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A Review of Synchronization Methods in Wireless Sensor Networks

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Abstract

Synchronization is required in all types of wireless sensor networks in any situation that requires time-based collaboration of one or more of the nodes of the network. A major example of this need for synchronization is a position location network in which the positions of objects are calculated based on time of flight measurements made at several nodes. The accuracy of synchronization becomes more important as the requirement for measurement accuracy increases. This paper reviews literature that is currently available on methods of achieving and improving the accuracy of synchronization in distributed sensor networks.

Keywords: Wireless, sensor, network, synchronization, reference broadcast, propagation delay, GPS timing, atomic clock, network timing protocol, ultra wideband.

1 Introduction

Synchronization of electronic systems has become more important as the requirement for more accurate time measurements has increased. This is especially true for systems with distributed nodes that must collaborate to perform some task, such as sensor data fusion operations, coordinated actuation and power efficient duty cycling.

Also, as the requirement for measurement accuracy increases so does the difficulty involved in keeping the various parts of a network synchronized.

This paper gives a review of the need for synchronization, the difficulties encountered when trying to synchronize a distributed network, and some methods that have been developed to overcome these problems. The methods described include reference broadcast, measured propagation delay, atomic clock, GPS time, network timing protocol, synchronization for communication systems, and ultra wideband synchronization.

2 The Need for Synchronization

Some examples of the need for synchronization are given below.

In a time division multiple access (TDMA) system each device is given a time slot to transmit data in. Occasionally the local clocks of all of the devices must be synchronized to ensure that one of the devices does not wander with relation to others. If the local clock were to fall out of synchronization with the other devices in the system it could transmit out of turn, thereby interfering with other transmitters. GSM mobile equipment is an example of such a TDMA system[1].

Another example is a position location network (PLN) in which a number of base stations of known position track the position of mobile nodes using a time based positioning method such as time of arrival or time difference of arrival[2]. GPS is an example of this type of PLN and its method of keeping accurate synchronization will be discussed later in this paper.

As the requirement for more accurate measurements increases, so to does the difficulty involved in increasing the accuracy of synchronization. For example, if the calculation requires the measurement of nanosecond scale events between multiple stations then those stations must be synchronized to the nanosecond and be stable enough to remain in synchronization until the measurements are complete.

It should be noted that synchronization is only required in applications where several nodes in a network must collaborate in a time based way. In other situations it may be possible to perform operations in an asynchronous fashion. Examples of asynchronous operations are frequency division multiplexed communication systems or asynchronous communication protocols.

The most important need for synchronising systems is the fact that the oscillators (usually quartz crystals) that control the speed of the local clocks in a network are prone to jitter. This means that the frequency that is output by these oscillators is not constant but instead randomly shifts by a small amount up or down. Many things cause jitter including: supply and substrate noise[3], environmental sources such as temperature fluctuations, analogue signal jitter[4], and variations in the manufacturing process[5]. The effect of jitter is that the local clocks in the network will advance at different rates. Eventually this will mean that the local clocks are at a significantly different value and significant errors will be present in any collaborative calculations.

3 Synchronization Difficulties

One of the major difficulties involved in synchronising components of a distributed network is the time it takes for a synchronization signal to reach the outlying components. Suppose, for example, we have a network of three nodes all in line with each other (see Figure 1).

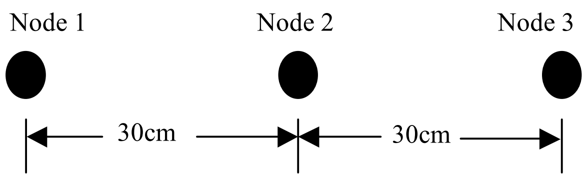

Figure 1: Three node, distributed network.

Next suppose that the node 1 is defined as the master clock. When synchronization is required node 1 will reset its clock and send a signal to nodes 2 and 3 to do the same. If the signal is travelling at the speed of light (approximately $3x10^8ms^{-1}$) then by the time the signal has reached node 3, the clock in node 2 is at 1ns and the master clock is at 2ns. This is a problem if the required accuracy is better than 2ns across the whole network.

