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Time Delay Estimation in Mobile Sensors for Underwater Networking

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Abstract

The time synchronization between any two sensor nodes in an Ad-hoc Underwater Sensor Networks (UWSNs) could be destroyed due to motion of these wireless sensors which induced Doppler shift. This synchronization obstacle can be sorted out by exploiting the mobility between sensor nodes. In the proposed system, the time delay between sensor nodes in both divergence and convergence scenarios are estimated based on estimating the time scaling factor. An improvement is introduced in terms of packet structure in order to challenge the channel effect and accurate estimation over the speed up to ±2 m/s. To verify the proposed system robustness, different levels of the nodes speeds have been considered in the simulation. Obtained results show that the proposed system is robust against severs channel conditions.

Keywords: UWSNs, time delay, time synchronization**.**

1. INTRODUCTION

Underwater acoustic communications (UWC) are a swiftly growing field of engineering and research as the applications, such as exclusively military, and extending into commercial scope [1]. Data transmission in the underwater environment between sensor nodes can be adopted by different signal types. For instance, radio signals, fiber optics, and acoustic. A radio signal requires an antenna of large size (because the carrier frequency is low) and consumes a massive amount of energy [2]. Light is not propagated over long distance hence it requires network infrastructures.

Thus, acoustic signal is the only and most appropriate way for long-range communication in the underwater medium with common water lucidity [3].

Due to unique characteristics of UWSNs, firstly low propagation speed of acoustic signal UWSNs up to 1500 m/s that lead to a considerable propagation delay in contrast with radio frequency signals [4]. Secondly, the limited sensor nodes mobility due to the nature of ocean, or human made consequent in an obstacle in estimating the propagation delay [5]. It causes variation in propagation delay in both exchanging by two-way message and among transmissions of multiple messages between sensor nodes [5].

Most of the protocols adopted to work with terrestrial sensor networks for the purpose of synchronization, such as Timing-sync protocol for sensor networks (TPSN) [6], flooding time synchronization protocol (FSTP) [7] and Reference-Broadcast Synchronization (RBS)[8], are invalid to work in UWSNs, since the propagation delay is ignored according to their assumption. The sensor node movements of the Autonomous Vehicles or the node movements due to currents destroy the timing synchronization between sensor nodes. This makes the synchronization of Underwater Acoustic Sensor Networks (UWASNs) very challenging.

A time synchronization protocol for mobile underwater sensor networks (TSMU), supported by the Kalman Filter proposed in [9], TSMU greatly progress the estimation of dynamic propagation delay through exploring the Doppler Effect .A time synchronization protocol which is novel for moveable UWSNs, called Mobi-Sync proposed in [10] that employs spatial correlation and geometrical relationship for propagation delay estimation with beacon nodes supplied with speed sensors. Furthermore it requires that ordinary nodes able to communicate to at least three beacon nodes in one hop. Moreover execution of twice linear regression for estimation skew and offset. The effect of node mobility on the clock skew was analyzed and designed in [11] through a novel time synchronization technique , called “Mc-Sync”, that counteract the effect of node mobility by exploiting two mobile reference nodes and designing trajectories for these nodes in UWSNs. Mc-Sync could improve time synchronization precision and eliminate the effect of node mobility; therefore, it was producing much better performance than existing techniques. A time synchronization technique for OFDM based on underwater acoustic communication (UAC) systems proposed in [12], this technique achieved by using only the guard interval (GI) to attain the time synchronization. Hence, no additive redundancy samples used for synchronization in this proposed method. In DA-Sync [13] the velocity estimated in physical layer through refining the Doppler shift and the delay was obtained based on the time and speed information collected in its data collection phases which is one of the five phases is considered to achieve the time synchronization in two-way message exchange.

