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Precision timing in TDMA-based Wireless Sensor Network through IEEE 1588 standard

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Abstract- This paper proposes an energy-efficient time synchronization scheme for Wireless Sensor Networks (WSNs) based on the IEEE 1588 standard. Although a number of methods have been studied for time synchronization of WSNs, some applications require high precision time synchronization with very low power consumption. This paper presents a reduced implementation of IEEE 1588 precision time protocol (PTP) for WSNs. Within the proposed synchronization approach, a sensor node is synchronized using the timing message generated by a master node synchronized with GPS. This paper also presents experiments to evaluate the performance of the precision time synchronization of a slave-master pair of sensor nodes.

I. Introduction

A Wireless Sensor Network (WSN) may be described as a network of small, autonomous, battery-powered nodes. When these devices are deployed over a wide geographical region, they can collect information about the environment and efficiently collaborate to process such information [1]. Data is generated using sensors on source nodes and routed (possibly through multiple hops) to a sink, which typically lacks energy constraints [2].
Nowadays, many studies are done in order to improve the functionality of such communication systems. One of their main features is the large number (up to hundreds of elements) of sensors that have to be distributed in different environments. This leads to the development of low-cost sensors [3], with limited processing capacity. A crucial problem in the WSN is to minimize energy consumption [4] and for this reason the time synchronization is critical in power management of any distributed system [5], [6].

Time synchronization in wireless sensor networks (WSNs) is essential to facilitate group operations such as time division multiplexing, sensor localization, data aggregation, distributed sampling, etc. [7]. The time signal delivered to the application depends on the quality of the master clock and the application service interface allowing all nodes to synchronize in the microseconds range. This is the precision required for time-stamping some data collected in smart grid. A number of time synchronization protocols for WSNs have appeared, such as Reference Broadcast Synchronization RBS[1], Timing-sync Protocol for Sensor Networks TPSN[2], Flooding Time Synchronization Protocol FTSP[3] with time synchronization accuracy of tens of microseconds. Other approach is to use the IEEE 1588 precision time protocol (PTP) [7] in WSN which can provide synchronization accuracy below microseconds. This IEEE 1588 standard defines a protocol enabling precise synchronization of clocks in measurement and control systems implemented with technologies such as network communication, local computing and distributed objects. However, most research on IEEE 1588 has been focused on Ethernet because the protocol is applicable to system communication that supports multicast messaging [8]-[11].

In this framework, we present our idea for a low-power method of clock and time synchronizing in a local area applying the IEEE 1588 standard in wireless sensor nodes. In order to achieve the scope of IEEE 1588 with WSNs, we designed a schema prototype to timestamp the messages between a master node and a slave node and a way to transmit the timestamps from master to slave into the communication messages. We also present an experiment that suggests this method is capable of precision on the order of 2µs using a clock period of 500 ns.

II. Detailed description

As specified by the IEEE 1588 protocol two types of PTP messages, event and general messages are defined and used for WSNs. The event messages are used to transmit accurate timestamps both for transmission and reception. The set of event messages consists of two messages, the Sync and Delay_Resp messages and the general messages consists of Follow_Up, Delay_Resp and Management messages. The Sync, Delay_Req, Follow_Up if is used, and Delay_Resp messages are used to generate and communicate the timing information needed to synchronize PTP clocks using the delay request-response mechanism. The general format of the PTP messages proposed to be used for WSNs is shown in Table 1.