Gershenfeld[6] describes the advantages of having a bit size greater than the physical size of a network. If we adapt this argument it can be said that, in general, if the required time accuracy is greater than the time it takes for a synchronization signal to reach all of the nodes in the network, then synchronization based purely on transmission of a pulse is not effective. In this situation it is necessary to use a more intelligent form of synchronization. Some of these methods are explained in the following sections.

Another major difficulty in synchronizing networks to a high degree is the non-deterministic delay in instructions being executed at a node. This will affect the time it takes to implement a synchronization operation and can result in nodes in the network being out of synchronization with other nodes. Temperature, humidity, power supply and manufacturing differences between the nodes all have a random effect on the speed of execution.

4 Reference Broadcast Synchronization (RBS)

In this scheme a signal is broadcast to all nodes. The signal does not contain a time stamp but the signal's time of arrival is used as a reference by all of the nodes in the network[7]. The local time of arrival of this reference at each node is retransmitted to all surrounding nodes. An average time is then computed which can be used as a local time reference for any operations that the network must perform. Since all of the nodes have the same time of arrival information, the average value calculated is the same at each node.

RBS has been described here in an implementation for a single hop network. That is, a network in which each node is in range of all of the others. The RBS method can also be used in networks where multiple retransmissions of a signal are required in order for the signal to reach all of the nodes in the network (referred to as a multi-hop network). RBS is implemented in multi-hop on a hop-by-hop basis, so long as each pair of nodes along the chain have a reference to synchronize to[7].

The major advantage of this system is that all of the nodes in the network are able to automatically come to a consensus about synchronization. The nodes are also able to synchronize regardless of the distance between nodes. This method can also be applied to mobile sensor networks so long as a consensus regarding synchronization can be reached fast enough to ensure that the movement of the nodes relative to each other does not adversely affect the accuracy of synchronization.

The limitation of RBS is that it is an event synchronization protocol and not a clock synchronization protocol. This means that, while events within the network will be synchronized they cannot be time stamped with a reference that will have any meaning outside the network.

For further reading on the reference broadcast synchronization method see Elson[8] who describes a reference broadcast system that can be used in distributed wireless sensor networks that has an accuracy of approximately 2 microseconds; Maróti[9] proposes a similar protocol called the Flooding Time Synchronization Protocol (FTPS), which has a reported accuracy of 1 microsecond. Palchaudhuri[10] proposes an adaptive synchronization protocol that can be tuned to the specific requirement of the application and the resource constraints.

5 Measured Propagation Delay Synchronization

This method employs a synchronization pulse as described earlier. However, this method also includes some calculation to increase the accuracy of synchronization.

Each node in the network must know its distance from the source of the synchronization signal. When the node receives the signal it can then adjust its local time taking into account the time of flight of the signal over the known distance. The effectiveness of this method will be based on the accuracy of the measured distance.

The advantage of this system is that it is simple to implement. Once the distance to each node is known the propagation delay will be approximately constant. If the network is spread over a large area then other factors such as temperature and humidity affect the propagation delay of the synchronization signal. Depending on the synchronization requirements and the distance between the nodes this variation may or may not be significant.

The major limitation of this system is that, unless the nodes are stationary, the distance of each node from the synchronising node must be recalculated before each synchronization pulse is sent to ensure that the correct offset is incorporated. This may be infeasible if the method of calculating the distance is by laser or some other manual ranging method. This limitation will not affect the system if the overhead in recalculating the distance is low enough to allow the system to still be viable.

6 Atomic Clock

As has been stated that one of the major disadvantages of local oscillators is that they have a component of jitter, which causes the various clocks in a network to get out of synchronization. One solution to improving this level of synchronization is to use a more stable oscillator. One such oscillator is a caesium atomic clock. These are considerably more stable than conventional quartz crystal oscillators and therefore stay in synchronization for longer.

To achieve synchronization in a distributed network using individual atomic clocks all nodes in the network would be switched on and synchronized when they are close to each other and then moved to where they are required. In this way the general rule for synchronization can be met.

However, currently available atomic clocks are too bulky and expensive to be efficiently used in distributed networks. Atomic clocks are priced between $50,000US and $100,000US each[11]. But research is in progress to miniaturize these atomic clocks to fit on an integrated circuit and also be to able to put them into mass-production[12].

