PRP and HSR Version 1 (IEC 62439-3 Ed.2), Improvements and a Prototype Implementation

J.A. Araujo, J. Lázaro, A. Astarloa, A. Zuloaga
Department of Electronics Technology
University of the Basque Country UPV/EHU
Bilbao, Spain

A. García
SoC-e (System-on-Chip engineering, S.L.)
Zitek Bilbao (ETSI)
Bilbao, Spain

Abstract— **The IEC62439-3: Industrial communication networks – High availability automation networks – Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR), defines two protocols which provides zero time recovery against a failure in the network. The first edition of the standard was published in 2010, and two years after a second edition has been published in July 2012. There have been some improvements which explain this actualization and an amendment between versions. This paper presents the most remarkable improvements included, others susceptible of being included and a software prototype to be run in PCs and/or FPGAs which implements this new version of the protocols.**

Keywords— Ethernet; availability; redundancy; HSR; PRP; IEC62439-3

I. Introduction

Ethernet networks are being extended to different fields in which a communication network is used, as industry or power supply substations. But for some of those applications the use of Ethernet is constrained by new requirements such as high availability and absence of single point of failure.

The Ethernet standard contemplates the possibility of having different paths from origin to destination so as to increase availability. The Spanning Tree Protocol, STP [1], and the evolved Rapid Spanning Tree Protocol, RSTP [2], removes loops in the LAN by managing redundant links, locking some of them to avoid frames to circulate uncontrolled and unlocking them when a failure occurs; but this reconfiguration takes some time not affordable for some applications.

The IEC62439-3 Industrial communication networks – High availability automation networks – Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) [3] defines two protocols that offer zero-switchover time when a failure happens. Besides, the IEC61850, Communication Networks and Systems in Substations – Part 90-4: Network Engineering Guidelines [4], presents those protocols as reference network topologies for the Station Bus and Process Bus in substations.

The first edition of the IEC62439-3, that includes the version 0 of the protocols, was published in 2010 [5] and in only two years a second edition has been published with some changes which aim at improving some aspects having into account time, implementation, bridging PRP-HSR or simplicity requirements.

This document analyzes some of those changes included in the second edition, and others not considered which could be considered for future versions or to be used together with those protocols. Then it will be presented an implementation of this version 1 of the two protocols which achieve high availability in the network and which can be very easily ported and used.

II. State of Art

The resilience provided by PRP and HSR is achieved using at least two independent paths simultaneously used to send duplicated information from origin to destination nodes. Thus, if a fault causes an interruption of one path, frame that crosses it cannot arrive to destination, but the other one, which uses the other independent path, still arrives avoiding loss of information.

PRP is based in the use of two parallel networks to which nodes are connected, so frames are sent in parallel using two networks ensuring the secure communication against one failure in the network. When there is no failure, frames arrive duplicated and destination has to manage them accepting the first copy and discarding other copies as depicted in Figure 1.

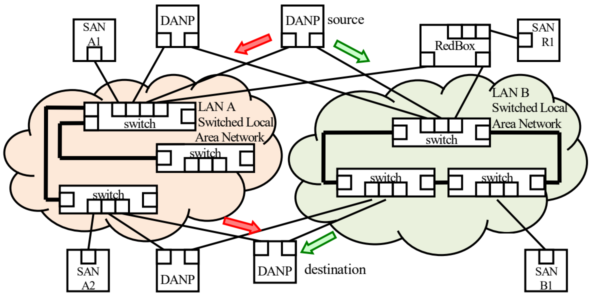


Figure 1. PRP network.

Nodes connected to two networks are named DANP, Doubly Attached Nodes with PRP. In this case SANs, Single Attached Nodes, are accepted directly connected to one of the networks or connected to two networks by using a Redundancy Box, RedBox.

In order to simplify the fact that PRP has to maintain and manage two networks, HSR achieves the same target using only one network in which information flows using two independent paths from origin to destination. Primal topology for HSR is a ring as sketched in Figure 2. Source node, Doubly Attached Node with HSR, DANH, sends frames via two directions and those frames arrive to destination node, another DANH, through two different ports taking the first frame and discarding the duplicated one. If an error occurs in one of the paths the delivering of the information is ensured by the other one.

