TIME SYNCHRONIZATION USING DISTRIBUTED OBSERVER ALGORITHM WITH SLIDING MODE CONTROL FOR WIRELESS SENSOR NETWORK

By

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LIST OF ABBREVIATION

ATS	Average TimeSync
CCS	Consensus Clock Synchronization
FTSP	Flooding Time Synchronization Protocol
GCS	Global Clock Synchronization
GPS	Global Positioning System
IoT	Internet of Things
NTP	Network Time Protocol
RBS	Reference Broadcast Synchronization
RFA	Reachback Firefly Algorithm
SMC	Sliding Mode Control
TDSP	Time Diffusion Synchronization Protocol
TPSN	Timing Sync Protocol for Sensor Network
TSDOS	Time Synchronization using Distributed Observer algorithm with Sliding mode control element
TSMA	Time Synchronization using Maximum and Average consensus protocol
WSN	Wireless Sensor Network

LIST OF SYMBOLS

τ	Physical Local Clock
$\hat{\tau}$	Virtual Clock Estimation
$\tilde{\tau}$	Consensus Clock Estimation Error
φ	Relative Skew
α	Clock Skew
β	Clock Offset
ρ	Tuning Parameter
ε	Relative Local Time Error

ABSTRAK

Kajian ini menghuraikan tentang pelaksanaan algoritma yang menggunakan aplikasi kawalan ragam gelincir sebagai pergantian jam pencongan untuk Wireless Sensor Network (WSN) dalam dunia Internet of Things (IoT). Algoritma ini dikenali sebagai Time Synchronization using Distributed Observer algorithm with Sliding mode control element (TSDOS).

Tujuan utama memperkenalkan TSDOS adalah untuk membolehkan semua nodes mentafsir masa jam global dalam suatu rangkaian deria tanpa-wayar atau *WSN* untuk tujuan komunikasi.. Tanpa masa jam global yang selaras, adalah mustahil bagi setiap nod untuk menghantar isyarat sesama sendiri kerana rujukan masa adalah berbeza. Dengan menggunakan maklumat setempat, TSDOS berupaya mentakrif kadar condong, kadar jidar dan kadar condong relatif jam maya bagi nod yang berkaitan. TSDOS direka bentuk bagi penyesuaian dalam keadaan yang dinamik dengan kelajuan penumpuan yang lebih cepat dan ralat penyelarasan yang minimal. TSDOS mempunyai ciri-ciri tertabur, tidak sekata, berskala melintasi struktur topologi jaringan yang berbeza dan mengukuhkan aturan ad hoc nod dan kegagalan rangkaian.

Dalam disertasi ini, TSDOS telah diuji keberkesanannya melalui simulasi eksperiment yang tertakluk kepada topologi jaringan yang berbeza dan ad-hoc nod penggunaan dalam MATLAB. Ini bertujuan untuk memperhatikan pretasi TSDOS dari segi penyelarasan kelajuan dan ralatan jam bagi setiap nod dalam WSN melalui keputusan eksperimen simulasi.

Akhir sekali, perbandingan dibuat antara TSDOS dan konsensus lain yang berasaskan protokol diedarkan sepenuhnya, Average TimeSync (ATS) dan TSDOS membuktikan sendiri untuk mencapai kelajuan penumpuan lebih cepat dan mengurangkan ralat penyegerakan teraruh dalam rangkaian melalui simulasi MATLAB.

ABSTRACT

This research describes a novel distributed observer algorithm which uses augmented sliding mode control element to compensate for clock skew for wireless sensor network (WSN), in the world of Internet of Things (IoT). The algorithm is known as Time Synchronization using Distributed Observer algorithm with Sliding mode control element (TSDOS).

The main purpose of proposing TSDOS is to estimate a common global clock time by which all nodes within the WSN can use it for communication purpose. Without a common global clock time, it is impossible for the nodes to exchange information since the time reference is different. By using only the local information, TDOS will be able to estimate the skew rate, the offset and the relative skew rate of the perceived virtual clock of the neighboring nodes. TSDOS is designed to be able to adapt to dynamic condition with faster convergence speed and reduced synchronization error. TSDOS has the characteristics of being totally distributed, asynchronous, scalable across different network topological structures and adaptable to ad-hoc nodes deployment and link failures.

