FEC IN DETERMINISTIC CONTROL SYSTEMS OVER GIGABIT ETHERERNET

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Abstract

Forward Error Correction (FEC) is a technique for recovering from bit errors and frame losses in real-time network applications. Classic recovering strategies, like TCP retransmission, are not suitable due to delay, timing and bandwidth constraints. In this paper, we introduce the FEC technique in a novel deterministic fieldbus, White Rabbit [1] (WR). WR is developed over frame-based computer networking technology, Gigabit Ethernet, GbE. WR provides an effective and resilient way to serve as a deterministic data transfer medium and to interconnect large distributed systems, like Control Systems for Particle Accelerators. The reliability of WR falls on the FEC, which provides the means to guarantee that only one control message per year will be lost or irretrievable as a result of the Bit Error Rate of the physical medium (fiber optic or copper). We propose in this paper a FEC base on LDPC [2], and tailored for broadcast communication in switched networks over noisy channels without retransmission.

INTRODUCTION

Control systems have distributed nodes that need to be connected under specific operation constraints: synchronization accuracy, determinism, bandwidth limitation etc... Besides, the medium over which the communication happens, is a noisy channel where the bits of the frame could be erased or modified. Also, the switches used to propagate the information can mislay or dump such information as a result of collisions in the routing process. So as to ensure an adequate performance of a control system, it has to be endowed with a mechanism capable of overcoming the errors in the communication. Such mechanism is called Frame Error Protection (FEP) and among the different alternatives, in this paper the Forward Error Correction will be discussed. We present the groundwork of an underway research to provide high reliability to time-critical control systems based on GbE and switched networks. The paper is organized in three sections. The first section presents the framework where the FEC is being developed, WR Project, and its boundary conditions. The second section presents how these boundary conditions affect the transmission of data over GbE. In the final section, we analyze the whole scenario and present a FEC scheme to ensure the required reliability.

CONTROL SYSTEMS AND WHITE RABBIT PROJECT

WR is a solution to the generic problem of transferring data in a fast, deterministic and safe manner. WR Protocol (WRP) [4] allows the delivery of timing and control data over a Gigabit Ethernet LAN. WR can be seen as an extension of Gigabit Ethernet, which provides synchronous mode, deterministic routing, bi-directional exchange of frames between nodes and precise delay measurement.

The synchronous mode is achieved by using Synchronous Ethernet along with IEEE 1588, PTP protocol. This combination of protocols provide the means to distribute through the physical layer a common clock within the entire network up to e.g. 2000 stations, allowing 1ns synchronization and 20ps jitter. The frame transmission delay between two stations will never exceed the sum of 64 byte clock cycle plus the propagation time in the longest communication path of the network.

To distinguish between WR and other possible Ethernet traffic in the network, two different frames are defined: SP, Standard Priority frame, which is non-deterministic, and HP, High Priority frame, which is deterministic. The latter frame type is specified in the WRP network to transport messages with the highest priority. HP are frames for time-critical control data, as a consequence, they are routed with lowest latency as possible, forcing fragmentation of non-HP traffic if required. These frames have absolute priority over SP frames and non-WR traffic to maintain low and deterministic transmission delay.

Coming along with the protocol, compliant hardware is being developed in order to support the protocol's features. There are three essential devices: White Rabbit Master, which generates the HP frames and is master clock as well, White Rabbit Switch and White Rabbit Receiver. As a consequence of the device's role and application requirements, the number of units needed in a standard network will consist of one WR Master, M WR Receivers, and $N_{WR_{Switch}}$ with P downlink ports each.

WR allows different approaches to organize the topology of the network depending on the specific requirement of the applications. The strategy for data transmission is based on the distribution from the master to all the other nodes of the network, directly or indirectly according to a Star or Tree topology. The HP frames will be broadcasted from the top of the network, where the WR Master dwells, to the bottom of the network reaching all the WR Receivers.

One of the principal features of the protocol is the notion of determinism, used to guarantee the execution of events within a certain period time. On account of the differential nature of the time, it is possible to create a slice of time in which everything is perceived as deterministic, what it's called in WR jargon, Granularity Window, GW, [3]. Once we define the span of determinism, size of the GW, WRP provides the means to the transportation of the HP frames and the execution of the events in the very same GW.

