20th IMEKO TC-4

INTERNATIONAL SYMPOSIUM

18th IMEKO TC-4

INTERNATIONAL WORKSHOP ON ADC AND DAC
MODELLING AND TESTING


BENEVENTO, ITALY

SEPTEMBER 15 – 17, 2014

PROCEEDINGS

IMEKO

IMEKO TC-4 Benevento 2014

Università degli Studi del Sannio

20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Hybrid time synchronization for Underwater Sensor Networks

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Abstract – **Time synchronization is an important part of distributed applications over a sensor network. In this work we investigate time synchronization problems over a shallow UWSN, taking into account all main communication challenges of the water channel and observing its behavior in simulation and real tests. It is proposed an hybrid frame based time synchronization using both, LFM and OFDM communication with channel impulse response equalization. Simulation results show how Hybrid synchronization outperforms existing synchronization protocols and how these results are affected in real water tests.**

I. INTRODUCTION

Underwater communication has recently drawn attention from industry and research in the way that many processes can be interconnected and share valuable information. In order to perform this information exchange and create collaborative tasks, time synchronization is one of the main fields to study in Underwater Sensor Networks (UWSN) for distributed applications such as target tracking, data acquisition systems or acoustic beam-forming.

Many cabled and terrestrial wireless synchronization protocols are capable to provide high precision time offset estimation. They are widely used in many systems which need high precision time synchronization and do not have access to a GPS reference. The best known protocol and most common in our daily lives is Network Time Protocol (NTP), which synchronizes over Ethernet our computers. Another cabled synchronization system that is used in industrial applications because of its high synchronization precision is Precision Time Protocol (PTP) IEEE 1588 standard. This protocol has been ported by [1] to a terrestrial wireless network with timing accuracy below few microseconds. The main issue is that all these synchronization protocols do not face some of the main problems of the underwater channel.

Hence, it is necessary to provide underwater time synchronization due to the lack of GPS signal under 1 meter of water column because the high attenuation of the electromagnetic waves over the water channel. Actually there are few protocols capable to provide time correction to underwater sensors, but some of them do not take into account all the underwater physical layer communication challenges, or they can be improved by including parameters such as Doppler Effect, drift between clocks or propagation time variability, which become significant with high latency communication caused by low celerity of sound in water channel.

In this work is presented a first approach of an hybrid synchronization system mixing Linear Frequency Modulation (LFM) for precise time arrival detection and Orthogonal Frequency Division Multiplexing (OFDM) communication with Channel Impulse Response (CIR) equalization in order to correct drift, Doppler velocity and detect propagation time variations between message exchange. This hybrid synchronization yields similar simulation results to [2], but in this case is carried out the study of synchronization in real water tests, and this results will be compared to the ones given by Time Synchronization for High Latency acoustic networks (TSHL) and Timins-sync Protocol for Sensor Networks (TPSN) underwater synchronization protocols which are the ones most used in actual underwater networks.

The paper will be divided in four main sections. First of all, in Section ii., are presented the challenges to face in UWSN synchronization. Before entering to our model design will be presented two of the main underwater synchronization systems and their weaknesses in subsection D. Then is presented the system model in Section iii., which will be used in Section iv. in order to perform simulations and water tests for verifying time error accuracy of the system. Conclusions and Future work will be discussed in the final paper publication.

II. PHYSICAL LAYER CHALLENGES IN HIGH LATENCY NETWORKS

When simulating underwater communications we can apply cabled synchronization algorithms techniques, but in underwater real tests, we will have some non-idealities to

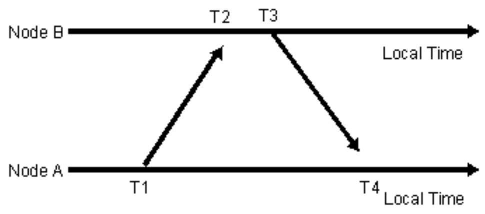

Fig. 1. Sender-Receiver synchronization.

face, and will be necessary to study how do they affect the system, in order to be able to go below hundreds of milliseconds of synchronization error.

As starting point, we take the basic message exchange based synchronization algorithm represented in Figure 1 which will be modified as we go deeper in this section.

This synchronization message exchange base, is used in the most of cabled and wireless message exchange based protocols.

