Study of Wireless Time Synchronization for Sensor Networks

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Abstract. The agenda of this study is to analyse various state of art trends available to handle the task of time synchronization on the low energy wireless devices. One such area of study is Wireless Body Area Network(WBAN) or Body Sensor Network(BSN) which is a network of wearable computing devices that has put forth a new paradigm of measuring body motions. Properties like Miniaturization and Energy Efficiency are of paramount importance where the devices can run on coin-cell batteries and last for years. To analyse the data acquired from various IMU sensors, there is a requirement of accurate time synchronization in the network. This study concentrates on investigating the various time synchronization standards like NTP, SNTP, FTSP, TPSN, their demerits related to energy efficiency and new time synchronization schemes that can be opted for Bluetooth Low Energy devices. We will also discuss various connection-event based schemes and current consumption's pattern for time synchronization. Also, a brief study on NFMI (Near Field Magnetic Induction) for efficient and low energy data transfer with methods for time synchronization will be made.

Keywords: BLE, NFMI, Time synchronization, Standards(NTP, SNTP, FTSP, TPSN), Energy efficiency, Wireless Sensor Network, Current Consumption Pattern, Connection-event based scheme

1 Introduction

The ongoing trend in the field of embedded systems roots its applications in a various field of studies like Medical Health, Home Appliance Management, Crowd Monitoring Systems etc. In such an application there exists a small set of sensors that are connected in wireless mode. This kind of network is called Wireless Sensors Networks (WSN). When these sensors are worn on a body it is termed as Wireless Body Sensor Network(WBSN). This constitutes an embedded system where each node/sensor is most probably communicating over WiFi, Bluetooth or Bluetooth Low Energy. The ongoing sensation of Internet of Things (IoT) promises to add billions of more items that are connected by 2020 [7]. Bluetooth Low Energy (BLE) and Near Field Magnetic Induction (NFMI) falls in those categories of devices that empower IoT to fulfil the properties like Energy Efficiency, Low Production Cost and Miniaturization. Even though there exist extensive studies concerning time synchronization for both wired and wireless networks, most of these are not applicable as they do not fulfil the above-mentioned properties due to algorithm complexity. There also exits a few algorithms [8][6] that access the internal clock of BLE but the drawback is since all BLE devices do not provide access to the internal clock and the ones that provide access do suffer from non-deterministic time delay, the accuracy of the time synchronization is heavily affected. In this study, we will understand the different time synchronization schemes and the structure of this study is as follows: In section 2 we will understand the detailed operations of BLE and NFMI. We will discuss various time synchronization schemes for BLE and NFMI is section 3 and we will conclude over study results in section 4.

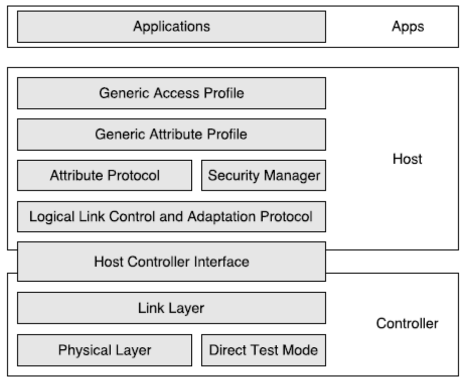


Fig. 1: The Bluetooth Architecture[3].

