Technological convergence for ethernet networks in railways process control systems

Convergência tecnológica para redes ethernet em sistemas de controlo de processos ferroviários

Convergencia tecnológica de las redes ethernet en los sistemas de control de procesos ferroviarios

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ABSTRACT
The tests carried out in the proposed implementation of an Ethernet network for railway signalling indicate that the topology in sections, with rings interconnected by optical fibre, offers an efficient solution in terms of throughput, latency and availability. Although a challenge was identified in the convergence time in Layer 3, exceeding one second, this is considered a calculated risk due to its occurrence being restricted to specific points in the network and the robustness of the equipment with high MTBF. The positive results in the bandwidth, latency and no frame loss tests in different scenarios reinforce the viability of the proposal to meet the demands of railway signalling. Careful implementation of the suggested topology, combined with redundancy strategies and proactive maintenance, emerges as a promising solution to meet the emerging challenges in railway traffic control automation, providing safety and operational efficiency. Continuous monitoring and preventive maintenance are key to ensuring the system's lasting and reliable performance.

Keywords: railways, ethernet, railway signage, technological convergence, ethernet convergence, ethernet for railways.

RESUMO
Os testes realizados na proposta de implementação de uma rede Ethernet para sinalização ferroviária indicam que a topologia em trechos, com anéis interligados por fibra ótica, oferece uma solução eficiente em termos de throughput, latência e disponibilidade. Embora tenha sido identificado um desafio no tempo de convergência na camada 3, superior a um segundo, este é considerado um risco calculado devido à sua ocorrência estar restrita a pontos específicos da rede e à robustez dos equipamentos com elevado MTBF. Os resultados positivos nos testes de largura de banda, latência e ausência de
perda de quadros em diferentes cenários reforçam a viabilidade da proposta para atender às demandas da sinalização ferroviária. A implementação criteriosa da topologia sugerida, aliada a estratégias de redundância e manutenção proativa, surge como uma solução promissora para atender aos desafios emergentes na automação do controle de tráfego ferroviário, proporcionando segurança e eficiência operacional. A monitorização contínua e a manutenção preventiva são fundamentais para garantir o desempenho duradouro e fiável do sistema.

Palavras-chave: caminhos-de-ferro, ethernet, sinalização ferroviária, convergência tecnológica, convergência ethernet, ethernet para caminhos-de-ferro.

1 INTRODUCTION

We are experiencing a major change in the area of railway traffic control automation. This automation, known in the railway industry as railway signalling, has its communication channels basically by deterministic means, which is a source of great comfort due to the fact that these deterministic channels are predictable in the face of a very conservative scenario required by the failsafe and mission-critical systems used by railway signalling. This comfort zone is being broken by the market's adoption of packetised technology for data transmission channels. Today, the use of Ethernet networks for data transmission is no longer an option, but a market requirement. The
convergence of data transmission channels to Ethernet technology is already very visible, and most manufacturers of railway signalling equipment already offer the Ethernet communication channel in their equipment, with fewer and fewer options for deterministic channels, such as RS232 interfaces. The big dilemma for railways is how to cope with the high latency and high resilience of alternative routes on Ethernet channels compared to deterministic channels (ARRUDA et al., 2008; NEVES, 2011).

2 CHARACTERISTICS OF A TRANSMISSION CHANNEL FOR A RAILWAY SIGNALLING SYSTEM

Today, railway automation is divided into auxiliary systems (non-failsafe) and railway signalling (failsafe). Railway signalling has to anticipate situations in which the railway furniture is in motion and therefore the correct decision making depends directly on time. A loaded heavy haul railway train needs a long distance/time to come to a complete stop. Using distributed power, the distance/time ratio drops, yet a loaded train at a speed of 60 km/h takes more than 250 metres to stop in an emergency (the most restrictive case of an Automatic Train Control braking curve in a distributed power system - Locotrol®) [16]. For this reason, the railway signalling interlocking equipment, in the event of a fault (human or otherwise), has to send a stop command to the trains in this fault area as quickly as possible. Faced with this scenario, the manufacturer of the railway signalling interlocks used in these tests considers the lack of communication between two pieces of equipment for more than one second to be a system failure and a safety routine blocks the entire system until the failure is normalised (ABB Power Systems, 2010). As a guarantee, after one second without communication, the equipment maintains the fault condition for at least thirty seconds. This is a reasonable loss of production for a high-traffic railway due to the time it takes to stop, start and resume cruising speed. A one-second interruption in communication can lead to an interruption of the railway line for hours if this fault occurs on an uphill ramp. In this case, the train stops due to the emergency braking curve and is unable to start again due to its high inertia. To get going again, another locomotive called a "helper" is needed (Neves, 2011).
In addition to time, the channels to serve a railway signalling system have to take into account a low error rate in an environment with high electromagnetic interference. For safety reasons, railway signalling discards any packet that contains an error and, if the error is detected in three consecutive packets, the safety routine is activated and paralyses traffic for at least thirty seconds. Another control that railway signalling makes is the sequence of the packets, which cannot be changed (ARRUDA et al., 2008).

