CLOCK SYNCHRONIZATION IN INDUSTRIAL AUTOMATION NETWORKS

Comparison of Different Syntonization Methods

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Abstract: Synchronization of distributed clocks is a critical task in many real time applications over Ethernet. The Ethernet protocol, due to its non-deterministic nature, is not suitable for real-time applications with very strict synchronicity requirements. However, the limit is continuously being pushed outwards by current research. The Precision Time Protocol (PTP), delivered by the IEEE 1588 standard, provides high synchronization accuracy and has been adopted in many real time applications in the areas of industrial automation, measurement & control, communications etc. This paper will discuss several issues aimed at improving the synchronization performance.

1 INTRODUCTION

Ethernet (IEEE 1997), due to its cheap cabling and infrastructure costs, high bandwidth, efficient switching technology and better interoperability, has been adopted in various areas to provide the basic networking solution. Many Ethernet-based applications require the networked clocks to be precisely synchronized. Typical examples include base station synchronization for handover or interference cancellation in telecommunication networks (Nieminen 2007), distribution of audio/video streams over Ethernet based networks (IEEE 2007a), and motion control in industrial Ethernet (Chen 2005). Standard Network Time Protocol (NTP) (Mills 1989, 1994) synchronization over Ethernet provides synchronization accuracy at the millisecond level, which is appropriate for processes that are not time critical. However, in many applications, for example base station synchronization or motion control, where only sub-microsecond level synchronization errors are allowed, a more accurate synchronization solution is needed. The Precision Time Protocol (PTP) of the IEEE 1588 standard (IEEE 2002) published in 2002, is a promising Ethernet synchronization protocol, in which messages carrying precise timing information, obtained by hardware time stamping in the physical layer, are propagated in the network to synchronize the slave clocks to a master clock.

Factors that affect the synchronization quality achievable by PTP include the stability of oscillators, the resolution of message time stamping, the frequency of synchronization message transmission, and the propagation delay variation caused by the jitter in the intermediate elements. The synchronization error can be reduced by carefully studying the sources that contribute to the error, by choosing the most suitable implementation of PTP for a specific application and by designing efficient synchronization algorithms that make use of all available information provided by the PTP protocol.

Some work has been done to enhance the performance of IEEE 1588 taking the mentioned factors into consideration. The authors of (Jasperneite 2004) introduced the transparent clock (TC) concept to replace the so-called boundary clock (BC). BCs adjust their own clock to the master clock and then serve as master clocks for the next network

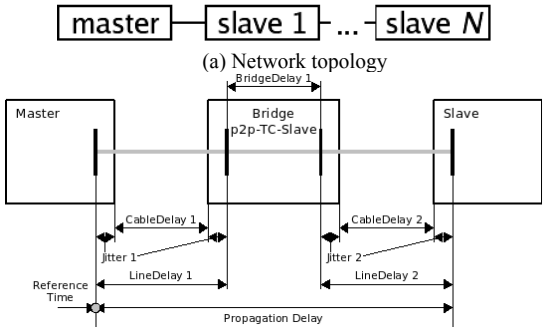
segment. Cascaded control loops are generated, which might lead to instabilities and deviation of the distributed clocks. Using TCs, intermediate bridges are treated as network components with known delay, which is compensated in the carried timing information. By doing this the synchronization at the time client is not dependent on the control loop design in the intermediate bridges. Hence performance is improved. The TC concept has been adopted in the new draft of IEEE 1588 published in 2007, and is used in this paper. In (Na 2007) we analyzed the influence of jitters and frequency drift and made suggestions for designing the parameters for higher synchronization accuracy. This study was extended in (Na 2008), where an algorithm to reduce the error was introduced.

In this paper, we discuss how to efficiently use the PTP messages to improve the synchronization performance, i.e. convergence speed and error. Problems arise when there is non-negligible frequency drift. In this case, clocks should first be syntonized, i.e. their frequency difference should be estimated and appropriate control applied to remove it. We study and compare different syntonization methods, and propose an improved solution for the syntonization and synchronization. Appropriate simulation results verify our analytic study.

The paper is organized as follows: Section 2 introduces the system model and briefly describes the PTP protocol. Section 3 introduces two methods for syntonization, master and peer frequency ratio estimation. In Section 4 we compare these methods and propose a synchronization algorithm which is based on both methods in section 5. Simulation results are presented in Section 6.

