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A Practical Distributed Lightweight Multi-Hop Time Synchronization Algorithm for Linear Wireless Sensor Networks Implemented on a PIC Based System with Realistic Experimental Analysis

Ahmet ERPAY[1], Md Abdullah AL IMRAN[*2], Ali KARA[3]

Abstract

Time synchronization is fundamental in the distributed networked systems, especially in Wireless Sensor Networks where a global time is essential to make sense of the events like collection of data and scheduled sleep/wake-up of nodes. There exists numerous time synchronization algorithms and techniques in the literature. Nonetheless, these proposed methods lack realistic experimentation of the synchronization process which is vital from the realization point of view. This study aims to bridge that gap by presenting a distributed lightweight time synchronization protocol implemented on an inexpensive PIC platform. Furthermore, PIC-based systems hadn't been investigated before and gives an idea of the simplicity of the algorithm. Experimental analysis was done to see the performance of the protocol. The core motivation of the experiments was to the study the impact of the environment (e.g. indoor, outdoors, temperature variations and interference) on the synchronization. Our findings show that temperature indeed impedes the synchronization accuracy.

Keywords: Clock drift and offset, Linear Wireless sensor network, Spanning tree network, Time synchronization.

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of small, low-power and inexpensive devices that can sense their surroundings such as temperature, humidity, sound and light [1]. WSN devices are called sensor nodes which can form spanning networks without any infrastructure. As these nodes are low-priced and have small form factors, they can be placed in diverse areas to monitor different type of environments on periodic time span or event based. The sensed data often in the form of current, voltage or their electrical derivatives is then sent to a certain node to be processed or routed to a base station. The collected data themselves are not useful if the time stamps are not attached.

Having said so, synchronization of time is essential in the WSN systems as well as all other networked systems. It creates global or reference time within the network. Data fusion, coordination of complex tasks or time division multiple access (TDMA) requires clock synchronization of the nodes [2]. Furthermore, the time synchronization is essential for power efficiency schemes; nodes wake up at precise time intervals with respect to other nodes and turn on/off their transceivers to reduce the power consumption. To synchronize time, there exists well-established methods like Network Time Protocol (NTP) [3] and Global Positioning System (GPS) [4]. NTP is the most widely used technique which necessitates internet availability and is complicated to implement due to computational requirements. GPS is costly and needs open-air to get the timing data from satellites.

These shortcomings lead to search for alternative solutions. The time synchronization process can be basically established by taking time measurements at each node as showcased in [5]. These measurements are susceptible to non-deterministic processes on the processor, communication modules and the environment. This is mainly because each node's local time is derived directly from the on-board oscillator, the inherent clock source. Therefore, the imperfection of the oscillator leads to time drift of the clock which accumulates to an overall offset, even when the clock was initially tuned. Needless to say, the oscillator based problems are related to manufacturing parameters and environmental conditions like temperature. As a result, these non-deterministic factors constraint the time synchronization process [6]. Additionally, these challenges contradict the requirements of synchronization schemes e.g. energy efficiency, scalability, precision and robustness where there may even be some trade-offs.

