Mixing Time and Spatial Redundancy over Time Sensitive Networking

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In this work we propose to mix time and spatial redundancy over a Time Sensitive Networking (TSN)-based network to increase its reliability while reducing resource consumption.

Cyber-physical systems (CPS) usually require the execution of critical applications. These applications traditionally relied on the use of specialised networks due to their high reliability and hard real-time requirements. Nevertheless, there is an interest in using Ethernet as the network technology for CPSs, due to its low cost, high bandwidth and IP compatibility. Moreover, there is also interest in developing CPSs capable of adapting to changes in the environment without interrupting their operation. Time Sensitive Networking is a set of technical standards that describe reconfiguration, real-time and reliability services for Ethernet. For these reasons, TSN is an appealing technology for the networks of the future CPSs. Nevertheless, TSN presents deficiencies in terms of the fault tolerance mechanisms it offers. This raises concerns about its actual suitability for critical applications with high-reliability requirements.

To increase the reliability provided by Ethernet-based networks, TSN describes spatial redundancy mechanisms. More precisely, the amendment IEEE 802.1Qca Path Control and Reservation [1] allows to create more than one path between nodes that want to communicate; whereas, the standard IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) [2] describes how to replicate streams in order to send several copies of each frame, one through each one of the paths created by IEEE 802.1Qca. Finally, FRER defines an optional mechanism to detect and remove frames that are repeatedly transmitted by a component failing as a babbling idiot.

TSN does not provide any time-redundancy mechanisms in this level of the architecture specifically designed to tolerate transient faults. Instead, TSN can use higher level protocols, such as those based in Automatic Repeat Request (ARQ). This can be a problem in real-time applications, where the delay and jitter caused by said protocols can result in missed deadlines. When these applications are also critical, the loss of frames may be catastrophic. Thus, it may seem appealing to relay on spatial redundancy to tolerate permanent and transient faults.

Nevertheless, using spatial redundancy to tolerate transient faults is not adequate. The communication channel is specially vulnerable to transient faults due to electromagnetic interference and other environmental factors. Thus, using spatial redundancy to tolerate them will have a high impact in the cost and size of the system. Moreover, when a permanent fault affects the channel, it may not be possible to tolerate transient faults any more. A more detailed discussion can be found in [3].

For these reasons, we proposed a fault tolerance mechanism for TSN that is based on time redundancy. This mechanism, called Proactive Transmission of Replicated Frames (PTRF), proactively retransmits each frame of any critical stream through the same path. The main ideas of a first version of PTRF were presented in [3]. PTRF sends several copies to ensure that at least one of them reaches the destination even in the presence of transient faults. Each one of the copies is called a replica. Proactive frame replication is a better strategy for real-time systems than ARQ, since it is deterministic in both, time and resource consumption.

We designed three different approaches, of which only two are described in the previously mentioned publication: (A) End-to-end estimation and replication of frames. Only the transmitter replicates frames, whereas bridges forward all frames they receive; (B) End-to-end estimation, link-based replication. Both, the transmitter and bridges replicate frames. When a bridge receives the first replica, it drops the rest and creates the same number of replicas; and (C) Link-based estimation and replication. Similarly to approach B, all components replicate frames, but the number of replicas transmitted by each component can vary depending on the reliability of the forwarding link. We will use error counters to estimate the reliability of the links.

Spatial and time redundancy can be combined to increase the reliability of the network while decreasing resource consumption. This is so as time redundancy allows to reduce the number of redundant paths to be used if we want to tolerate both, permanent and temporary faults. In this work we propose to combine the spatial redundancy offered by TSN with our proposed proactive time replication mechanism. Moreover, we propose several ways to combine the redundancy to achieve different levels of reliability.

First, we propose to use both spatial and time redundancy throughout all the network to achieve the highest levels of reliability, as expected in critical applications. To that, both bridges and end-stations must have PTRF and FRER mechanisms. Nevertheless, FRER's mechanism to remove repeated frames transmitted by a babbling idiot component must be disabled. In the case of approach A of PTRF, that mechanism would cause bridges to remove the correct time replicas created by PTRF and in the case of approaches B and C it is not needed, as they already remove time replicas.

