Clock Offset Estimation for Cognitive Global Clock Synchronization Algorithm in Ad-hoc Wireless Sensors Networks

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ABSTRACT

Clock synchronization is a very promising domain in WSNs. Communication delays makes clock synchronization crucial and vulnerable. Every individual sensor node has its own local internal clock and the clock synchronization application requires all nodes to agree on a common time. Contribution of this article is double folded. First this paper introduces a novel fault tolerant algorithm for time synchronization namely cognitive global clock synchronization (CGCS) algorithm in ad-hoc wireless sensors networks. The algorithm is cognitive i.e. it checks effectiveness of master node and the expected master node during regular intervals of time and takes decisions accordingly. Propagation time is reduced because lesser number of transmissions is required for clock synchronization through CGCS. In this technique sensor network will be synchronized through a minimum traffic or by sending and receiving less number of packets which makes this scheme efficient. Second we checked its performance by clock offset estimation through a simple convex optimization application assuming that there is no clock skew between the nodes [20].

Keywords: Clock synchronization, Clock offset estimation, CGCS, Sensor networks.

1. INTRODUCTION

Wireless sensor networks (WSNs) have attained significant importance in modern science like MEMS technology, because of their variety of applications, ranging from domestic to medical and industrial to military fields. With these tiny devices we can monitor the physical world [1]. Sensor nodes are deployed in ad-hoc fashion and are not deployed in some special infrastructure; this yields multi-hop communication in sensor networks. In distributed systems every sensor has its own physical clock, and these clocks are required to be synchronized on a common notion of time.
Wireless sensor networks are popular because of their smaller size, easy handling capability, ad-hoc structure deployment and low cost. Achieving all the potential benefits from these networks is not always easy due to certain limitations like limited energy, smaller hardware etc. [2], [3]. Clock synchronization is a core issue in WSNs because internal hardware clocks of sensors are often mismatched and as a result packet data delay occurs and sometimes data is lost. Difference of time between two sensor nodes is also a bottleneck. Nodes get synchronized by messages exchange between them, which can be adjusted and estimated for relative offset reported by the local clocks.

These limitations are hurdle in efficient message transmission. To overcome this issue time synchronization is necessary so that all nodes agree on the same time, to achieve all benefits of the sensor network. When a node generates timestamp to synchronize other node in the network it may encounter variable delay until it reaches the destination. These are classified mainly into four components: send time, access time, propagation time and receive time.
To agree all the clocks more or less on common time is useful in many applications. Sensor nodes have to synchronize their clocks by exchanging messages of their recent states. Clocks can be matched by GPS but sensors are inexpensive devices and this expensive solution increases cost effectiveness leading to low cost of sensor nodes which is counterproductive. Secondly sensors are often deployed in remote and dense areas, in hostile environments or inside the buildings where line of sight is not clear to GPS satellites.
Wireless sensor networks are built up of several nodes. Each node is connected to one or several sensors. Each such sensor node is composed of various parts like transceiver, micro-controller, internal and external antenna connections, and network interfacing unit. Sensors nodes are connected to the gateway sensor node.

Implementation of cognitive algorithm is essential to discard malicious nodes. If master node becomes faulty another node must take over immediately so that the network remains synchronized. Considering all bottlenecks like limited energy, smaller bandwidth and presence of faulty nodes, our aim turned into a novel clock synchronization algorithm which not only checks for the faults but also encounters with those faults very well. Cognitive global clock synchronization algorithm executes into two phases i.e. synchronization and cognition.
The cognitive global clock synchronization (CGCS) algorithm is a new approach in clock synchronization domain to cope with the faults occurring in sensor networks. The algorithm not only synchronizes the sensor nodes on global time but also checks for the faulty nodes and takes decisions likewise.
This paper proposes a system model to estimate the clock offset for CGCS algorithm to check its performance.

2. LITERATURE REVIEW

Wireless sensor networks have variety of applications and usage in daily life and this industry is growing faster. Looking into the needs it's required to synchronize all nodes to a global clock because the basic operation is data fusion. Sensor network applications require that sensors in the network agree on the common time. By matching the sensor location and the sensing time, the sensor network may easily predict the transmitted information. But this is not an easy task as clock skew and clock offset disturb clock synchronization a lot. Node's hardware oscillator shows clock as approximation $Ci(t)$ of real time t as

$$Ci(t) = \omega i(t) + \phi i \quad (1)$$

Where ωi denotes the rate of hardware oscillator and ϕi denotes the time difference. Due to the imperfections and environmental changes rate of clock can be expressed as