Even if it is not feasible to have an atomic clock in every device in a distributed network there are two popular methods for utilizing the stability of atomic clocks for synchronization.

6.1 GPS Time Synchronization

The first method is to use the time signal present in GPS satellite transmissions to synchronize the node of a distributed network. Installing a GPS receiver in each node of the network does this; the receiver uses the redundant information in the satellite transmissions to synchronize the clock at the node with GPS time. The accuracy of such a system is reported to be approximately 50ns with minimal processing and approximately 1ns with careful processing[13].

The major advantage of this system is that the only cost involved in using GPS timing is the cost of the receivers and integration, it is free to use any non-encrypted signals transmitted by the satellites. The other advantage is that this system can be implemented anywhere in the world with the same equipment.

The major limitations of using GPS signals to synchronize a network are that the GPS receiver will increase the size and cost of each node and each node must be able to receive a signal from the GPS satellites. Because of this GPS time synchronization may not be suitable for applications where the size and cost of each node must be kept to a minimum, and also, applications where the nodes are not in view of at least four satellites.

For further reading about the applications of GPS timing and synchronization see Lisowiec[14], who describes a system to augment the short term stability of quartz crystal oscillators with the long term stability of the GPS timing signal; Zhao[15], who describes the position location function of 3G mobile equipment; Martin[16], Pflieger[17], Dierks[18] and Houlie[19], who describe GPS synchronized systems for taking measurements from mains power grids; D'Antona[20], who describes GPS timing for synchronizing nodes placed around a lake; and Lewandowski[21], who proposes a GPS timing system with an accuracy of 4 nanoseconds.

6.2 Network Timing Protocol (NTP)

This protocol is often used in network servers to ensure that the time stamps on log entries are correct[22]. This is advantageous in the event of a security breach or power failure as it allows accurate reconstruction of the events that led to the failure.

In this protocol a server is coupled to an atomic time standard. This server is defined as the primary server or stratum 1. This server is used to synchronize another level of computers, called stratum 2. This can continue until stratum 16. Computers further down the hierarchy are less accurate compared to those higher up.

The actual synchronization process involves multiple packets of data being sent back and forth between the computers. These packets are used to update the clock on the computer that is querying the NTP server. The synchronization continues until the two clocks are in agreement to a given level of accuracy.

Note that the level of accuracy that can be attained using NTP depends heavily on the real time property of the operating system that is being used[23]. Approximations of the accuracy of clocks on machines running NTP software suggest that accuracy is of the order of milliseconds[24], however research is in progress it increase this level of accuracy, including Mills[25] who proposes changes to the Unix operating system kernel to realize sub-millisecond accuracy.

It is interesting to note that NTP does not aim to synchronize individual computers to one another but instead to synchronize all clients to the UTC (Universal Coordinated Time)[26]. Synchronization of machines to one another is a serendipitous effect.

The advantage of NTP is that it can be used to synchronize the internal clocks of a large number of computers over a wide area. Each computer will automatically attempt to synchronize with an NTP server that is closest to the UTC as possible (defined by its stratum number).

The major limitation of NTP is the time taken for the client's clock to converge with the server. NTP requires several hours to a day for the two clocks to synchronize with UTC. This makes NTP inappropriate in situations where nodes of a network must be synchronized often (on the order of more than once in a week). However, Butner[27] proposes a system that can be used for timing nanosecond scale events that is able to converge to synchronization in approximately one minute.

For further reading on NTP and its applications see Gurewitz[28] and Nakashima[29].

7 Communication Synchronization

The requirements for synchronization placed on most point-to-point and point-to-many-point communication systems are less than those required by other synchronous systems. However, there is still the need for a level of synchronization

In most synchronous communication techniques absolute time synchronization is not necessary, instead the receiver must be synchronized to the transmission so that it can correctly identify the start of the data and so it can sample the received waveform at the correct time. Figure 2 illustrates a receiver that is in synchronization with the transmitter and one that is not.

