Extended Abstract (ISPCS)

Synchronization of Wireless Sensor Networks Using a Modified IEEE 1588 Protocol

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***Abstract*— A method of precise time synchronization of wireless sensors employing an IEEE 802.15.4 transceiver, and specifically employing the 6LoWPAN protocol, was developed. It uses the IEEE 1588 synchronization standard and the IEEE 1451.5 Smart Transducer Data standard. A Wireless Transducer Interface Module (WTIM) was designed and fabricated. It utilizes the IEEE 802.15.4 transceiver model TI CC2430 which allows access to a hardware sync signal. The difference in timestamps between two WTIMs was measured. The results show that the synchronization precision is better than 10 µs for short synchronization intervals but increases to about 100 µs for longer synchronization intervals (1 sec for crystal accuracies of 50ppm). The method was tested for 6LoWPAN wireless protocol but would apply to other wireless sensors based on the IEEE 802.15.4 protocols.**

Keywords-1588; 1451; wireless sensor network; synchronization

I. INTRODUCTION

The timing of sensor data or actuator control in a wireless network often is critical to the data acquisition or control process. The IEEE 1588 standard describes the time synchronization process for wired network nodes, in particular using Ethernet, but does not explicitly address how this might be extended to wireless networks. Wireless sensors are difficult to synchronize because the total transmission time is comparatively long and quite variable, especially if re-transmission and relaying of messages between nodes is involved. Also energy and bandwidth restriction limit the length and frequency of synchronization messages. The sensor (or actuator) data are formatted using the IEEE 1451.0 and 1451.5 smart transducer standards which provide a standard sensor protocol. These standards do not explicitly specify a method of synchronizing time clocks between the different nodes, or Wireless Transducer Interface Modules (WTIMs), of the network and we have combined methods in this research.

Specific features of this research are (1) synchronization pulses are derived from a source close to the physical layer of the transceiver without hardware modifications, (2) implementation with the Internet-compatible 6LoWPAN protocol and (3) a precisely synchronized real time clock module with IEEE 1451/1588 format fabricated from commercial components.

II. DETAILED DESCRIPTION

A. *Wireless Block Diagram*

A block diagram of a Wireless Transducer Interface Module (WTIM) and an associated gateway or NCAP front end is shown in Fig. 1. The gateway also functions as a wireless router for the 6LoWPAN network. Both consist of a RF transceiver with IEEE 802.15.4 capability, a microcontroller (which is integrated with the receiver for our system) and a clock module (which here is separate).

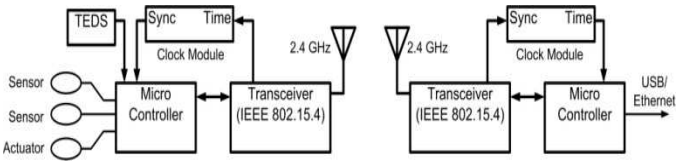

Figure 1. Block Diagram of WTIM (left) and NCAP front end or gateway/router (right)

B. *IEEE 802.15.4 Transceivers*

The transceiver selected (Fig. 2) is the TI model CC2430 (2.4 GHz) because it is well suited for the synchronization process. In addition to being based on IEEE 802.15.4 protocol, two key advantages are access to a hardware synchronization signal and the integration of a microcontroller with the transceiver in the same chip. The time synchronization signal selected is SFD (start frame delimiter), as shown in Fig. 2. It goes high when the initial, required preamble of the message is received (or transmitted). The signal is used for an interrupt on the microcontroller which then immediately sends a sync signal to the clock module. Because the software for this function is deterministic (non-branching), and crystal controlled, it has little jitter (under 1 µs). The SFD function is similar to the beacon signal, which is optional.

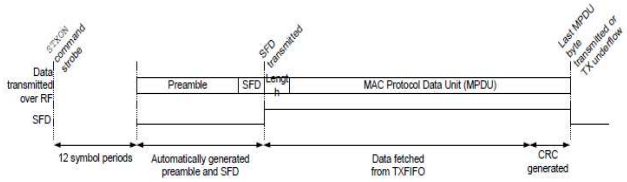

Figure 2. IEEE 802.15.4 Message Timing
-- The SFD functions as the time sync pulse

C. Synchronized Clock Module

The synchronization clock module (Fig. 3) is a small, fast microcomputer [17] with a precision oscillator crystal. It is a real time clock with the format and features needed for the IEEE 1588 standard synchronization. There is one on each WTIM and also on the NCAP. The crystal may be either standard (20 to 100 ppm) or precision (1 to 10 ppm). A timer within the microcomputer has a resolution equal to the oscillator period (0.0625 µs or better). Since our highest target synchronization precision is within 1 µs (with rapid updating), the timer resolution is a better than required for all of our intended applications.