2 SYSTEM MODEL

Fig. 1 illustrates the time synchronization in a system with cascaded bridges. $N+1$ elements are connected in a line topology. The first element is the time server, also called (grand)master, which provides the reference time to the other N elements, called slave elements, via time-aware bridges (TCs). The master element periodically sends Sync messages which carry the counter state of the master clock stamped at the time of transmission. The interval between two consecutive Sync messages is T. The ith Sync message, generated by the master element at time t_i, consecutively passes through all slave elements. Quantities, certain or uncertain, linked with the Sync message transmitted by the master at time t_i are labelled by the superscript i. We call the propagation time between the nth slave and its preceding element line delay and denote by LD_n^i (also known as peer-to-peer delay in PTP).



(a) Network topology

(b) System parameters

Figure 1: System Model.

The message will be forwarded to slave element $n+1$ via a time-aware bridge after the bridge delay BD_n^i. We define LB_n^i to be the sum of line delay plus bridge delay of Sync message i at slave n. As the line delays and bridge delays are not necessarily constant in time, we define $\delta_{LB}^{i,n} = LB_n^i - LB_n^{i-1}$ to be the difference between the true LB value at slave n that affected Sync messages i and $i-1$. All the delays we have mentioned up to now are defined in the absolute time. A delay D measured by a local clock takes the form $D \cdot f$ where f is the clock frequency (this product is replaced by an integral in the case of frequency drift).

The transparent clock synchronization protocol is depicted in Figure 2.

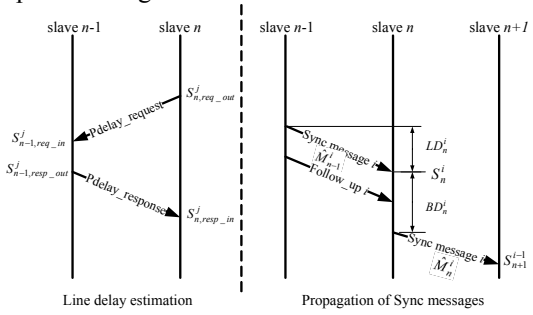


Figure 2: Illustration of PTP with transparent clocks.

The PTP has a master/slave structure. Timing information is packaged in special telegrams and propagated along the network. The synchronization relies on two processes, the delay estimation process and the timing propagation process. The delay

estimation process relies on 4 time-stamps, S^j_{n,req_out}, S^j_{n-1,req_in}, $S^j_{n-1,resp\_out}$ and $S^j_{n,resp\_in}$: slave n sends a delay request message to slave $n-1$ (which is the master in the case of slave 1) and records its time of departure (1st). Slave $n-1$ (or master) replies with a delay response message which reports the time-stamps of receiving the delay request message and sending the delay response message (2nd and 3rd).

Slave n records the time it receives the response message (4th). If slave n and $n-1$ have the same clock frequency or the frequency drift is negligible, the line delay can be calculated by:

$$\hat{S}^j_n(LD) = \frac{\left(S^j_{n,resp\_in} - S^j_{n,req\_out}\right) - \left(S^j_{n-1,resp\_out} - S^j_{n-1,req\_in}\right)}{2} \quad (1)$$

where $\hat{S}^j_n(LD)$ is the j^{th} estimated line delay using slave n's local clock (and equal uplink and downlink line delays are assumed). The true line delay, measured in slave n's local clock ticks, is $S^j_n(LD) = LD^j_n \cdot f_{S_n}$ for constant frequency.

In the timing propagation process each slave propagates the timing information of the master and uses that information to adjust its own clock. The master sends out a Sync message which contains the timestamp M when this message was sent. A more precise timestamp of the transmission of the Sync message will be sent by a so-called "follow-up message". Slave 1 forwards the Sync message to Slave 2, augmenting its content by the sum of its line and bridge delays (converted to master time – it will be explained presently how this is done), effectively transmitting its estimate of the master time for the time-instant of forwarding. This process is repeated in each slave until the message reaches the time client.

Consider for the moment that all the clocks have the same frequency. Then the updating of the content in slave n (i.e. his estimate of the master time) follows:

$$\hat{M}^i_n = \hat{M}^i_{n-1} + \hat{S}^i_n(LD) + \hat{S}^i_n(BD) \quad (2)$$

where $\hat{S}^i_n(LD)$ comes from the line delay estimation in (1). The bridge delay $\hat{S}^i_n(BD)$ is taken to be precisely known by using the time stamped at the reception and the forwarding of the Sync message.