In order to compute offset between nodes A and B are necessary four time stamps (T1,T2,T3 and T4), which also estimate propagation time between nodes, making possible a precise synchronization without non-idealities as is described in equation 1 for the offset (β) and equation 2 for the propagation time (τ). T2 and T3 are enclosed in the message in order to make them available at the slave side (node A):

$$\beta = \frac{(T2 - T1) - (T4 - T3)}{2} \tag{1}$$

$$\tau = \frac{(T2 - T1) + (T4 - T3)}{2} \tag{2}$$

Where propagation time τ is denoted by propagation time from A to B (τ_1) plus propagation time from B to A (τ_2) over two. This means that this algorithm assumes that both times are the same so τ is equal to the arithmetic mean between τ_1 and τ_2.

We also observe the dependence between time stamping precision and offset estimation. The way that this ideal hypothesis is affected by non-idealities is studied below.

First subsection A. studies time stamping error of each message arrival and departure and how does it affects the main algorithm. Time stamping issue is handled also in cabled synchronization algorithms, so we will discuss how do they solve this uncertainty and how it can be applied to UWSN. Then in sections B. and C. are introduced the main problems added by the water channel, which may be negligible in cabled networks but not in high latency ones such as underwater sensor grids.

A. *Time stamping*

Considering a non deterministic time stamping for the message input or output, equations 1 and 2 are reformulated as:

$$\begin{aligned}\beta(\varepsilon) = &\frac{(T2+\varepsilon2) - (T1+\varepsilon1)}{2} + \\ &- \frac{(T4+\varepsilon4) - (T3+\varepsilon3)}{2}\end{aligned} \tag{3}$$

$$\begin{aligned}\tau(\varepsilon) = &\frac{(T2+\varepsilon2) - (T1+\varepsilon1)}{2} + \\ &+ \frac{(T4+\varepsilon4) - (T3+\varepsilon3)}{2}\end{aligned} \tag{4}$$

Where $\varepsilon1$, $\varepsilon2$, $\varepsilon3$ and $\varepsilon4$ stands for the time stamp uncertainty in both message input or output. This uncertainty use to be around hundreds of microseconds for software time stamps and some nanoseconds for hardware time stamps such as the one presented in PTP. Hardware time stamping has bigger precision due to messages are referenced to a time base in the Medium Access Controller (MAC), avoiding this way unpredictability introduced by OS or medium access algorithms, what can be about hundreds of microseconds.

Hence, is necessary to port the mechanisms used in cabled time synchronization algorithms for hardware time stamping to the underwater communication algorithms in order to have similar performance.

A common workaround for solving time stamping ambiguity is to use a preamble before each frame, which will be recognized by the MAC making possible time reference acquisition by hardware before any processing of the frame.

B. *Propagation time variation*

Regardless of time stamping issue, we will notice propagation time variations between $\tau1$ and $\tau2$. This alteration may be due to different communication paths in cabled communications.

Analogously it happens with a multi path channel such as the underwater one, with the further difficulty added by moving nodes in a communication with high latency, what increase propagation time variation ($\Delta\tau = \tau1 - \tau2$).

Developing equations 1 and 2 with $\tau1 \neq \tau2$ we get:

$$\beta(\Delta\tau) = \beta_{ideal} - \frac{\Delta\tau}{2} \tag{5}$$

$$\tau(\Delta\tau) = \tau1 + \frac{\Delta\tau}{2} \tag{6}$$

Where the real clock offset β_{ideal} will estimated in β with an error equal to: $\frac{\Delta\tau}{2}$.

C. *Clock drift and Doppler effect*

Besides clock offset between two nodes, there is another timing factor that must be taken into account when synchronizing two clocks. This is drift between clocks, which is the variation between a clock frequency compared to an ideal one given in parts per million.

This factor gets importance as the network has bigger latency. The reason of this assumption lies in the amount of time that the protocol needs to compute the offset, while synchronization is being computed one clock is drifting, so by the end of the computation of the offset, we will have the initial offset to be compensated plus the drift of this second clock. Therefore, with small latency network, time offset estimation is computed fast enough for neglecting the error introduced by the drift, as happens in NTP protocol. But, in high latency networks, let's assume few seconds of propagation time, we can have an error caused by drift equal to hundreds of microseconds at the end of the offset estimation protocol.

In literature most of synchronization protocols manage time stamping issue, some of them also offer solutions for propagation time variations, but it is quite difficult to find studies of the drift compensation if we do not go deep in high precision synchronization protocols, such as IEEE-1588 (PTP) or in underwater networks TSMU scheme and TSHL protocol.