Table 1: Granularity Window for 100 μs

Granularity Window	$\approx 5\mu s$	Info Frame Preparation
	t_1	Coding
	$\approx 12\mu s$	Transmission
	t_2	Decoding
	$\approx 12\mu s$	Info Frame Interpretation
	$\approx 12\mu s$	Fail-safe time

GbE AND SWITCHING NETWORKS

Gigabit Ethernet [5] uses as a physical medium optical fiber or twisted-pair cable for sending Ethernet frames. Such frames can be altered due to noise, interference, distortion or bit synchronization errors. The Bit Error Rate or Bit Error Ratio (BER) is the number of bit errors divided by the total number of bits transferred. If a bit error in a frame leads to the complete loss of the frame, the Figure 1 illustrates that a frame would be lost in every $8\ 10^4$ frames sent. It can be also deduced from the figure that small frames are less susceptible to interference, as they are statistically more likely to miss noise caused by internal or external sources.

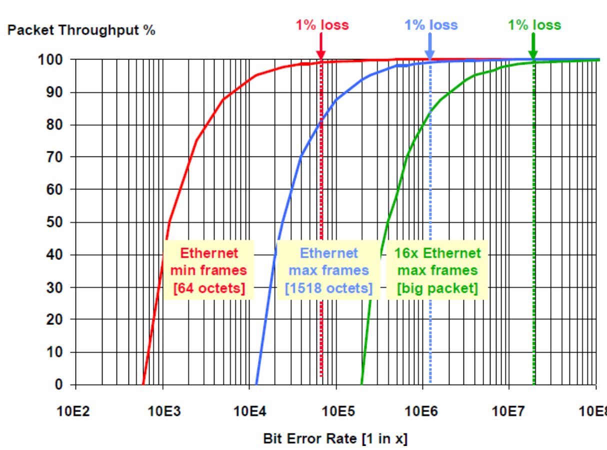

Figure 1: Bit Error Rate in GbE.

The BER can be considered as an estimation of the Bit Error Probability (BEP) in a channel. The sample space Ω of BER will be defined by the collection of all possible outcomes, which means for a single bit:

$$\Omega = E, N_E, Error, Not\ Error \tag{1}$$

and it is determined by the experimental results of the physical medium.

Broadcast communication is a non thrifty method to convey information in a switched wired distributed system, but terrible effective for simple communication networks. As we presented in the first section, the frames with control events, HP frames, will be broadcasted from the Master throughout the network in order to reach all the WR Receivers, even though the information is not relevant for all receivers. The downside of this approach is a higher global BER. The transport medium that physically consists of a number N of wires, can be considered as an equivalent single cable with a higher BER, as many times as wires are. In other words, the BEP of the system as a whole, is the union of all the probabilities of every single medium path. Since the events defined by the BEP are not mutually exclusive, the union of their probabilities is:

$$BER_{system} = BEP(BEP_1 \cup ... \cup BEP_n) \tag{2}$$

WR protocol is thought to be a full compliant extension of Ethernet, therefore Cyclic Redundancy Check algorithm is calculated and introduced into the HP frames according to the standard IEEE 802.3 [5]. This field allows early detection of header corruption during HP frame routing. If the header is corrupted, it will be detected and this frame is immediately dropped.

FORWARD ERROR CORRECTION

In the previous sections we presented the scenario for which we are developing a FEP system for data transmission. In short, the master codes the information, adding redundant bits to the frame. This allows the receiver to decode the frame, which implies the detection and correction of errors. In addition the error control has to be able to deal with the following requirements:

- Time constraints due to Granularity Window.
- No feed back channel and not retransmission.
- Stream of HP events within a Granularity Window.
- Recovery of lost and flawed frames.
- Small length of the frame .
- Fully Ethernet compliant.
- One lost frame per year.
- Code Hardware implementation.

The time constrains for WR disqualifies a great number of slow FEC, like Reed Solomon,of which decoding time is proportional to $\theta(k^3)$, with k number of bits in the frame. As can be seen in the Table 1, in a GW of 100 μ, the total time available for coding and decoding is $\approx 70\mu s$. Not only the limitation of time, but also the limitation of upstream traffic, rules out the possibility of positive/negative feedbacks from receivers to sender and the retransmission of a lost o flawed frame, like TCP. This fact reduces drastically the range of suitable strategies. To some extend the GW may limit the length of the frames as well. This reduces the performance of some FEP algorithms that find their optimal operation with a minimum length. Moreover, the compatibility of WR with Ethernet forces the frame structure, disallowing other suitable organization of the information in the frame. Also, CRC introduces frame losses in the case of an error in the header, disqualifying all the FEP based on one frame transmitted and redundant date on it. The only suitable strategy for WR, capable of overcoming and achieving one lost HP frame per year, is the Forward Error Correction in combination with a repetition strategy.