The most common way of achieving this synchronization is to add a block of bits to the beginning of each data transmission[30]. This data, called the preamble, is the same for each transmission and is known to the receiver. A common example of a preamble would be a string of alternating ones and zeros. The edges of the preamble are used to synchronize the oscillator of the receiver thereby ensuring that it will be running at the proper frequency and phase when the data is transmitted. After this synchronization signal has been sent another code word is sent to inform the receiver that the data bits will follow. Because of this the receiver does not need to have received and correctly interpreted the preamble from the start.

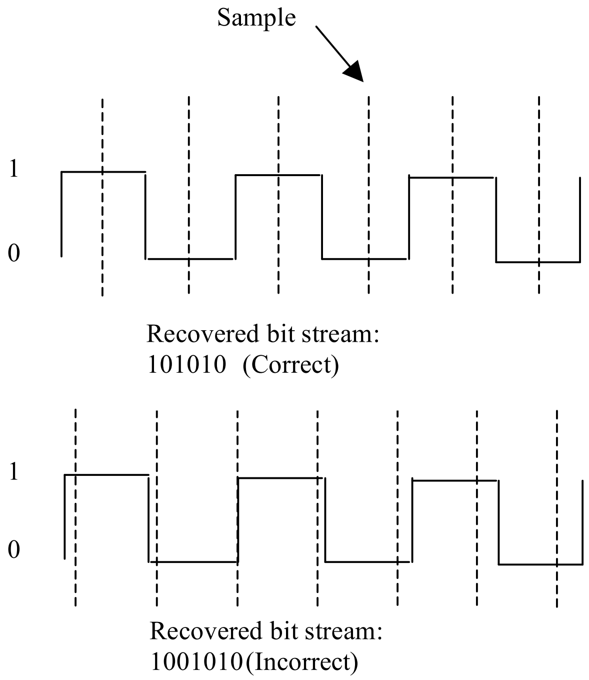

Figure 2: (a) Received data waveform being sampled at the correct time. (b) Received waveform being sampled at incorrect frequency and phase.

Other research into synchronizing communications systems include: Spalink[31], who describes a method which involves establishing a "single shared sequence of communication events" which can be used as a time reference among all of the nodes on the network; and Sun[32], who describes a system for synchronization without preamble for systems using turbo codes.

8 Ultra Wide Band Synchronization

Ultra wide band (UWB) is a special class of communication system with some unique synchronization requirements. A UWB transmitter works by sending electromagnetic pulses with a very short duration (in the order of hundreds of picoseconds to tens of nanoseconds). These transmissions occur at specific times. In order for the receiver to correctly receive one of these signals it must sample the input from the antenna at the specified time. Because of the short duration of the pulses, the nodes of a UWB network must have a high level of synchronization so that the window in which the receivers are monitoring the activity of the antenna can be kept to a minimum to reduce interference.

Research is in progress to increase the accuracy of the synchronization of UWB systems. Some examples are given below.

Yang[33] presents a blind method for time synchronization that involves an integrate-and-dump operation over the duration of one symbol period and exploits the multipath diversity allowed by UWB transmissions. This method has a better performance when compared to other blind templates and is comparable to data-aided methods.

Zhang[34] describes a system called transmitted reference ultra wideband (TR-UWB) and also describes how the relatively poor bit error rate of TR-UWB can be improved while retaining the ability to resolve multipath signals and timing attributes.

Tian[35] compares blind methods of timing acquisition with training based methods and proposes a new blind method that has an enhanced timing offset estimation that is comparable to most training based methods.

9 Conclusions

This paper has highlighted the need for synchronization in distributed wireless sensor networks and some of the major difficulties in achieving it. Several methods have been described that cover a wide range of situations. The selection of technique and the accuracy that can be attained is heavily dependant on the equipment and software used for implementation.

While in some systems it may be easier and advantageous to use asynchronous protocols, the systems in which synchronization is a requirement can be implemented by using one of these methods.

It is clear that by using one or more of the methods described, synchronization can be achieved in systems that are distributed in the meters to hundreds of meters range by using one of the transmitted reference methods. Synchronization can be achieved in the kilometres to thousands of kilometres range by using either NTP or GPS timing synchronization.

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