Equation (2) can be used for proper time synchronization only if all clocks have the same frequency for all the time. If there is frequency difference between the clocks, the last two terms in (2), corresponding to the slave's counter increase during the two delays, are not equal to the counter increase during this time of the master clock. Therefore, it is not suitable to use local time to update the master clock estimate, as shown in (2). To solve this problem, it is necessary to estimate the frequency offsets, i.e. syntonize the clocks.

3 SYNTONIZATION AND SYNCHRONIZATION IN PTP

As discussed in the previous section, if there are clock frequency drifts or the clocks have different frequencies, (1) and (2) are unsuitable for time synchronization. The problem with the line delay estimation in (1) is that $S^j_{n-1,resp\_out}$ and S^j_{n-1,req_in} are measured by the clock in slave $n-1$, whereas $S^j_{n,resp\_in}$ and S^j_{n,req_out} are measured by the clock in slave n. To convert all into the same metric, the frequency difference between slave $n-1$ and n, i.e. neighboring slaves, needs to be known. And in (2), the last two terms should be translated into master time, i.e. the frequency difference of grandmaster and the slave needs to be known.

We define the rate compensation factor (**RCF**, also called rate ratio, (IEEE 2007b)) to be the ratio between the frequencies of two different clocks. We use $RCF_{X/Y}$ to denote the frequency ratio between X and Y, i.e. $RCF_{X/Y} = f_X / f_Y$. Then the correction of (1) is:

$$\hat{S}^j_n(LD) = \frac{\left(S^j_{n,resp\_in} - S^j_{n,req\_out}\right)}{2} - \frac{\left(S^j_{n-1,resp\_out} - S^j_{n-1,req\_in}\right) \cdot RCF_{S_n/S_{n-1}}}{2} \quad (3)$$

The master counter estimation equation of (2) should be changed to:

$$\hat{M}^i_n = \hat{M}^i_{n-1} + \left(\hat{S}^i_n(LD) + \hat{S}^i_n(BD)\right) \cdot RCF_{M/S_n} = \\ = \hat{M}^i_{n-1} + \left(\hat{S}^i_n(LD) + \hat{S}^i_n(BD)\right) \cdot \frac{1}{RCF_{S_n/M}} \quad (4)$$

To compute RCF, observe that a time interval measured by two different clocks will result in different clock counter values. RCF can be calculated as the ratio of the clock counter values. The same time interval Δt is measured by clock 1 as $\Delta C_1 = \Delta t \cdot f_1$, and by clock 2 as $\Delta C_2 = \Delta t \cdot f_2$. Then, if the propagation time (latency) of messages was always the same, RCF could be precisely computed as $\Delta C_2 / \Delta C_1$ of two consecutive messages, since then their inter-departure and inter-arrival interval would be the same. In reality this is not the case, so a number of obtained RCF values have to averaged, to remove as far as possible the zero-mean

error due to the latency variation. The effects of congestion are minimized by assigning highest priority to the IEEE 1588 messages.

In the rest of this section, we introduce two methods which estimate $RCF_{S_n/S_{n-1}}$ and $RCF_{S_n/M}$ respectively RCF_{M/S_n}. Both methods are based on the timing information carried in PTP messages, but use it in different ways.

3.1 Peer RCF Estimation

The RCF of neighboring elements can be estimated using two consecutive delay estimation messages, as depicted in Fig. 3.

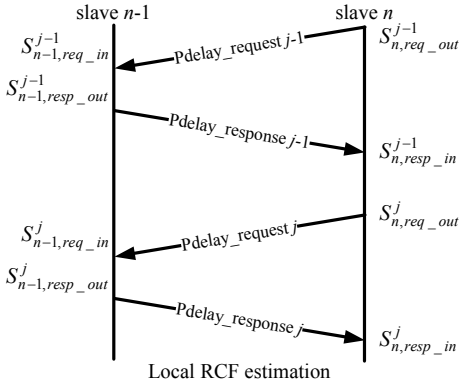


Figure 3: Peer RCF estimation.

$RCF_{S_n/S_{n-1}}$ can be calculated as:

$$RCF_{S_n/S_{n-1}} = \frac{S^{j}_{n,resp\_in} - S^{j-1}_{n,resp\_in}}{S^{j}_{n-1,resp\_out} - S^{j-1}_{n-1,resp\_out}} \quad (5)$$

Since the RCF calculated in (5) reflects the frequency difference of the neighboring elements and the estimation is only based on the message between neighboring elements, we call it peer RCF.