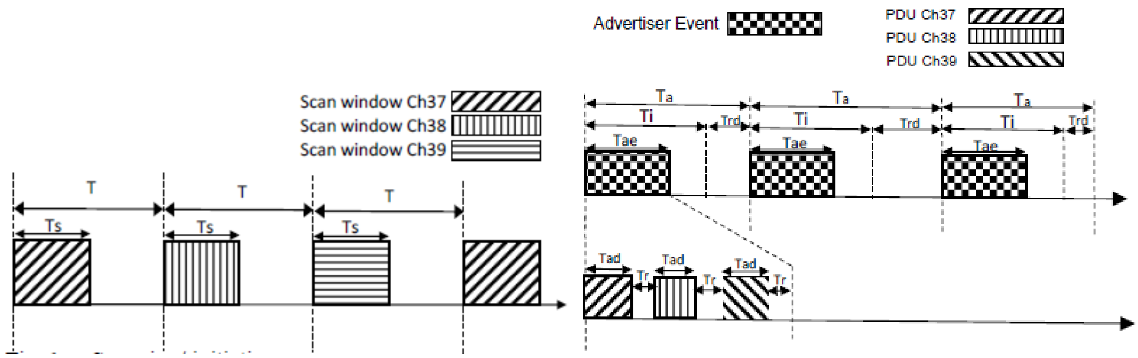
2 BLE and NFMI Operations

2.1 BLE operation

BLE protocol stack is categorized into three main components as depicted in the figure 1 namely:- Controller or Radio, Host and Applications. Tasks like transmission of data packets, frequency modulation, data packet size are handled by the physical layer. Link-Layer manages operation like scanning, advertising and creating/maintaining connections. The Host Controller Interface(HCI) provides an interface which facilitates the host to communicate with the controller. Logical Link Control and Adaptation Protocol(L2CAP) manages two crucial tasks. First, the data packets received from the upper layer is broken down into the size which fits into the payload size of BLE's packet. Second, it accepts the various protocols defined by the upper layer and encapsulates them into the packet format. Attribute Protocol(ATT) exhibits the role of simple client/server protocol and Generic Attribute Protocol(GATT) adds data model and hierarchy which dictates rules for how data is organized and exchanged between different applications. Generic Access Profile(GAP) controls the connections and advertising phase of BLE device which manages the roles like advertising, scanning and initiating.

When BLE is in advertising mode it is referred as an Advertiser and when it is scanning and initiating mode it is referred as a Scanner and Initiator respectively. The only difference between scanner and initiator is, the scanner only discovers the advertisers whereas the initiator can make a connection request to the advertiser after receiving the advertising message. Figure 2a shows the various operation that a device undertakes as a Scanner/Initiator as the time elapses. T as per figure 2a is a referred to as Scan Interval, i.e, the interval between two consecutive times when the scanner wakes up and listens to the advertising messages. T_s is the actual scan window and is less than the scan interval. The scanner listens on three advertising channels, 37, 38 and 39 in a round-robin fashion. The value of T and T_s is in the range of $0 \leq T_s \leq T \leq 10.24s$ as per the BLE specifications.

The other role of BLE is as an advertiser. In this role, the advertiser periodically generates advertising events consisting of a sequence of Protocol Data Units (PDU's). As shown in the figure 2b, the device spends T_{ad} duration of time and then listens for T_r duration of time before moving to the new predefined channel. Value of T_{ad} is determined based on the transmission time of PDU. The size of PDU as per the BLE specification is $80 \leq PDU \leq 376bits$. The value of T_r is adjusted to a tolerable time so that it waits for the response from initiator[4]. T_a is the time interval between two advertising events and is composed of two parts. First, T_i, a fixed time interval which is in the multiple of 0.625ms and second, T_{rd}, a pseudo-random delay. Based on the BLE specifications the bounds of T_i and T_{rd} are $20ms \leq T_i \leq 10.24s$, $0 \leq T_{rd} \leq 10ms$.



(a) Scanning/Initiating process. (b) Advertising process.