In this dissertation, TSDOS has been implemented in several experimental simulations subject to different network topology and ad-hoc nodes deployment in MATLAB. The purpose is to observe the performance of TSDOS in terms of synchronization speed and clock error of each individual node in the WSN through the simulation results.

Last but not least, a comparison is made between TSDOS and another fully distributed consensus based protocol, Average Time Sync (ATS), and TSDOS proves itself to achieve faster convergence speed and reduced synchronization error induced in the network through MATLAB simulations.

CHAPTER 1

INTRODUCTION

Internet of Things (IoT) is a novel paradigm describing a trend advocating that all sorts of physical artifacts become connected to and controllable from the Internet (Pande and Padwalkar 2014). The basic principle is to demonstrate a technology trend where “things” of everyday life (which include wearables, vehicles, home/working environment, etc) are prolonged with sensors, actuators or processors, and connected to the IoT gateway wired or wirelessly. IoT Gateway here acts as a middleman which (1) allows users to monitor, control and track all the “things” remotely from the Internet and (2) forwards the data collected from the “things” to cloud servers to perform data analytics. Internet of Things is the succeeding evolution of Internet (Pande and Padwalkar 2014), wide-spreading both the hardware and software side of it: hardware deployment of wireless sensor network (WSN) and software analytics, visualization and data storage. This research is mainly focusing on the hardware of IoT architecture interacts via WSN.

WSN generally refers to a distributed, ad-hoc, self-organized, multi-hopped kind of network (Potnuru and Ganti 2003, Sivrikaya and Yener 2004), where wireless devices gather together and spontaneously form a network without the necessity of any infrastructure (Sivrikaya and Yener 2004). Some of the peculiar characteristics which make wireless sensor network so different from other kind of networks are low cost, low bandwidth, low power, low energy, high redundancy and more power-constraint (Potnuru and Ganti 2003). One of the significant functions of a sensor network is to observe and monitor the real-world phenomena (Römer, Blum et al. 2005). For such monitoring capabilities, physical time often plays a crucial role for many sensor network applications.

1.1 Problem Statements

IoT is playing progressively as a key role in several market segments, such as smart home and building, smart energy, retail, agriculture, healthcare, transportation and so on. Let's imagine that there are over billions of smart things connected to WSN through the IoT gateway (via ZigBee, 6lowpan, Z-Wave, etc) everyday, it is really essential and crucial for all the smart things to have the capability of being interoperable, self-configuring, self-optimizing and scalable instantaneously.

However, it is really a challenging task for each of the smart things to arrive and operate in real time as the world of things is much more unpredictable than the world of computers, with data exchanging rapidly in the busy sensor network (Pande and Padwalkar 2014). The fundamental idea is where all of the smart things connected to IoT network need to be synchronized, coordinated and instantaneously denoting to a global reference clock. The coordination requires physical time as the vital parameter to perform concurrency control, authentication, data consistency and most importantly communication protocols (Liskov 1993).

Hence, time synchronization is playing an important role in a distributed WSN. The purpose of time synchronization is to provide a common time scale for local clocks of all nodes in the sensor network (Sivrikaya and Yener 2004). However, providing synchronized physical time is a complex task due to various challenging attributes of sensor networks (Römer, Blum et al. 2005). First of all, local clocks of nodes tend to drift away from each other in time due to the imperfections of hardware clocks; therefore, observed time of time intervals may vary for each node in the network (Sivrikaya and Yener 2004). Moreover, it is difficult for sensor network to achieve a global clock synchronization when a large set of sensor or actuators nodes are connected to one another over a single-hop or multi-hop communication because it is impossible to directly select a reference node so that all the other nodes can be directly synchronized to it or even for the nodes to exchange clock values instantaneously.

Furthermore, it is more impossible for nodes to calculate the instantaneous global average time of all the physical clocks of the connected nodes in such network topology.

Then again, many of the WSN applications still require a common view of time exists and is available to each and every nodes in the network topology at any particular instant (Sivrikaya and Yener 2004). Henceforth, numerous time synchronization protocols have been introduced to achieve a global reference clock in the past research history, however it still cannot avoid the challenges of suffering from unpredictable packet losses and dynamic environment conditions in terms of communication link and number of nodes. Ad-hoc deployment to the network for example nodes randomly join and drop from the network also impacted the nodes to be globally coordinated and synchronized.