In this work, the scenario of a real railway system (described above) operating between the north/northeast regions of Brazil was considered, so a data transmission channel for railway signalling with at least the following characteristics was used for this test:

- A data band with a theoretical throughput in UDP with 64-byte frames of at least 5 Mbps. This value is empirical and was obtained by adding up all the existing serial channels (64Kbps) (RP 2000 protocol remotes) in an interlocking section of a railway in operation today. Auxiliary voice channels were added for system maintenance (five simultaneous VOIP channels) (GAMESS; SURÓS, 2008).

- A system latency of less than 20 milliseconds. We have empirically considered this value based on a network of 60 devices. The resilience of the system, which cannot exceed 1 second, must be taken into account (HUYNH; GOOSE; MOHAPATRA, 2010).

- An availability of more than 99.98% (widely used by telecommunications systems) with a convergence time of less than 1000 milliseconds when using contingency routes. In this parameter, the most important thing to note is the convergence time, which is a direct requirement of the interlocking equipment used (HUYNH; GOOSE; MOHAPATRA, 2010).

- A very high level of quality. A packet loss rate of less than 0.1% was considered in these tests (PRAKASH; VIRANI, 2014).
3 ETHERNET NETWORK PROPOSED FOR RAILWAY SIGNALLING ON A HEAVY HAUL RAILWAY

The configuration of an Ethernet network covering a thousand kilometres, with a large amount of equipment on a single ring, would present challenges related to traffic, data containment and traffic convergence via contingency routes. In order to overcome these issues, it was decided to divide the network into rings made up of approximately 60 elements each, corresponding, in a railway signalling network, to around 170 kilometres of track. These rings are referred to as "sections". In a specific scenario, a 1000-kilometre railway would be divided into eight sections, distributed between two railway legs and six trunk network sections, as illustrated in the diagram in Figure 1.

![Figure 1 - Topology of an Ethernet network with protection proposed for railways.](image)

Each section is a Layer 2 network, which guarantees Ethernet communication between all the internal elements of the section. Each switch in the section is interconnected with adjacent switches via fibre optics at a bandwidth of 1,000 Mbps (1 Gbps) and with E-MRP protection. With this section topology, the channels between the interlocking devices would be serviced with one exception. The last element in a section...
needs to communicate with the first element in the next section. A Layer 2 connection would lead to all the sections coming together, which is undesirable. To solve this problem, the sections need to be interconnected at Layer 3, which is done using a router. In this case, there will be a need for an equipment shelter between the sections where we will have the last switch of one section, the first switch of the subsequent section and a router (GAMESS; SURÓS, 2008).

Considering the addition of routers to the topology, the routers need to be protected in order to maintain system availability. This protection was guaranteed through the VRRP (Virtual Router Ring Protocol) protocol, but it generated an extra need for communication between the routers in order to guarantee the communication route even when one or all of the switches' interconnections with the routers in the same shelter were interrupted. In this case, a Layer 2 network was built using EOS (Ethernet Over SDH) to interconnect the routers. To protect this network via EOS (Ethernet Over SDH), the ERP protocol (Ethernet Ring Protocol) provided by the SDH network was used. This interconnection between the routers and the use of VRRP has made route planning on these routers quite complex, since several routes with the same objective (origin-destination) and different priorities are required. The use of automatic routes is inadvisable (OSPF, RIP...) for mission-critical systems (PRAKASH; VIRANI, 2014; IEEE, 1998).

With this topology, there is a satisfactory bandwidth of 1 Gbps in field-to-field channels, a quality guaranteed with the use of professional switches and fibre-optic interconnections. Latency was controlled by dividing the network into sections and availability was achieved by using protection rings with very high speed switching protocols (PRAKASH; VIRANI, 2014; IEEE, 1998).

Within the same section, traffic is Layer 2 and availability is guaranteed by implementing the proprietary E-MRP protocol (MRP protocol - IEC 62439-2 - modified by the manufacturer ABB). In this case, the ring network switches have their traffic released in both directions (East/West). In this way, the network traffic would be in a loop, causing serious traffic problems. To avoid the loop, one of the switches is elected master and blocks traffic in one direction. The master switch exchanges information with
the other switches on the network and if a network disruption is detected, the master switch unblocks traffic from its blocked port and sends a command to all the other switches so that they can "clean up" their MAC tables and learn a new path for the traffic. This mechanism of blocking and unblocking the master switch port can take, depending on the size and latency of the network, less than 50 milliseconds (IEEE, 1990; RAMAMURTI et al., 2004).