Table 1 PTP message fields for low-power WSNs

Bits								**Octets**
7	**6**	**5**	**4**	**3**	**2**	**1**	**0**	
PTP control								1
Two step flag	**PTP control**							1
Origin timestamp (optional)								8

The basic pattern of synchronization message exchange in WSNs is illustrated in Figure 1. This network is constituted by different master-slave pairs and the synchronization pattern is as follows:

1. The master nodes, in this example node A or C transmits a Sync message in the network and notes the time T1 at which it was sent.
2. The master sends the timestamp T1 embedded in the Sync message, which requires the use of trigger transmission, or embedding the timestamp T1 in a Follow_Up message.
3. The slave nodes, in this example nodes B and C, receives the Sync message from node A and slave nodes D and E receives the Sync message from node C, and notes the time of reception T2.
4. The slaves send a Delay_Req message to the master and note the time T3 at which it was sent.
5. The master nodes receive the Delay_Req messages and notes the time of reception T4.
6. The master node conveys to the slaves the timestamp T4 by embedding it in a Delay_Resp message.

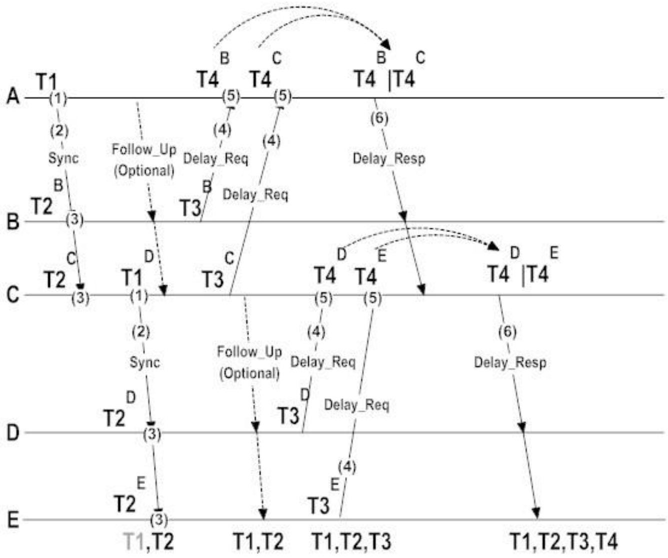

Figure 1 Synchronization message exchange for hierarchical topology. The slave node exchange PTP messages with master or boundary clock

III. Performance evaluation

This section provides a detailed quantitative analysis of our time synchronization implementation based on IEEE1588 standard. The accuracy of synchronization has been tested for star and linear topologies. The communication period rate of the networks has been set-up to 5s with sensors clock reference of 2 MHz (500 ns counter tick) [12]. In these experiments the offset has been measured with a Tektronix TDS 784D digital Oscilloscope of 1GHz, 4GSa/s and 4 Channel. With the Oscilloscope we measure the delay of the Pulse per Second (PPS) signals generated by each device. The PPS signal in both modules is generated at a GPIO pin each time in the Event Timer the "current time" is equal to the comparator value of a new second. In Figure 2, the experiment setup to get the clock offset between unsynchronized pairs (slave/master) of sensor nodes and the results of the measurements are presented.

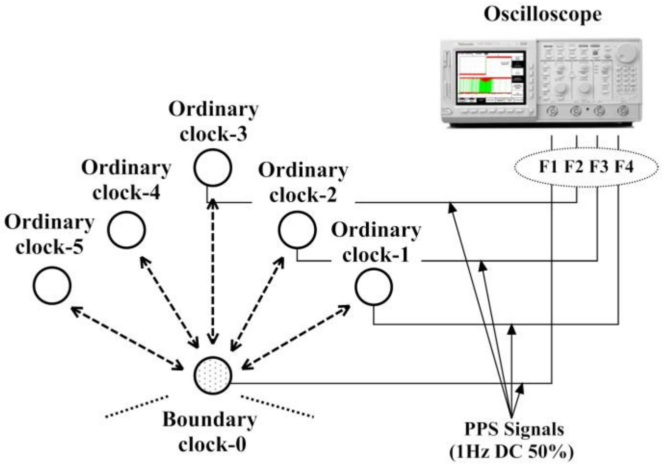

Figure 2 Illustration of the offset measurements setup

The measurements have been done between a GM Clock 1 that generates a pulse-per-second (PPS) signal (F1) and three slave sensors 1, 2 and 3 that generates three pulses-per-second (PPS) signal (F2, F3 and F4). The PPS offset between the three nodes and the GM clock before synchronization is presented in Figure 3.