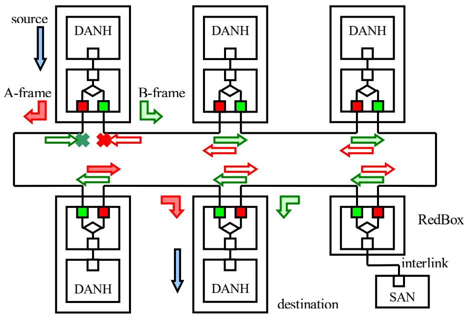


Figure 2. HSR Network.

HSR does not admit SANs directly connected to the network because DANHs must be capable of forwarding frames and this function is not implemented in common SANs, so that RedBox becomes completely necessary.

Another device defined in the IEC62439-3 is the QuadBox used to interconnect two HSR rings; they have 4 ports (2 for each ring) and can be considered as 2 RedBoxes connected through interlinks. In order to avoid a single point failure 2 QuadBoxes are needed to interconnect 2 HSR rings (Figure 6).

Redundancy included by those protocols is at link level and is transparent for upper OSI layers. A Link Redundancy Entity (LRE) is included and is the element which manages PRP/HSR functions.

III. Changes and Improvements

The basic idea for PRP and HSR remains inalterable in the second edition of the standard, information is sent from source nodes to destination nodes through two different paths, and destinations receive information twice discarding duplicated frames in a transparent way for upper layers.

Second edition of the standard has introduced some modifications in order to improve and implement those protocols in a more efficient way. Following, the most remarkable changes are going to be analyzed.

A. PRP Trailer and HSR Tag

1) PRP-1 Suffix (0x88FB)

These protocols add extra information to original Ethernet frames. PRP defined in IEC62439-3 Ed.1 (version 0) [5] added a 4 Bytes trailer at the end of the frame: Redundancy Control Trailer (RCT) but the second edition [3] extends PRP trailer to 6 Bytes adding a new PRP-1 suffix (0x88FB) at the end of the frame which will help detecting PRP traffic; this makes both versions incompatible. This kind of suffix distinguishes PRP frames from other protocols that also append a trailer to data. Figure 3 shows PRP frame with the RCT and the new PRP-1 field suffix.

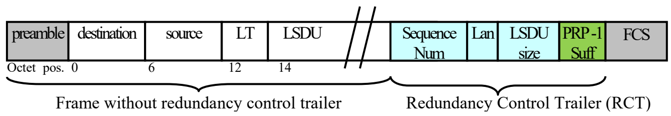


Figure 3. PRP frame.

With this change, HSR tag (see next paragraph) and PRP trailer have the same length (6Bytes), therefore frames have the same length and the same LSDU (Link Service Data Unit) size too; this is another target achieved with this action which will help for PRP and HSR networks interconnection which can be done with RedBoxes.

2) HSR Ethertype (0x892F)

The extra information added by HSR to original frames is the HSR tag, it is composed of 6Bytes and, as RCT in PRP, it is used to manage traffic, duplicates, circulating frames, etc.

First edition of the standard [5], version 0 of the protocol, used for HSR the ethertype 0x88FB shared with PRP which used it only for supervision frames. The second edition [3] introduces a new exclusive ethertype only for HSR traffic, 0x892F. So that all the HSR traffic will be directly recognized just looking at the ethertype. The structure of the frame does not change as seen on Figure 4. On the other hand it clearly makes both versions of the standard incompatible since they have different ethertype.

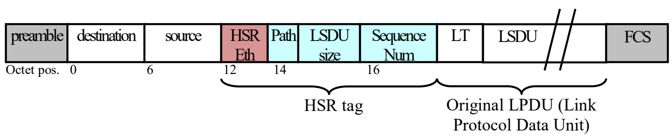


Figure 4. HSR ethertype changed: Vers.0 uses 0x88FB and Vers.1 uses 0x892F.

B. Frames Length

1) Maximum

First edition of the standard limited Ethernet frames in 4 Bytes for PRP to obtain a maximum frame length determined in the Ethernet standard when RCT was added, so that standard Ethernet switches and nodes could be used. On the other hand, HSR had not that limitation because every node in HSR network must understand HSR traffic, so that the maximum length permitted was the length of a normal Ethernet frame plus the length of the HSR tag (6 Bytes), frames were oversized but every element of the network knew about it.

Second edition eliminates the restriction of PRP maximum length because of being considered that every network component in the LANs will support oversized frames up to Ethernet standard plus the length of the trailer/tag (6 Bytes).

2) Minimum

The minimum frame allowed in PRP and HSR networks has been changed too. Version 0 fixed minimum length for frames to 64 Bytes (68 for VLAN tagged frames) as the Ethernet standard says including RCT/Tag.