To verify the real capacity of this suggested network to support railway signalling, a test Giga was built and commissioned (PRAKASH; VIRANI, 2014; RAMAMURTI et al., 2004).

4 TEST GIGA

The test jig was designed with two sections made up of industrial equipment from ABB's ruggedising family.

- 9 Switch model AFS 650 (ABB Power Systems, 2012);
- 3 ABB AFR 677 routers (ABB Power Systems, 2010);
- 3 SDH Multiplexers model FOX 660 (ABB Power Systems, 2012);

According to the topology in Fig. 2, a two-section system was set up consisting of a ring of switches interconnected by an optical port. The interconnection at Layer 3 was made by routers, one at the beginning of section 1, another between sections 1 and 2 and the last at the end of section 2. The routers were interconnected via three SDH multiplex devices with an Ethernet Layer 2 ring configuration in EOS and with ERP (Ethernet Ring Protocol) protection.
The IP numbering adopted in this test jig was assigned with numbers only for testing purposes, but respecting all aspects of a real network. The users in section 1 are on a different IP network (192.101.0.0/16) to the IP network (192.102.0.0/16) of the users in section 2. Two VOIP telephones were used just to simulate voice traffic within the proposed system.

The equipment was housed in eight racks simulating railway shelters. The racks were numbered from BAS1 to BAS 8 and the equipment in each rack was labelled with the same number as the rack it was housed in. Rack 5 (BAS 5) simulates the railway shelter that divides the sections and therefore has a switch for each section.

5 TESTS CARRIED OUT

Two Ethernet traffic measurement devices manufactured by JDSU, model SmartClass™ Ethernet, software version 4.1.0_B522D9010000 (JDSU, 2010), were used for measurement.

In the Layer 2 availability test, the SmartClass™ instruments on BAS 2 port 5 and BAS 4 port 5 were used. The IP numbers of each instrument were chosen from the same
network as in section 1. Initially, the instruments were configured to generate symmetrical traffic with 256-byte frames at a rate of 22,645 frames per second (50 Mbps). Several failures were triggered and the convergence time was measured. The measurements were taken several times and the average taken as the result.

The first failure considered was the total shutdown of BAS 3, and the traffic interruption time between BAS 2 and BAS 4 was 5,016.83 microseconds in BAS 2 and 4,435.20 microseconds in BAS 4. When BAS 3 was switched back on, the interruption was approximately 3,000 microseconds. This difference in the time taken to switch to the contingency route and return to the main route is normal, since the switch to the contingency route is made in an untimely manner and its return is only made when the master switch identifies stability throughout the network and sends the switch command.

The second fault simulated was the disconnection of the optical link between BAS 3 and BAS 4. In this case, the interruption was 3,029.26 microseconds in the instrument in BAS 2 and 18,663.39 microseconds in BAS 4. This difference was caused because the optical link was disconnected mechanically and one of the fibres (TX and RX) is removed first, in which case the traffic on the fibre removed last suffers a smaller interruption. The return of this link caused an interruption of 3,200 microseconds in both instruments.

The third fault caused was in Layer 3 and for this, the BAS 2 instrument was positioned in BAS 6. The IP of the BAS 6 instrument was changed to a section 2 number. Traffic was reduced to 18,117 frames per second (40 Mbps) because the links between the routers (FOX 660) were in EOS (Ethernet Over SDH) limited to 48 Mbps. Several failures were simulated with the disconnection of various links. The longest interruption time was seen when the power to AFR BAS 5 was switched off. Initially, the traffic route was symmetrical and passed through AFR BAS 5. After the power was switched off, the route was switched and the traffic was routed through the two end routers (AFR BAS 1 and AFR BAS 8). Receive traffic on the BAS4 instrument (IP 192.101.1.11/16) was interrupted for 2,001,998.18 microseconds (36,451 frames lost) and the BAS6 instrument (IP 192.102.1.11/16) had its receive traffic interrupted for 1,680,353.22 microseconds (30,644 frames lost). This variation between instrument A and B can be caused because the Layer 3 protection protocol (VRRP) imposes a latency of up to 1,000,000
microseconds due to the VRRP "keep alive" parameter, which in this case is 1,000,000 microseconds. When the router in BAS 5 was reconnected, the interruption time was 9,429.22 microseconds (200 frames lost and 5 OoS) on instrument A (IP 192.101.1.11/16) and 65.92 microseconds (0 frames lost and 2 OoS) on instrument B (IP 192.102.1.11/16). Once again we see that the interruption time is shorter when the system returns to its original condition. This is due to the fact that the system controls (Layer 2 and Layer 3) only return the system to its original condition after ensuring that there is stability.