1.2 Objectives

This research seeks to embark the following research objectives:

- To propose time synchronization algorithm based on distributed architecture which guarantees fast convergence of synchronization error to a bounded compact set close to zero.
- To characterize the performance of the proposed TSDOS in a series of two topological condition scenarios, i.e. ring topology and tree topology.
- To compare the performance of proposed TSDOS over the ATS algorithm in terms of tolerance to dynamic changes.

1.3 Scope of research

The scope of research includes the design and simulation of the proposed time synchronization algorithm named Time Synchronization using Distributed Observer algorithm with Sliding mode control element (TSDOS) in this research. The performance and scalability of the TSDOS across different topological structures in a wireless sensor network will be tested through experimental simulation. Furthermore, the adaptation of the TSDOS in handling dynamic changes in wireless sensor network will be observed in this research as well. Last but not least, the overall performance of the TSDOS in terms of speed of convergence and estimation accuracy is compared with another fully distributed time synchronization protocol, named Average TimeSync (ATS) (Schenato and Gamba 2007) protocol.

1.4 Layout of Thesis

Chapter 2 discusses the Literature Review where two major types of time synchronization protocol are introduced in this chapter. They are centralized and distributed time synchronization protocol specially designed to achieve global time synchronization in WSN. Based on the review, distributed time synchronization protocol has the advantage to be very robust to node failure and new node appearance because the algorithm is distributed which does not require any special nodes as roots, and all nodes run exactly the same algorithm. The advantages of being distributed is failure of one of the agent node do not lead to failure of the whole network like the case of centralized. However, the distributed time synchronization has the disadvantages of slow convergence speed and large synchronization error compared to centralized time synchronization protocol. To eradicate these particular shortcomings, a sliding mode control element is being introduced in this chapter to force the synchronization errors induced in the network to zero in a fast rate. In the end of the literature review, Time Synchronization using Distributed Observer algorithm with Sliding mode control element (TSDOS) with the characteristics: distributed, asynchronous and scalable is being proposed in this research.

Chapter 3 deliberates the Research Methodology of TSDOS by inheriting relative skew estimation, skew compensation and the offset compensation from Average TimeSync (ATS) (Schenato and Gamba 2007) by Schenato. The main contribution of TSDOS is to enhance both relative skew estimation and skew compensation with sliding mode control element. Several experimental simulations have been designed to characterize the adaptation properties of TSDOS algorithm subject to different network topology and ad-hoc/new nodes deployment. Finally, the performance in terms of the convergence speed and synchronization error of TSDOS is being studied and compared with ATS (Schenato and Gamba 2007) protocol in this chapter as well.

Chapter 4 presents the Results and Discussion of TSDOS based on the several experimental simulations designed in Chapter 3. All simulation results for different topological structures in WSN and ad-hoc nodes deployment in WSN are discussed in this chapter. Last but not least, the comparison results of the performance between TSDOS and ATS are detailed in this chapter as well.

Chapter 5 is the Conclusion which summarizes and evaluates the achievements and contributions in this research.

1.5 Summary

This chapter gives an overview of this research which includes the introduction and background of Internet of Things (IoT). This research mainly emphasizes the hardware deployment side of IoT architecture which is wireless sensor network (WSN). The problem statements for every node in a distributed WSN to carry the capability of being interoperable, self-configuring, self-optimizing and able to operate in real time are highlighted in this chapter as well. Each of the nodes in the IoT network needs to be synchronized in order for them to be able to perform their tasks in real time. Therefore, the objective of designing a time synchronization protocol using distributed observer algorithm with augmented sliding mode control element is proposed in this research to solve the problem statements aforementioned.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the beginning of this chapter, the network topology of wireless sensor network (WSN) is studied and analyzed using graph theory. The subsequent subsection then discusses the importance and challenges of achieving time synchronization in WSN. The following subsection describes the characteristics and differences between several time synchronization protocols which have been proposed in the past and present which include centralized and distributed. Last but not least, control paradigm - sliding mode control element with the purpose to reduce synchronization error is deliberated and encompassed as part of the literature review as well.