The main issue of estimating clock drift in non-cabled networks resides in the mobility of the nodes. When a node have velocity relative to the medium it is affected by Doppler effect, consequently it suffers sampling base time variation. As described in [3] this sampling time variation is also produced by drift, what increase the difficulty to estimate drift and Doppler velocity separately.

Equations 7 and 8 describe how β and τ are modified introducing clock drift (θ) affecting only one of the clocks.

$$\beta(\theta) = \frac{(T2 - T1(1+\theta)) - (T4(1+\theta) - T3)}{2} \tag{7}$$

$$\tau(\theta) = \frac{(T2 - T1(1+\theta)) + (T4(1+\theta) - T3)}{2} \tag{8}$$

D. *Related work*

Despite the growing interest on the UWSN during the last years, there are not too much underwater wireless high precision synchronization algorithms in literature.

TSHL is designed for high latency acoustic networks. It splits time synchronization in two phases. In the first phase they estimate the clock drift to a centralized time-base, and the second one determine offset by a message exchange protocol. In order to perform clock drift estimation is computed a linear regression over several beacon messages sent within a known time. And time deviation of the message arrival at the receiver side is assumed to be caused by clock drift. The main problem of this assumption is that instead of having all the nodes completely quiet, multi-path and water currents will affect the messages propagation time between nodes, causing a wrong measurement of clock drift.

Table 1. Notation Summary

β	Estimated clock offset
β_{ideal}	Real clock offset
τ_1, τ_2	Propagation delay of A-B and B-A
$\Delta\tau$	$\tau_1 - \tau_2$
$\varepsilon 1$, $\varepsilon 2$, $\varepsilon 3$, $\varepsilon 4$	Time stamp uncertainty
θ	Doppler scaling
Δtp	Bidirectional propagation time
t_0	Initial time
t_{wait}	User defined time between messages

Both PTP and TSMU protocols estimate drift jointly with Doppler effect, and then by analyzing Doppler scaling, they are capable to determine which part is due to Doppler velocity and to clock drift, as described in [2]. So they are capable to improve TSHL or TPSN performance by introducing Doppler movement to the offset and propagation time equations. However, PTP is designed for cabled networks, so it cannot work directly with high propagation times, and TSMU is an scheme which had not been tested in real tests where the complexity of Doppler scaling estimation increase due to multi path noise.

III. HYBRID TIME SYNCHRONIZATION MODEL

In this section we present an alternate time synchronization algorithm that can overcome main underwater channel challenges. For this first approach, Doppler scaling effects are not taken into account since they will be presented in a future work.

Thus, main issues discussed in this paper will be frame time stamping and propagation time variations detection, and how to feedback these parameters to the system.

Output framing detection or time stamps, can be performed by most of commercial DAQ systems due to they are capable to trigger DAC output at a certain time with a HW pulse, what means that the output time stamping has a deterministic and negligible error.

Input framing time stamping, is performed by main communication algorithms in order to detect where is the raw data placed inside of an acquisition window, this way it can be sent to a DSP and demodulate desired data. Then, these algorithms can be used to detect the exact arrival time. This is done by performing firstly a coarse estimation in order to window a 'Pilot' signal [4], and then analyze Channel Impulse Response (CIR) of this Pilot for

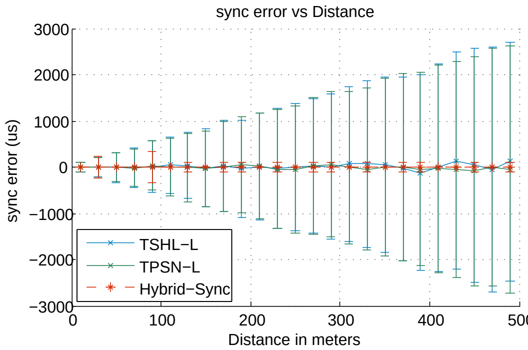

Fig. 2. Quiet shallow water synchronization.

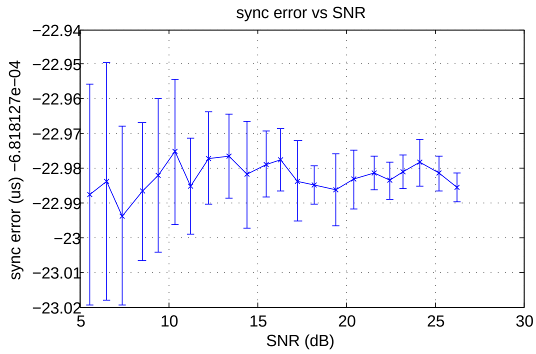

Fig. 3. SNR vs synchronization performance

detecting, with 1 sample of error, first sample arrival.

