Application Layer Synchronization for Wireless Sensor Networks using WWVB

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Abstract

Wireless sensor networks (WSN) are widely used as they allow various computing and data acquisition applications to be performed. Their popularity is also attributed to the low cost of sensor nodes and their increasing computational capabilities. The main functionality of these networks is data agglomeration from different sensors and hence synchronization of different nodes proves to be a challenge. WSN are designed with stringent constraints on size, cost and especially power consumption and this imposes limitations on any synchronization scheme to be implemented. The synchronization method we propose in this paper targets the application layer and will use an already available universal time signal, WWVB, to time-stamp each measurement.

I. Introduction

WSN prove to be of great significance when it comes to data acquisition and remote sensing applications. They find their usage in a wide variety of applications, and particularly in climate monitoring, intruder detection, home automation, seismic studies, battlefield surveillance, traffic control... The basic operation performed by WSN after acquisition is data fusion which is the process of aggregating data from all sensors to a single meaningful result [1]. This aggregation process needs to be performed on measurements taken with reference to the same time from different sensors; otherwise we lose the inherent time correlation among readings. Hence the need for a common notion of time in the different sensors, and ultimately clock synchronization.

Many variations of clock synchronization protocols for WSN can be found in the literature. These protocols must deal with the stringent constraints imposed. Energy constraints come from the fact that sensors equipped with a limited energy source might be deployed in remote or hostile areas where maintenance is impossible. Thus the need to maximize the battery life of nodes. Another constraint is the limited bandwidth which affects message exchange among sensors necessary for synchronization and this is basically due to the relatively high power consumption that transmitting requires as compared to processing. These constraints are also added to the limited size and thus hardware in a sensor node and unstable network connections.

The scope of this paper only includes single-hop communications and concentrates on a star topology network whereby the peripheral nodes will be the sensor nodes all communicating with a central node with high processing power that is the sink of information and where the fusion of data will be performed. The sensor nodes have minimal processing power so that their sole purpose is data collection and forwarding. As mentioned earlier, our focus is on clock synchronization of different sensor nodes from the application level point of view.

II. Existing Research

One of the most popular protocols used for synchronization is the Reference Broadcast Synchronization (RBS) protocol. As explained in [1], it uses a transmitter that broadcasts a reference packet to two receivers. Each receiver records the time at which the packet was received according to its own clock. Assuming that the message in single-hop transmission reaches the intended receivers at the same time, the two receivers calculate the clock offset between them depending on the local time recordings. Using this differential method for synchronization yields high accuracy since it removes some non-deterministic delays such as the send time and access time that are spent by the transmitter before the data get access to the transmit channel. The performance can be also improved by averaging the estimates over multiple send and receive trials to get a more accurate offset and skew values. Since correcting the clock time requires lot of energy, this technique does not correct the clock, but keeps a table at each node that stores the offset and skew of all the other nodes. It also conserves energy by doing synchronization only when it is needed. The drawbacks for this protocol are the big number of messages exchanged for synchronization as well as the table storage and both require additional energy consumption.

Another way to obtain accurate time synchronization is through Global Positioning System (GPS) which comprises of 24 satellites each of which has an atomic clock synchronized to GPS Time - offset by a constant from the International Atomic Time TAI. To correct for clock offsets, time reception from only one satellite is required. Most of GPS receivers are designed for navigation and provide time output with low accuracy. More accurate receivers provide a one pulse-per-second (PPS) output signal and can be used for clock synchronization. As an example the CNS Clock from CNS Systems can give an accuracy of $20\,ns$ [2]. But such receivers cost in the order of $1000 which is a very high price compared to the cost of sensors. Other receiver modules such as Garmin GPS18-PC cost in the order of a hundred dollars and provide serial data and 1PPS outputs [3]. In addition to the high cost, GPS receivers consume a high amount of energy, for example the Garmin GPS18-PC requires an input current of $50\,mA$ at $13.8\,V$ [3].

Different types of IEEE 802.11 time synchronization are also mentioned in [4]. These use a single time server to transmit an absolute time-stamp periodically to synchronize target clocks. The drawback for such techniques is the high energy required by the time server to enforce its notion of time as well as the collisions that might occur between 802.11 data and synchronization data.

III. Method

A. WWVB Description

WWVB is a time standard radio station run by the National Institute of Standards and Technology (NIST). It is located near Fort Collins, Colorado. WWVB is the station that radio controlled clocks throughout North America use to synchronize themselves. Note that WWVB is just the name of the station and not an acronym.

The WWVB signal is continuously broadcasted on a $60\,kHz$ carrier. The propagation characteristics of such low-frequency radio wave make it well suited for time transfer. The signal itself is identified by its unique time code which is derived from a set of atomic clocks and then transmitted at a rate of 1 bit per second using pulse width modulation (PWM) followed by amplitude shift keying (ASK) [5], [6].