2.2 Wireless Sensor Network represented by a Graph

WSN can be modeled as an directed graph, $G = (V, E)$, where $V = \{1, 2, \dots, n\}$ represents the nodes in the WSNs and the edge set E represents the available communication links, for example $(V_i, V_j) \in E$ if node j can communicate with node i. V_i and V_j are indicating the tail and head of the edge (V_i, V_j), respectively (Ren and Beard 2005). The orientation of the graph is a choice of heads and tails for each undirected edge. The set of edges of a fix orientation of the graph is represented by E_0. Therefore, E_0 consists of one and only one of the two edges $(V_i, V_j), (V_j, V_i) \in E$.

In this research, WSN connectivity graph $G = (V, E)$ is assumed to be directed for example:

1. It consists of only self-loops: $(V_i, V_j) \in E$ if and only if $(V_j, V_i) \in E$

These hypotheses are proven to be practical since the wireless channel is symmetric, each node has access to its own information, and the graph is not disconnected. This research now provides a significant theorem which delivers sufficient conditions to guarantee the convergence of time-varying consensus algorithms. The proof of this theorem and more general conditions for time-varying stochastic matrices can be found in Moreau (Moreau 2005).

2.2.1 Network Topology in WSN

To form a network topology in WSN, three types of nodes required, i.e. coordinator (a.k.a. gateway), router and end device. Coordinator creates a personal area network identifier (PAN ID) and allows nodes like router or end devices to join to it. Router must join to the PAN ID created by coordinator before it allows another router or end device to join to the network and assist in routing data. Last but not least, end device is allowed to join a PAN ID either through coordinator or router, it does not allow devices to join the network and cannot route data.

There are several types of network topology which can form a wireless sensor network (WSN). For example, star topology as shown in Figure 2.1 (a), tree topology as shown in Figure 2.1 (b), ring topology as shown in Figure 2.1 (c) and mesh topology as shown in Figure 2.1 (d).

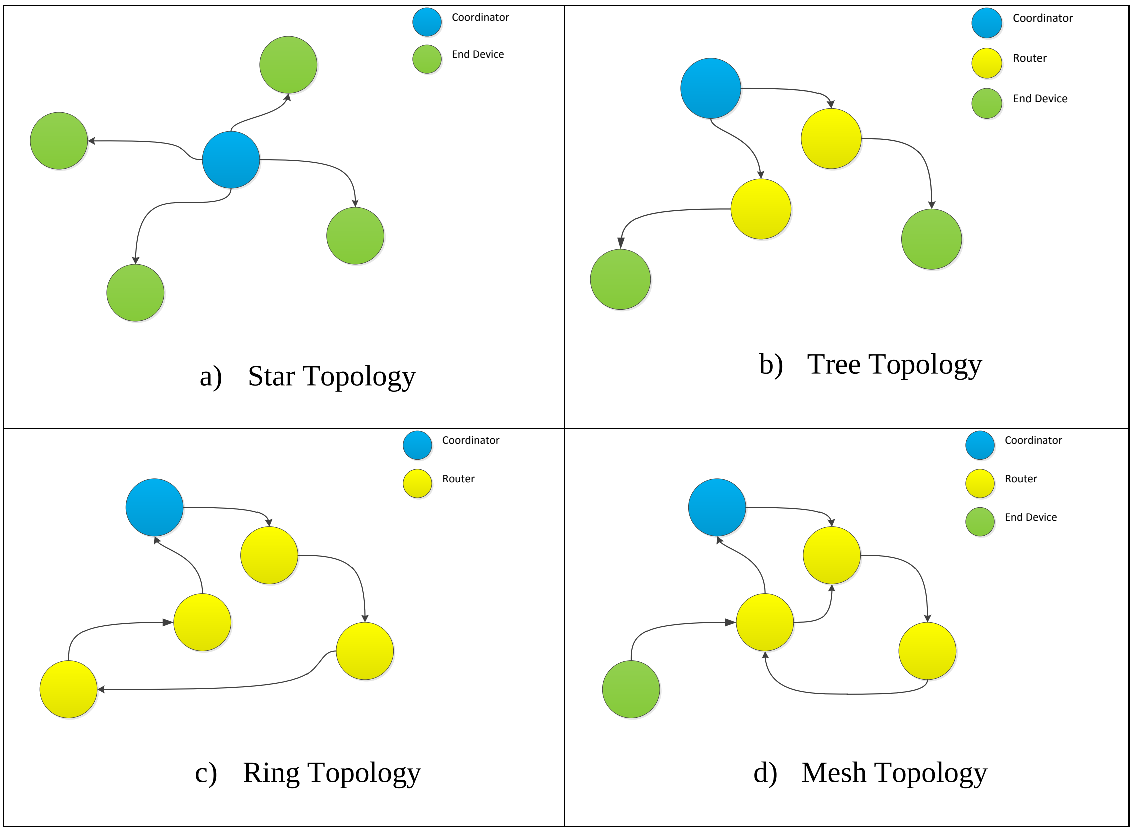
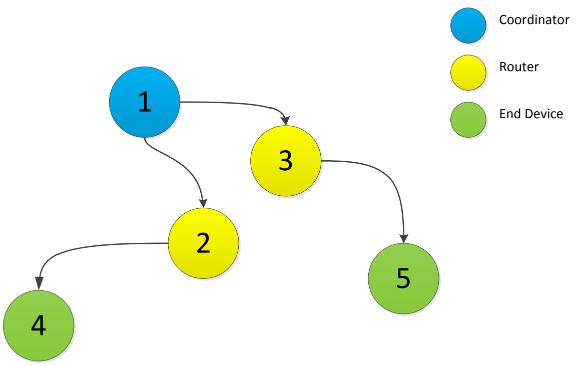


