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Towards a Radio-Controlled Time Synchronized Wireless Sensor Network: A Work in-Progress Paper

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Abstract

Wireless sensor networks are deployed to monitor real-world phenomena, and are seeing growing demand in commerce and industry. These networks can benefit from time synchronized clocks on distributed nodes. The precision of time synchronization depends on error elimination or reliable estimation of errors associated with synchronization message delays. This paper examines an approach to time synchronize motes using onboard radio-controlled clocks. The advantage will be the minimisation of non-deterministic sources of errors in time synchronization amongst receivers. This approach of synchronization using out-of-band and dedicated time source is aimed to achieve network-wide, scalable, topology-independent, fast-convergent and less application-dependent solutions.

1. Introduction

In recent years, the widespread adoption of wireless technologies in consumer goods industry has seen enormous success on the back of rising demand for low-cost and mobile connectivity solutions. Advantages of absence of cables can also be of significance in many other sectors including but not limited to, factory and process automation, medical and healthcare monitoring, environmental monitoring and structural integrity monitoring [1]. The identification of such benefits has led to the development of standards like ZigBeePRO, WirelessHART and ISA100.11a, which is an evidence of growing industrial interest. The use of wireless networks in industrial applications stresses the need for a reliable, secure, energy-efficient and resilient network which can withstand and address such unique industrial requirements [2].

Wireless Sensor Networks (WSNs), refers to a spatially distributed network of wireless sensor nodes which monitor the phenomena of interest, and communicate the sensed information to the host application wirelessly. The building block of a WSN is a wireless sensor node, often referred to as a mote. A typical mote comprises of: sensor(s), radio transceiver, memory, microcontroller, antenna and a power unit [3]. In addition to the resources available on-board, other requirements often include *precise time* information at the node [1], which is a middleware service, often provided at the expense of increased protocol complexity and burden on the network resources [4].

As WSNs are penetrating into the industrial domain, new research opportunities are emerging; one such opportunity is within time synchronization. Existing approaches based on time synchronization protocols have been able to address application specific solutions, but they have their relative shortcomings [5]. There is a need for a new solution for time synchronization in a WSN, which is scalable, energy-efficient, topology independent, fast convergent and less application dependent, a view shared by many researchers such as referred in [5].

This paper proposes a new solution for time synchronization in a WSN which is scalable, topology independent, has rapid convergence and is application independent. The approach to achieve the above mentioned is to use hardware-assisted synchronization, by means of radio-controlled clock receivers, MSF receiver in this case, on the motes.

2. Time Synchronization in Wireless Sensor Networks

Time synchronization is the process of ensuring that the distributed nodes share a common notion of time, and the synchronisation algorithms provide a mechanism to synchronize local clocks of the nodes either relative to each other or to a global clock [6].

Importance of Time Synchronization

Time synchronisation is very important in a distributed wireless network for the following reasons:

- *Data fusion*: The sensory data collected from distributed nodes have to be integrated and interpreted to form a big picture, which mandates the need for accurate time stamps.
- *Time interval calculation*: In some cases, the phenomena of interest can be the time intervals

between occurrences of events at various nodes in a network. In this case two nodes need to have information about local times to calculate the time interval between events [7].

- *Contest-free access to radio channel*: Setting up a Time Division Multiple Access (TDMA) schedule also requires nodes to be highly synchronised in order to avoid packet collisions [8].
- *Coordination*: Forming a network in which devices coordinate amongst themselves to assign tasks to each other or place order for sequence of events again calls for synchronised network [9].

Some other reasons include energy-efficiency (important to prolong the network lifetime) and cryptography.

Challenges of Time Synchronization in WSNs

The clock in a mote is an electronic timer that counts oscillations in an accurately-machined quartz crystal. The authors in [6] have explained that most hardware clocks are not accurate because of inaccuracies in the crystal frequency. Therefore in a distributed wireless network, nodes clocks may run at slightly different frequencies leading to divergence from one another known as *clock skew* [6]. Synchronising a network requires removing clock offsets from distributed nodes. Synchronisation challenges in WSNs include limited energy, limited bandwidth, hardware limitations, protocol complexity, network topology and unstable network connections.

Time Synchronization Strategies

In order to attain time synchronisation two different approaches exist [6]:

- Distributed clocks can be synchronised to an actual time standard like Universal Coordinated Time (UTC), referred to as physical clocks.
- Distributed clocks can be relatively synchronised to one another, referred to as logical clocks.

Time synchronization relative to UTC is not necessarily an absolute requirement, but it can be an added benefit as explained in [10]. This research focuses on hardware assisted synchronization approach.

Sources of Error in Time Synchronization:

In general the exchanges of messages which occur during synchronization are subject to various delays. The four components which contribute towards synchronization error are [11]:

- *Send time:* It is the time spent at the sender node to construct the message and access the network interface.
- *Access time*: It takes into consideration the time taken to access the communication channel.
- *Propagation time*: Time for the message to travel from source to destination.
- *Receive time*: This is the time taken by the receiver to receive the message and notify the host.