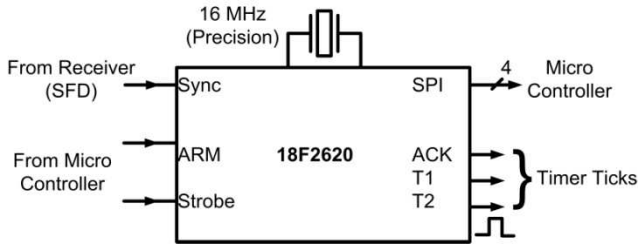

Figure 3. Synchronized Clock Module
-- This functions as a real time clock which can be synchronized and frequency compensated

The time format specified in the IEEE 1451.0 standard is the 64-bit TAI format which is the same as PTP except without the leap seconds (see below for more details). The upper 32 bits is the number of seconds since 1900 (Epoch). The lower 32 bits is the number of nanoseconds. It is based on Greenwich Mean Time, not local time. TAI is optional for IEEE 1588 and it is necessary to convert between it and the NTP time format used on the Internet (1900 Epoch with leap seconds and binary fractions of a second). Normally this is done outside the NCAP (or WTIM).

The precision required of the timestamp, and thus the synchronization precision, depends very much on the application. For many wireless applications, including most industrial control and monitoring processes, a timestamp precision with an error under 1 ms, or perhaps 0.1 ms, is sufficient. By contrast wired (Ethernet) networks with IEEE 1588 protocols are able to provide much closer synchronization.

Synchronization of wireless sensors under 100 µs is a challenge because of the round-trip message times are of the order of 100 ms and have high variability depending on message length and traffic. The RF message itself is about 2-5 ms but is precisely timed, that is, has little jitter. Our focus here is on reliability and low wireless power requirements, in particular for manufacturing and monitoring applications, rather than on high precision applications which may require frequent updates.

D. Gateway/NCAP/Router

This unit has three functions: Wireless router, wireless gateway and NCAP (Network Capable Application Processor), as shown in Fig. 4. The gateway connects the wireless devices to the Internet and functions as an NCAP which implements the IEEE 1451 protocols. The microcontroller implements the IEEE 1451.5 NCAP format and communications over the Internet using HTTP protocol [17].

Another function of the gateway is the router for the 6LoWPAN network. It manages the traffic between the various nodes of the system.

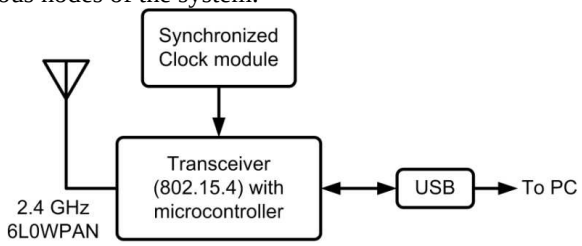

Figure 4. Block Diagram of NCAP or Gateway with Router
-- Functions as the wireless network router, IEEE 1451 NCAP and Internet Driver

Still another function of the gateway will be to implement the IEEE 1588 precision clock synchronization protocol over the Ethernet so that other nodes employing 1588 clocks are compatible with the wireless devices

E. 6LoWPAN Stack Refinements

The 6LoWPAN Low power Wireless Personal Area Network was designed to enable IPv6 Internet-compatible datagrams over the lower power and bandwidth IEEE 802.15.4 radio. In effect the protocol subdivides the verbose IPv6 messages for efficient transmission over the limited bandwidth and message size radio. The protocol is well suited for sensor data being interfaced with the Internet. While the protocol adds complexity on the RF communication side, it simplifies the process from the user point of view.

The 6LoWPAN stack, although under development for several years by various groups, is not yet fully developed. Many 6LoWPAN stacks available from proprietary sources are unsuitable for implementing the IEEE 1588 synchronization process but we were able to make the software stack from Sensinode [11] operational for our WTIM.

F. Modified IEEE 1588 Time Synchronization Protocol

The IEEE 1588 Precision Time Synchronization Protocol [13] provides a standard method of synchronizing clocks of the nodes of networks. The standard was developed for wired networks, specifically Ethernet. Our goal is use the IEEE 1588 core concepts with wireless networks but realize that it cannot be done without modifications for a practical implementation. The problems of directly applying the wired standard without modification to wireless are:

- The standard IEEE 1588 synchronization message (166 bytes) is too long for IEEE 802.14.4 (128 byte limit) which is used for 6LoWPAN (and Zigbee). It must be shortened or fragmented.
- The data rate of wireless is far less than wired (e.g. 250 kbits/sec for 6LoWPAN and 100 Mbits/sec for Ethernet). At least buffering and retiming is required.

- The computer resources for standard, wired IEEE 1588 require a large amount of processing power (and storage) which is inadvisable for battery-operated wireless systems

These problems are discussed in the paper "Precision Time Synchronization using Wireless Sensor Networks" by Cho et al [18] and other papers describing the HRTS, TPNS and RBS protocols [16].