Figure 2.1: Structures of Network Topology in WSN

Each of the network topology can be modeled as graph using graph theory where each of the node is V, and edge represents the link between each nodes. Figure 2.2 below illustrates an example of a tree topology models using graph theory $G = (V, E)$.



$$G = (V, E) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

Figure 2.2: Representation of Tree Topology by a graph

2.3 The importance of Time Synchronization in WSN

Time synchronization is playing an important role for several applications in WSN, one of the examples is efficient duty cycling for each of the sensor nodes. Since most of the sensor nodes are made to be low cost and low power, sensor nodes may enter sleep mode to cycle through power saving mode by switching off the microcontroller, sensors and radio transceivers most of the idle time, and only wake up when necessary. All the WSN nodes including IoT gateway, actuators and sensors are required to be closely synchronized so that all nodes could sleep and wake up at a coordinated time, to avoid missing of incoming radio transmission or sensor events.

Another significant example will be data fusion where all the data collected from distributed sensor nodes will be forwarded to the cloud server through IoT gateway to perform analytics process by integrating all the distributed data into a coherent, consistent and meaningful result which denotes the real world phenomenon. It is crucial for all the nodes to follow a global reference clock especially for time-critical data fusion applications, for example, localization, velocity estimation, range estimation, object tracking, distributed beamforming, and acoustic positioning. The estimation will not be accurate if all the nodes are not synchronized (M. K. Maggs, 2012).

Time synchronization is important for network scheduling and routing which uses time division channel access method. For example, Time Division Multiple Access Network (TDMA) uses time domain to schedule transmission to avoid packet collisions and conserve energy(Maggs, O'Keefe et al. 2012). TDMA requires time synchronization in order to function efficiently. Besides, Frequency Hopping Spread Spectrum (FHSS) (Avery, Cooper et al. 1994) allows nodes to switch radio transmissions between different carrier frequencies in a pseudo-random order also requires time synchronization (Maggs, O'Keefe et al. 2012). FHSS can be used as a multiple access method such as in FH-CDMA (Chung and Metzner 1992) and it also provides resilience to narrowband interference, jamming attacks and eavesdropping (Maggs, O'Keefe et al. 2012).

Some of the security protocols with encryption algorithms implemented in the IoT also require time synchronization between nodes to facilitate keys changing process. For example, all the data packets being transported using ZigBee protocols will be encrypted with profile and network key (Nguyen and Rong 2007). The recipient needs to share the same profile and network key as the sender in order to decrypt the packets being received. Time synchronization is indeed important to ensure the data being received is encrypted in real time as some of the data packets contain high priority contents.