WWVB requires one minute to send its time code which contains the current minute, hour, day of year, the last two digits of the current year, the UT1 correction, leap year and leap second indicators, as well as information about daylight and standard time. The time code is sent in binary coded decimal (BCD) format in which each decimal digit is represented using four bits. At the start of each second, the carrier power is reduced by $10\,dB$. Restoring full power after $200\,ms$ indicates a binary 0, $500\,ms$ indicates a binary 1, and $800\,ms$ indicates a frame marker. Of the sixty bit times transmitted each minute, forty-two relevant bits and seven frame markers convey the UTC time. Each frame begins with a frame marker at the 0th second and ends with another frame marker at the 59th second. Hence, two consecutive frame markers, called an on-time marker (OTM), in the received data indicate the start of a new time frame indicating the exact time at the OTM [5].

For the purpose of our targeted application, WWVB is quite beneficial. In fact, WWVB is transmitted by a single station which provides a non-stop continuous signal. Thus, receivers can tune in at any instant, detect the start of the time frame and read the transmitted time. Also, if we ignore propagation delay, WWVB transmitted time is accurate to UTC within $0.1ms$ making it very reliable [5]. Hence, geographically distributed sensor nodes can use the timing content of this signal as a common notion of time in order to time-stamp readings and successfully correlate network wide measurements at the central node.

B. Procedure

Consider a wireless sensor network having a star topology. Sensor readings are generated and transmitted to the central node for further processing and data fusion. Because time progress differently on each node, we will not be using internal clocks to time-stamp readings. In other words, the central node, responsible for agglomerating all acquired data and producing a single global result, will be correlating faulty data and generating erroneous observations.

Our solution to this problem involves equipping each sensor node in the network with the necessary hardware to receive and decode the WWVB signal: a WWVB receiver with a $60\,kHz$ antenna and a WWVB decoder module. The top-level block diagram of a network node will be as shown in Fig. 1.

Assuming data acquisition at a node is instantaneous and occurs at time t_0, we are interested in time-stamping this reading with the closest estimate possible, denoted by $\widehat{t_0}$. Now, since both the sensor and WWVB modules are controlled by the same processor, we configure the node to acquire data and start WWVB reception at the same time, t_0. But in order to decode the transmitted time frame, the receiver must first detect an OTM as a sign of the start of the new frame. In other words, the time at which WWVB reception starts does not necessarily coincide with the start of a new time frame and may be off by a maximum of $59\,seconds$. We designate t_1 to be the time at which the OTM is detected. So, full reception of the WWVB time frame will be completed at $t_1 + 60\,seconds$.

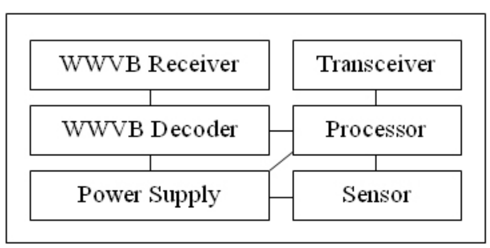

Fig. 1: Block Diagram of Sensor Node

The desired estimate $\widehat{t_0}$ can be expressed as

$$\widehat{t_0} = t_1 - \widehat{\Delta}_{OTM} \tag{1}$$

such that

$$\widehat{\Delta}_{OTM} = \widehat{t_1 - t_0} \tag{2}$$

is the time between the start of WWVB reception and OTM arrival.

Since the decoded WWVB signal provided the exact time when the OTM was detected, i.e. t_1, our task is now to estimate the time difference $\widehat{\Delta}_{OTM}$. To do so, we exploit the unique format of the WWVB signal. Since the receiver is continuously decoding the WWVB signal which is transmitted at a rate of $1\ bps$ until an OTM is found, one can simply count the number of received but discarded bits and use that as an estimate for $\widehat{\Delta}_{OTM}$ whose uncertainty will be less than $0.5\ seconds$.

Once the estimate $\widehat{t_0}$ is available, the acquired data may be time-stamped accordingly and forwarded to the central node. If the same algorithm is implemented on all nodes in the WSN, all sensor readings will be with respect to the same timing reference and thus data fusion is made feasible.

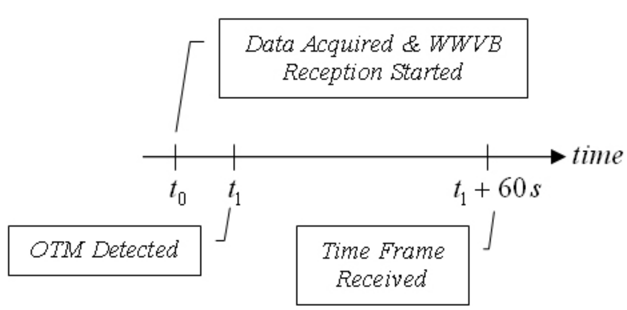

Fig. 2: Event Progression at Node

C. Simulation

We simulated a WWVB transmitter/receiver pair in LabVIEW. Our transmitter continuously transmits the coded time frame which is generated every minute and the receiving node runs a WWVB receiver to recover the coded time. This physical layer transceiver simulation is the basis for a larger simulation that will include a star topology wireless sensor network that implements the above algorithm for synchronization. We did not have the time to complete this simulation, but hopefully it will be our objective for future work on this topic.

