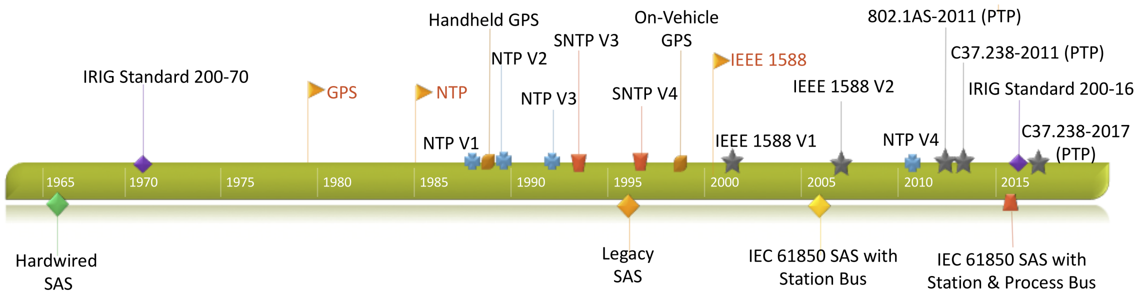

Fig. 2. SAS evolution and synchronization technology progress

GPS continued to be used for mission-critical applications. However, failures of GPS due to jamming, radio bursts, tunneling etc. facilitated invention of newer solutions in the area of microsecond level synchronization. IEEE 1588 based synchronization techniques (e.g., PTP) were introduced and became popular in SASs for high precision applications. Newer versions of NTP and its light weight variant Simple Network Time Protocol (SNTP) [11] were introduced in SASs. The growing trend of digitalization in industrial automation promoted the use of NTP and SNTP for most applications.

Industrial automation systems such as SASs are traditional and slow-moving in terms of new technology usage due to reasons such as huge capital investment, skilled resource unavailability and limited domain knowledge in implementing new technology. Overall, we can conclude that the adoption of synchronization techniques in industrial networks have been slower compared to the technical advances in the areas of synchronization.

III. Synchronization in Industrial Automation Systems

Synchronization requirements in industrial systems are largely driven by applications, and their implementation. The performance of synchronization techniques depend heavily on industrial networks. The system communication in typical automation systems is based on Ethernet and TCP/IP networks, which are functionally, and, in most cases, also physically, structured in levels.

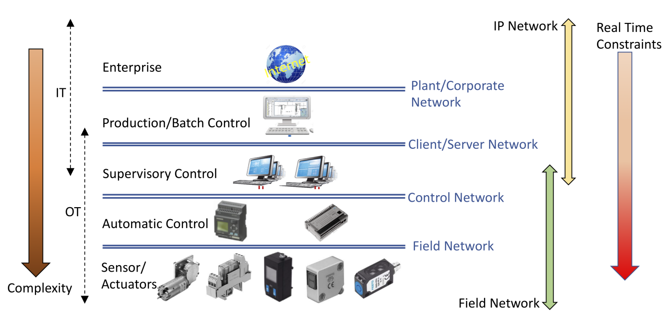

Fig. 3. Typical network topology in industrial automation systems

As shown in Fig. 3, a traditional industrial network follows a hierarchical structure consisting of three levels, field, plant and corporate IT. The top corporate IT or enterprise level supports administrative functions, production control/scheduling. The plant, field, control communication networks tie all these levels together. A plant network used for process automation purposes is part of already available intranet at the plant site. A client/server network is used for communication among servers, and between client workplaces and servers. A control network is a local area network (LAN) that is optimized for high performance and reliable communication, with predictable response times. Controllers and Connectivity Servers are connected to a control network. Typically, the system complexity increases and real time performance requirement tightens as we go from higher to lower levels.

