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Improving Scalability and Energy-Efficiency using Clock Synchronization for Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSN) has specific constraints and stringent requirements in contrast to traditional wired and wireless computer networks. In the wireless sensor networks, the energy consumption is a significant factor and it is the major impact on the network lifetime. Another significant application obligation is to make sure data sensing synchronization, which leads to extra energy consumption as a high number of messages is sent and received at each node. So, in order to overcome this problem the existing system considers to develop a integrated synchronization protocol based on the IEEE 1588 standard that was designed for wired networks and the PBS (Pair wise Broadcast Synchronization) protocol that was designed for sensor networks, as none of them is able to provide the needed synchronization accuracy for our application on its own. The main goals of this synchronization protocol are: to ensure the accuracy of local clocks up to a tenth of a microsecond and to provide an important energy saving. But in this method the scalability is an important consideration in wireless sensor networks. So, in order to overcome this problem we introduce an innovative technique called Integration method for clock synchronization (IMCS) in the wireless sensor networks. In this technique the Reference Broadcast Synchronization (RBS) and Time sync Protocol for Sensor Networks (TPSN), which are two prominent examples of receiver-receiver and sender-receiver synchronization methods are integrated. This performance analysis demonstrates that combination of RBS and TPSN can work better than using these techniques separately. In the proposed ETSP protocol, to identify conditions to toggle between RBS and TPSN based on a threshold value. An experimental result shows that when compared to the existing system, in the proposed system there is high scalability and less energy consumption.

Keywords: Wireless Sensor network; energy efficiency; Reference Broadcast Synchronization (RBS).

I. INTRODUCTION

A Wireless sensor network is a group of specialized transducers with a communications infrastructure intended to monitor and record conditions at diverse locations. Commonly monitored parameters are temperature, humidity, pressure, wind direction and speed, illumination intensity, vibration intensity, sound intensity, power-line voltage, chemical concentrations, pollutant levels and vital body functions. Time-synchronization is a vital element of sensor networks infrastructure, in which clocks synchronize with each other or by global time using a common reference [10]. Furthermore, it can be used by power saving schemes to improve network life time. For example, sensor nodes can sleep and wake-up at a coordinated, common time-scale among the sensors. Since packet transmission in sensor networks use much more energy then local computation, it is imperative to improve upon it. This work is primarily based upon the assumption that by reducing transmission rate we can improve upon energy used by a network to prolong its life time. This is significant issue in energy limited Wireless Sensor Networks (WSN) where battery recharging and depleted nodes are tricky.

In the past works [19] [4] explored routing, scheduling, radio power management, agent and sentry based schemes, to design energy-efficient schemes. There are number of protocols that use time synchronization [12] for the same purpose. They work well in WSN but energy-efficiency is not often significant design consideration. The goal is not to achieve highly accurate time synchronization but to make it energy-efficient.

In a control solution for energy transmission for each node is proposed in order to extend the lifetime of the network without affecting the functionality of the system. Another proposal consists in making routing decisions in order to reduce the energy consumption. In the proposal is to determine which node should be active (awake mode) at a time or not (asleep mode).

Depending on the application requirements, ensuring synchronous network functionality is currently a challenge. More specifically, the sensors collect information which they then send to the collector. The collector must receive the information from all sensors in a minimal timeframe: the time synchronization problem as described. This has lead, in traditional computer networks, to the design of many protocols used to maintain the synchronization of physical clocks. For instance, a protocol such as NTP (Network Time Protocol) is not a good choice for WSN, because of assumptions not valid in WSN.

The most important requirement in this application is the synchronization and precision of these readings in a very small temporal window of about several nanoseconds, so as to allow the correlation of the collected data and to improve the fluid dynamics modeling. So it was mandatory to ensure the synchronization performance without decreasing the lifetime of the network. In the existing work describes the proposal based on the extension of IEEE1588-PBS (Pair wise Broadcast Synchronization). Then we show its implementation and simulation and how its performance is compared to the one of IEEE 1588 [7]. The work proposes a state of the art of existing research regarding the minimization of energy consumption and the problem of ensuring proper synchronization for Wireless Sensor Networks. But the scalability is a main problem in this method. So, in order to overcome this innovative technique is introduced which is Integration method for clock synchronization (IMCS) in the wireless sensor networks. In this technique the Reference Broadcast Synchronization (RBS) and Timesync Protocol for Sensor Networks (TPSN), which are two prominent examples of receiver-receiver and sender-receiver synchronization methods are integrated.