Since there exists hierarchical relationship between the nodes in a WSN system, it is possible to carry out synchronization using one of the two methods: single-hop or multi-hop. A node directly synchronizing with another node in the network is called a single-hop network. Alternatively, in a multi-hop network two nodes can only communicate via one or more intermediary nodes. The abundant synchronization methods can be categorized into these abovementioned network structures. Reference Broadcast Synchronization (RBS) is a single-hop method where master node broadcasts beacons and others benefit from that periodic beacon [7]. While RBS is freed of some sender-based uncertainty, it is not highly scalable. Flooding Time Synchronization Protocol (FTSP), a single-hop type, is presented in [8]. FTSP method can choose a root node dynamically which then broadcasts periodic messages in the network. Every node that receives this message rebroadcasts it while recording a time stamp at every received message. FTSP can accommodate network topology variations and is robust against failure of nodes. It is also energy efficient. Delay Measurement Time Synchronization (DMTS) is another single-hop type where the leader node broadcasts its time. Nodes hearing this message measures the delay and adds it to the leader's time to set their own clocks [9]. This technique is efficient and simple but precision is low. All single-hop type methods can be extended to multi-hop types with some minor changes. The multi-hop types are: Timing-Sync Protocol for Sensor Networks (TPSN) [10] which consists of two stages: discovery of levels and the system synchronization. In the level discovery phase, one node is selected as a root (level 0) and others are assigned different levels according to the closeness of the nodes. Nodes synchronize with pair-wise synchronization method from level 0 to the last level in synchronization phase. TPSN has good accuracy but does not allow dynamic topology. Lightweight Tree-based Synchronization (LTS) presented in [11] is constructed based on pair-wise synchronization. LTS has two different approaches: first one starts with creating a spanning tree with a sink node that has some reference point. Then it uses $(\mathrm{n}-1)$ pair-wise synchronizations for n nodes in the network. It is a flexible method but complexity can be high or low due to sink node. In [12], Average Time Synchronization (ATS) is presented where the average times are found for every node in the network using pair-wise message exchanges. In ATS, the sequence of averaging nodes is important and uses more energy compared to the classical pair-wise method. In Time-Diffusion Synchronization Protocol (TDP) there is an equilibrium-time that is agreed throughout the network by all the nodes and all local clocks are bounded around this time with a small deviation [13]. TDP is flexible and fault tolerant but needs high time for convergence.

The synchronization methods for both single and multi-hop networks with experimental analysis are presented in [14-17]. These tests were generally carried out in indoor environment and run in ideal conditions. It is seen that in many cases temperature, RF interference and realistic conditions were neglected for implementations on different motes. Additionally, various multi-hop topologies have been established experimentally with the exception of linear topology. It is worthwhile to note the possible application areas of the linear topology e.g. curvilinear entities like roads, tunnels and pipelines [5]. And experiments should be performed in harsh environments e.g. rural or sylvan areas where sensor nodes are usually used for practicality.

In this paper, we propose a linear topology featuring multi-hop time synchronization algorithm experimented on the rural area where different conditions were investigated. Our goal is to demonstrate time synchronization for practical usage. The remainder of the paper is structured as follows: Section II describes the methodology. Section III explains the experiment setup and results. Finally, the conclusions are drawn in Section IV.

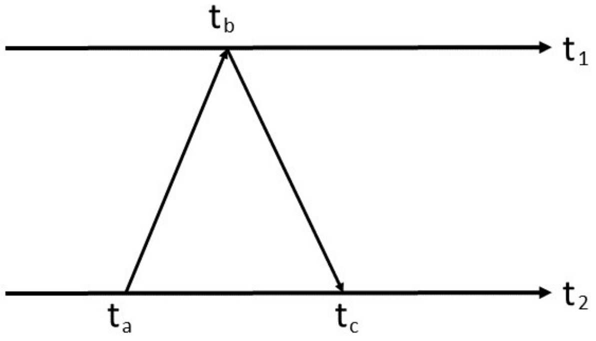

Figure 1 Two-way handshaking

2. METHOD AND IMPLEMENTATION

In this section, we present the time synchronization procedure along with the related implementation details including the system setup.

2.1. Time Synchronization Method

A sensor node's clock is generally represented by Equation 1.

$$t_a = \alpha_a + \beta_a t_u, \tag{1}$$

where t_a is local time, α_a and β_a are the respective offset and drift terms of the node a and t_u is the universal time [17-20]. In an ideal clock, α_a should be zero and β_a should be one; the local time is equal to the universal time (UTC). However, a real clock behaves differently. There is always an offset difference α_a and a clock rate difference which is β_a. Drift and offset values may vary disproportionately for each of the nodes while appearing to be constant for a short period of time. Assuming β_a does not change for a long period or has a very slow rate, Equation 1 can be extending to formulate the local time in a pair-wise synchronization as Equation 2.

$$t_1 = \alpha_{12} + \beta_{12} t_2 \tag{2}$$

On the above equation, parameters t_1 and t_2 are the clocks of nodes 1 and 2 respectively, α_{12} is the relative offset, β_{12} is the relative drift between two clocks. Assuming clocks of two nodes are well-synchronized, relative offset and relative drift should be zero and one respectively. However, since two nodes generally have different clock rates, these ideal values cannot be achieved. In essence, the time synchronization can be carried out if the relative offset and drift are known. A two-way handshake between nodes 1 and 2 can be performed to compute the relative offset and relative drift terms.