For the master time estimation, we need $RCF_{S_n/M}$ (or RCF_{M/S_n}), which can e.g. be calculated by using the peer RCFs calculated in the previous elements, i.e. slave 1 to $n-1$:

$$\begin{aligned} RCF_{S_n/M} &= \frac{f_{S_n}}{f_M} = \frac{f_{S_1}}{f_M}\cdot\frac{f_{S_2}}{f_{S_1}}\cdot\ldots\frac{f_{S_n}}{f_{S_{n-1}}} \\ &= RCF_{S_1/M}\cdot\prod_{i=2}^{n} RCF_{S_i/S_{i-1}} \end{aligned} \quad (6)$$

We call the RCF calculated this way cumulative RCF. To calculate $RCF_{S_n/M}$, slave n needs to collect all the peer RCFs in its uplink. This can be achieved recursively by modifying the Sync messages so that they contain not only the time information but also the cumulative RCF. So slave n calculates $RCF_{S_n/M}$ by multiplying the cumulative RCF contained in the Sync message from slave $n-1$ with its peer RCF, i.e.:

$$RCF_{S_n/M} = RCF_{S_{n-1}/M}\cdot RCF_{S_n/S_{n-1}} \quad (7)$$

3.2 Master RCF Estimation

The RCF can also be estimated using exclusively the timing information contained in the Sync messages. This is illustrated in Fig. 4.

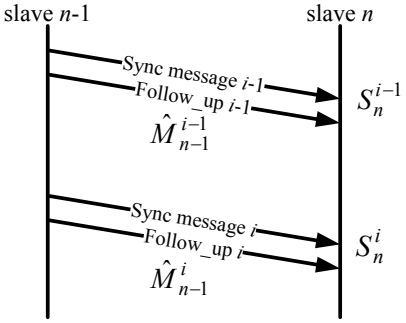


Figure 4: Master RCF estimation.

The estimation of RCF_{M/S_n} can be achieved by:

$$RCF_{M/S_n} = \frac{\hat{M}^{i}_{n-1} - \hat{M}^{i-1}_{n-1}}{S^{i}_n - S^{i-1}_n} \quad (8)$$

Since (8) calculates directly the ratio of the clock frequencies of the grand master and a slave, we call it master RCF calculation.

The frequency ratio of two neighboring slaves i.e. $RCF_{S_n/S_{n-1}}$ is then obtained as the quotient of the two master RCF values:

$$RCF_{S_n/S_{n-1}} = \frac{RCF_{M/S_{n-1}}}{RCF_{M/S_n}} \quad (9)$$

4 MASTER VERSUS PEER RCF

In this section, we will compare the two RCF calculation methods introduced in the previous section based on two criteria: convergence speed of the synchronization and the synchronization performance in the case of constant frequency drift.

4.1 Evaluation of Convergence Speed

Next we ask how much time a slave element needs to get the first correct timing information of the master since the start of the synchronization. Eq. (4) shows that an element has to have correct estimates of line delay and RCF_{M/S_n} in order to provide its downlink slave the correct master clock estimate.

Master RCF, RCF_{M/S_n}, is calculated using (8), and at least two Sync messages are needed. For correct line delay estimation, $RCF_{S_n/S_{n-1}}$ is necessary. It is calculated via (9) after RCF_{M/S_n} and $RCF_{M/S_{n-1}}$ are available. So, line delay estimates are correct after at least two Sync messages are received, and therefore a slave gets a correct master time estimate at the earliest after 3 Sync messages.

For peer RCF we first calculate $RCF_{S_n/S_{n-1}}$ using line delay estimation messages. Once $RCF_{S_n/S_{n-1}}$ is available, line delay can be calculated. Since $RCF_{S_n/S_{n-1}}$ and line delays are calculated locally, the estimation can be done in parallel, which accelerates the convergence speed. If the first Sync message is sent out when the first line delay is finished, it can carry all correct information to the slaves so that the slaves can estimate the master time correctly. Another advantage of peer RCF is its invariance to a change of (grand)master. The $RCF_{S_n/S_{n-1}}$ and line delay estimations are not affected, whereas in the master RCF calculation case, two Sync messages from the master are needed for the line delay estimation. So it always takes more time for synchronization via master RCF methods to converge if a new master is elected in the network.