$$1 - \rho \leq \omega \leq 1 + \rho \quad (2)$$

Energy, bandwidth and hardware are the limitations of sensor network. Energy limitation and hostile deployment makes WSNs vulnerable [4]. Lack of energy and environmental damage also causes failure of sensor nodes [5]. During implementation of the synchronization algorithm and messages exchange between sensor nodes, a small proportion of energy is consumed. Wireless sensor networks are composed of small sensors with limited energy. Sensor nodes remain unattended for a long time in working condition and they run on small batteries so energy efficient synchronization protocols are highly desired.
When nodes become faulty the communication link is lost resulting in a significant change in the network topology. Network must remain functional even in the presence of faults. This reliability is called fault tolerance and if network is healed by itself it's called as cognition. In cognition the network continuously performs its service by inner treatment. Robust fault management techniques are necessary for the reliability of the network but no existing fault tolerant approach covers all types of faults exhibited in WSNs [6]. To conserve energy we need both accurate and low complexity synchronization protocols. Every sensor node in the WSN has its own clock but there may be a clock drift due to various factors such as difference in oscillations environmental factors and temperature [7]. So high accuracy is needed while launching an algorithm.

Energy efficiency is a big concern while designing an algorithm. Limited energy at the end of sensor node makes clock synchronization more difficult. Life of a sensor network depends upon its batteries life [8]. Sensors are typically disposable and last until their energy drains [9]. Nodes can save energy when they are in idle state and also can save energy during packet data transmission by adjusting the transmission range. Dynamic integration of both approaches can lead to save more energy [10]. Perfect synchronization is said to be achieved when relative drift is equal to 1 and relative offset is 0. Elson et al. defined global clock synchronization and clock offset estimation parameters in [11]. A system failure occurs when delivered service deviate from the specified service [12]. Schenato et al. proposed a consensus based protocol for clock synchronization in Wireless sensor networks, and his interest in the field is because node cannot communicate directly rather they do it in multi hops and there is always a chance of packet loss in wireless sensor networks due to its unreliability. His work is a cascade of two algorithms and the main theme is to average local information [13]. The clock synchronization problem needs exact estimation of clock offset. There is vast and tremendous research in the field of WSNs and especially in the field of clock synchronization. Xuanyu et al. concluded that pairwise broadcast and joint estimation of skew and offset are effective ways of energy saving and estimated JMLE and JMLLE [14].
RBS and TSPN are the pioneer protocols of this field [15], [16], they use receiver-receiver and sender-receiver synchronization schemes for clock synchronization respectively. Another relevant and useful work is done by Chaudhari et al. [17]; they focused on clock synchronization and adopted sender-receiver, and receiver-receiver synchronization schemes. In the first case, two nodes exchange timing message with each other while in the second case receivers share timing message with the common sender. Chaudhari et al. [18] represented an algorithm for ML joint estimation of clock skew and offset via two way timing exchange mechanism for exponential delays.

Estimation of clock skew and clock offset for inactive nodes is described in [19], the node that reside nearby it gets synchronized by over hearing only, without communicating neighboring nodes. It saves energy and increase life span of the network. Lee et al. estimated clock offset by assuming there is no clock skew present between sensor nodes [20]. Leng et al. also used maximum likelihood estimation to estimate exponential delays in [21]. Lin et al. proposed a new protocol for estimation purposes using two way message exchange mechanism [22]. MTS and WMTS protocols for WSNs conduct the skew and offset compensations simultaneously. The main idea is to drive all clocks to the maximum value among the network. Both algorithms are fully distributed, asynchronous, and robust to dynamic network topologies [25]. Uncertainty effect on synchronization accuracy under both ATS and MTS is studied [26].

3. MOTIVATION

Sensor network deployment in remote and hostile areas demands energy efficient communication because recharging these sensors is impossible. Due to environmental factors, physical damages and battery drainage sensor nodes may become faulty and communication path is lost. Similarly most often replacement of malicious node(s) is also not possible. So looking into the need our aim is to develop energy efficient, fault tolerant and fault recovery clock synchronization algorithm. Smaller hardware, limited energy at end sensor node and less bandwidth are the limitations of a sensor network. Presently wireless communication is restricted to a data rate in the order of 10–100 Kbits/s [23]. Energy required to transmit 1 bit over 100 m, which is 3 joules, can be used to execute 3 million instructions [24]. Bandwidth limitation directly affects messages exchange among sensors whereas synchronization is impossible without messages exchange. CGCS mechanism is briefly described below:

A node is selected as master node among the set of communicating nodes. Master node broadcasts timing message to the expected master node, which compares its clock value and adjusts its clock with the master's local clock value. Then expected master node sends ACK message to the master node. To reduce round trip time; expected master node shares master node's timing information and computed offset value to the next hop which sets its local clock upon global time and sends ACK message to the master node. This procedure is represented in Fig. 3.