Referring to Figure 1, t_a is the local time of node 2 transmitted to node 1. Upon reception of this message at node 1, it responds with its own clock t_b. Node 2 then notes the time of reception, t_c, as it receives the reply from node 1. Finally a data-point or a tuple consisting of the three time-stamps (t_a, t_b, t_c) is formed. This data-point is then utilized by node 2 to make an estimate of node 1's clock. To improve the estimation, several data-points are taken. After enough data-points are recorded, equations 3 and 4 can be employed to put constraints on the relative drift term.

$$\beta_a(i) = \frac{t_a(i) - t_a(i-1)}{t_b(i) - t_b(i-1)} \tag{3}$$

$$\beta_b(i) = \frac{t_c(i) - t_c(i-1)}{t_b(i) - t_b(i-1)} \tag{4}$$

If the clocks' rates are equal, the time duration between consecutive points should be same; the numerator and the denominator ratio in the Equation 3 and 4 should be equal. Usually the drift limits, β_a and β_b, are in the vicinity of one. By using these drift values, upper and lower bounds of relative offset is found as of Equations 5 and 6.

$$\alpha_a(i) = t_a(i) - \beta_a(i) t_b(i) \tag{5}$$

$$\alpha_b(i) = t_c(i) - \beta_b(i) t_b(i) \tag{6}$$

The variation of relative drifts causes variation on α_a and α_b. Large variations of the relative drift can cause accumulations on the relative offsets. Using upper and lower values, estimation parameters α and β can be obtained as Equation 7 and 8.

$$\alpha(i) = \frac{\alpha_a(i) + \alpha_b(i)}{2} \tag{7}$$

$$\beta(i) = \frac{\beta_a(i) + \beta_b(i)}{2} \tag{8}$$

For n consecutive data-points (n − 1) different relative offset and relative drift values are estimated. Taking average of these estimated values eliminates the effect of random delays [17].

$$\alpha_{avg} = \frac{1}{n-1} \sum_{j=1}^{n-1} \alpha(j) \tag{9}$$

$$\beta_{avg} = \frac{1}{n-1} \sum_{j=1}^{n-1} \beta(j) \tag{10}$$

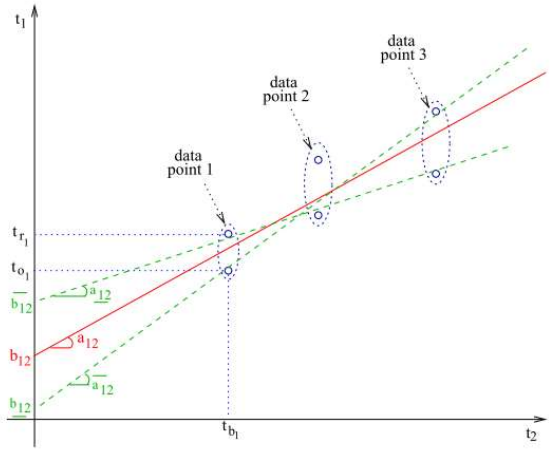

Figure 2 Limitation of the consecutive data-points

In Figure 2, from [10], the limitations of the consecutive data-points are illustrated. When all points are combined, the deciding line should pass between every t_b and t_r pair, where t_b and t_r are equal to t_b and t_c respectively in Figure 1. As the deciding line can not pass between all data points practically, this limitation method is not exactly applicable, however it gives general idea about how to handle data-points like averaging.