Recently, many time synchronization algorithms, such as time synchronization for high latency acoustic networks (TSHL) [14], MU-Sync [15], Mobi-Sync [10], D-Sync [16], and DA-Sync [13] have been planned to transact with UWSNs and the issue of low propagation speed. However, these protocols disregard one issue or more. For example, the assumption of TSHL is based on fixed sensor nodes, which eliminate it to cope with mobile underwater network. While MU-Sync is designed for mobile underwater networks, but is consumable energy. In addition, the estimation of the time scaling factor in [16] was done in term of correlation of cyclic prefix part and its replica in the received signal in a long search to reach such estimation in frequency domain due to the rang of its search lays in the whole symbol in along its 2048 subcarrier and estimate the limited speed not exceed 0.25m/s.

In this paper, the time delay between the two nodes are estimated based on estimating the time scaling factor proposed in [17]. Furthermore, an improvement is added on this algorithm in terms of designing a packet structure to tackle the channel delay spread and to deal with different speeds in either expansion or compression. In addition, this improvement triggers the proposed system to work efficiently in estimating the speed up to ± 2 m/s at long delay spread compared with [17] where the maximum speed estimation was ± 0.25 m/s.

2. SYSTEM MODEL

The OFDM packet shown in Figure (1) was transmitted from sensor node to another. The OFDM is selected to achieve immunity against a frequency selective channel. Moreover, the autocorrelation of the OFDM frame with its cyclic prefix replica can be exploited to detect the maximum peak of lag under such type of channel.

The OFDM packet was transmitted from sensor node to another over distance between 200 to 500 m.

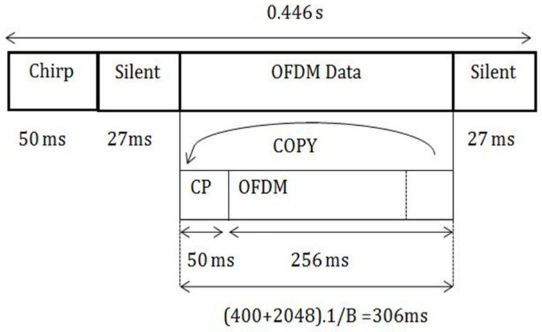

Figure1: Packet structure for 2048 subcarrier

The proposed structure contains preamble that include 50 ms LFM (Chirp) signal, 27 ms silent period followed by an OFDM frame of 306 ms for the purpose of simulation. The main reason for selecting the chirp signal due to its robustness against the Doppler shifts as well as its performance in environments corrupted by noise.

In order to satisfy the synchronization between two nodes, a simple approach of pairwise synchronization presented when one packet transmitted from node at known time T_{tr} to another at the time T_{sr} and since the latter is required to estimate the delay accurately in that transmission due to the channel affect. The proposed system parameters that was prepared to deal with the acoustic signal in order to delegate the effect of such transmission and used in MATLAB simulation are depicted in Table 1.

Table 1. Simulation Parameters

Parameter	Value
Distance between nodes	200-500 m
Transmission Frequency Band	8-16 KHz
Bandwidth	8 KHz
Maximum Delay Spread	50 ms
Number of sub-carrier	2048
CP interval	50 ms
Silent period	27 ms
Chirp period	50 ms
Symbol duration	256 ms
Number of bit per subcarrier	2 (QPSK bit)
Carrier Frequency	10KHz
Sampling Frequency	48KHz

3. SCALING FACTOR ESTIMATION

Estimation of scaling factor $(1 + \varDelta)$ plays an impact role in term of determining the time delay in the packet at the receiver side. Since the scaling factor affects all paths in the channel.

Sampling rate conversion by $(1 + \varDelta)$ is adopted to estimate effectively Doppler shift and any change in the sampling frequency which expand and/or compress the received signal, where the sampling interval T_{st} =

$\frac{T_{sy}}{N_c}$ in sender node where T_{sy} is the symbol time interval. Thus the received signal can be represented as [18]:

$$\boldsymbol{y_r(t)} = \boldsymbol{x_{tr}}\ [(1 \pm\ v_c)t\text{-}\tau_{pt}] \tag{1}$$

Where
v_c: Relative motion velocity of two nodes,
c : Propagation speed of acoustic signal,
τ_{pt} : Time varying path delay.

