

# Opportunities and Specific Plans for Migrating from PRP to TSN in Substation Automation Systems

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**Abstract**—Electrical substations are vital for the power grid, and Substation Automation Systems (SASs) have been employed to enhance substation functionality and safety. As the energy landscape evolves, substations face new challenges such as accommodating an increasing number of prosumers. Thus, SASs require a reliable substation communication network (SCN) capable of supporting real-time control and diverse applications. While Ethernet-based SCN technologies have emerged, they often fall short in meeting all requirements, including TCP/IP support, cost-effective fault tolerance, and managing traffic with different real-time demands. Time-Sensitive Networking (TSN) standards have shown promise in addressing these limitations by providing novel mechanisms. In this paper we compare TSN with the Parallel Redundancy Protocol (PRP) demonstrating that TSN offers better functionality and efficiency. In the direction of designing a comprehensive TSN-based architecture for SASs' Distributed Control Systems (DCSs) we start here by proposing a roadmap for the fault tolerance aspects.

## I. INTRODUCTION

The electrical substation is a fundamental asset in the whole power grid infrastructure as it performs some of the most important functions of the electrical grid. In the past decades, substations have adopted Substation Automation Systems (SASs) to deal with the increasing complexity of the power grid and to improve its safety. Nowadays, substations face new challenges in order to reliably support a more sustainable and complex energy grid (increasing number of consumers, adoption of *prosumer* models, integration of distributed and intermittent resources such as renewable energies). There is a demand of more services from the substations and their SAS to achieve a Smart Grid.

The SAS functions are supported by a distributed control system (DCS) that is composed of different computational nodes (merging units for sensors, intelligent electronic devices for protection and control tasks, SCADA systems for supervision, etc.) that communicate by means of a substation communication network (SCN).

As SASs develop and advance towards the Smart Grid, their SCNs must exhibit high reliability and provide hard real-time communications for the typical control applications, but also support the so-called smart applications, which have soft real-time requirements for their communications. Some more specific examples of the requirements for these SCNs are TCP/IP support, cost effective fault tolerance, support

for traffic with different real-time requirements (i.e., network convergence) or manageability.

Current technologies for SCN have migrated from different fieldbus protocols to Ethernet-based networks. These Ethernet-based SCNs have addressed features such as reliability by means of the standard IEC 62439-3 which is relevant for SCNs. IEC 62439-3 describes two different protocols for space redundancy for full duplex switched Ethernet networks: the High-availability Seamless Ring (HSR) and the Parallel Redundancy Protocol (PRP). However, these protocols are not capable of supporting all the requirements imposed by novel SAS applications on the SCN that were mentioned above. For instance, networks based on these protocols cannot integrate different kinds of traffic. In contrast, Time-Sensitive Networking (TSN) standards have the potential to actually overcome that limitation by providing a set of novel mechanisms for medium access control that enables that traffic integration.

There is a work [1] that already compares HSR to the FRER mechanism (802.1CB), which is one of the TSN Standards (TSNS). Thus, that work only compares the replication mechanisms and concludes that FRER is more functional and efficient than HSR. Other works, such as [2], explore the adaptation of HSR/PRP network topologies to TSN ones with redundancy. However, authors in [2] do such thing by means of a toy example lacking generality and complete evaluation.

In order to improve this state of the art, this work compares PRP with the TSNS to identify the opportunities that arise from the differences between both protocols. As a result of this discussion we observe that TSN does much better than PRP in several aspects. It is then worth it to design a complete TSN-based architecture for SASs' DCSs. This is a complex task which we decide to start with a roadmap to create the fault tolerance related part of such architecture.

## II. DESCRIPTION OF THE PROTOCOLS

### A. Full-duplex Ethernet Parallel Redundancy Protocol

The Parallel Redundancy Protocol, standardized in IEC 62439-3, is a data link layer (layer 2 of the OSI stack) that aims at providing space redundancy, i.e. redundant communication paths for tolerating the permanent failure of some of them, to switched Ethernet networks. These networks do not naturally allow space redundancy, thus, PRP networks achieve it by means of two independent and parallel Local Area Networks (LANs). For the sake of clarity, we will use the terms *PRP* or *PRP networks* to refer to full duplex switched Ethernet with space redundancy provided with PRP.

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Nodes send Ethernet frames at the same time in each parallel LAN. Nodes add a control tag in the frame for the destination node, and no one else, for managing redundancy. In a fault free scenario, that node receives two copies of the same frame, one via each LAN, and it identifies and removes one of the copies thanks to the control tag.