2.4 NTP and GPS

Traditional synchronization scheme such as network time protocol (NTP) and global positioning system (GPS) are no longer suitable for wireless sensor network (WSN) because of its intrinsic properties for example limited resources of energy, computation, power, storage and bandwidth (Sivrikaya and Yener 2004). NTP is one of the oldest and most widely adapted protocols for clock synchronization which efficiently synchronizing the computers on the Internet (Mills 1994). However it is not designed to fulfill the unique requirements of wireless sensor network, for example battery powered sensors nodes are commonly limited by energy consumption and computational issue (Mills 1994). GPS receiver would be a hardware solution as well but often too heavyweight, costly and energy consuming in sensor nodes, and GPS service may not be available everywhere. Furthermore, GPS signals may not be trusted in adversarial environments.

2.5 Time synchronization in WSN – Challenges and Solutions

A new methodology to achieve time synchronization in WSN has been proposed to particularly perform the characteristics of WSN. It actually refers to the capability of synchronizing clocks across a set of sensor nodes which are connected to one another over a single-hop of multi-hop wireless networks. Several challenges to be faced to achieve time synchronization in WSN will be discussed in this section.

2.5.1 Nondeterministic delays

There are multiple sources of message delivery delays. One of the examples is physical channel access time where the orders of magnitude may be greater than the synchronization precision required by the network. Synchronization errors might occur due to the latency estimations which are affected by these asymmetric round-trip delays. It is really important to decompose the source of message delivery delays in order to compensate the synchronization errors. Kopetz and Ochsenriete (Kopetz and Ochsenreiter 1987) describe the components of message latency, which they call the Reading Error, as being comprised of 4 distinct components plus the local granularity of the nodes clocks. Their work was later expanded by (Ganeriwal, Kumar et al. 2003) to include transmission and reception times. The commonly sources of message delivery delays are send time, access time, transmission/reception time, propagation time and receive time (Maggs, O'Keefe et al. 2012). Among the aforementioned delivery delays, the most significant one is access time which is acquired at MAC layer waiting for access to the transmit layer. MAC layer time stamping is often used to reduce the effects of delivery delays (Schenato and Gamba 2007).

2.5.2 Clock Drift

Based on Zhao (Dengchang, Zhulin et al. 2013), manufacturers of crystal oscillators specify a tolerance value in parts per million (PPM) relative the nominal frequency at 25^{o} C, which determines the maximum amount that the skew rate will deviate from 1. For the nodes used in WSNs, the tolerance value is typically in the order of 5 to 20 PPM. If no drift compensation is applied, two synchronized nodes will be out of step soon.

2.5.3 Energy efficiency

Limited energy resource is one of the aspects to be considered in the design of time synchronization algorithm for a sensor network (Elson and Römer 2003). A good synchronization protocol should drive the estimates of each individual virtual clock to converge to a common (ie. consensus) respective global reference clock with the minimum number of transactions or transmissions.

2.5.4 Scalability

Sensor network applications normally require a numerous number of sensor node to be connected for that reason, it's important to design a synchronization protocol which has the ability to scale well with the increased network size and ad-hoc nodes deployment.

2.5.5 Precision

The requirement of synchronization precision may vary greatly depending on the specific application of the sensor network. For example for some monitoring applications simple ordering of events may be sufficient, whereas for others, microsecond accuracy may be required.

2.5.6 Robustness

Synchronization protocols should be robust against link and node failures due to the dynamic topology of wireless sensor network. An example of inter-link communication/node failures is sensor networks which are often left unattended for long periods of time in possibly hostile environments. Mobile nodes can also disrupt routing schemes and network partitioning may occur (Maggs, O'Keefe et al. 2012). The synchronization protocol needs to have the ability to reconnect and converge the global reference time of a partitioned network.

2.5.7 Lifetime

As most of the sensor nodes are powered with battery, hence the lifetime of the sensor is limited and they needs to remain low power. Therefore, it's really challenging while developing the time synchronization algorithm as it needs to be designed in a simple and low complexity which does not draw a lot of power or energy from the sensor nodes. The duration which sensor nodes remain synchronized may be instantaneous, or it may last the entire lifetime of the network (Elson and Römer 2003).

2.5.8 Cost and Size

Sensor nodes are normally designed to be small and low-priced devices. Therefore, hardware solution of time synchronization such as GPS receivers or temperature compensated clocks