IV. Analysis and Comparison

In this section, we evaluate the feasibility and performance of the proposed method and compare it to other widely used schemes.

A. Accuracy

As mentioned earlier, the WWVB transmitter time is kept within $100\,\mu s$ from UTC [5], [6]. Hence, the received performance will inherit this initial inaccuracy. In addition, the received performance depends on the distance separating transmitter and receiver, the quality of the received signal and the type of antenna used at the receiver. The WWVB signal, being a radio wave, propagates at the speed of light, and so, the longest possible delay in the continental United States can be calculated to be less than $15\,ms$ [5]. Advanced receivers that produce a 1 pulse per second (PPS) signal can have a switch or a software that allows advancing the time by the value of the delay. The low frequency characteristic of the signal means that the signal has a long wavelength so when it reaches an obstacle the angle of incidence is very small hence most of the signal penetrates the obstacle, so that the dominant path from the transmitter to the receiver is line-of-sight or ground-wave for distances less than $1000\,Km$. The second path, called the sky-wave, is the part of the signal reflected from the ionosphere. The sky-wave is useful in cases where the ground-wave is very weak at long distances. But the sky-wave suffers from phase shifts at sunrise and sunset when the ionosphere lowers and rises respectively and the receiver might lose track of the carrier. This adds multiple of $\frac{1}{60\,kHz} = 16.67\mu s$ delay to the signal. Summing up all those delays we get a total delay of around $16\,ms$ in a worst case scenario. And since all nodes in the WSN are located in a relatively small area, the incurred delay will be the same for all nodes.

Examining the relative time accuracy between nodes in a ZigBee network for example where nodes are confined to a small geographical area and the spacing between them does not exceed $100\,meters$, we note that the corresponding offset will be restricted to the propagation delay and will be in the order of $0.66\,\mu s$.

Looking at different classes of data acquisition WSN, we notice that the most common classes are ones with periodic sampling where data such as temperature is constantly acquired or event-driven networks such as fire alarms where data acquisition is performed after a certain threshold has been reached [7]. And in both cases the sampling frequency will be very low compared to the relative inaccuracy of $0.66\,\mu s$.

B. Energy Consumption

When it comes to energy, the primary concern in WSN design, synchronization using WWVB consumes very little. This is why we offer ourselves the luxury of time-stamping every measurement with the WWVB derived time directly for applications with low sampling rate. This extreme method is traded-off with the high energy consuming clock correction for applications where a very high sampling rate is needed since clock correction, at a rate of once per day for example, will turn out to be more power efficient than WWVB based time-stamping for a large number of times. The Galleon EM2S WWVB receiver whose technical details are specified in [8] operates in the range of less than $0.6\,mA$ for a voltage of $3\,V$. And when in standby mode, the current consumption drops to less than $5\;\mu A$. The maximum energy required to perform one synchronization for the mentioned specifications is $108\,mJ$ compared to a constant value of $4.14\,J$ for one GPS synchronization using the Garmin GPS18-PC specifications mentioned earlier [3]. These figures were calculated based on the signal characteristic of both systems; WWVB needs one minute to transmit its time frame while GPS sends the time frame in $6\,seconds$ at a rate of $50\,bps$. As for RBS, the overhead of message exchange is not power efficient at all since $3\;Joules$ are required to transmit $1\,bit$ over $100\,meters$ [1]. These figures give a clear view on the power efficiency of using a WWVB based synchronization method.

C. Cost

WWVB compliant hardware are nowadays being deployed in millions of wall clocks, wrist-watches and other devices that synchronize themselves to NIST time. The cost of producing large quantities of a $60\,kHz$ antenna, a WWVB receiver and decoder modules can be as low as a few dollars which is quite appealing.

V. Conclusion and Future Work

In this paper, we presented an application layer synchronization scheme for WSN using WWVB. We have shown this method to be very beneficial from an accuracy point of view since it uses an exact universal time reference. In addition, it is energy efficient and representationally cost effective as it avoids the energy-consuming clock correction step that other schemes perform, and instead relies on the relatively cheap WWVB reception circuitry.

Future work includes generalizing this scheme for a multi-hop network as well as attaining higher levels of accuracy by implementing chatter among network nodes in order to estimate small scale delays.

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