### B. Time-Sensitive Networking

TSN standards (TSNS) aim at integrating different kinds of traffic with different real-time or reliability requirements for supporting all kinds of applications, i.e., for network convergence. For this reason, TSNS are built around IEEE 802.1Q and they propose additional tools such as traffic shapers for enforcing real-time schedules (802.1Qav, 802.1Qbv), clock synchronization protocols (802.1AS), for enabling space redundancy in the same LAN (802.1CB) and more standards with other purposes.

Any TSN device, whether node or bridge, can support TSN mechanisms, this calls for novel designs that combine the wide range of mechanisms for integrating different kinds of applications. TSNS are easier to comprehend if they are taken as a set of tools that can be combined for specific objectives. Thus, for the sake of generality and clarity, we use the terms *TSN* or *TSN networks* to refer to any combination of TSN standards that could be adequate for a specific context.

## III. OPPORTUNITIES OF TSN FOR SASS

This section discusses the potential opportunities that TSN brings for improving SASSs in terms of 3 attributes, namely real-time (RT), fault tolerance (FT), and network management (management for short). To support this discussion Table I divides each one of these attributes in sub-attributes and, then, for each of them specifies the main features of PRP and TSN.

### A. Real Time

The 1st RT subattribute worth to consider is clock synchronization. In PRP each LAN has its own independent clock, whereas in TSN a single clock is provided for the whole network. As a consequence, in PRP either the nodes have to deal with two time domains, or the LANs have to be provided with additional hardware to synchronize with each other. Using TSNS then opens up the opportunity to simplify the applications running at the nodes, or reduce the hardware used for clock-synchronization.

The 2nd subattribute considered in Table I is the suite of *Medium Access Control* (MAC) mechanisms used for guaranteeing RT communications. Although PRP switches provide different traffic priority queues, they do not include any further mechanism to take advantage of these priorities to actually enforce RT. Thus, RT in PRP can only be enforced by using additional mechanisms (not standardized in PRP) at the nodes, or by overprovisioning the network. In contrast, TSNS include not only traffic priorities, but also traffic shapers and frame pre-emption mechanisms that can be natively used in both bridges and nodes. This opens up several opportunities, such as natively enforcing RT, allocating in the same network different types of hard-RT and soft-RT traffic and reduce network cost.

### B. Fault Tolerance

Table I considers several FT subattributes. 1st, as concerns the topology and its redundancy efficiency, note that it has to provide some sort of redundancy to tolerate faults in the channel. In PRP, channel faults are tolerated by duplicating the whole LAN it relies on, so that PRP actually relies on two independent LANs. Moreover, the frame de-duplication mechanisms at PRP nodes require both LANs to have a very similar latency, which in practice requires both LANs to have almost the same topology. Conversely, in TSN, channel faults are tolerated by using a single LAN, which can have an arbitrary topology as long as it provides redundant paths, e.g. a mesh topology. Hence, TSN provides opportunities like using more than 2 redundant paths per frame to increase FT, and topological flexibility to explore different redundant channel configurations to provide FT in a most cost-efficient manner.

2nd, routing frames through redundant paths is a key aspect to attain FT. As said, in PRP the channel is duplicated resulting in 2 independent LANs. Thus, in PRP a frame is simply routed in one LAN without considering the other one and, therefore, the routing only needs to take care of guaranteeing the RT/performance requirements in each LAN separately. Conversely, in TSN a frame needs to be routed through several paths in parallel within a single LAN, which is much more complex, as the routing must also consider aspects that can affect FT, e.g. fault independence of the routes.

3rd, by using the term redundancy management granularity we refer to the variety of devices that are able to (de)duplicate frames. In PRP only the nodes are able to do so; whereas in TSN, frames can be (de)uplicated –in fact, (de)replicated– in any bridge or node. Thus, TSNS enable more alternatives for deciding where to (de)replicate, which in turn can potentially lead to more FT and/or cost-efficient designs.

4th, subattribute *regular node FT connection* refers to the way in which a regular Ethernet node, i.e. with no redundant interfaces, can connect to a redundant channel. In PRP, since bridges cannot (de)duplicate frames, this requires the use of special devices (RedBoxes), each of which can connect one or more nodes to two bridges (each bridge belonging to one of the 2 PRP LANs). Conversely, as said above, in TSN there is a single (redundant) channel and bridges can (de)replicate frames. Consequently, a regular node can simply connect to a single TSN switch, which in turn (de)replicates frames for that node (and for others). In this sense TSNS eliminate the need of RedBoxes and, thus, the cost and bottleneck they represent.