The remainder of this thesis is structured as follows. Chapter 2 presents the Literature Survey of the research. Chapter 3 presents the existing work and proposed work of the research, in which the methodology and procedures that are used in this research are explained in detail, and then also presents the System Specification. Chapter 4 presents System Implementation. Chapter 5 presents Results and discussions, which describes the performance comparison results for the research. Chapter 6 summarizes the conclusion and future direction for the research.

II. Related Work

The problem of the synchronization of wired networks has been solved thanks to the development of successful protocols, in terms of their accuracy. Unfortunately, they are unsuitable for wireless sensor networks because the differences between wired and wireless networks are manifold. One of the most important differences is that sensors can suffer from power failure, which limits the use of existing technologies and communications protocols.

Terms of accuracy and energy consumption.

A. Synchronization Problems and Protocols

The process of clock synchronization for distributed systems is to provide a common notion of time across the entire system [2]. But the time of a software clock cannot be perfect. That is why we are interested in its accuracy, which can be calculated by analyzing parameters such as: the clock frequency, the clock offset, the skew and the drift of the clock. Thus, NTP uses the method of Offset Delay Estimation, and performs the time synchronization of the central server with the UCT (Universal Coordinated Time). The disadvantage of this solution is that although it ensures high synchronization, it does it at the expense of message complexity.

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Several clock synchronization protocols have been proposed for wireless sensor networks, with better or worse performance [22]. The Reference Broadcast Synchronization (RBS) is the most representative protocol with a receiver-receiver scheme. By exploiting the broadcast property of the wireless communication medium, this protocol is able to achieve synchronization of a group of nodes that are in the communication range of a reference sender. Nodes which receive the broadcasted beacon will record the time of arrival and exchange this information with others. Timing-sync Protocol for Sensor Networks (TPSN) is an implementation of the sender-receiver synchronization method. This concept consists of two phases: the discovery and the synchronization.

B. Energy Problem

One of the most important parameters for a WSN is its energy consumption, because of the limitations imposed upon it. For this reason existing studies propose different strategies to achieve this challenge.

The first proposal is to improve routing protocols, which can be divided into three major categories: data-centric, hierarchical and location-based. Data-centric protocols show the advantage of eliminating many redundant transmissions; the hierarchical ones, through aggregation, can achieve energy savings, while the last category (location based protocols) is designed to provide some QoS (Quality of Service) capabilities along with the routing function.

As we can see, satisfying the need for synchronization and energy saving is not an easy task because these criteria are in opposition in terms of performance. More specifically, to ensure proper synchronization, the network will consume a significant amount of energy.

Table I. Classification on Synchronization and Energy Issues

Protocol	Synchronization issues				
	Scheme used	*Number of messages*	*Time clock precision*	*Implementation level*	*Power Consumption*
IEEE 1588[11]	Single hop	4*N*L	200 ns	App/ Physical	High
RBS[13]	Receiver-to-Receiver	$N*L^2$	29.1 µs	App	High
TPSN[14]	Sender-to-Receiver	2*N*L	16.9 µs	MAC	Average
FTSP[15]	Sender-to-Receiver	N*L	1.7µs	MAC	Low
PBS[10]	Single et Multi hop	2*N	29.1 µs	App	Low

III. Our Proposed Solution

By analyzing how each of the aforementioned protocols is designed and considering our application requirements we concluded that none of the existing solutions is suitable for our system. So we envisioned the development of a new synchronization protocol.

The proposed system, an innovative technique is introduced which is called integration method for clock synchronization (IMCS) in the wireless sensor networks. In this technique the Reference Broadcast Synchronization (RBS) and Timesync Protocol for Sensor Networks (TPSN), which are two prominent examples of receiver-receiver and sender-receiver synchronization methods are integrated. The main goal is to achieve highly accurate time synchronization but to make it energy-efficient. The traditional sender-receiver sync method or receiver-receiver method is used to keep the clocks ticking. We have studied in their comparative analysis that they could save more energy if used together, alternatively. Furthermore they are suitable for different applications. For example, sender-receiver synch is good for larger networks and receiver-receiver sync work better in smaller networks. TPSN does not performance so well in sparse networks where as RBS performance deteriorates in denser networks. This performance analysis demonstrates that combination of RBS and TPSN can work better than using these techniques separately. In the proposed ETSP protocol, to identify conditions to toggle between RBS and TPSN based on a threshold value. By using this integration method for clock synchronization there is high scalability and less energy consumption when compared to the existing system.