It must be avoided to append padding after RCT in PRP because it would hinder the recognition of PRP traffic, so that if it is ensured a minimum frame size it is not going to happen. HSR has not that problem due to the position of the tag, but fixed minimum length is the same. So that, minimum frame size is increased as seen in (1) to 70Bytes (74Bytes for VLAN tagged frames):

$$
\begin{aligned}
&64B(\text{Ethernet minimum frame}) + 6B(\text{RCT/Tag}) \\
&[+4B(\text{VLAN Tag})] = 70B[+4B(\text{VLAN Tagged})]
\end{aligned} \tag{1}
$$

New minimum permitted length has into account that PRP trailer has been increased in 2 Bytes and that a LRE or a RedBox can remove the RCT.

C. Sequence Number

As occurred in previous version, the detection and elimination of duplicates and circulating frames is based on the Sequence Number, the 2 Bytes field that appears in both, PRP trailer and HSR tag. This number is common to both frames generated from each original frame delivered from upper layers and sent through the two different paths. Destination can detect if a frame has been received before or not looking to this sequence number.

Each PRP/HSR node and RedBox in version 0 (IEC 62439-3 Ed.1) had a counter per each other nodes in the network, correspondent sequence counter was increased by one each time a frame for that node was sent. Second edition improved this using only one counter in each node without differentiating the destination node.

Version 0 identified each frame in the network from others using source address (6Bytes), destination address (6Bytes) and sequence number (2Bytes), therefore that was the information that should be remembered for each frame in order to delete duplicates and circulating frames: 14Bytes/frame. The changes introduced by the second edition involve that each frame in the network now is identified using source address and sequence number: 8Bytes/frame. A reduction of 42% of the information to save per each received frame.

Moreover each node only has to maintain one sequence counter; unlike before that each node maintained one counter for each node in the network.

This improvement has special importance because devices for PRP/HSR are susceptible to be implemented on FPGAs whose resources are limited and should be optimally used.

D. Modes

PRP version 0 had two operation modes:

- Duplicate accept mode: Sender LRE sends original frame through two LANs and receiver LRE forwards every frame received to upper layers, including duplicates that should be eliminated by usual network protocols (TCP…).
- Duplicate discard mode: Sender LRE appends RCT to frames and receiver LRE checks received frames and does not forward duplicates to upper layers.

PRP version 1 limits the use of the Duplicate Accept mode for testing.

HSR version 0, apart from normal operation, had PRP mode in which HSR nodes had not forward frames and were connected to two networks, in other words, a PRP network using HSR Tag instead PRP RCT. Version 1 eliminates PRP mode and includes some new modes: one mandatory and some optional:

- H: Mandatory, HSR normal operation, explained before.
- N: Not forwarding equivalent to PRP mode.
- T: It sends and forwards frames without tag.
- M: It is defined a local criteria to add or not tag, and non-HSR are handled as in a conventional Ethernet.
- U: As mode H but forwarding unicast traffic too.

E. Duplicate Handle

First edition presents an algorithm (Drop Window) in order to discard duplicates at the link layer for PRP; it looked sequence numbers, source, destination and ports through which frames had arrived, although it did not exclude other possible methods. This previous version did not establish any method for HSR in which not only duplicates had to be taken into account but also circulating frames, frames that circulate round the HSR network.

Second edition of the IEC 62439-3 does not specify any discarding method, not for duplicates neither for circulating frames. It lets in implementer's hands the use of node tables, hash tables, FIFOs or sequence number tracking. The chosen algorithm only has to comply that a legitimate frame never must be rejected, while occasionally a duplicate can be accepted. Besides, the standard presents some time requirements for discarding frames in proper manner.

F. Node Tables

Version 0 maintained node tables in each node, that is to say, every node analyzed arrived and sent traffic (supervision and data frames) through all used ports to construct a table of the network; thus they were aware of the health of the network, and who was in it.

Version 1 makes this node tables optional, it does not consider necessary to record information of every node in the network, only if the network is wanted to be supervised a node with node tables becomes necessary. Nevertheless structure of those node tables is described to be implemented with fewer elements than in the previous version.

The no obligation of maintaining node tables simplifies considerably the implementation of devices on FPGAs.