In discrete time modeling of the Doppler Effect can be presented as a complete scaling of sampling period of the received signal waveform [19]

$$\boldsymbol{y_r}[kT_{sr}] = \boldsymbol{x_{tr}}[k(1 \pm \Delta)T_{sr}] \tag{2}$$

Where,
k : An integer,
T_{sr}: Time interval of the received packet,
$\boldsymbol{x_{tr}}(kT_{sr})$: The sampled transmitted signal,
$\boldsymbol{y_r}(kT_{sr})$: The Doppler shifted sampled received signal.

And the (-) sign indicates a compression of the packet since the distance is decreased between the two nodes and vice versa. The compression and expansion model results in inescapable symbol timing shift Equivalent to Eq. (2) therefore the drifted samples in the received packet can be modeled as

$$T_{sr} = T_{st} \pm \delta \tag{3}$$

Where,
T_{sr} : Time interval of the received packet,
T_{st} : Time interval of the transmitted packet,
δ : drifted samples.

In this paper, two scenarios were counted:

1) **Expansion case:**
When the two nodes are diverge from each other due to the effect of sea current or due to the Autonomous Vehicles (AUVs) that pass close to the wireless sensor nodes, in such cases the Doppler shift will affect the transmitted packet. Consequently, an increasing in the of number of samples in the packet that deliver to receiver node which can be represented as

$$\hat{f_s} = f_s(1 + \frac{v_c}{c}) \tag{4}$$

This case is depicted in Figure (2).

2) **Compression case**:
When the two nodes are converge from each other due to the effect of the sea currents and/or by the effect of AUVs that passes nearly to sensor nodes and/or any other effect may cause such motion in nodes. In such cases the Doppler shift will affect the transmitted packet and compress it causing decreasing in number of samples in packet that deliver to receiver node [18]

$$\hat{f_s} = f_s(1 - \frac{v_c}{c}) \tag{5}$$

Where $\hat{f_s}$ is a new sampling frequency that results from the Doppler shift, and f_s is the sampling frequency as in the sender node. This case is shown in Figure (3):

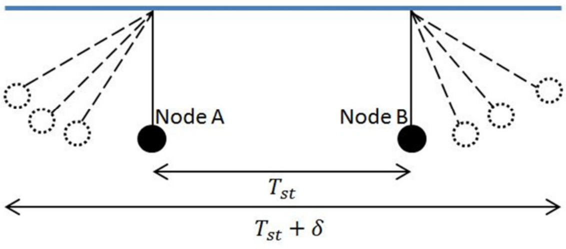

Figure 2: Expansion Scenario

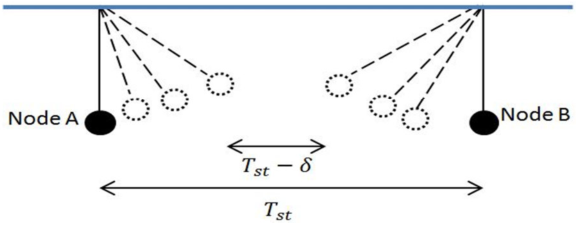

Figure 3: Compression Scenario

The drifted samples δ can be represented in the Figure (4). It can be noticed from this figure that once the signal is compressed, the sampling interval of the packet is reduced whereas in the case of expansion the same parameter (T_{st}) is increased by δ. In both cases, the delay between the two nodes is also affected. Exploiting these two scenarios, the delay can be estimated accordingly. However, the synchronization between the two nodes required to be manipulated. Hence it can be shown in the figure that in the ideal case the time should be (T_{st}).

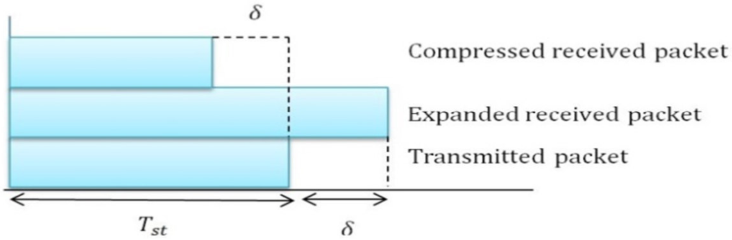

Figure 4: Drifted Samples in (compressed/expanded) Packet

The time scaling factor $1 + \Delta$ is required to be estimated to extract this drift that occurs in samples which causes the time delay.