Consequently, this system will reach a maximum frame detection precision equal to $\frac{1}{BW}$. This accuracy will be translated to seconds by computing the inverse of the signal Band Width (BW). A bigger BW will result in better timing accuracy. This could lead us to increase the signal BW to improve timing precision. The problem, is that we must keep in mind that boosting the BW will produce communication robustness to decrease due to Inter Symbol Interference (ISI), so it is necessary to find a deal between this robustness and synchronization accuracy.

The proposed workaround in this paper is to use an LFM (chirp signal) in addition to CIR frame arrival detection. This will allow us to keep low BW for communication and increase it in the LFM. Thus LFM can be used in order to detect frame arrival by performing the correlation between received signal and the expected chirp, then is performed center of gravity computation, this way is possible to narrow the frame detection around the estimated value given by correlation algorithm, and finally, CIR is used to detect signal arrival without the necessity of using a threshold, due to Schmidl & Cox algorithm properties, and also it will be used to correct carrier frequency offset which is modulating main signal and the LFM.

We can send the global time stamp in the acoustic OFDM message and detect frame arrival with the LFM corrected with CIR parameters.

IV. RESULTS

In this section results are discussed with Hybrid synchronization using LFM and CIR, in order to perform time stamping and estimate β and τ by adding both τ_1 plus τ_2 without the indeterministic time errors given by low BW time stamping procedure.

A. Workbench description

In order to perform real underwater tests, we are using water 'test tank' of dimensions 150 x 40 x 40 cm, with 1 meter separation between hydrophones. Since this study is not a matter of communication robustness but time synchronization and detection, we can extrapolate the results obtained in this test tank to shallow water sea communication in terms of timing accuracy.

For both simulations and real 'test tank' tests are used a master clock and a slave one. Since we are not implementing it in hardware, and for evaluation of the algorithms is necessary to know the delay between clocks a priori, we will use an slave base time relative to the master one, instead of separate base times.

As described in Figure 1, we define in a $Matlab^{®}$ script T1 as base time (t_0), T2 is given by T1 plus propagation time from slave to master (τ_1) plus an offset and drift between clocks, T3 is T2 plus a user defined time between messages (t_{wait}), and finally T4 will be determined by T1 plus both propagation times ($\Delta tp = \tau_1 + \tau_2$) plus the user defined time between messages. Equations from 9 to 12 describe how time stamps are defined in the script in order to simulate two different clocks.

$$T1 = t_0 + \varepsilon_1 \tag{9}$$

$$T2 = T1 + tp_1 + \beta_{ideal} + \theta_{ideal} + \varepsilon_2 \tag{10}$$

$$T3 = T2 + t_{wait} + \varepsilon_3 \tag{11}$$

$$T4 = T1 + \Delta tp + t_{wait} + \varepsilon_4 \tag{12}$$

With this definition, we are able to simulate time stamp uncertainty, clock drift and offset in the script, and verify the proper detection of our algorithms of each one of the mentioned time synchronization uncertainties.

B. Main results

Here we present results given by simulations, which are compared to TPSN and TSHL, and also real tests demonstrating Hybrid-sync performance.

Comparison with TPSN and TSHL were made by implementing a TPSN-like (TPSN-L) and TSHL-like (TSHL-L) protocols in $Matlab^{®}$ simulations. By this nomenclature we mean that the simulation captured the essence of both protocols as described in [5], but has been included uncertainty due to propagation time variations for this work, what lead this protocols to bigger uncertainty in synchronization precision.

Figure 2 is a simulation comparing TPSN-L, TSHL-L and Hybrid synchronization performance. For this test was used a propagation time variation with an standard deviation of 15 Parts Per Million (PPM) relative to the distance between nodes.

Due to the fact that we can estimate propagation times with higher precision, is possible to compensate $\frac{\Delta\tau}{2}$ resulting in Hybrid synchronization outperforming actual systems time offset and delay estimation accuracy.

Then, in Figure 3 is performed an underwater test in the 'test tank' described in subsection A.. This verifies the proper performance of the synchronization algorithm over SNR variations, we can observe the mean estimation accuracy of the synchronization algorithm and the variance due to propagation time variations.

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