G. Clock Synchronization

First edition of the standard did not specify clock synchronization methods to use, it only had some recommendations. Second edition has a whole annex dedicated to the use of Precision Time Protocol (PTP) [6] with PRP and HSR, in which operation of those two characteristics are analyzed to function together as they are based on opposed considerations [7]:

- Redundancy (PRP/HSR): does not care about the path followed by frames, its target is availability and it is not important which links were crossed.
- Synchronization (PTP): centers on maintaining clocks of different nodes synchronized; paths followed by frames must be known to calculate delays and offsets in order to adjust clocks.

H. More Possibilities (Not Considered in the Standard)

1) Quick Removing

Adopting Quick Removing (QR) approach introduced in [8], multicast traffic could be considerably reduced in an HSR ring. The idea is quite simple, when a correct frame is received through one port means that every previous node in that direction has received it too, so that if the same frame is correctly received through the other port it is not necessary to be resent, and this will be made in both directions. Figure 5 shows an example in which DANH5 does not forward frame in one direction (green arrow) because it has been correctly received before in the other direction (red arrow).

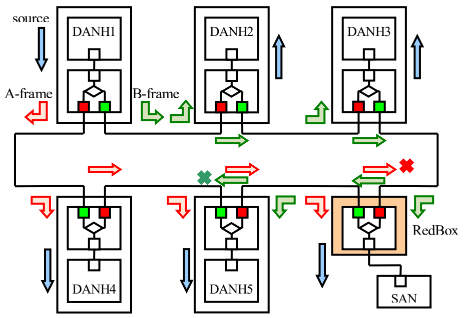


Figure 5. Multicast frames correctly received reducing traffic method.

Moreover, when a frame is received with error through one direction and then the same frame is received in the other one correctly, this correct frame will be resent to every node to be received by the rest of nodes.

The proceeding does not suppose any variation for unicast traffic which is not resent when arrives to destiny through two directions. But it supposes a considerable reduction of multicast traffic [8], the most common in Process and Station Buses in substations and which consumes the highest percentage of the bandwidth in the network [4].

This operation keeps the high availability of the original HSR, that is to say, communication is maintained when an error occurs. Besides, maintaining some multicast traffic in both directions could help in order to manage the network: supervision frames could be maintained without applying this traffic reduction. This supervision traffic could be helpful to control and detect possible faults to correct them. Although a fault does not mean a loss of information it should be solved as soon as possible, because one failure makes the network vulnerable in case of a second fault at the same time.

2) Traffic Separation: Virtual Rings and VLANs

Those options can be applied directly in PRP and HSR networks to separate traffic within the network in order to reduce the amount of traffic in the whole network.

- According to [8] if some Virtual Rings, similar to VLANs, are defined within a meshed HSR network traffic is reduced to some paths avoiding the expansion of all multicast traffic throughout the network.
- IEC61850-90-4 [4] proposes PRP and HSR for substations and puts forward that multicast traffic is so huge that Process Bus must have its own multicast or VLAN domain to separate its traffic from the Station Bus traffic.

3) Links Reduction

Paper [9] presents a single design method for smart grid communications with HSR ring networks. A HSR network formed of HSR rings uses two QuadBoxes to interconnect one ring with the adjacent one; if there is no node between them one of the links that connects two Quadboxes could be removed maintaining the high availability against a simple failure in the network and reducing network costs and complexity. Figure 6 shows an example in which there are two direct connections between each pair of Quadboxes.

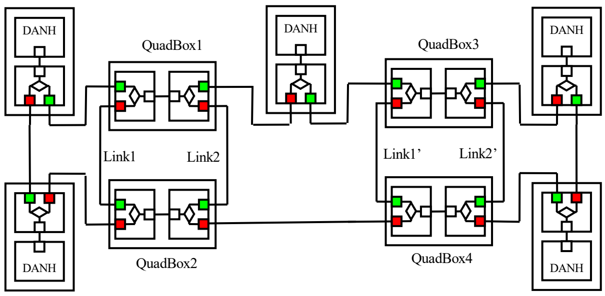
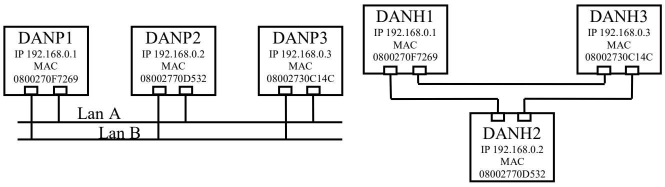


Figure 6. HSR rings interconnection.