The auto correlation method between cyclic prefix part of the symbol and its replica is adopted as in [17]. The cyclic prefix is inserted not only to avoid the long delay spread, but also to protect the OFDM data from ISI, thus long cyclic prefix is adopted.

The samples of the cyclic prefix with its replica are well correlated whilst the remaining samples are remaining mutually uncorrelated, the autocorrelation in receiver as following formula:

$$r_{yy}(\delta) = \sum_{i=1}^{N_c} y_r(i) y_r(i - \delta) \tag{6}$$

Where δ =0, $\pm 1, \pm 2, \pm 3, \ldots,$

The samples shift in the received packet can be approximated from the autocorrelation argument and it can be represented as:

$$\delta_{peak} = arg\, max\, r_{yy}(\delta) \tag{7}$$

It is assumed that the noise is AWGN $n_\circ$, then the magnitude of r_{yy} is maximum at the zero lag δ= 0, and the non-zero lag is

$$\delta = \delta_{peak} = \frac{N_c T_{st}}{[(1 + \Delta) T_{sr}]} \tag{8}$$

As shown in Figure (5) that demonstrates the first and second maximum peak of δ for correlation of the received signal in term of cyclic prefix.

Due to the channel effects such autocorrelation operation may be not accurate because the channel manifests itself as the signal amplitude. In addition, the relative motions of nodes can also disturb the detection of the autocorrelation peak.

In Figure (5) is to present that for speed of 0.5 m/s for example, the first and second peaks are appear, therefore the detection algorithm is possible. However, in most cases and due to an increasing speed there is a difficulty which proportional to the speed to detect these two peaks. Thus an ambiguity in estimating the samples drifts. In such case, the proposed algorithm spends more time to search for some parameters.

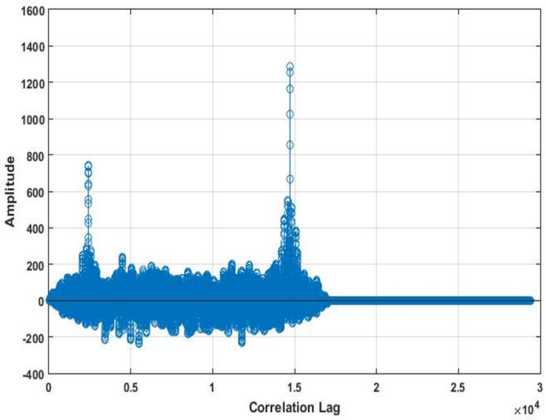

Figure 5: Autocorrelation of $|r_{yy}|$ for lag detection at 0.5 m/s.

Thus, the $(1+\Delta)$ time scaling factor is estimated by measuring the time lag δ_{peak} between the first and second peak of r_{yy}. And it is estimated from the phase Θ_{peak} of r_{yy} at the second maximum at (δ=δ_{peak})

$$\Theta_{peak} = -2\pi\,[(1+\Delta)\,T_{sr} - T_{st}]\,\delta_{peak} f_{\circ} \qquad (9)$$

Due to numerical errors and noise, the estimation of $(1+\Delta)$ from Eq. (8) and Eq. (9) may be different, but if:

1) The estimations are accurate and equal.

2) And if the sampling interval $T_{sr} = T_{st} / (1+\Delta)$.

Then the peak position of δ_{peak} in Eq. (8) becomes equal to number of subcarrier N_c and the phase Θ_{peak} in Eq. (9) becomes equal to zero.

Based on those conditions, Figure (6) shows the flow chart that can summarize the iterative approach at receiver to estimate the time scaling factor.

4. TIME DELAY ESTIMATION

In order to estimate the time delay between the sensor nodes, the time delay of the packet is exploited as:

$$D = \delta * T_{sy} \qquad (10)$$

Where $T_{sy} = \frac{1}{f_s}$.