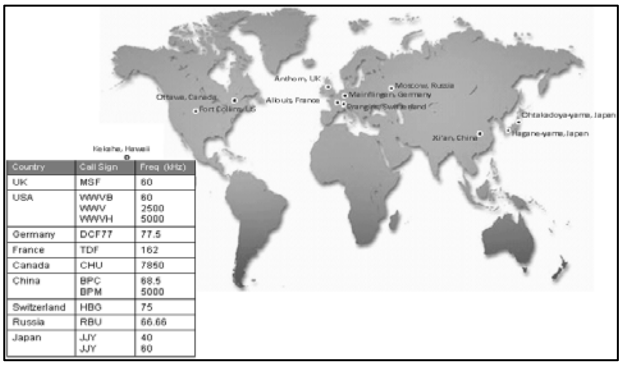
Clock synchronisation protocols address these components. In order to achieve higher accuracy, uncertainties in these components are to be minimised.

3. Hardware-Assisted Time Synchronization

The proposal to achieve a network-wide, topology-independent, fast-convergent and scalable solution for time synchronization is achievable using broadcast medium. Some applications outside WSNs already use time broadcasting sources to synchronize local clocks. The various available options include:

Global Positioning System (GPS): It can be used to achieve physical time accuracy within few microseconds of UTC [12]. It can provide good time accuracy for the entire network but current adaptation of GPS is limited in WSN because GPS receivers are expensive, power-hungry, require line-of-sight to work and can take few minutes to lock onto the signal [13]. Hence, this option is not considered in this research.

Terrestrial Time Broadcasting Radio Stations: There are various dedicated radio signals available around various regions of the world which are disseminating accurate and reliable civil time. These terrestrial time broadcasting stations are controlled by atomic clocks at the radio station [14]. The majority of these stations operate at the Low Frequency (LF) spectrum, which makes it possible to a cover wider area and the signal can be received indoors. LF receivers are not limited to line-of-sight range [14]. The receivers are also relatively cheaper compared to GPS modules and are less power consuming. Figure 1 highlights the various terrestrial time broadcasting stations around the world, they differ from one another in aspects such as transmit frequency, transmit power and signal format.



Country	Call Sign	Freq (kHz)
UK	MSF	60
USA	WWVB WWV WWVH	60 2500 5000
Germany	DCF77	77.5
France	TDF	162
Canada	CHU	7850
China	BPC BPM	68.5 5000
Switzerland	HBG	75
Russia	RBU	66.66
Japan	JJY JJY	40 60

Figure 1. Terrestrial Time Broadcasting Radio Stations, sources include [14], [15] and [16].

Code Division Multiple Access (*CDMA*)*:* Cellular signals originating from synchronous CDMA base stations operate in compliance with IS-95 [17]. They require time synchronized base stations [17]. GPS timing receivers are located at these base stations, which act as repeaters of GPS time [14]. This option is available in areas where cellular systems offer such services.

Long Range Navigation (*LORAN*)*:* Terrestrial based radio navigation systems utilize various ground stations to determine the location of the receiver. This broadcast does not contain time information; however receivers can produce on-time UTC pulse [19]. LORAN systems are being phased out [18], hence are not a viable option.

Amongst the different options examined above, a radio-controlled clock receiver synchronized to terrestrial time broadcasting station appears promising and will be examined in detail in this research.

Elimination and Minimisation of Sources of Error in Sender-Receiver Synchronization Paradigm

Equipping motes with radio clocks will help to achieve time synchronization using out-of-band communication. It will eliminate the need to use in-band synchronisation protocol. This will help to reduce the burden on the limited bandwidth available in the communication channel. In sender-receiver synchronization, the sources of synchronization error are confounded by random events. There are four sources of errors in time synchronization as mentioned in section 2 contributed by latency delays. The proposed solution using radio-controlled onboard clocks will help eliminate *send time* and *access time*, as all motes will experience the same effect of these two sources of error. Regarding the *propagation time*, the further the devices are relative to the transmitter; this error will increase relative to UTC. However, if the motes in a WSN under investigation are within close proximity of one other, say meters to kilometres, this error relative to one other is still within few microseconds. Therefore, the synchronization error within this approach comes down dominantly to receive time error.

Advantages of using radio-controlled clock module on motes

- Elimination of the need for in-band time synchronisation protocols.
- Scalability is not an issue and the coverage of the signal around the UK and Ireland is high.
- There is no need to run algorithms on the local nodes for estimating the offset amongst the nodes; all nodes will receive same information from the MSF signal.
- There is no need to keep information about the timestamps of neighbouring nodes and to transform them into local time. All nodes will share same notion of time.
- Time to achieve network-wide synchronization is independent of network size, and receivers will be synchronized concurrently.
- The nodes which will join a network in an ad-hoc manner will not require resynchronisation.

4. MSF Time and Date Code Signal

The dedicated RF signal for disseminating time and date code information in the UK is known as MSF signal, which is broadcast from Anthorn, Cumbria in England. This signal is available round the clock, all over the UK [15]. The radiated power of the receiver is 17 kW and is operated on a frequency of 60 kHz [15]. The frame format of MSF signal is shown in figure 2.