After estimation values are calculated, node 2 can update its clock to the reference clock i.e. the clock of node 1 by using Equation 11.

$$t_{2-estimate} = \frac{t_2 - \alpha_{avg}}{\beta_{avg}} \tag{11}$$

2.2. Implementation

Adaptation of synchronization protocol is performed on a PIC platform to investigate the extent of this protocol on a different platform. The *MikroE Clicker 2* board was chosen as the PIC platform where Microchip's *PIC18F87J50* is used as the microcontroller. In conjunction with this base board, the *CC1200* radio manufactured by Texas Instruments as the RF module, powered with Li-ion battery, a node is formed. It is worthwhile to note that, the constructed nodes in this context are used to verify the realization of the time synchronization algorithm rather than a fully functional system.

These nodes are distributed in a wide geographical area where one-hop distance ranges between 1-2 km. A representative distribution of n nodes is seen in Figure 3. Although distances between nodes vary, it is made sure that every node can establish one-hop communication with neighbor nodes.

Nodes' distribution resembles to a bus topology; however, a tree topology is more feasible in this case. Although the structure does not fit in any basic topologies, it is close to a spanning tree where it is a tree topology or mimics a partially connected mesh topology in some sense. There is a root (master) node and other nodes are connected to it preserving the hierarchical relationship in a single branch as shown on the Figure 4.

Figure 3 Distribution of nodes

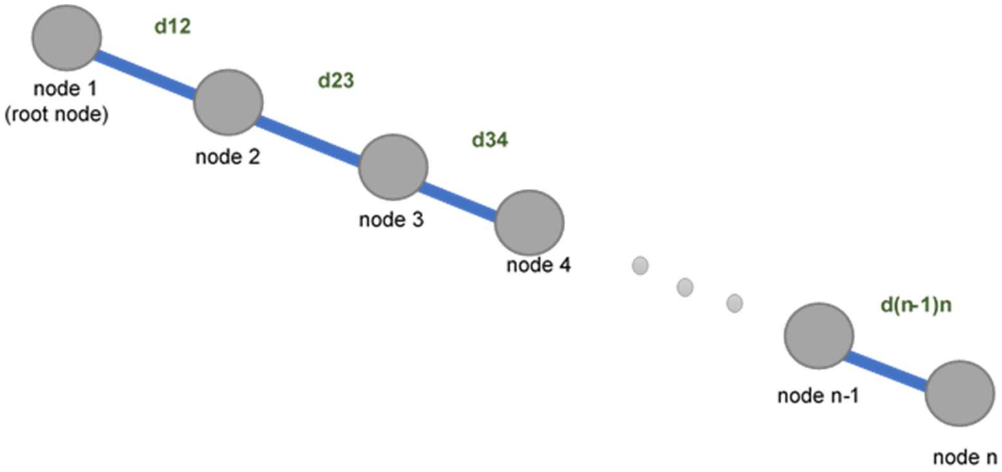

Figure 4 Spanning tree network of nodes

The time synchronization method is implemented such that a parent-child dual is constructed throughout the network from root node to the last node. Parent and child nodes perform pairwise synchronization, where child node updates its time with respect to its parent node. Every node in the WSN network is assigned a distinctive ID which help establish the parent-child relationship. All nodes except root and last node can be parent and child while root node is always parent and last node is always child.

Network's time synchronization process starts with the root node. Root node connects to the second node as a parent. The child node updates its current time with pairwise synchronization with respect to parent node, and then it disconnects from parent node. Then, the previously denoted child node becomes a parent itself whereas the next node down in the hierarchy becomes the child node. This iterative process continues until the last node updates its current time and disconnects from its parent. At the end of the process, the network is considered to be synchronized. Parent-child structure is the place where time synchronization algorithm is applied as explained in section 2.1.

3. EXPERIMENTS AND RESULTS

In this section, the experimental setup and the finding of the experiment are presented.