Industrial automation can be divided into several sub-areas; building automation (BA), process automation (PA), factory automation (FA), and substation automation (SA) [12]. Synchronization requirements in each of these sub-areas vary based on functions. The synchronization techniques used in each sub-area are primarily based on the applications. Typically, monitoring applications need a low-level of synchronization accuracy. Synchronization requirements become stringent when it comes to control applications. Table I provides typical applications for each sub-area and synchronization techniques being used by the respective plants. For low accuracy applications, plants widely use NTP or similar synchronization methods, whereas for higher accuracy applications, GPS, IEEE 1588 based or similar synchronization techniques are common.

IV. Synchronization Challenges

The study of synchronization in current automation systems revealed important aspects in terms of how synchronization is achieved among industrial devices, which protocols are used for synchronization, and what accuracy level is required for typical automation use cases. The study identified following important challenges related to synchronization systems in the present industrial automation world.

A. *Higher Synchronization Accuracy*

Current automation systems typically require one to a few thousands of milliseconds of accuracy for most of their applications. All the synchronization means that are used with existing devices are software based, and hence the

TABLE I. SYNCHRONIZATION IN INDUSTRIAL AUTOMATION SYSTEMS

	Examples of functional activities warranting synchronization	Synchronization accuracy requirement	Typical synchronization techniques
PA	-Periodically or on event sensing of process parameters -Execution of real time control algorithms on event -Reporting of sensor failures to controller for immediate action	Milliseconds to Seconds	SNTP, NTP
FA	-Real time Sensor data acquisition -Prioritization of actuator commands received from controllers -Logging of alarms and events for action and predictive maintenance	Milliseconds to Seconds	SNTP, NTP
BA	-Sensing of duct temperature, smoke, occupancy, admittance etc. -Control of HVAC, fire, access, intrusion, lighting etc. -Alarm notifications to users and processes	Milliseconds to Seconds	SNTP, NTP
SA	-Current, voltage data acquisition in IEDs, MUs, RTUs -Transmission of GOOSE control signals -Waveform data recording for fault and disturbance analysis	Microseconds to Milliseconds	GPS, NTP, PTP, IRIG-B, DCF 77, Serial ASCII

accuracy is limited to tens to thousands of milliseconds. Factory automation is going through a transformation due to the fourth industrial revolution (also known as Industry 4.0), and it requires converged networks that support various types of traffic in a single network infrastructure. IEEE 802.1 Time-Sensitive Networking (TSN) [13] is becoming the standard Ethernet-based technology for converged networks. TSN can be deployed to offer solutions for demands of ubiquitous and seamless connectivity with the deterministic QoS, which is required by control applications as shown in Fig. 4.

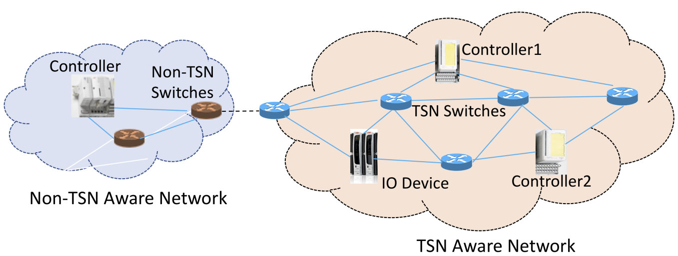

Fig. 4. Synchronization accuracy mismatch

A TSN network uses 802.1AS [14] as a synchronization profile that guarantees a synchronization accuracy in the order of tens to hundreds of nanoseconds. Highly accurate synchronization of TSN devices is an enabler for critical data delivery in a deterministic fashion. While the TSN networks operate at the synchronization accuracy of ns order, most of the legacy industrial devices that are to be integrated to TSN operate at millisecond synchronization accuracy levels. The challenge is how to integrate a low synchronization accuracy legacy device in a higher accuracy network and achieve deterministic data delivery of critical messages.