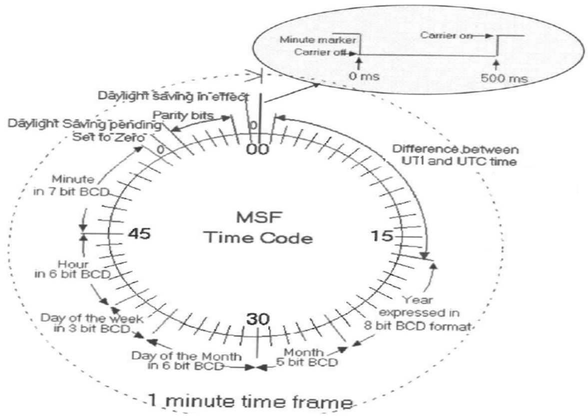


Figure 2. MSF time and date code signal format, 00-59 seconds, source [15].

Distinct and Repetitive Pattern in MSF Code

In order to synchronize a WSN a distinctive and repetitive pattern in time has to be identified from figure 2. Key distinct markers in MSF signals are as follows:

Start of Frame (SOF): The first second of every minute begins with a period of 500ms of carrier off [15].

Second Marker: The start of every other second is marked with at least 100ms of carrier off and ends with at least 700ms of carrier on [15].

Minute Identifier: Two bits are transmitted every second in the MSF signal. Bits 53A to bit 58A are permanently set to '1', with prior and post bits set to '0'. This sequence 01111110 only appears once [15].

5. MSF Radio-Clock Receiver Design

In order to evaluate the effectiveness of the proposed methodology, there is a need to design a radio clock receiver module which can be used with motes. The initial part of the design focuses on receiving and decoding the MSF signal and evaluation of the signal performance before stacking the module on a mote. The evaluation module developed is shown in figure 3.

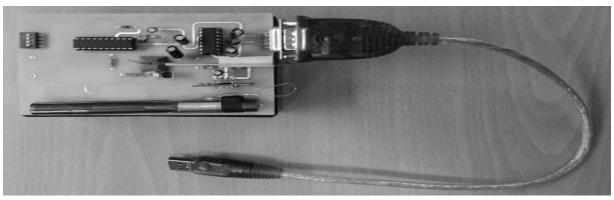


Figure 3. Evaluation module of MSF receiver.

6. Initial Results

The received MSF signal is evaluated over time and the distinct marker of the start of frame was identified. Figure 4 illustrates the oscilloscope trace obtained.

The output from MSF receiver at the start of a new minute is shown in figure 4(a) with a distinct pattern of

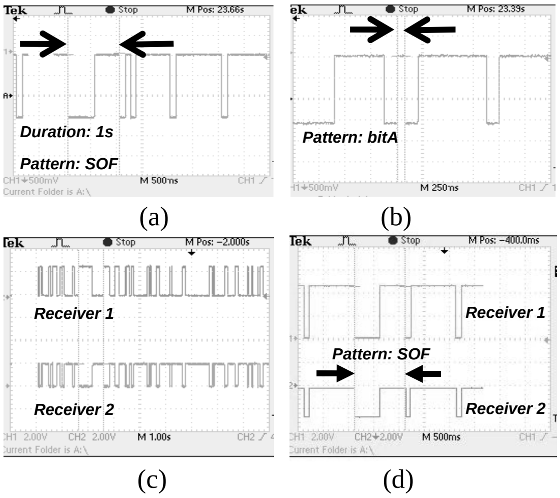


Figure 4. Signals captured from the evaluation module. Panels (a) to (d) are explained in the text.

500ms of carrier off, followed by 500ms of carrier on. BitA in the time code is transmitted after 100ms of start of every new second as shown in figure 4(b). Figure 4(c) shows the traces of two MSF receivers operating independently. This illustrates the signal stability over time. Figure 4(d) illustrates the SOF as detected at two different receivers.

7. Future Work

As part of the future work, several motes will be equipped with radio clocks and a WSN will be established. Performance evaluation of this approach will be carried out in relation to synchronization accuracy, convergence time, energy-efficiency and coverage. Some industrial concerns regarding the use of external sources have been identified by industrial collaborators, and will be addressed later in the research.

8. Conclusion

The proposed approach of network-wide time synchronization in a WSN using MSF radio-controlled clock receivers appears to be a promising solution, with some encouraging initial results. This approach is relatively new in WSNs and will help to eliminate and minimize three sources of synchronization error introduced in normal sender-receiver synchronization systems namely the send time, access time and propagation time. These errors remain between the sender and receiver, but amongst the receivers themselves, they get cancelled out. The network hence becomes susceptible merely to receiver-related error.

This approach is independent of network-size, and hence is scalable. It is also a topology-independent synchronization solution, as it does not matter whether the network is single-hop based star connection or multi-hop mesh network, as all devices can concurrently get synchronized. All in all, this approach is aimed at achieving scalable, topology-independent and fast-converging time synchronization solution.

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