A. *Network Model Organization*

As mentioned earlier, our network is composed of a large number of items (64 active elements on each wing) that must communicate in flight, in order to centralize the collected information to the aircraft cabin (Fig. 1).

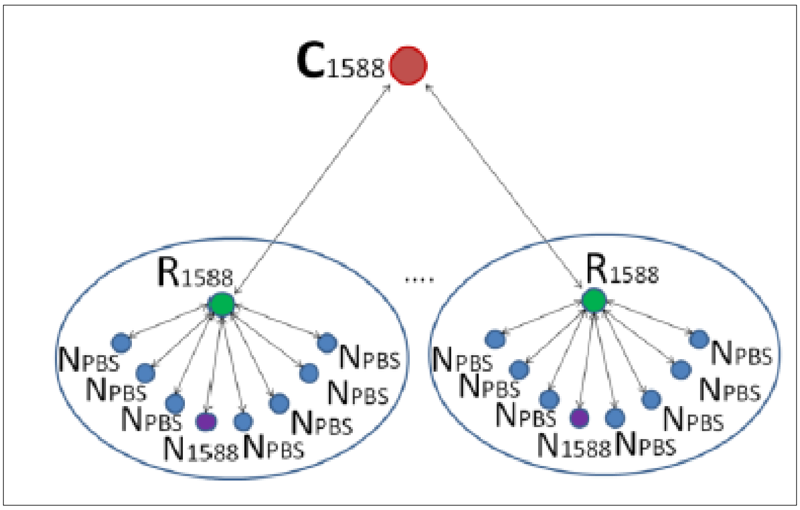


Figure 1. Network organization

Thus we propose a hierarchical organization solution which is composed of three distinct categories of elements (the concentrator, routers and nodes) in Fig. 1. The concentrator is designed to gather all information from routers and transmit them to the cockpit. Further, each one of the eight routers collects information from its nodes (which are eight in number as well).

B. *Synchronization of nodes*

At the end of the synchronization session, X has received T_1^{M},T_2^{X},T_4^{M},T_4^{X} contained in received broadcasted messages. Let Δ_{XM} be the clock offset between X and M and d_{XM} the propagation delay between X and M. We assume that the messages sent by S arrive at the master and at the PBS node at the same time. So, the offset and the propagation delay between the nodes M and X become:

$$\Delta_{XM} = T_4^{X} - T_4$$

$$d_{XM} = T_2^{X} - T_1^{M} - \Delta_{XM}$$

The calculations performed to synchronize the node (X) of the network are given by:

$$T_2^{X} = T_1^{X} - \Delta_{XM} + d_{XM}$$

$$T_4^{M} = T_3^{S} - \Delta_{SM} + d_{SM}$$

$$T_4^{X} = T_3^{X} - \Delta_{SX} + d_{SX}$$

$$\Delta_{XM} = \Delta_{SX} + \Delta_{SM}$$

$$T_4^{M} - T_4^{X} = \Delta_{XM} + d_{SM} - d_{SX}$$

C. *Integration method for clock synchronization*

This method works upon the supposition that there are number of smaller islands of 3 or less nodes. We define performance as the measure of transmissions used by a time synchronization algorithms to synchronize a network. Transmissions can also be referred in term of energy. This energy is proportional to the number of transmissions (or packets) and current drawn for single reception and transmission by the underlying mote hardware.

Energy = No of Tx + No. of Rx (Rx/Tx)

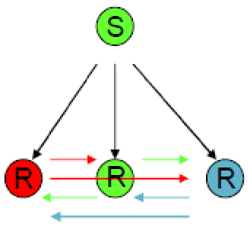
This Rx/Tx ratio is fixed and can be obtained from a mote's data sheet but varies depending upon type of the sensor mote being used.