The protocol we use is shown in Fig. 5. It is similar to the standard IEEE 1588 diagram (Fig. 20) except that the follow-up transmissions are optional since there is a fixed time between the sync message initialization time T1' and T1, as well as T3' and T3. It also can be compared with Fig. 6 of Cho et al [18] where several fragmented messages are sent wirelessly rather a single message which we send

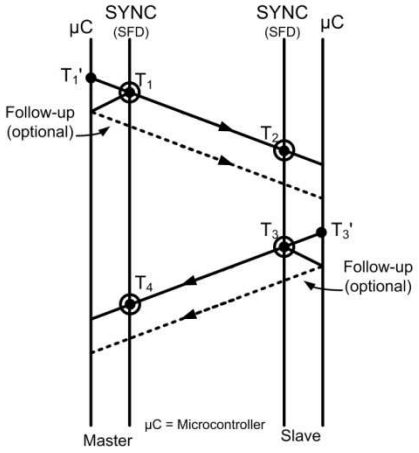

Figure 5. Time Synchronization between Master (NCAP/gateway) and Slave (WTIM)

The primary differences between the wired and wireless versions of IEEE 1588 are:

- The on-the-air sync message is abbreviated (required for IEEE 802.15.4 unless message is fragmented, requiring more power).
- Follow-up messages are normally not used for the modified version (but are with the full-format version) because the time between the sync message initialization and sync time are fixed, known quantities (saves power and precision not affected).

We believe that the on-the-air message format is not critical to whether the protocol can be properly termed "IEEE 1588 protocol" but rather that {1} the procedure must adhere to the core method of 1588 which involves determining and compensating the clocks offset and transmission delay times, {2} there must be conformity to the 1588 format on the network (Ethernet) side, and, of course, {3} it must provide precision clock synchronization. It may be possible to extend the IEEE 1588 standard to include wireless in the future

Full IEEE 1588 Protocol Option

A version of the wireless IEEE 1588 protocol which uses the full IEEE message (fragmented transmission) and the follow-up messages (Fig. 5) is available. The differences in timing precision and power consumption are discussed.

G. IEEE 1451.5 Protocols and Formats

The IEEE 1451.5 (Dot 5) smart transducer was partially implemented based on the IEEE 1451.0 (Dot 0) standard [4]. Dot 0 specifies the TEDS (Transducer Electronic Data Sheet, located in the WTIM) sensor, commands and data structure in detail, but without reference to the specific physical layer of the network or digital interface. Dot 5 adds the physical layer for several (currently 4) wireless sensor networks, including 6LoWPAN. The 1451 protocol is implemented at the application layer and does not directly affect the 1588 synchronization process which occurs at the MAC layer.

III. RESULTS

As shown in Fig. 6, the clock error is dependent on the WTIM to NCAP crystal frequency differences and increases linearly with the time after the synchronization pulse is applied. Note that the intercept and jitter are under 1 μs suggesting that with frequent updates a precision of 1 μs may be achieved. Since the drift is predictable from one sync interval to another, we expect that it can be compensated to a high degree (10x to 100x better). Software method for correcting the internal clock frequency resulted in significantly improving the time clock precision whether standard or precision crystals are used.

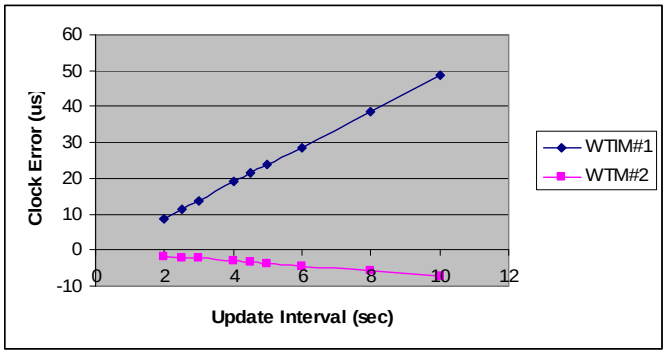

Figure 6. Timing Error (μs) vs. Sync Update Interval
-- Clocks on WTIMs drift apart after sync due to small crystal frequency inaccuracies

IV. CONCLUSIONS

Each time sync update requires battery power and therefore battery power requirements are minimized by increasing the update intervals. The WTIM transceiver and microcontroller must be kept in a sleep mode except for brief, timed intervals (when the beacon or sync pulse, SFD, is sent). We prefer 10 to 100 second intervals and the precision of the WTIM clock permits theses long intervals.

As pointed out above, there is a trade-off between power consumption and synchronization precision. As is, without the frequency compensation, the drift due to crystal frequency inaccuracy requires frequent sync updates. An update rate which is 100x faster will result in a 100 x more precise timestamp.

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