B. Co-existence of Multiple Synchronization Profiles

Industrial controllers use a variety of synchronization protocols where NTP, SNTP and PTP are common and CNCP (Control Network Clock Synchronization Protocol) and MMS (Manufacturing Message Specification) Time Service are less utilized and vendor specific protocols [15]. The challenge is whether so many protocols can co-exist on the same network. Examples of PTP profiles are IEEE C37.238 (for electrical power systems) [16] and IEEE 802.1AS (for audio-video bridging, TSN). There can be a situation where multiple synchronization protocols have to reside on a same network. Kirrmann et al., presented such a use case in electric plant that integrate process and power area, e.g., Profinet (synchronized with 802.1AS) for the automation part and IEC 61850 (synchronized with C37.238) for the substation part [17] have to co-exist.

The idea of having different protocols on the same network gives rise to multiple scenarios. For example, a NTP client can receive a message from a PTP master or a TSN compliant device clock. In such cases, the devices should be able to recognize the other protocol messages and make sure they do not disturb the intended functionality. Kirrmann et al. considers the example of IEEE 1588, C37.238 and 802.1AS synchronization profiles existing on the same network. Table II shows the feature comparison of these three synchronization protocols.

TABLE II. SYNCHRONIZATION PROFILES IN INDUSTRIAL AUTOMATION (SOURCE: [17])

	1588 default profile	C37.238	802.1AS
Profile Identifier	00-1B-19-00-02-00	1C-12-9D-00-00-00	00-80-C2-00-01-00
Clocks	Boundary and transparent	Ordinary and transparent	Boundary-transparent
Steps	One and two step	One and two step	Two steps
Ethertype	0x88F7 0	x88F7	0x88F7
Subtype	0	0	1
Tau default	1s	1s	125ms
Announce Period	(1-16)s, default 2s	1s (mandatory)	1s (mandatory)
Synch Period	(0.5-2)s, default 1s	1s (mandatory)	125ms (default)

Difference in the specifications of each synchronization profile indicates that configuring a device to support multiple synchronization protocols is a challenging task. The devices need to support multiple synchronization protocols but identifying each protocol message and then differentiating it from one another is not an easy task. A device could fail to identify its own master clock device that it needs to listen to, for synchronizing the time. Thus, co-existence of different synchronization profiles on same network can lead to major technical issues.

C. Loading of Synchronization Related Traffic

Synchronization-specific network traffic has always been considered negligible in the whole scheme of network traffic planning, designing and deployments. Nasrallah Ahmed, et al. investigated the importance of studying the traffic of synchronization in comparison with overall traffic [18]. There is a possibility that the periodic synchronization messages among network devices can significantly affect the overall traffic. If the size of synchronization-related traffic becomes significantly high, it can occupy more data bandwidth than planned. This could affect the timely delivery of critical messages in the network. The loading and congestion issues caused by synchronization can ultimately impact low latency applications.

A distributed timing infrastructure in which almost all clock devices exchange messages with each other, is a good candidate for synchronization related messages loading the critical data load. A centralized timing infrastructure, with message exchanges between a central master clock device and remaining slave network clock devices can reduce the load on critical messages. However, such a centralized timing infrastructure creates a single point of failure for the entire timing system.

D. Absolute and Relative Synchronization

Synchronization in typical industrial plant is based on the principle of relative synchronization. All entities in a plant such as field devices, controllers, IEDs and other operator-facing computers are synchronized to each other. The centralized timing system chooses one device as a master and all other devices receive timing information from the master. The slave devices just listen to the master device and synchronize their clocks to the master device. For most of the applications, such a synchronization approach is sufficient. There is no explicit need to understand the absolute timing information for smooth functioning of plant operations. However, the emerging applications such as remote monitoring, autonomous controlling etc. need external devices to be connected to plant devices. External devices also need to collect data from plant devices and make decisions based on that data. Such applications require plant devices to be aware of the absolute time in order to support remote operations.