This time delay between sensor nodes necessitates to be compensated. This requires adopting an inverse time scaling factor in the destination node based on the estimating time scaling factor. In such method; it is equivalent to altering the sampling rate of the signal by $(1+\Delta)$ in discreet time processing. However, in this paper it is focused on estimate the delay between sensor nodes without compensation.

In order to estimate the drift in sample need to estimate the Doppler shift that causes this drift and inverse it on the received signal if the compensation is considered.

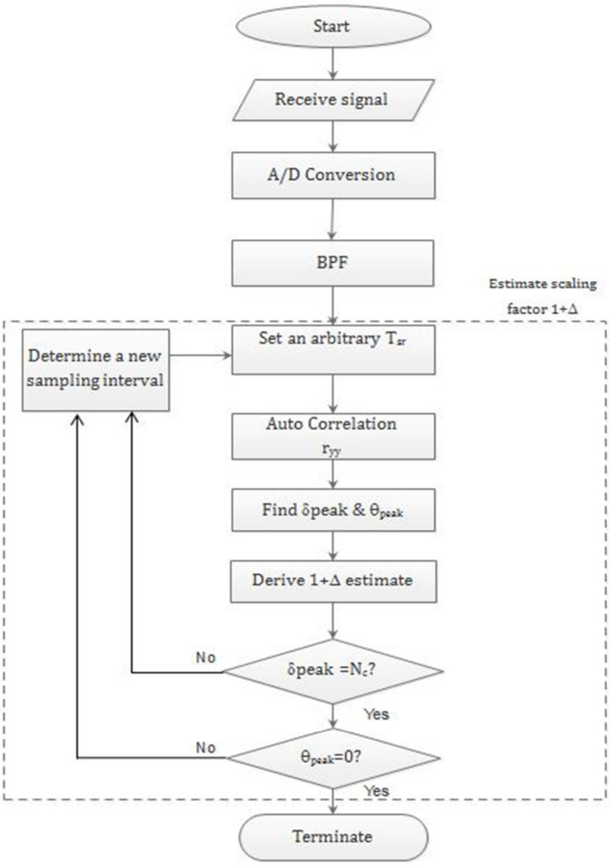

Figure 6: Scaling factor estimation based on iterative search

5. SIMULATION RESULTS

In the simulations, the transmitted packet was organized as 50 ms of chirp signal followed by 27 ms silent period and then the OFDM data as shown previously in this paper. A packet of 12288 samples were transmitted. The carrier frequency of the proposed system was set to 10 kHz while the sampling frequency of the system was $f_s = 4f_\circ$ .The guard interval in transmitted packet was set to be long to protect the packet from maximum delay spread of the channel.

It's worth mentioning that the packet structure was designed for the estimation purpose to tackle the time synchronization not to achieve the high data rate or take into consideration the channel efficiency.

In order to tackle the time synchronization the estimation are based on two scenarios: expansion which simulate the case of two nodes that diverged from another whereas the compression scenario simulate the convergence between the sensors nodes. Two parameters are considered in the proposed scenarios which includes time scaling factor, and the time delay over speeds of (±0.1 m/s to ±2 m/s)

The aforementioned parameters are compared with an alternative technique presented in [18] to evaluate the performance under the following channel characteristics [17]:

Underwater channel with maximum delay spread of 50 ms, coherence bandwidth 20Hz, and The channel impulse response over 9 path:

$h(n)=0.9\delta(n)+0.7\,\delta(n-1)+0.7\delta(n-2)+0.62\delta(n-3)+0.5\delta(n-4)+0.5\delta(n-5)+0.4\delta(n-6)+0.3\delta(n-7)$, and the time delays at n to $n-7$ be 0, 0.5, 0.95, 1.5, 23.3, 24.8, 47.8, 48.3 ms.

The system tested the previously mentioned scenarios as the following subsections:

A. *Scaling Factor Estimation*

In Figure (7), it can be shown that the time scaling factor is estimated of the sensor nodes in expansion scenario. The performance of the proposed system is perfectly adequate for the required needs.