This massage includes ID information and energy level of the sensor nodes. Each receiving node sends a message to its next hop. This mechanism reduces message overhead leading to reduction in propagation time. It is not essential for any individual receiver to send back the ACK to its sender except to the master node. Meanwhile master node and expected master node communicate with each other to check their effectiveness. If node "N" is unable to receive message from master node then node "N" appears as master node and broadcasts the request message to the next hop to change and update their receiver ID. On the other hand if master node "M'' is unable to receive ACK message from "N" continuously three times then it means that node "N" is down. So parent node checks its table and sends a request message to "C" to communicate with it as a secondary expected master node. Each node sends an ACK message to the parent node, due to centralized system and low overhead round trip time is minimized. Only parent node maintains the table which contains the ID information and clock time of all the nodes. Step by step summary of the CGCA is shown below:

1. Node M is selected as master node among the set of communicating nodes.
2. M broadcasts its local clock value to node N (Expected master node).
3. N compares and adjusts its clock value with M and sends ACK message to M.
4. N shares timing information of M and computed offset to node C.
5. C adjusts its clock value as per received information and sends ACK message to M.
6. M builds a table containing energy level and ID information of all nodes which it receives via ACK messages.
7. If node N or C get faulty, M takes decisions accordingly and if M gets faulty node N starts working as master node.

Fig. 1 represents the global clock synchronization phenomenon for the smaller ad-hoc network and for larger sensor networks same algorithm can be applied via inter clustering and intra clustering synchronization as shown in Fig. 2.

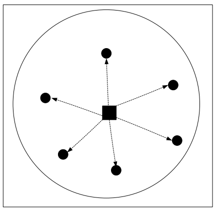

Figure 1. Global clock synchronization.

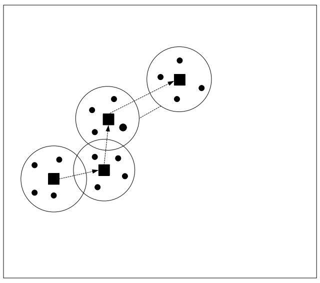

Figure 2. Cluster based global clock synchronization

In centralized clock synchronization mutual exclusion is guaranteed by a coordinator and fair sharing is possible without starvation. It is easy to implement. Due to less number of messages exchange this scheme is efficient. While in distributed system, synchronization is achieved after a lot of messages exchange and is really messy.

4. CLOCK MODEL

Communication link between master node and expected master node is always interpersonal in CGCS algorithm, while link between master node and rest of the nodes is impersonal communication link, as illustrated in Fig. 3.

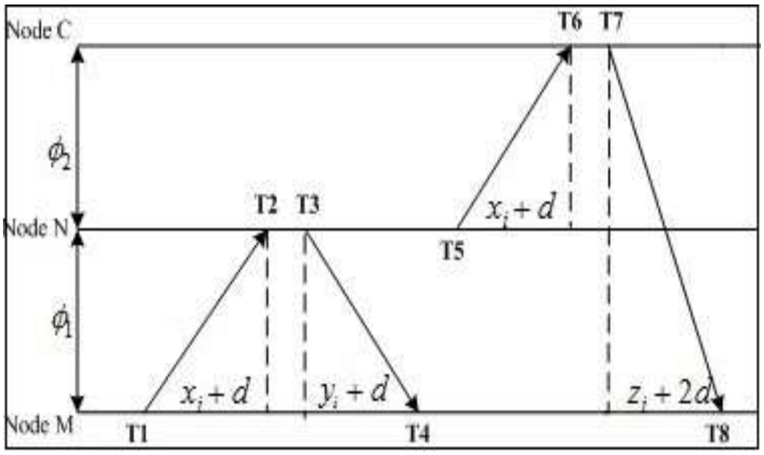

Figure 3. Messages exchange mechanism for CGCS algorithm

Mathematical description of (Figure 3) is expressed as

$$T_2 = T_1 + x_i + d + \phi_1 \quad (3)$$

$$T_4 = T_3 - y_i + d + \phi_1 \quad (4)$$

$$T_6 = T_5 + x_i + d + \phi_2 \quad (5)$$

$$T_8 = T_7 - z_i + 2d + \phi_1 + \phi_2 \quad (6)$$

Where $T_1,.......,T_8$ are time stamps between the three nodes, ϕ_1 is the clock offset between node M and node N while ϕ_2 is the clock offset between node N and the node C. d is the fixed propagation delay and x_i, y_i, z_i are random delays. Since all delays are considered positive so equations (3), (4), (5) and (6) can be written as