IV. SOFTWARE IMPLEMENTATION

A prototype of the second version of PRP and HSR node has been developed. This software prototype implements the two protocols, runs over Linux and has been tested over virtual machines showing that it functions properly (machines have been implemented over VirtualBox 4.0.4 and use GNU-Linux operating system, Ubuntu 10.04 and 10.10). So as to test PRP three machines have been connected to two parallel networks; and HSR has been tested configuring those machines in a ring, as depicted in Figure 7. Developed PRP and HSR maintain communication even if one of the two links of one of the nodes is broken, in other words, high availability with zero time recovery has been achieved as expected.

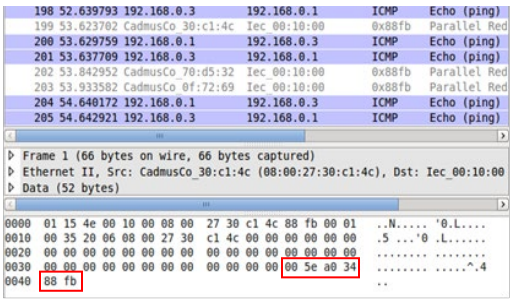


a) PRP Network. b) HSR Network.

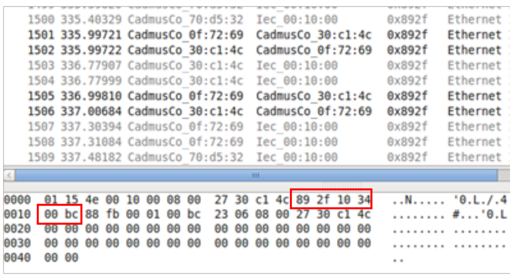
Figure 7. PRP and HSR networks implemented to test protocols.

This version uses node tables to manage duplicates and circulating frames; those node tables are used to control if a frame has arrived before or not. When a frame arrives it is searched in the node table and if it is found there, it is checked how old the entry is to decide about the discarding or not.

Figure 8 shows some captures of a PRP and HSR traffic taken with Wireshark 1.2.7. Both cases a) and b) show on the top a list of sent and received frames through one of the ports of DAN1 when it makes ping to DAN3. On the bottom, bytes of one of the frames are shown with PRP RCT and HSR tag marked respectively.



a) PRP traffic.



b) HSR traffic.

Figure 8. PRP and HSR traffic captured with Wireshark.

This prototype has also been tested with different machines, providing the same high availability, with an heterogeneous network using two PCs and an FPGA with a System-on-Programmable-Chip (SoPC) running the PRP and HSR software compiled for Petalinux [10] (System Development Kit –SDK– specifically targeting FPGA-based System-on-Programmable-Chip designs for Embedded Linux on Xilinx FPGAs [11]).

The SoPC has been implemented in the XC6SLX45T Spartan Xilinx FPGA. The evaluation board used for the evaluation is the SP605 and in order to give two new Ethernet ports needed a module with two Ethernet ports has been added (ISM Networking FMC Module).

The design developed with Xilinx SDK 12 software for the FPGA includes the following elements: Microblaze (A Xilinx 32-bit RISC Harvard architecture soft processor core [12]), Digital Clock Manager (DCM), Microblaze Debug Module (MDM), 3 Ether Lite MAC (One to communicate the FPGA with a PC to load the program to Microblaze and another two to implement PRP and HSR communication, RS232 UART (To provide RS232 communication).

The system takes up the resources summarized in Table I.

TABLE I. BASIC IMPLEMENTATION ON A SPARTAN-6 FPGA (XC6SLX45T)

Resource type	Resource utilization
Slice LUTs	6729 (24%)
Slice Registers	6177 (11%)
Occupied Slices	2841 (41%)
16B BlockRAM	17 (14%)

This first step with a PRP/HSR node has been modified to obtain a RedBox for one PC (SAN) which does not use PRP/HSR [13]. The prototype running over an FPGA has participated in a PRP/HSR interoperability testing in Winterthur in June 2012, and then in the CIGRE 2012 International Exhibition in August [14]. The prototype box is shown in Figure 9.

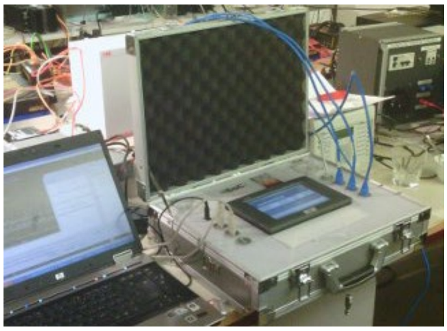


Figure 9. Box with the prototype in the interoperability testing in June 2012, which has been also presented in the CIGRE 2012 International Exhibition [15].