4.2 Synchronization Performance for Constant Frequency Change

Next we compare the two RCF estimation methods' ability to track the frequency drift in the master.

We investigate the scenario where the master frequency is uniformly changing, e.g. due to heating, and the clock frequencies at the slaves stay constant. For analytic simplicity transmission and reception jitter is neglected, and hence the line delays can be perfectly determined. They are not neglected in our simulation in Section 6. Fig. 5 plots the frequency of each element as a function of the absolute time.

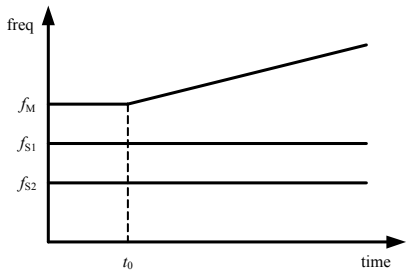


Figure 5: Frequency profile in master heating scenario.

The frequency of all elements is constant until t_0, then the frequency of the master element increases linearly. In the case where the frequency change depends nonlinearly of the underlying cause, our analysis can be seen as a local first order approximation.

Let the slope of the frequency change of the master clock be Δ_M. So the master's frequency follows:

$$f_M(t_i) = f_M(t_{i-1}) + \Delta_M \cdot (t_i - t_{i-1}) \text{ with } t_i > t_{i-1} > t_0 \quad (10)$$

where t_i is the time when the i^{th} Sync message is transmitted by the master. The counter value increase of each element from time t_{i-1} to t_i is obtained by integrating the element's frequency over the interval (t_{i-1}, t_i). For the slave element, whose frequency is constant, the counter value evolves as:

$$S(t_i) = S(t_{i-1}) + f_S \cdot (t_i - t_{i-1}) \quad (11)$$

For the master element, the counter value increase is calculated as:

$$\begin{aligned} M(t_i) - M(t_{i-1}) &= \int_{t_{i-1}}^{t_i} f_M(t) \cdot dt = \int_{t_{i-1}}^{t_i} \left[f_M(t_{i-1}) + \Delta_M \cdot (t_i - t_{i-1}) \right] \cdot dt \\ &= f_M(t_{i-1}) \cdot (t_i - t_{i-1}) + \frac{\Delta_M}{2} \cdot (t_i - t_{i-1})^2 \end{aligned} \quad (12)$$

Due to the linearity of the frequency change, (12) can be alternatively expressed as the product of the frequency in the middle of the time interval times the interval length, which is sometimes a more useful form:

$$M(t_i) - M(t_{i-1}) = f_M\left(t_i - \frac{t_i - t_{i-1}}{2} \right) \cdot (t_i - t_{i-1}) \quad (13)$$

The error study for the synchronization with master RCF calculation can be found in (Na 2007, 2008), where we derive the general expression for the error in the master counter estimate of slave N, at the time when it forwards the Sync message to slave $N+1$. For simplicity of derivation, here we let all line delays and bridge delays be constant in time (the general expression can be found in (Na 2008)). Then in the time period of unchanged frequency gradient the error in the master counter estimate of slave N takes the form:

$$M - \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} \approx \frac{\Delta_M}{2} \cdot \left[T \cdot \sum_{n=1}^{N} LB_n^i + \sum_{n=1}^{N} (LB_n^i)^2 \right] \quad (14)$$

where $M(t)$ is the true counter value at time t, and $\hat{M}$ is the estimated one.

We use Fig. 6 to illustrate the error in (14). The area under the linearly rising master frequency f_M corresponds to the true master counter. The white portion thereof is the estimated master counter value at slave 2, which is the sum of the master counter value in the original Sync message plus the product of local delay times RCF estimate at each slave. It is

based only on the master frequency curve between t_{i-2} and t_i, shown solid, and holds regardless of the further gradient, shown dotted. The gray area is the estimation error in (14), which has two parts. The 1st is proportional to the time elapsed between Sync messages, and to the total delay (grey rectangles in Fig. 6); the 2nd is the sum of squares of local delays (grey triangles in Fig. 6). We see that the propagation of Sync messages let the slave elements partially follow the recent-past frequency change of the master. As the calculation of RCF uses two consecutive Sync messages, slave elements learns the trend of the frequency change of the master from the counters delivered in these two Sync messages.