$$x_i = T_2 - T_1 - \phi_1 - d \tag{7}$$

$$y_i = T_4 - T_3 - \phi_1 - d \tag{8}$$

$$x_i = T_6 - T_5 - \phi_2 - d \tag{9}$$

$$z_i = T_8 - T_7 - \phi_1 - \phi_2 - 2d \tag{10}$$

Maximum likelihood function for the above equations can be represented as

$$L(d, \phi_1, \phi_2) = \lambda^{-3N} \exp[-\frac{1}{\lambda}\sum_{i=1}^{N}[x_i + y_i + z_i]]. \prod_{i=1}^{N} u(x_i); u(y_i); u(z_i) \tag{11}$$

$$= \lambda^{-3N} \exp[-\frac{1}{\lambda}\sum_{i=1}^{N}[T_2 - T_1 + T_4 - T_3 + T_8 - T_7 - 3\phi_1 - \phi_2 - 4d]]. \prod_{i=1}^{N} u(T_2 - T_1 - \phi_1 - d); u(T_4 - T_3 - \phi_1 - d);$$
$$u(T_8 - T - \phi_2 - \phi_1 - 2d) \tag{12}$$

Such that

$$u(x) = \{^{1 \quad if \quad x \geq 0}_{0 \quad if \quad x < 0}$$

The ML estimate of λ is given by

$$\hat{\lambda}_{ML} = \frac{1}{3N}\sum_{i=1}^{N}[T_2 + T_4 + T_8 - T_1 - T_3 - T_7 - 3\phi_1 - \phi_2 - 4d] \tag{13}$$

The reduced likelihood function can be shown as

$$L' = e^{-3N}[\frac{1}{3N}\sum_{i=1}^{N}[T_2 + T_4 + T_8 - T_1 - T_3 - T_7 - 3\phi_1 - \phi_2 - 4d]]^{-3N}. \prod_{i=1}^{N} u(T_2 - T_1 - \phi_1 - d); u(T_4 - T_3 - \phi_1 - d);$$
$$u(T_8 - T_7 - \phi_1 - \phi_2 - 2d) \tag{14}$$

Let

$U_i = T_2 - T_1, V_i = T_4 - T_3, W_i = T_8 - T_7$

By putting these values in (14) we get

$$L' = e^{-3N}[\frac{1}{3N}\sum_{i=1}^{N}[U_i + V_i + W_i - 3\phi_1 - \phi_2 - 4d]]^{-3N} \tag{15}$$

Where U_i, V_i, W_i are first order statistics of random variables. The likelihood maximization problem can be shown by convex form [19].

$$(\hat{d},, \hat{\phi}_1, \hat{\phi}_2) = \min \sum_{i=1}^{N}[U_{(1)} + V_{(1)} + W_{(1)} - 3\phi_1 - \phi_2 - 4d] \tag{16}$$

Such that

$$u_1 - \phi_1 - d \geq 0$$
$$v_1 - \phi_2 - d \geq 0$$
$$w_1 - \phi_1 - \phi_2 - 3d \geq 0$$

The closed form for the (16) is expressed as

$$\begin{bmatrix} \hat{\phi}_1 \\ \hat{\phi}_2 \\ \hat{d} \end{bmatrix} = \begin{bmatrix} 2U_{(1)} + V_{(1)} - W_{(1)} \\ U_{(1)} + 2V_{(1)} - W_{(1)} \\ W_{(1)} - U_{(1)} - V_{(1)} \end{bmatrix} \tag{17}$$

5. SIMULATIONS

Simulations are carried out via matlab to assess the performance of MLE for estimating clock offset ϕ_1 and ϕ_2 for CGCS in WSNs. Clock offset ϕ_1 between node M and node N is estimated for number of observations ranging from 10 to 20. Similarly ϕ_2 between node N and node C is estimated for number of observations ranging from 10 to 20. Exponential decay in simulation result clearly proves positive only nature of the link delays justifiably modeled in section 4.

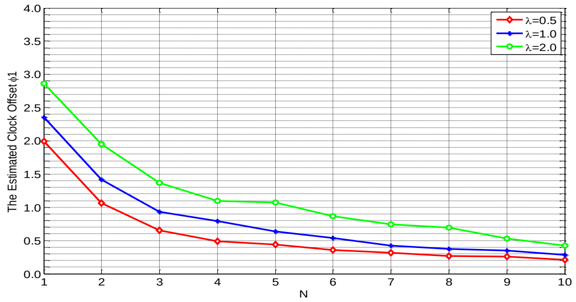

Figure 4. The estimated clock offset between the node M and the node N with n=10.