$N^2 - 3N - 2/à = 0$; where à = Rx/Tx

This equation represents the Rx/Tx ratio and Threshold value (N) in terms of number of nodes. For an à value for a given sensor mote one could determined the threshold value N, good for that sensor mote. The proposed solution assumes that parent node knows about number of children of a parent node. So it decides on each parent node which algorithm is better for given size of network. It compares the switching threshold value with the number of nodes. If a parent node has children less then or equal to *switch_threshold* it uses receiver-receiver or else sender-receiver synchronization method. Next subsection we study an optimal value of *switch_threshold.*

D. Receiver-Receiver sync method

This novel sync method was employed in Reference Broadcast Synchronization (RBS). It is clear that in RBS, transmissions are linear but receptions are quadratic with increase in sensor nodes. This property makes it infeasible when there is large number of receivers. In this method a reference packet is flooded in the network. All receiver nodes record the receive time locally. Then each node exchanges its observation, to all others. This sync method is explained in the following figure 3.4.



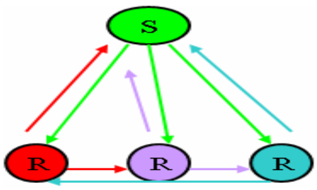
The information possessed by a node can be used to synchronize its' clock either by taking their simple mean or by linear regression method. The relationship of packets needed to sync n number of nodes in RBS.It is clear from the equation that in RBS, transmissions are linear but receptions are quadratic with increase in sensor nodes. This property makes it infeasible when there is large number of receivers. In this method a reference packet is flooded in the network. All receiver nodes record the receive time locally. Then each node exchanges its observation, to all others. The information possessed by a node can be used to synchronize its' clock either by taking their simple mean or by linear regression method. The relationship of packets needed to sync n number of nodes in RBS is given by,

$Tx_{RBS} = n \;\; n-1$

$Rx_{RBS} = n + \Sigma\, i = (n^2 + n)/\,2$

i=1

E. Sender-Receiver sync method



The conventional three-way-handshake method used to sync a network is shown in Figure 3.5. This is mostly used technique in wired and wireless media. Here we are interested in how many transmissions it needs to sync a network. It performs pair wise sync in the network to correct clocks by taking care of propagation delay. Here we are interested in how many transmissions it needs to sync a network. It performs pair wise sync in the network to correct clocks by taking care of propagation delay. A typical example of this method is TPSN. Following is relationship of number transmissions and receptions used to sync a network of *n* number of nodes

$Tx_{TPSN} = n + 1$

$Rx_{TPSN} = 2n$

In TPSN, number of transmission and receptions are both linear. This is found to be good for large denser networks. It does not perform well for spare networks with 3 or less nodes per parent node. So we use this technique for more then 3 nodes per parent node. In TPSN, pair-wise synchronization is performed between sender and receiver using two way handshakes. A parent node **A** sends a synchronization request to a child node B, time-stamped at time T_1 by A and T_2 at node B. Then B sends ACK packet back to A at T_3. The ACK packet finally arrives A at T_4. This needs two packets; first one is broadcast other as unicast ACK.

$\Delta = [(T_{1-}T_2)-(T_{3-}T_4)]/2$

The drift can be used by node B to correct its clock accordingly, so that it could synchronize its clock to the receiver. The B gets drift information from A, Correct its clock and ACK back to A. Thus four packets are required to sync one pair of nodes. This process is carried out throughout the network so that eventually every node is synchronized to the root node.

F. Performance Evaluation

In this section, the performance of the existing and the proposed system is compared. In the existing system, a combined synchronization protocol based on the IEEE 1588 standard that was designed for wired networks and the PBS (Pair wise Broadcast Synchronization) protocol that was designed for sensor networks. In the proposed system, Integration method for clock synchronization (IMCS) is used in the wireless sensor networks. When compared to the existing system, there is high scalability and energy efficiency in the proposed system.

IV. RESULT AND DISCUSSION

This section provides a detailed quantitative analysis comparing the performance of our RBS Protocol and TPSN and the standard IEEE1588-PBS Protocol. The criteria taken into account in this evaluation are:

- the accuracy of synchronization,
- the power consumption in the nodes,
- the number of synchronization messages.