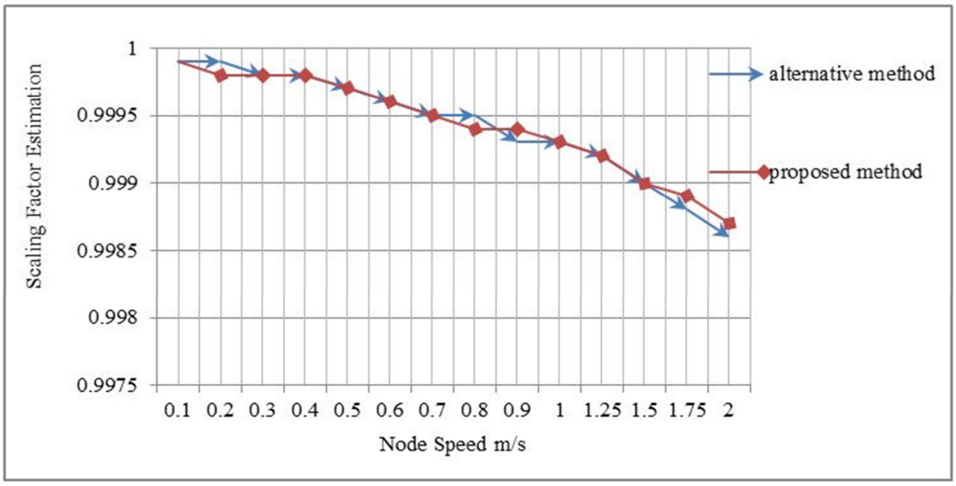

Figure 7: Estimation of Scaling Factor in Expansion case

In Figure (8), it can be shown that in case of nodes convergence (packet compression) the samples length is reduced based on the velocity variation. Thus, the time scaling factor is increased proportionally with the speed. It is noticeable that at a speed of (-0.1 m/s), the proposed algorithm accuracy is outperforming the alternative method, however, it's failed in estimating (-0.7 m/s) accurately compared with the alternative. This shortcoming in fractional samples is come from that reducing the symbol time which mitigate the immunity against the channel. Furthermore, reducing the symbol length in a fraction format in the proposed system will make the search on the correlation peaks less.

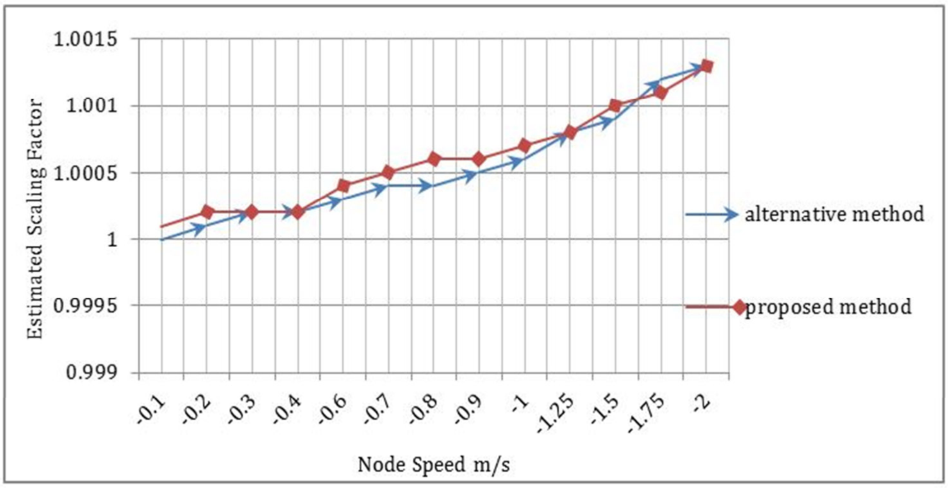

Figure 8: Estimation of Scaling Factor in Compression Case

B. *Time Delay Estimation*

In order to demonstrate the time delay estimation of the expansion scenario Figure (9) confirms that there is a strong relationship between the time scaling factor estimation and the time delay. It can be concluded that the deviation in the samples due to the relative motion between sensors nodes will be reflected on the time delay and consequently destroys the synchronization.