I. CONCLUSIONS AND FUTURE WORK

IEC62439-3 Ed. 2 has introduced some improvements analyzed in this document for a better implementation and extension of PRP and HSR protocols for high availability automation networks; moreover, there have been presented more ideas for future versions or to be used in combination.

IEC62439-3 has been developed for industrial automation networks, and as IEC61850-90-4 [4] contemplates and proposes, particularly for communications in substations for Process Bus and Station Bus. But, the idea could be applied to any network in which high availability with no loss of information should be assured when an error happens in the network.

IEC61850-90-4, in case of substations, indicates that Process Bus is expected to provide hard real-time response and Station Bus soft real-time response with a minimum delay and reliability requirements. In the same way it states an HSR forward time from port to port in less than 5µs which forces a hardware support using cut-through mode, that is to say, just receiving destination address, source address and sequence number of a frame, the node should decide to forward it and to start forwarding it before the frame is entirely received.

Although a software implementation could not be appropriate for that particular application with those time restrictions in HSR, the developed solution is simple, low cost and valid for other applications; moreover PRP has not that demands of forwarding times and IEC62439-3 by itself does not include that time restrictions. This is the reason why this kind of solution is appropriate for: PRP networks; HSR networks in mode N (HSR with no forwarding); HSR networks with few nodes in order to control maximum delay; HSR applications in which time is not so restrictive; and for testing: easily a device with two Ethernet ports (i.e. laptop plus a cheap USB-Ethernet adapter) can be connected to a PRP or HSR network just running the software. Furthermore, this software version is a good basis for a hardware version in order to achieve more restrictive time requirements.

Acknowledgment

This work has been carried out inside the Research and Education Unit UFI11/16 of the UPV/EHU and supported by the Department of Education, Universities and Research of the Basque Government within the fund for research groups of the Basque university system IT394-10 and the research program SAIOTEK (project S-PE12UN008).

References

[1] *IEEE Std 802.1D, IEEE Standard for Local and metropolitan area networks Media Access Control (MAC) Bridges,* IEEE, 1990.

[2] *IEEE Std 802.1D, IEEE Standard for Local and metropolitan area networks Media Access Control (MAC) Bridges,* IEEE, 2004.

[3] *IEC 62439-3 Ed.02: Industrial Communication Networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and Hig-availability Seamless Redundancy (HSR),* IEC, 2012.

[4] *IEC 61850-90-4 (draft): Communication Networks and Systems in Substations - Part 90-4: Network Engineering Guidelines.,* Geneva: IEC, 2012.

[5] *IEC 62439-3 Ed.01: Industrial Communication Networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and Hig-availability Seamless Redundancy (HSR),* IEC, 2010.

[6] *IEC 61855 (IEEEE1588) Precision Clock Syncronization Protocol for networked measurement and control systems,* IEC, 2009.

[7] J.-C. Tournier, K. Weber and C. Hoga, "Precise Time Synchronization on a High Available Redundant Ring Protocol," 2009.

[8] S. Allawi and J. Myung, "Improvement of High-availability Seamless Redundancy (HSR) Traffic Performance," 2012.

[9] K. Lee, Y. Lee, Y. Kim and J.-K. K. Rhee, "Efficient Network Design for Higly Available Smart Grid Communications," 2012.

[10] Petalogix, "Petalinux," 2009. [Online]. Available: www.petalogix.com/products/petalinux.

[11] Xilinx Inc., [Online]. Available: www.xilinx.com.

[12] "Xilinx microblaze," [Online]. Available: http://www.xilinx.com/tools/microblaze.htm.

[13] H. Kirrmann, K. Weber, O. Kleineberg and H. Weibel, "Seamless and low-cost redundancy for Substation Automation Systems (High availability Seamless Redundancy, HSR)," in *Power and Energy Society General Meeting, IEEE*, 2011.

[14] CIGRE, the Council on Large Electric Systems, "CIGRE 2012 International Exhibion," August 2012. [Online]. Available: www.cigre2012.com.

[15] SoC-e, System on Chip engineering, S.L., "SoC-e News," August 2012. [Online]. Available: www.soc-e.com/news.html.