A. Performance Analysis

To check and validate the behavior and the performance of the proposed solution, the essential settings needed in our evaluation have to be given first. Thus, we started the synchronization mechanism in the first-level (concentrator-routers) at 0.3s and in the second level (routers-nodes) after 7s. In this way, nodes change their internal clock by taking as reference the clock of the router which is already synchronized. To obtain precise time synchronization in WSN, it is necessary that the clock of the processor be controlled by a TCXO (Temperature Compensated Crystal Oscillator) at 37.5MHz [9], which has a 1.5PPM frequency tolerance, in order to reduce the drift rate. For our simulation, the internal clock of each node in the network was implemented with a drift of 1.5 microseconds per second. To achieve high performance and then to compare our protocol with the IEEE1588 – PBS Protocol standard, it was also decided to time-stamp the messages at the Physical layer. This information is then used in the synchronization scheme at the Application level. Another important aspect is the hierarchical organization of our system, which is achieved through cooperation between the MAC, Routing and Transport levels.

B. Synchronization accuracy

Our simulations were performed for the complete network (one concentrator, 8 routers and 64 nodes). Due to the hierarchical organization, the behaviors for a subgroup of one concentrator (C), one router (R) and eight nodes (N) is similar to that of any other subgroup. For this reason and because we are limited in number of pages, the graphical results only concern one such subgroup. It is shown in Figure. 4 that the accuracy of the synchronization between the concentrator and the routers is around 1 to 2 hundred nanoseconds. We note that throughout the simulation the network elements remain synchronized at a high level (50-250ns).

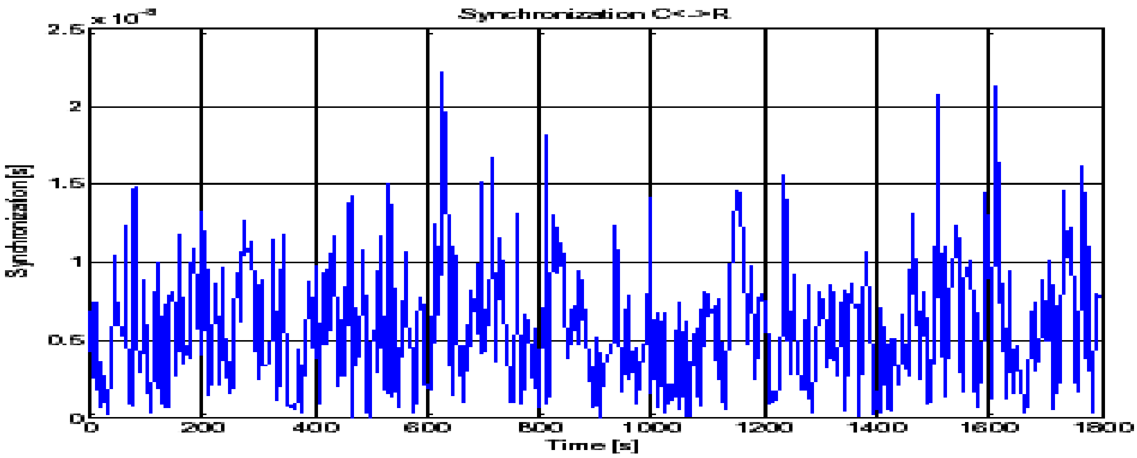


Figure 4 IEEE1588-RBS C<->R synchronization

Please remember that the IEEE1588 protocol results are quite the same (100-200ns), which is normal as the synchronization algorithm is the same. At the Router-Nodes level (Fig. 5), we notice that for the Router-Node1588 pair the synchronization has an order of magnitude of hundreds of nanoseconds and for the Router-Node pairs it varies between 1µs and 46 µs.