Figure 3 - Band test results

The graph shows that the throughput in Layer 2 and Layer 3 is lower for frames with fewer bytes and tends towards the nominal bandwidth for frames with 1518 bytes. In this case, the nominal bandwidth is 48 Mbps, limited by the EOS links that interconnect the routers. Another observation we can make on this graph is that the higher the traffic layer, the lower the throughput. So in railway signalling, where the bulk of the information has few bytes (less than 64) and the traffic layer used is Layer 3, we can say
that the throughput of this network shown in "graph 1" is approximately 30 Mbps. This is interesting, especially for managers, because there is a tendency to confuse Layer 1 bandwidth with system throughput. In the case of this network, the interlocking equipment is interconnected to the system with an interface (Layer 1) of 100 Mbps, which could lead the uninformed to think that we would have a network bandwidth of 100 Mbps. Another interesting point to note in Graph 1 is the Layer 1 curve, which shows a throughput of 53 Mbps in 64 bytes, which is higher than the 48 Mbps of bandwidth on the EOS links. This discrepancy is due to the fact that some of the system's fields, such as "inter frame gap on wire" and "Preamble", are not propagated internally in the equipment and are restricted to the system's physical layer (Layer 1).

Latency tests were carried out within the same section and between sections. We'll only cover the results of the tests between sections here, since the results within the same section were well below one millisecond. In Layer 3 the instruments were positioned on the BAS 4 switch and the other on the BAS 6 switch.

- Using the RFC 2544 standard, tests were carried out on three different routes, called Route A, Route B and Route C.
- Route A - was the shortest with symmetrical traffic and passing through only one router, AFR BAS 5.
- Route B - was also symmetrical and traffic was routed through the AFR BAS 1 and AFR BAS 8 routers.
- Route C - had traffic from BAS 4 to BAS 6 via routers AFR BAS 1 and AFR BAS 8. Traffic from BAS 6 to BAS 4 was only via the AFR BAS 5 router. The results of the latency tests can be seen in Figure 4.
Latency in an Ethernet network is a direct correlation between the number of devices and the traffic layer of each device. As such, we can't measure real latency using a giga, but we can extrapolate the measurement in giga considering that the individual latencies of all the devices are the same. With these considerations, we can use the worst measurement (Route B with 1518 Bytes = 1.8 milliseconds / 8 devices) and extrapolate it to a real situation of 60 devices. The result would be 13.5 milliseconds (1.8/8*60). This figure of 13.5 milliseconds would be an estimate of the worst latency in an Ethernet network for railway signalling in a network similar to the network shown in "Fig. 1". For the lower end (Route B with 64 Bytes = 0.283 milliseconds / 8 devices) the latency would be 2.12 milliseconds. Considering that in railway signalling the frame sizes are concentrated in 64 Bytes, we can consider that in this parameter we won't have any problems for railway signalling.

It was noted that in RFC 2544 the latency measurements are made with a non-severe bandwidth load (below the measured throughput value). If the network is stressed
with a severe bandwidth load, these measurements will be quite different. For the purposes of this work, we consider that this communication system will only serve railway signalling equipment, so the bandwidth load is not severe.

The error test carried out by the RFC 2544 standard showed a loss of zero frames with all the standard's frame sizes (64, 128, 256, 1024, 1280 and 1518 bytes) and in all traffic simulations.

6 CONCLUSION

In conclusion, the results of the tests carried out indicate that the proposal to implement an Ethernet network to serve railway signalling is viable in most of the parameters analysed. The sectional topology, dividing the network into rings with switches interconnected by optical fibre, proved efficient in guaranteeing satisfactory throughput, low latency and high availability.

However, it is important to emphasise that the convergence time in Layer 3, greater than one second, presents a significant challenge. This potential failure can be considered a calculated risk, given that the points likely to generate this failure are limited (only in the first and last element of each section). In addition, the equipment used is chosen on the basis of a high level of MTBF, which contributes to mitigating the impact of this limitation.

The positive results in the bandwidth, latency and no frame loss tests at different sizes indicate that the proposal meets the basic requirements of railway signalling, offering a robust and reliable solution. However, the continued importance of monitoring and maintaining the equipment is emphasised to ensure the effective operation of the system.

Therefore, given the transition to Ethernet networks in railway automation, the careful implementation of the suggested topology, combined with redundancy and preventive maintenance strategies, could be a promising solution to meet the emerging challenges and guarantee safety and efficiency in railway traffic control.
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