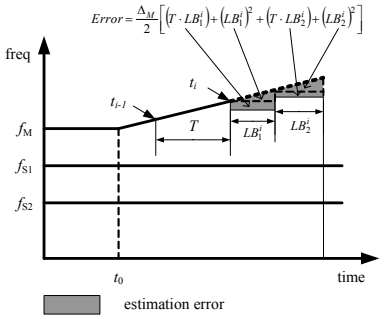


Figure 6: Sync error at the second slave (using master RCF).

For the synchronization with peer RCF, the Sync messages carry the cumulative RCF which is a product of the peer RCFs. Since the frequencies of all slaves stay constant, their peer RCFs, i.e. $RCF_{S_n/S_{n-1}}$ (n=2 … N) don't change and are:

$$RCF_{S_n/S_{n-1}} = \frac{f_{S_n}}{f_{S_{n-1}}} \tag{15}$$

A Sync message sent at time t_i by the grand master arrives at slave 1 at time $t_i + LD_1^i$. To estimate the master time, slave 1 needs the latest peer RCF and line delay estimates. Suppose that for some j with $t_0 < t_{j-1} < t_j \le t_i$, the estimation was done based on the delay response message received at $t_{j-1} + LD_1^{j-1}$ and $t_j + LD_1^j$. Then the peer RCF between slave 1 and the grandmaster is estimated as in (11) and (13):

$$\begin{aligned} RCF_{S_1/M} &= \frac{S_1(t_j + LD_1^j) - S_1(t_{j-1} + LD_1^{j-1})}{M(t_j) - M(t_{j-1})} \\ &= \frac{f_{s_1} \cdot (t_j - t_{j-1} + \delta_{LD}^{1,j})}{f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right) \cdot (t_j - t_{j-1})} \approx \frac{f_{S_1}}{f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right)} \end{aligned} \tag{16}$$

The error in this estimation is due to the small variation in line delays due to jitter. Inserting (15), (16) in (7), the cumulative RCF for each slave is:

$$\begin{aligned} RCF_{S_n/M} &= \frac{f_{S_1}}{f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right)} \cdot \frac{f_{S_2}}{f_{S_1}} \cdots \frac{f_{S_n}}{f_{S_{n-1}}} \\ &= \frac{f_{S_n}}{f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right)} = \left(RCF_{M/S_n}\right)^{-1} \end{aligned} \tag{17}$$

The master counter value estimated at each slave when it forwards the Sync message according to (4) with the help of cumulative RCF is:

$$\begin{aligned} \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} &= M(t_i) + \sum_{n=1}^{N} \hat{S}(LB_n^i) \cdot RCF_{M/S_n} \\ &= M(t_i) + \sum_{n=1}^{N} LB_n^i \cdot f_{S_n} \cdot \frac{f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right)}{f_{S_n}} \\ &= M(t_i) + \sum_{n=1}^{N} LB_n^i \cdot f_M\left(t_j - \frac{t_j - t_{j-1}}{2}\right) \end{aligned} \tag{18}$$

We have assumed that the line delay estimation is correct. The true master counter value corresponding to this time point is:

$$\begin{aligned} M\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} &= M\left(t_i + \sum_{n=1}^{N} LB_n^i\right) \\ &= M(t_i) + f_M(t_i) \cdot \sum_{n=1}^{N} LB_n^i + \frac{\Delta_M}{2} \cdot \left(\sum_{n=1}^{N} LB_n^i\right)^2 \end{aligned} \tag{19}$$

Comparing (18) with (19), the estimation error using cumulative RCF is:

$$\begin{aligned} M - \hat{M}_{S_N out}\Big|_{t_i + \sum_{n=1}^{N} LB_n^i} \approx \Delta_M \cdot \left(t_i - t_j + \frac{t_j - t_{j-1}}{2}\right) \cdot \sum_{n=1}^{N} LB_n^i + \\ + \frac{\Delta_M}{2} \cdot \left(\sum_{n=1}^{N} LB_n^i\right)^2 \end{aligned} \tag{20}$$

and is shown in Fig. 7 (grey area) for the 2nd slave.

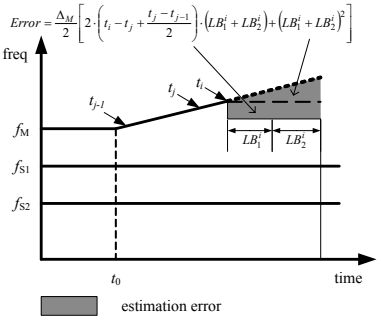


Figure 7: Sync error at the second slave (using peer RCF).