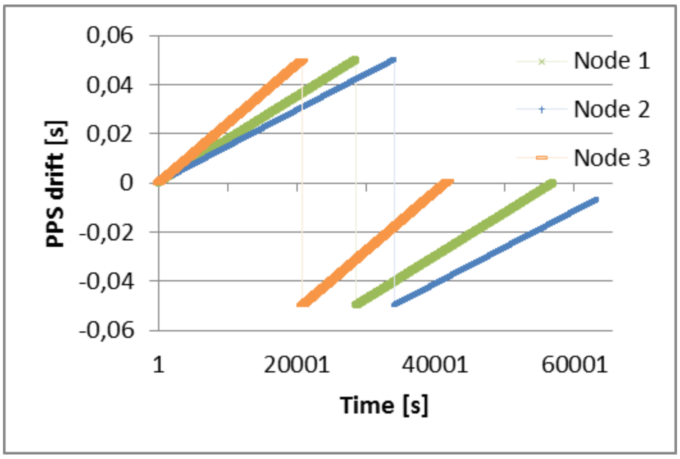

Figure 3 Clock offset between GM node and slave nodes without synchronization

This graph shows that the clock offset in node 2 is about 1.74µs/s. Using the same configuration the offset measurements of the slave clock synchronized every 5 seconds have been gathered over a period of approximately 24 hours. The mean time delay is 481.19 ns, with a standard deviation of 350.62 ns and a maximum value of 2283 ns. The histogram presented in Figure 4 represents the time deviations between the slave clocks and the GM clock.

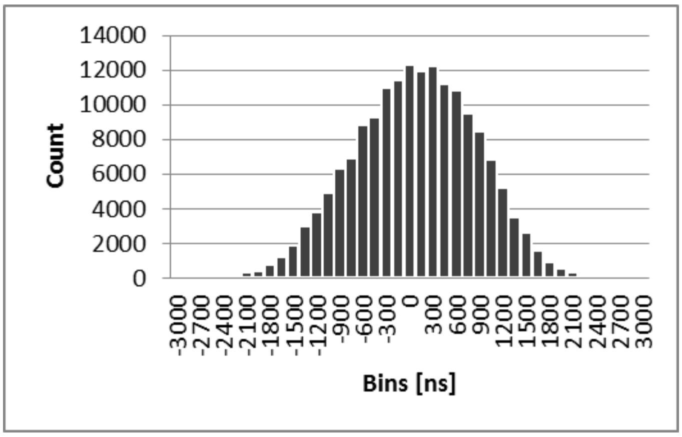

Figure 4 PPS signals delay histogram in star network with communication rate of 5s

IV. Conclusions

An experimental setup and the results obtained have been presented in order to evaluate time delays between a master-slave pair of wireless sensors. An energy-efficient time synchronization schema was implemented using IEEE1588 standard. Based on the number of messages and the length of packages transmitted between a master node and a sensor node an approximation of energy consumption per synchronization cycle is done for an Xbee module. The specifications of XBee module are:

- Transmit current: 215 mA (@ 3.3 V)
- Receive current: 55 mA (@ 3.3 V)
- Package transmission/receiving time: 4.256 µs for maximum payload of 125 bytes.

The energy consumption of a sensor node per synchronization cycle through this implementation of IEEE 1588 standard is approximately 0.772 mJ.

The time synchronization and frequency adjustment for a master-slave pair have been tested. The obtained results show that this solution is able to obtain synchronization accuracy at a level of microsecond with efficient energy saving. An improvement may be done using a higher operating clock in order to obtain sub-microsecond accuracy. With these results one can conclude that the protocol developed for WSN based on IEEE 1588 standard is a valid strategy to synchronize distributed wireless nodes when low power consumption and accurate clocks are required.

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