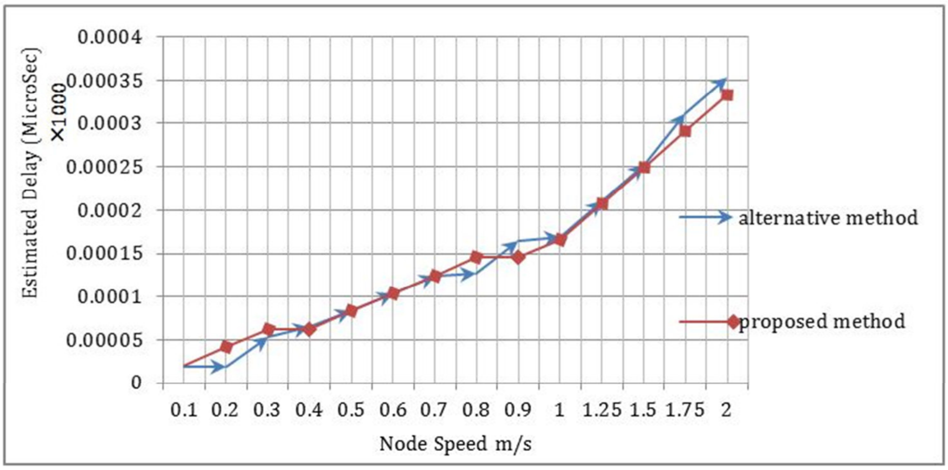

Figure 9: Estimation of Time Delay in Expansion Case

While Figure (10) confirms the previously mentioned about a strong relationship between the time scaling factor estimation and the time delay. The occurrence of time delay in the received packet is due to the compression in samples that happened by the effect of increasing the time scaling factor with increasing the nodes speeds and consequently destroy the time synchronization.

This time delay estimation required to be compensated in order to deliver reliable packet. Both methods succeeded in estimating the delay when the sensor nodes move toward each other or when the sensor nodes move apart from each other's.

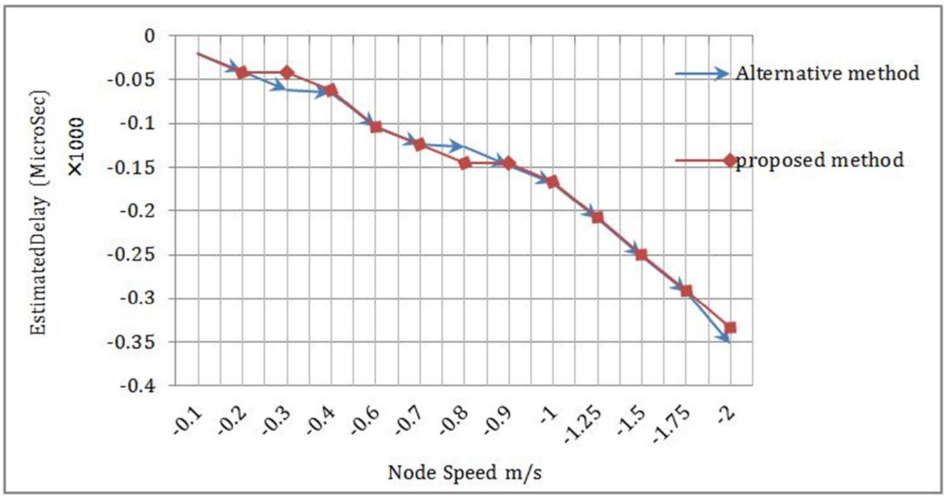

Figure 10: Estimation of Time Delay in Compression Case

6. CONCLUSIONS

This paper proposed a contribution in order to deal with time synchronization in different scenarios and velocities of the sensor nodes. The assumption was the speed variation between sensor nodes is linear.

Based on this assumption estimation of time scaling factor then time delay to cope with the synchronization impairments. An improvement is added to the proposed algorithm throughout adapting packet structure suitable for underwater links. However, it was presented that as the speed is increased, the accuracy of time scaling factor is decreased, thus requiring more signal processing techniques to combat this challenge.

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