Compare the error expressions in (20) and (14): since $t_j - t_{j-1}$ (interval of delay messages) is usually greater than $T = t_i - t_{i-1}$ (interval of Sync messages), the 1st term in (20) is greater than the first term in (14). So are the 2nd terms. Our study shows that master RCF calculation performs better than peer

RCF calculation in estimating the master counter in the case of constant frequency drift in the master.

5 IMPROVED SYNTONIZATION AND SYNCHRONIZATION

In the previous section we have evaluated the performance of synchronization algorithms with peer RCF calculation and master RCF calculation. Peer RCF makes the convergence of synchronization faster, while master RCF tracks the frequency drift better. To improve the overall performance of PTP synchronization, we propose a method which combines both estimation methods.

The improved synchronization algorithm contains two phases: initial phase and steady phase. The initial phase starts at a restart. Each slave estimates peer RCF, i.e. $RCF_{S_n / S_{n-1}}$ and line delay locally using (5) and (3). The 1st Sync message is generated by the master.

Between the 1st and the 2nd Sync message there are 2 options. Either cumulative RCF is transmitted in the 1st Sync message, in which case the slave elements calculate the cumulative RCF using (7) and then estimate the master counter value using (4). This has the advantage of a convergence sped up by one Sync interval, at the cost of allowing for transmission of cumulative RCF, for which there is however enough free space in the Sync message. Or, nothing is done until the 2nd Sync message.

The steady phase begins with the 2nd Sync message. Since two Sync messages are now available, master RCF can be estimated as in (8). From the 2nd Sync message onward, master RCF will be used in (4) for the estimation of master counter value and the cumulative RCF will not be propagated any more. For the line delay estimation, we still use peer RCF calculation.

By using peer RCFs and possibly cumulative RCFs in the initial phase, the time for convergence is shortened. In the steady phase, using master RCF provides higher synchronization accuracy.

6 SIMULATION RESULTS

We have developed a MATLAB simulation tool to test and analyze the synchronization performance of IEEE 1588 in a line with cascaded bridges. We have used this tool to simulate PTP in PROFINET (Jasperneite 2005). The model parameters, summarized in Table 1, are given by the Siemens Automation & Drive department. Comparative runs with other parameters have yielded similar results. In the simulation, the master temperature increases with a speed of 3K/s, resulting in a frequency drift of 3ppm/s. The temperature change starts at 20s, increases from 25°C to 85°C in the next 20s, then stays constant again. The frequency of slave elements never changes.

Table 1: Simulation settings.

Parameter	Value
Number of elements	80
Nominal Frequency	100MHz
Cable delay	100ns
Bridge delay	Uniform [5 15]ms
Temperature change	3K/s
Frequency Change	1ppm/K
Interval of Sync Message	32ms
Interval of Pdelay_request	8s
Interval of RCF calculation	200ms
Number of RCF averaging	7

In Fig. 8 we test the PTP synchronization with master RCF calculation, showing the synchronization errors for slaves 19, 39, 59 and 79. We observe large errors at the beginning of the synchronization. As discussed in Sect. 4.1 each element doesn't get the correct master counter value until the 3rd Sync message arrives. There is a biased error between 20 and 40s, which is caused by the constant frequency change in the master clock.

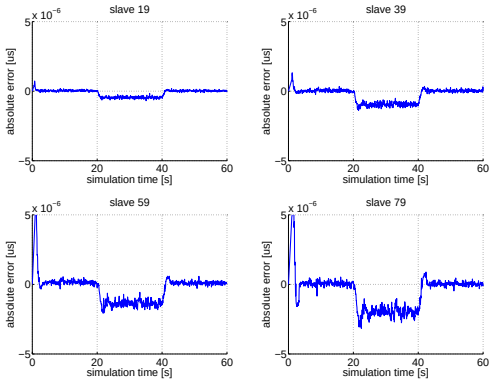


Figure 8: Synchronization error when using master RCF.

In Fig. 9 we repeat the simulation with peer RCF calculation. We see that the synchronization using peer RCF has a very smooth initial phase as the 1st Sync message already contains the correct information of RCF (by cumulative RCF) and line delay estimate. However, if we look at the time period between 20s and 40s when the frequency drift

in the master clock takes place, we observe a larger error (deviation from 0) than for the same slave in Fig. 8, which validates our analysis in Sect. 4.2.