3.1. Experiments

Experimental setup is composed of two computers and six sensor nodes to demonstrate the discussed method in section 2.1. The general setup is shown in Figure 5 with the test procedure in Figure 6. Initially, the computers' clock is synchronized with each other. Then, first and sixth node are connected to the two computers to see and record their clocks using a custom developed computer application well-suited for this purpose. The program can detect IDs and initiate a time synchronization if ID equals to one which means that is the first node. Test procedure proceeds with the following steps:

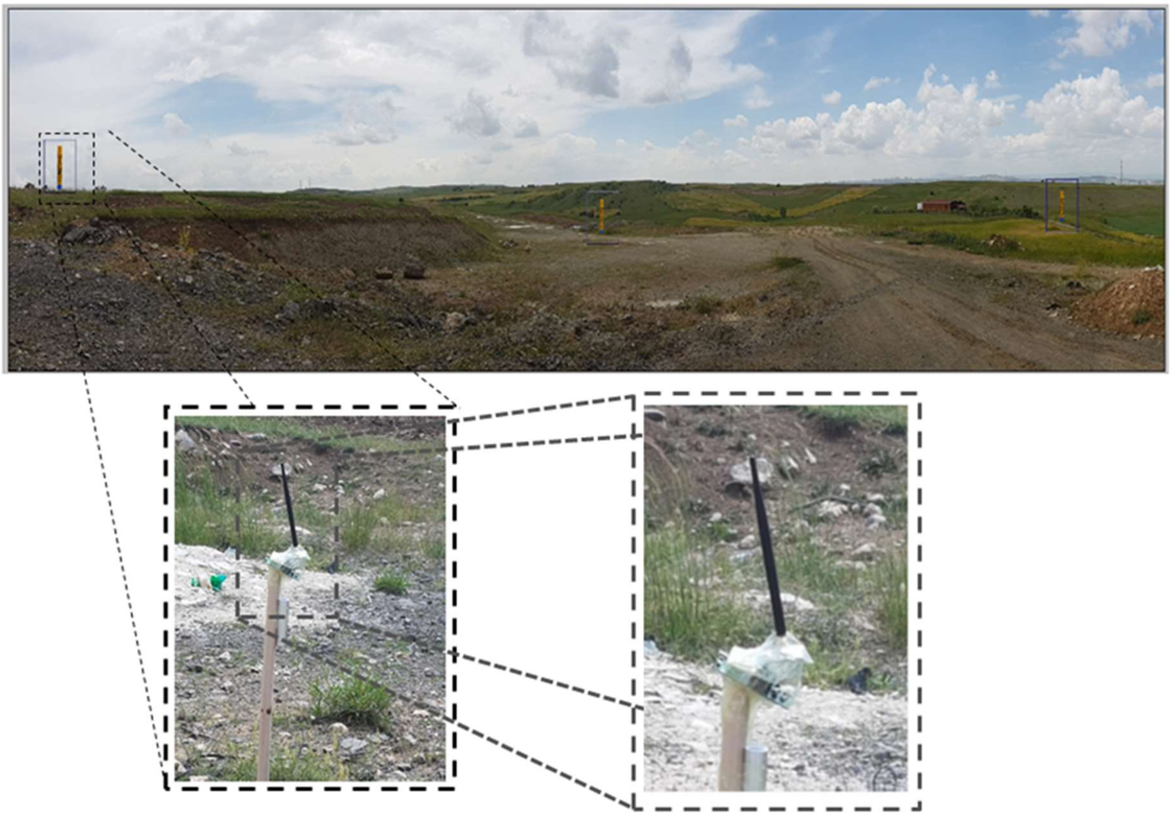

Figure 5 Distribution of nodes in a realistic environment

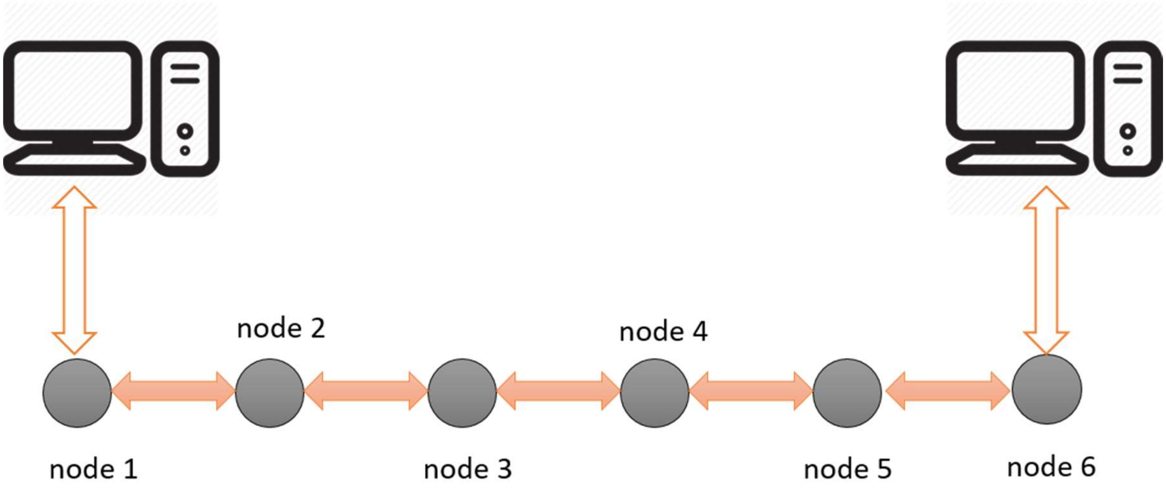

Figure 6 Distribution of nodes in an experiment

- A link is established with different but fixed distances between the nodes.
- 10 data-points of time synchronization process is recorded along with the environment temperature.
- Two random nodes where they are not starting or ending nodes are heated using a heater and the second step is repeated.

Experiments are divided into two types as indoor and outdoor. First two experiment sets are performed at a rural area where different outdoor effects take place like RF interference, fluctuant temperature, humidity, obstructed line of sight links and various RF reflector materials are present. Time synchronization algorithm's performance is tested at different hours of the day where these conditions also vary with time.

Last two experiment sets take place in a closed area where some sensor nodes have only walls as an obstruction and some has line of sight links. In this area, stable temperature and humidity are kept with an air conditioner and the time synchronization algorithm performance is observed. Then some of nodes' temperature is increased using a heater and performance is observed once again. Various uncontrollable factors like infrequent failures to establish a connection and low voltage levels of the battery during these tests resulted in a slightly varying outcomes of the experiment.