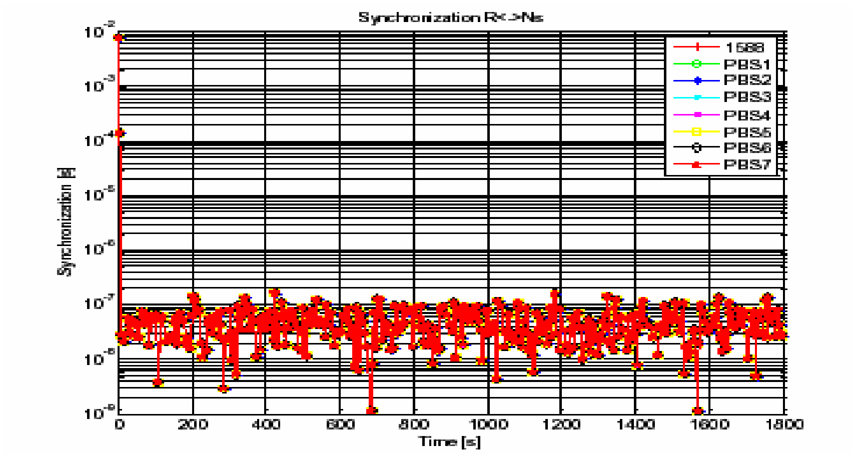


Figure 5. IEEE1588-PBS Rs<->Ns synchronization

The results for the IEEE1588 standard in the R<->Ns level are comparable with the accuracy of the Router-Node1588 pair in our solution (100-250ns). We specify that the network wide synchronization is achieved in about 20 seconds after the beginning of the simulation. So it is clearly shown by these results that the achieved accuracy is very good, close to the best ones found in literature.

C. Energy evaluation and number of messages

In this section we are interested in the analysis of the energy consumption of our system, but especially the consumption in the nodes. We decided to use the energy consumption parameters of a Berkeley mote [12] in order to simulate real life conditions. In our network the energy consumption of sending a message is evaluated by NS-2 as 7mW and that of receiving a message as 4.5mW. Total initial energy is 2700J, which matches a CR2032 cell (3V, 230mA). What interests us is the difference between energy consumption for the two protocols. Fig. 6 shows that the difference in energy consumption between a PBS node and a 1588 node is in the order of 15.07J. In other words, a PBS node consumes 84% less than a 1588 node. This is directly related to the number of messages required to achieve synchronization.

Thus we present in TABLE II the number of synchronization messages for the two analyzed protocols:

Table II. Synchronization Messages

Protocols	Number of Messages	
	Level C<->Rs	Level R<->Ns
IEEE 1588-RBS	120 messages/cycle	24 messages/cycle
IEEE 1588-PBS	120 messages/cycle	1024 messages/cycle

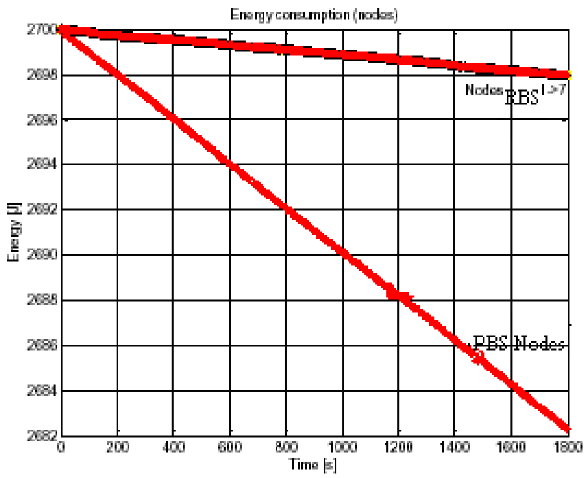


Figure 6. Energy Consumption for RBS and PBS Nodes

This analysis allows us to see why our solution is more suitable for a wireless sensor network. We proved that with good synchronization accuracy our solution achieves at the same time satisfactory energy savings.

V. Conclusion And Future Work

The behavior of Wireless Sensor Networks (WSN) is nowadays widely analyzed. One of the most important issues is related to their energy consumption, as this has a major impact on the network lifetime and also the data sensing synchronization. The existing method consists in implementing a combined synchronization protocol based on the IEEE 1588 standard that was designed for wired networks and the PBS (Pair wise Broadcast Synchronization) protocol that was designed for sensor networks, as none of them is able to provide the needed synchronization accuracy for our application on its own. In the proposed system, we introduce an innovative technique called Integration method for clock synchronization (IMCS) in the wireless sensor networks. In this technique the Reference Broadcast Synchronization (RBS) and Timesync Protocol for Sensor Networks (TPSN), which are two prominent examples of receiver-receiver and sender-receiver synchronization methods are integrated. By using this method there is high scalability and high synchronization accuracy.

For future work, consider the security in wireless sensor networks. Because security is an important consideration to protect the sensing data. Security is a broadly used term encompassing the characteristics of authentication, integrity, privacy, nonrepudiation, and anti-playback. The more the dependency on the information provided by the networks has been increased, the more the risk of secure transmission of information over the networks has increased. So, in future we focus the security in the wireless sensor networks.

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