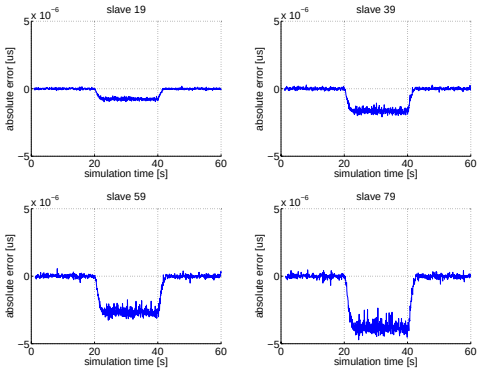


Figure 9: Synchronization error when using peer RCF.

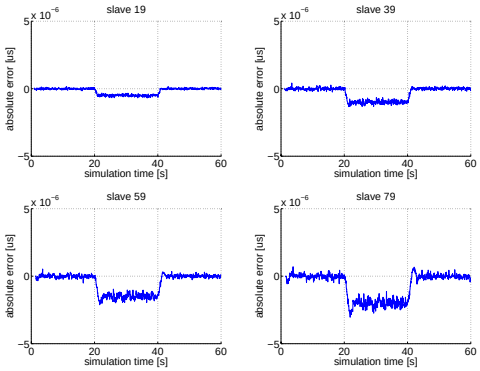


Figure 10: Synch. error with peer RCF and master RCF.

In Fig. 10 we simulate the algorithm where peer RCF and master RCF are combined. We see a better initialization compared with the result in Fig. 8 and smaller error during the frequency drift compared to Fig. 9. This confirms the improved performance we expect for the combination of peer and master RCF calculation.

7 CONCLUSIONS

In this paper, we have introduced two methods that calculate the frequency ratio of two elements based on the information contained in PTP messages. The *peer* RCF calculation utilizes delay messages locally and leads to fast convergence. The *master* RCF calculation use Sync messages to calculate the frequency ratio between the grandmaster and the slave. It performs better when there is constant frequency drift in the master clock. It has been shown both through analysis and simulation results that a combination of both methods improves synchronization performance. Future work could illuminate the optimal combination of master RCF and peer RCF estimation for widely different system parameters or system requirements.

REFERENCES

Chen B., Chen Y.P., Xie J.M., Zhou Z.D., Sa J.M., 2005. Control methodologies in networked motion control systems. In: *Proc. of 2005 International Conference on Machine Learning and Cybernetics*, Guangzhou.

IEEE, 1997. *Standard for LAN/MAN CSMA/CD Access Method*, IEEE, New York.

IEEE, 2002. *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*. IEEE, New York. ANSI/IEEE Std 1588-2002.

IEEE, 2007. *Standard for Local and Metropolitan Area Networks - Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks*, IEEE, New York.

IEEE, 2007. *IEEE P1588^{TM} D2.2 Draft Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE, New York.

Jasperneite J., Shehab K., Weber K., 2004. Enhancements to the time synchronization standard IEEE-1588 for a system of cascaded bridges. In: *Proc. of 2004 IEEE International Workshop on Factory Communication Systems*, Vienna.

Jasperneite J., Neumann P., 2004. How to guarantee real-time behaviour using Ethernet. In: *Proc. of 11th IFAC Symposium on Information Control Problems in Manufacturing (IN-COM2004)*, Salvador-Bahia.

Jasperneite J., Feld J., 2005. PROFINET: an integration platform for heterogeneous industrial communication systems. In: *Proc. of ETFA 2005, 10th IEEE International Conference on*, Catania.

Mills, D.L., 1989. Internet time synchronization: The network time protocol. *Network Working Group Request for Comments*.

Mills, D.L., 1994. *Precision synchronization of computer network clocks*. Available: citeseer.nj.nec.com/ mills94precision.html.

Na, C., Obradovic D., Scheiterer R.L., Steindl G. and Goetz F.J., 2007. Synchronization Performance of the Precision Time Protocol. In: *2007 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication*, Vienna.

Na, C., Obradovic D., Scheiterer R.L., Steindl G. and Goetz F.J., 2008. Enhancement of the Precision Time Protocol in Automation Networks with a Line Topology. Submitted to: *IFAC 2008*, Seoul.

Nieminen, J., 2007. Synchronization of Next Generation Wireless Communication Systems. *Master thesis*, Helsinki University of Technology, Helsinki.