Some applications may not need the reliability achieved

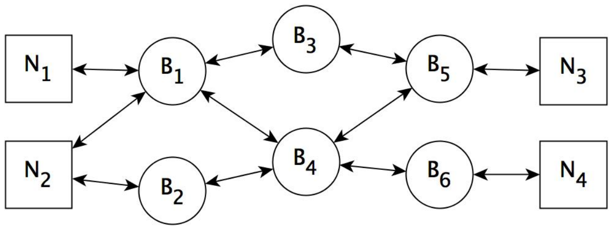

Fig. 1: Network with six bridges and four nodes, that do not count with spatial redundancy in the paths between any pair of nodes.

by combining both, spatial and time redundancy throughout the whole network. Thus, in these cases we propose to use proactive time replication only when spatial redundancy is not available. We consider two different scenarios.

First, even in networks with spatial redundancy it is possible to have a single link connecting end stations to bridges. In Fig. 1 nodes N_1, N_3 and N_4 are just connected to one bridge. This can be due to a number of reasons, from which we will list some. 1) Cost. The addition of cabling implies an increase in the cost of the system. 2) Space and weight. Certain applications have strict space and weight limitations, e.g. cars, planes, autonomous underwater vehicles... 3) Reachability. The physical location of the end station is a key aspect. If the end station is located far from the bridges it may not be feasible to connect it in a redundant manner. 4) Propagation of hazards. Cables may be the means for the propagation of damaging phenomenon, such as fire.

In this case we only want time redundancy between end nodes and edge bridges. End nodes send several copies of each critical frame. When a first edge bridge receives the replicas, it forwards the first one through the redundant paths and drops the rest. When a critical frame is received by the edge bridge in the other end of the network, the bridge merges the replicas received through different paths; creates the new time replicas and sends them to the receiver through the single link. This solution can not be applied to more complex scenarios where the redundant paths are unknown.

In our second scenario, we tackle these complex scenarios. Let us consider that nodes N_2 and N_4 from Fig. 1 want to communicate. The network counts with spatial redundancy between N_2 and B_4, but not between B_4 and N_4. Note that this case includes scenarios where end stations are connected to more than one bridge and may not need time redundancy.

In this case we want the network configuration to be done autonomously. Thus, we propose to use the Centralized Network Configuration (CNC) [4], where a central element with a complete view of the network performs its configuration. The CNC is proposed in the IEEE 802.1Qcc amendment to the Stream Reservation Protocol (SRP) of TSN. We will refer to the central element as the CNC element (CNCe).

For our mechanism to work, both time and spatial redundancy must be implemented in every component of the network. That is, each node and bridge must carry out the PTRF and FRER mechanisms. We selected the PTRF approach C, which allows to configure a different number of replicas in each link.

Next we will describe how the configuration of the proactive time replication should be done. We differentiate three main phases: 1) Distinguish fully from partially redundant paths. 2) Select the appropriate level of time redundancy for each segment. 3) Enforce the desired configuration in the network.

With regard to phase 1 we need to gather information from the network. IEEE 802.1Qca [1] provides path redundancy and defines different ways to create the communication trees. In this work we propose to use Maximally Redundant Trees (MRT). This means that redundant paths are created when possible, even if the created paths are not disjointed. Moreover, we assume that we have MRTs with cautious restoration, that is, the MRTs are recalculated after a topology change, for example, after the failure of a link or bridge. Moreover, if we use MRTs with cautious restoration only two MRTs can be created in the network. We also assume that the MRTs protect each other, i.e. frames are transmitted through both MRTs in parallel. The information regarding the existing paths in the network is stored in the Path Computation Elements (PCE). Thus, our mechanism will gather the information from the existing PCEs to identify partially redundant paths.

Regarding phase 2 the information extracted from the network must be processed by the CNC element. The CNCe will determine the amount of frames to be transmitted through each port of each bridge. The decision will depend on the existence of partially redundant paths, the reliability of each link and the criticality of the streams. It is important to note that we will use approach C of PTRF, so the level of time replication can be different in each bridge.

Finally, in phase 3 the CNCe must communicate the selected configuration to the bridges. Regarding that communication of the configuration, the protocol we will use is NETCONF, a network management protocol standardized by the IETF. Regarding bridges, IEEE and other standardization organizations are developing a series of new standards to define YANG data models for the configuration of bridged network.

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