3.2. Results

In the Experiment 1, six nodes were placed in an outdoor environment with nodes being approximately 150 meters apart. The initial temperature was 23°C and rose to a temperature of 27°C at the end of the experiment for all nodes. The temperature rise was natural; it is not obtained from a heater or artificial sources. Environment of the experiment was selected as an empty remote rural area. Experiment was started early in the morning so RF interference is relatively low. The nodes were attached to a wooden stick at a height of 1m from the ground. The synchronization results varied from 20ms to 54ms contributed by the long intermediate distances between the nodes and the fluctuations on the ambient temperature. The findings depicted in Figure 7 shows a linear increase in the time difference as temperature rises. This behavior is expected as crystal response against temperature is seen in [21].

Second experiment is also carried out at the same location of Experiment 1, so the environmental features remained the same. However, the experiment took place at the noon so RF interference is different. In addition, the temperature rose from 27 °C to 33 °C during the experiment. Results of Experiment 2 (refer to Figure 8) shows that the clock difference starts from 38ms and ends at 102ms. In this experiment a smooth start is observed but then a sudden increase is seen.

Experiment 1 and 2 show similar trends in the results. The first synchronization time values of Experiment 1 and 2 are 20ms and 38ms respectively. But second experiment time values are larger because the initial and end temperatures were higher as it is concluded from [21]. The total temperature difference definitely has a decisive effect on these results.