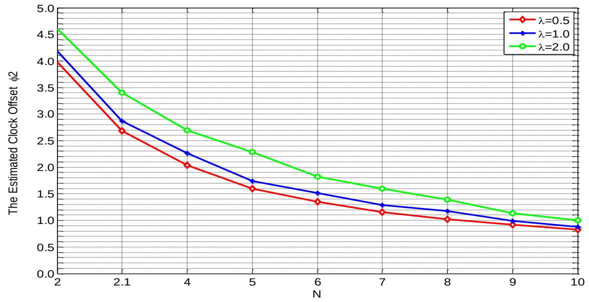

Figure 5. The estimated clock offset between the node N and the node C with n=10.

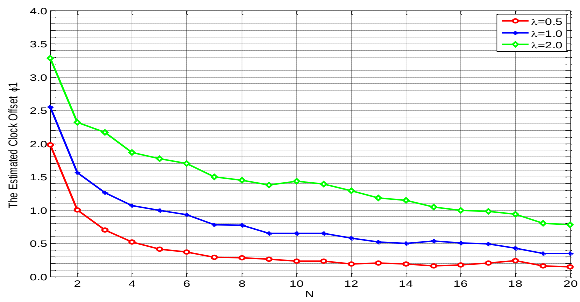

Figure 6. The estimated clock offset between the node M and the node N with n=20.

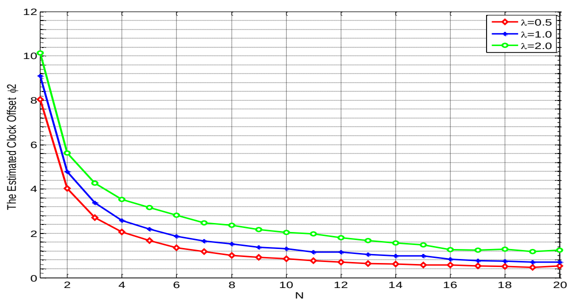

Figure 7. The estimated clock offset between the node N and the node C with n=20.

Maximum likelihood function is considered under exponential distribution. Clock offset is estimated w.r.t λ for different observations. It is obvious in Fig. 5 and Fig. 7 that as long as number of observations is increased clock offset estimation curve settles uniformly. Clock offset is estimated for multiple observations, since clock offset of each receiving node follows exponential distribution, each receiving node compares and adjusts its clock according to the master node's local clock value.

It is obvious from all numerical simulations that all the curves converge asymptotically to a constant. This proves the effectiveness of our MLE method. It can also be seen that different λ lead to different MSEs of the estimated clock offsets. The bigger the scaling parameter λ is, the bigger the MSE of the estimated clock offset is. If the mean λ decreases, the MSE of the estimated clock offset decreases.

The theoretical analysis and simulations results show that CGCS has good synchronization precision and less number of messages exchange reduce the round trip time. It can be seen that performance of MLE is close to the number of observations, it shows its accuracy and curve approaches to zero as number of observations are increased. This approach from all simulation results show accuracy of the proposed estimator, consistency and asymptotic efficiency.

6. CONCLUSIONS AND FUTURE WORK

Cognition is an important, useful and new feature introduced in clock synchronization algorithms designing. Due to various random delays and clock offset, clock synchronization does not hold for a long period of time and as a result data fusion suffers. In this paper clock offset is estimated for CGCS algorithm in WSNs as network wide synchronization provided that no clock skew is present between the nodes. ML estimators are evaluated by using a simple convex optimization application. Simulation results prove the exponential decay in accordance with the system model and synchronization is precise. In the past researchers estimated these parameters in two way timing exchange mechanism for two active nodes only and if they did it for three nodes they assumed third node as an inactive node which overhears without communicating by itself. According to our knowledge for the very first time this era is opened for all active nodes where cognition is also applied. The proposed algorithm is computationally simple and easy to implement. Simulation results show that the lower bounds converge to zero as N increases. The approach is simple, accurate, consistent and asymptotically efficient.

In future we aim to investigate CGCS from other aspects also. As an open research questions cluster based cognitive time synchronization is being suggested, this will help researchers to implement the algorithm in relatively larger sensor networks.

7. ACKNOWLEDGEMENT

This work was financially supported by Shanghai Science and Technology Foundation (13510500400).

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