5th, the error-containment subattribute refers to the capacity of bridges and nodes to contain the propagation of errors at their reception ports. In PRP and TSN, any frame that is deemed as syntactically incorrect (corrupted) at a reception port is dropped. Additionally, TSN bridges and nodes are provided with per-stream filtering and policing mechanisms, which allow them to drop not only syntactically incorrect frames, but also received frames that are incorrect according to other criteria, e.g. untimely frames. In this sense TSNS open up the opportunity to use error-containment to restrict

TABLE I  
COMPARISON OF FULL-DUPLEX ETHERNET-BASED PRP AND TIME-SENSITIVE NETWORKING

Attributes	Subattributes	Full duplex Ethernet based PRP	Time Sensitive Networking
Real-Time Comms.	Clock sync.	One clock per LAN (IEEE 1588 - PTP)	One clock for the whole system (802.1AS - gPTP)
	MAC for RT comms.	802.1Q priorities	802.1Q priorities, shapers (Qav, Qbv) and preemption
Fault Tolerance	Topology and redundancy efficiency	2 independent LANs, both with similar topology $\leq 2$ redundant paths can be used	Single LAN with arbitrary topology Arbitrary level of redundant paths
	Routing	Only needs to consider RT/performance	Needs to consider also FT
	Red. manag. granularity	(De)Duplication only in nodes	(De)Replication in nodes and bridges
	Regular node FT connect	Connection through specific (RedBox)	Direct connection via bridge
	Error containment	Only Eth corrupted frame dropping	Adds per-Stream Filtering and Policing (802.1Qci)
	Fault diagnosis support	Detection of omissions in nodes	Detection of omissions in bridges and nodes
Network Management	Configuration domains	Three: one per LAN, one for the nodes	Single config. domain (nodes and bridges)
	Architectures for config.	None	3 architectures (802.1Qcc)
	Management profiles	Profiles just for clock sync.	Enriched profiles for several aspects

the failure semantics of the nodes, i.e. to reduce the harshness with which an node failure is perceived by the rest of the nodes. This is a relevant advantage because the more benign the failure semantics of nodes is, the easier it is to provide mechanisms to tolerate their failure.

6th, as concerns fault-diagnosis support, note that when a subsystem fails, it should be diagnosed as faulty to either repair it or to undertake other specific FT actions. TSN provides better support for fault diagnosis than PRP, by means of a better capacity for detecting traffic errors. On the one hand, note again that TSN can drop (and thus detect) more types of erroneous frames; hence TSN can help in diagnosing with higher precision which kind of fault provoked the error. On the other hand, when a frame is dropped in PRP, only the destination nodes will detect that situation, i.e. they will detect a frame omission. In contrast, in TSN also the bridges can detect frame omissions. This can help in diagnosing with higher precision which subsystem is provoking the errors. This better fault-diagnosis support opens room for increasing the availability and/or the reliability of SASs' DCSs.

### C. Network management

As for network management, Table I considers 3 subattributes. 1st, regarding the number of configuration domains, note that a PRP network is divided into 3 independent domains to be configured, i.e. one per LAN plus one for all nodes; whereas a TSN network represents just 1 domain. This opens up several opportunities like reducing the configuration overhead, and increasing the capacity to find better configurations by considering a holistic view of the network.

The 2nd subattribute refers to the availability of reference architectures for configuration; whereas the 3rd one refers to the availability of configuration profiles (guidelines for different cases). PRP does not specify any reference architecture, and it includes a profile just for configuring the clock-synchronization mechanisms. In contrast, TSN specifies 3 architectures (802.1Qcc), namely fully decentralized, distributed user/centralized configuration, and fully centralized; and includes quite detailed profiles for covering a reasonable amount of configuration aspects. As a consequence, thanks to TSNS, the configuration of SASs' DCSs can be less error prone and have less engineering costs. Moreover, TSNS open

up the opportunity to achieve a seamless interoperability among configuration tools from different vendors.

### IV. A ROADMAP FOR TSN IN SUBSTATION AUTOMATION

After the above discussion it is even clearer the interest of using TSNS for SASs. Thus, it would be ideal to have a complete architecture, based on TSNS, for building Distributed Critical Systems (DCSs) that allow SASs to take advantage of the above-identified opportunities. This architecture should cover the 3 aspects analyzed in Sec. III, i.e., real-time communication (RT), fault tolerance (FT), and network management.

Regarding RT, there are many TSN standards (TSNS) and profiles, as well as many publications, that propose solutions that could be adopted in such architecture for guaranteeing RT communications. For example, TSN profiles specify how to use gPTP clock synchronization in automation; also, many schedulers have been proposed for TSN networks [3] and, thus, there are many scheduler candidates for SASs.

As concerns FT, TSN profiles hardly provide information on how to use the FT mechanisms already proposed in TSNS. In fact, although we have identified that TSNS and the related literature offer some FT mechanisms that can be used for SASs; TSNS still lacks a complete and integrated suite of FT mechanisms for automation systems in general and for SASs in particular. Thus, it is necessary not only to provide additional FT mechanisms that are fully compatible with TSNS, but also to integrate them with the rest of the TSNS mechanisms that are to be included within a complete architecture.