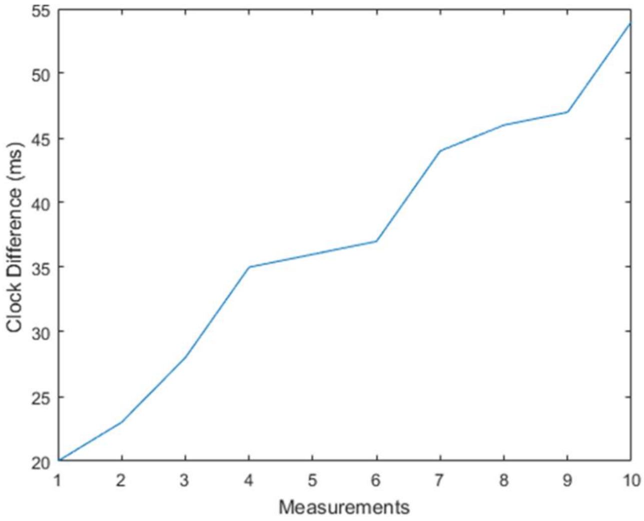

Figure 7 Clock difference in Experiment 1

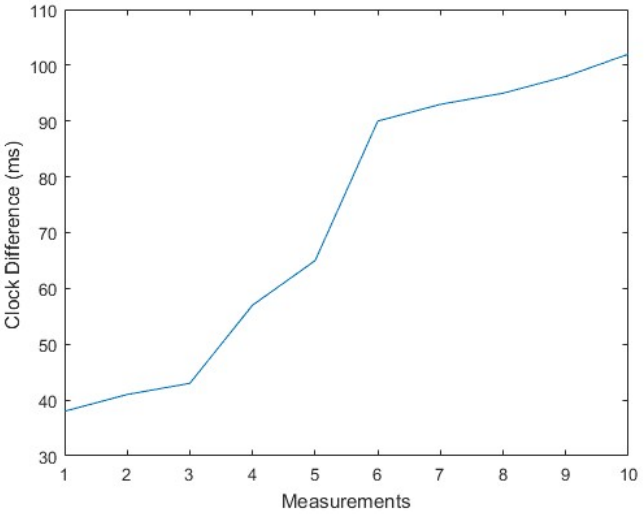

Figure 8 Clock difference in Experiment 2

In Experiment 3, nodes were placed in an indoor environment where walls acted as the obstructions between nodes. Temperature was stable at around 24°C. Experiment was carried out midday. Nodes were placed randomly in rooms where the distances between the nodes ranged from 20 to 40 meters. The environment was busy i.e. numerous people moving at random time and directions. The result is a fluctuating decreasing trend in clock difference as of Figure 9.

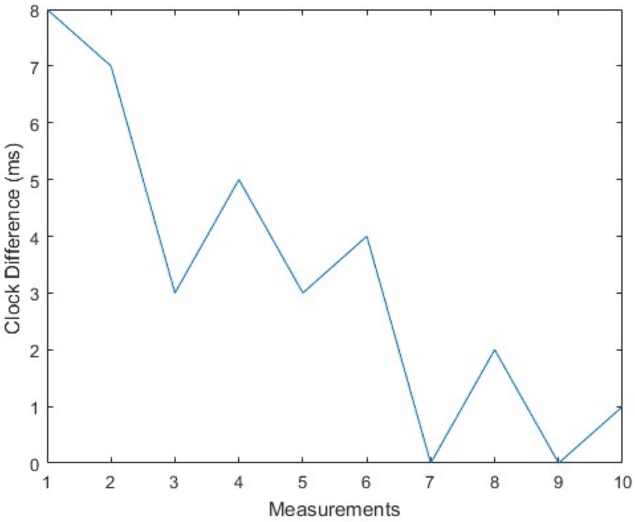

Figure 9 Clock difference in Experiment 3

Experiment 4 took place at the same environment as Experiment 3 but at a later time in the day i.e. afternoon. Two of the nodes were heated from 24°C to 35°C and others were kept at around 24°C. The motivation is to simulate the real-life scenario where nodes are kilometers apart and are exposed to varying temperatures due to geographical locations e.g. mountain valleys and humid forests. This requires the experiment location's temperature to be controlled and what easier way than indoors. The distance between the nodes were same as of Experiment 3. First synchronization time increased to 11ms and the results varied between 8-15ms. The rate of decrease seen in Experiment 3 had slowed down in Experiment 4. This is illustrated in Figure 10. Unlike Figures 7-8 where drastic changes were witnessed, some small scale fluctuations are observed due to the difference in the stability of the environment.