E. Heterogeneous communication networks (last-mile connectivity)

Achieving adequate synchronization levels in heterogeneous industrial communication networks is particularly challenging due to combined effect of different network dynamics. We take an example of smart energy meters from SA. The important aspect of smart grid is to collect the metering data automatically from customer places using last-mile communication network called Automated Meter Reading (AMR) network. AMR network uses wireless solutions based on zigbee, wi-fi, bluetooth, however they suffer from intermittent connectivity and interference problems. AMR network also uses wired solutions based on powerline communication (PLC) network or fixed networks like RS-485 however, their disadvantages are higher installation, maintenance cost and reliability issues. Hybrid (wired and wireless) solutions for AMR are widely found due to complementary benefits. Establishing and maintaining synchronization in such a heterogeneous last-mile network is technically cumbersome as the network inaccuracies from different types get integrated and make the dimensions of problem even wider.

F. Secured Synchronization

Initially industrial automation systems were not built by keeping in mind security features as the requirements did not demand a secured environment. However, in last few decades, industrial communication is facing a growing number of security and privacy-related incidents. Synchronization systems within industrial communication include devices to be synchronized and the communication message exchange among them required for synchronization. Both devices and communications are prone to security incidents [19].

The NTP protocol is based on the client-server principle. The NTP time servers need to be authenticated by clients. The initial NTP protocol came with a pre-shared key mechanism for authentication of time servers. As the number of NTP-compliant devices increased, this basic authentication scheme could not work efficiently. To satisfy the authentication needs of a growing number of NTP devices, the Autokey Authentication Protocol (RFC 5906) that uses public key infrastructure was published in 2010 as part of NTP V4. However several NTP security reports have revealed flaws in implementations of the autokey scheme so far [20].

The first version of IEEE 1588 (IEEE 1588 V1) published in 2002, did not cover any security aspects as the focus of the standard was to provide high precision network synchronization for distributed systems. The second version of IEEE 1588 (IEEE 1588 V2) published in 2008, included an annex for security. Annex K specified the security solutions for authenticating PTP devices, maintaining integrity of synchronization messages and providing protection against security attacks. However, several reports on PTP implementations have revealed that the annex K was not very well adopted by vendors. Additionally, there are number of issues related to security have been reported even after implementation of annex K [21].

The secured synchronization systems are critical for overall security of industrial automation systems. Though late, the efforts to protect synchronization systems from cyber attacks have already started by building resilience at device and protocol levels. However, there is a need to address security challenges in a thorough and systematic manner.

G. Standardization

Around the decade of 1970s, computer-based systems were introduced for industrial automation systems. This facilitated the use of software-based synchronization techniques. The NTP standard was initially published in 1985 with the current version NTP V4 being published in 2010 as shown in Fig. 2. The NTP standard is widely used since then. A lighter variant of NTP, SNTP, is becoming popular in lightweight applications. IEEE 1588 V1 was published in 2002 to synchronize the nodes of distributed system that communicate using a network. Subsequently IEEE 1588 V2 was published in 2008 with additional features. PTP profiles and extensions of IEEE 1588 have recently been standardized as IEEE C37.238 and IEEE 802.1AS.

As can be seen, there are a number of synchronization protocols and standards available in the industrial automation domain. It is challenging to select a particular synchronization protocol from a plethora of synchronization protocols. It is all the more difficult to change the synchronization protocol after starting to use it as most of the synchronization protocols are not inter-operable. Thus, harmonization of synchronization standards across industrial automation systems is a major challenge to address when going forward with their development.

V. Conclusions

Synchronization among devices, controllers and various other subsystems of an industrial automation system is critical for accurate, efficient and optimal performance of automation functions. Citing the practical difficulties in achieving synchronization and lack of a research knowledge base in this area, a comprehensive and structured literature review of synchronization in present industrial systems was carried out by taking into account the eco-system around synchronization techniques such as industrial networks, network topologies and applications based on synchronization rather than concentrating on synchronization systems in silos. The study brought out the typical applications of major automation systems, their dependency on synchronization and the synchronization techniques being used by present industrial networks. This holistic literature review approach helped us to identify the synchronization requirements of present industrial networks and the current solutions fulfilling these requirements. Building on this baseline, the study investigated the important challenges related to synchronization in present industrial networks. The issues such as a higher synchronization accuracy, higher precision levels, an increased security level and harmonization of different standards are important and need to be addressed in the immediate or short-term future.

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