So as to reckon the magnitude of the problem, we present a case where a WR network is made up of 2000 WR Receivers, WR Switches (1 up-link port and 15 down-link ports each) and one WR Master. There are deployed 144 16-ports WR Switches, 1 up-link port and 15 down-link ports. The connection among WR Switches - WR Switches, and WR Master - WR Switches is established by fiber optic with a BER of 10^{-12}. The connection among WR Switches - WR Receivers is established by fiber optic as well, or copper cable, CAT-5 with a BER of 10^{-10}. The frame consists of 23 bytes in the header and 1000 bytes in the payload. The GW of the system is $100\mu s$, and in every GW only one frame will be sent.

The numbers of cables and global BER of the network is detailed in Table 2.

Table 2: Global BER

	No. FO .	No. CAT-5	BER FO.	BER CAT-5
FO	2144	–	$\simeq 2.144\ 10^{-9}$	–
FO & CAT-5	144	2000	$\simeq 1.44\ 10^{-9}$	$\simeq 2\ 10^{-7}$

Hence, the probability of getting at least one bit error in the header of the frame $P(b_e\_header)$, is expressed by:

$$P(b_e\_header) = \sum_{n\_errors=1}^{bits\_header} \binom{bits\_header}{n\_errors} BER^{n\_errors} \cdot (1 - BER)^{frame\_length\ -n\_errors} \quad (3)$$

The probability of getting at least one error in the header of the frame and not in the body can be fairly understood as the Frame Loss Ratio, since a frame with a single error in the header will be always dropped. Through the course of one year, according with the wording of the case, there are $3.145\ 10^{11}$ windows. It leads to assume that within one year the system will suffer $12.4\ 10^{4}$ losses using fiber optic and $11.5\ 10^{6}$ using fiber optic and CAT-5.

Table 3: Lost Frames in One Year

	P At least one Error in Header	Frame Lost per Year
Fiber Optic	$3.94\ 10^{-7}$	$12.4\ 10^{4}$
Fiber Op. & CAT-5	$3.67\ 10^{-5}$	$11.5\ 10^{6}$

This scenario shows that the coding scheme has to guarantee that a control information frame reaches the receivers even if during the routing the header is been corrupted and dropped. The quick and first answer to this quandary would be to use a repetition scheme. Repetition code repeats bits across a channel to achieve error free communication. Repetition generally offers a poor compromise between data rate and bit error rate. The main attraction of the repetition code is the ease of implementation and straightforward decoding process in case of free errors communication , otherwise, the Maximum Likelihood algorithm has to be used to determine which symbol was transmitted. We have performed simulations where it has been proved that this strategy alone is not suitable. Furthermore, we have evaluated others codes, without success, like Convolutional, LT or Raptor Code. The first code doesn't fullfil our time requirements and the last two codes are protected under patent, or Therefore the current research is aimed to develop a clever scheme of repetition in combination with the codes Low-Density Parity-Check (LDPC) to protect the information as well. LDPC codes is a class of linear block code and are defined by a sparse Parity-Check matrix, H_{mxn}, the encoded bit string, Y_m and a given bit string X_m . This sparse matrix is often randomly generated, subject to the sparsity constraints, which contains only a few 1's in comparison to the amount of 0's.

$$Y_n = H_{m,n} * X_m \quad (4)$$

The main advantage of LDPC is the close performance to the capacity for a lot of different channels and linear time complex algorithms for decoding. Furthermore they are suited for implementations that make heavy use of parallelism. The algorithm used to decode LDPC in our case is the belief propagation algorithm.

The testing implementation of the FEC is developed in VHDL and integrated on the nodes. The test-bed is set up with several WR Switches, providing the networking infrastructure, the WR Master prototype will generate the encoded frames and a WR Receiver prototype will decode and check the integrity of the data. In order to alter the normal behavior of the channel, the cable and nodes will be subjected to artificial noise and errors. From this research is expected to find out and tune up the best parameters for the repetition strategy and the best structure of the Parity-Check Matrix.

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