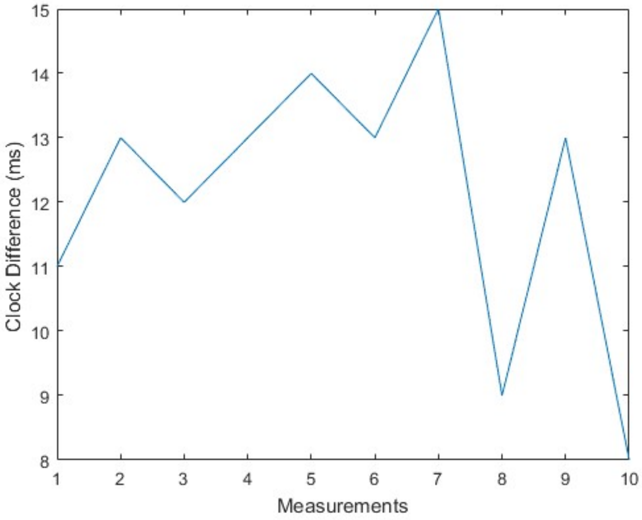

Figure 10 Clock difference in Experiment 4

Table 1
Mean & standard deviation of the experiments

Experiment Number	Mean (ms)	Standard Deviation (ms)
1	37.00	11.00
2	72.30	26.15
3	3.30	2.75
4	12.10	2.18

The mean and standard deviation values of clock differences are tabulated in Table 1. A complete analysis can be done by combining these values with the experiment figures. Experiment 1 and 2 have relatively higher initial synchronization time while the latter being the highest due to high temperatures. Thus, the second experiment has approximately twofold synchronization time values i.e. the mean and standard deviation is doubled. This suggests that higher temperature change in experiment 2 has an effect on the standard deviation. Experiment 3 and 4 have relatively small first synchronization time and a non-spreading behavior of values, indicated by the standard deviation results. Furthermore, the two heated sensor nodes directly have an impact on synchronization time and the mean value takes a big leap; by a factor of about 3.5. Nonetheless, the deviation is slightly less dispersed. The change of standard deviation in Experiment 4 is also the evidence of the influence of ambient temperature on the synchronization, yet it is not high as one would expect.

4. CONCLUSION

Time synchronization is an essential entity in all WSN systems. We intended to investigate the impact of environmental factors on the time synchronization through an effective adaptation of distributed light weight time synchronization implemented on a PIC. Although the board's crystal is not quite appropriate for this purpose, a custom design with handpicked components can be chosen to fit the needs. We employ bare metal programming thus every detail of synchronization is considered and complexity is avoided to the fullest possible extent in order to discard timing uncertainties. Additionally, design of a network system to support variable number of nodes arbitrarily demands a generic algorithm. Conversely, rising number of nodes can affect performance of synchronization in linear spanning tree networks.

Time synchronization in both indoor and outdoor areas were studied. The impact of temperature and rural effects on the linear spanning tree WSN is significant. Nonetheless, the results are within the limits of expected time intervals. Every clicker board has identical oscillator but since they don't necessarily have the same skew behavior, the time shifts are inevitable. Outdoor and indoor results also point out some flaws in algorithm whereas the effectual parameters like rounding and averaging increases, the performance decreases. Last two experiments (Experiment 3 and 4) have the numeric high mean difference but small standard deviations; only two nodes' temperature change does not affect general synchronization values as opposed to outdoors.

Regardless of the interference and temperature instability, most nodes show acceptable results for these experiments. Nevertheless, the disturbance needs to be overcome and still calls for attention. While mean value is high, the standard deviation is small where the time synchronization values are consistent in consecutive samples. In some cases, the result can be better like this where similar experiment is done in [11] and good result is seen.

Of course, use of limited hardware might require further optimizations as presented in [22]. Nevertheless, the objective of this study was to use this algorithm in the outdoors and the results were acceptable, although can be improved by finding the optimum resynchronization interval and forming a temperature based clock formula for generic crystal oscillators.

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The Declaration of Conflict of Interest/ Common Interest

The authors do not have any conflict of interest or common interest with any institution or person that they know that could affect their work.

Authors' Contribution

All authors have contributed in experimental study and writing of the manuscript equally.

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