As regards network management, although there are TSN profiles, e.g. [4], and TSN standards (802.1Qcc) that propose different guidelines, architectures and mechanisms for management, there are still many open issues regarding how to provide a complete management infrastructure that can be used in practice in RT and/or fault-tolerant automation systems.

Achieving a complete architecture that covers these three attributes (RT, FT, management) is a cumbersome task. Thus, as a first step towards such complete architecture we have decided to focus on providing a complete TSN-based architecture for correct fault-tolerant behaviour of SASs' DCSs. The justification of focusing on FT is twofold. On the one hand, since a lot of solutions have been already proposed for guaranteeing RT in TSN, we can benefit from them while concentrating on the FT open issues. On the other hand, note

that the architecture and mechanisms for management have to be FT themselves. Thus, it makes more sense to focus on developing FT solutions first and, after that, to propose appropriate management mechanisms based on the lessons learned from those solutions.

In order to accomplish this complete FT architecture we have proposed a roadmap, which is the basis of an ongoing research project called *FT4TSNgrid* [5]. Generally speaking, this roadmap is divided into 4 main tasks, namely: (CFT) *Provide mechanisms to tolerate faults in the channel*, (NFT) *Provide mechanisms to tolerate faults in the nodes*, (INT) *Integrate the FT mechanisms within a complete architecture*, and (VAL) *Verify and validate the complete architecture in a real SAS' DCS prototype*.

Task CFT basically includes 3 subtasks. 1st, proposing different redundant topologies to efficiently tolerate permanent faults in the channel when using FRER. 2nd, combining the space-redundancy mechanisms of FRER with the time-redundancy (proactive retransmission) mechanisms known as PTRF proposed in [6], so as to efficiently tolerate, also, temporary faults in the channel. 3rd, developing tools to route in the same network both hard RT critical traffic and soft RT non-critical ones. Note that, to guarantee the RT requirements of critical traffic and the quality of service of non-critical ones, routes have to be calculated in conjunction with the RT schedule. We have already proposed some strategies for combining routing and scheduling of spatially replicated traffic in [7]. However, note that as a result of combining FRER and PTRF it can be decided to replicate each frame of a critical stream not only spatially but, also, in the time domain. Thus, we need to extend the work in [7] to route each temporal replica of each critical frame through several paths in parallel.

Task NFT includes also 3 subtasks. 1st, identifying what are the critical nodes of SASs, i.e., the nodes whose failures must be tolerated; for instance, the nodes that execute electrical protection functions in a substation. 2nd, developing the necessary mechanisms for critical nodes to tolerate and recover from faults that prevent them from correctly communicating and/or operating. We plan to adapt many of the solutions we proposed for doing so in DCSs based on FTT-Ethernet [8]. These solutions include mechanisms such as active replication with majority voting for nodes, which provides error compensation; as well as several recovery and reintegration mechanisms to prevent redundancy attrition. 3rd, proposing error-containment mechanisms to restrict the failure semantics of nodes, i.e. to reduce the harshness with which node faults manifest, and, thus, ease the rest of the FT mechanisms pointed out in this paragraph. For this, we will investigate how to take advantage and/or extend the error-containment mechanisms already proposed in TSNS.

Tasks INT and VAL include a set of transversal subtasks, to be carried out in parallel with the subtasks of CFT and NFT. On the one hand, INT is fundamental to guarantee a correct systemwide integration of the FT mechanisms. This is because, even if the FT mechanisms are designed to be as independent as possible, potential conflicts may arise when putting all of

them together. On the other hand, VAL is essential to experimentally verify the correctness of the complete architecture, as well as to validate its benefits for SASs.

Note that although we have presented this roadmap mostly as a sequence of tasks/subtasks, many of them must be partially overlapped in time. For instance, we have already started in parallel several subtasks that address the combination of FRER and PTRF, the proposal of cost-efficient fault-tolerant topologies, and the provision of a node-replication scheme based on majority voting.

## V. SUMMARY

PRP-based SASs encounter some limitations to meet the requirements of a proper SAS for the Smart Grid. By means of a thorough comparison, we have observed that TSN provides many advantages that make it closer to meet those requirements. The technological advantages identified, such as traffic shapers, the replication of traffic in different ways, new error containment mechanisms and management features, represent remarkable opportunities for the next generation of SAS.

Regarding the RT communication opportunities, there are already several works that address them. On the other hand, taking advantage of the network management opportunities is not an immediate priority, since this type of features are not critical for the correct operation of SAS. Then we have proposed a roadmap which focuses on providing a complete fault-tolerant TSN-based architecture for SASs' DCSs and describes a specific list of tasks. From the roadmap, we have already started to work on some tasks such as combining time and space redundancy mechanisms, designing cost-efficient topologies and designing a node-replication scheme.

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