Fig. 2: Scanning/Initiating and Advertising process.[2]

2.2 NFMI Operation

When a Bluetooth signal is transmitted over an antenna, it travels as far as it can i.e, until it does not completely attenuate. This is called Far-Field transmission. Penetration of Bluetooth signal through the human body is yet another problem. This is because of highly conductive nature of body tissues. To the rescue comes the NFMI technology which is short-range and communicates over tightly coupled magnetic field and most importantly it is human body-friendly. Figure 3 depicts how NFMI communication works. Here the modulated signal (T_x Signal) is sent from a transmitter coil T_x, in the form of a magnetic field. The magnetic field induces a voltage in the receiver coil R_x and the voltage is measured at NFMI receiver end. This signal attenuates at the rate that is inversely proportional to the distance to the sixth power compared to the second power of the Bluetooth signal [11]. This implies that to travel the same distance NFMI signal is 10000 times weaker than the Bluetooth signal. This type of wireless transmission is termed as Near-Field Communication. The reading distance of NFMI is up to 9 feet and at around 13MHz, NFMI provides a data rate of over 400Kbps per frequency channel, up to 10 separate frequency channels and 10 sub-channels per frequency channel using time division[11]. The techniques like distributed beam-forming for Magnetic induction is one such technique that can be very efficiently used in the field of Body Sensor network where the proximity of two sensors is within the range of NFMI devices. In this technique, the basic idea is to align the phases of signals from multiple nodes in such a way that a virtual multiple-input multiple-output(MIMO) system with favourable properties is created[5] .

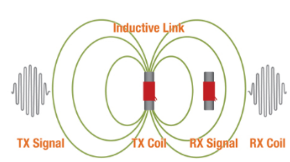


Fig. 3: NFMI Communication.[11]

3 Time Synchronization Approach's

Mounting of the GPS receivers on the BLE circuit to acquire accuracy is one possible method available to achieve time synchronization with a precision below 1μs. But the energy, cost and satellite coverage for indoor location imposes a huge constraint. The typical protocol involved in the wired network includes the Network Time Protocol(NTP) and Simple Network Time Protocol(SNTP). NTP is very robust and has very high time precision but is not optimized for energy efficiency simply because the wired distributed system has no such constraint [9]. Due to the involvement of multiple servers and methods including fudge factor, the time accuracy is high but complexity is more. Whereas, SNTP, which is the minimalistic version of NTP solves this problem at the cost of accuracy and more importantly, SNTP is not designed for a wireless network. NFMI, on the other hand, is not a client-server based model. Rather it works on a peer-to-peer model where communication when two magnetic coils are compactly coupled [1]. Thus, methods to overcome the above-mentioned time synchronization issues in BLE and why NFMI is not prone to time synchronization related issues are discussed is below section.

3.1 Time Synchronization using Connection-Based Event [2]:

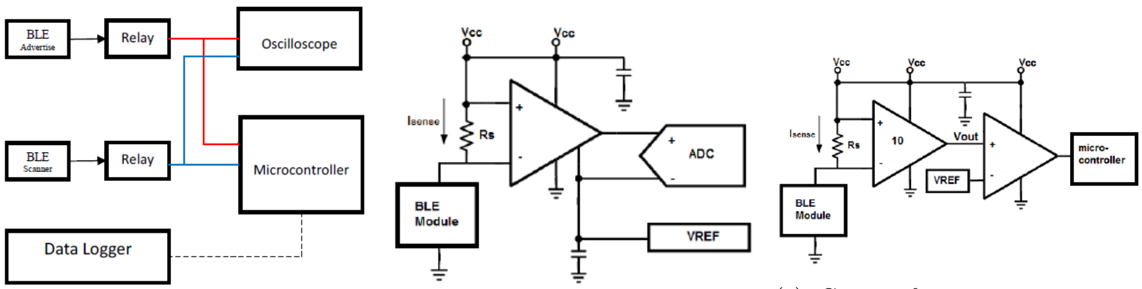
In this scheme, all the slaves detect an event generated by time master and then put their timestamp on the event. Then the synchronization procedure will be carried out in two steps. First, offset correction between the timestamp of time master and slave is done. It should be noted that the oscillator frequency is slightly different from the operating frequency. It is affected by conditions like temperature and ageing. This adds major time drift between master and slave in distributed over a long run. Second, to reduce the drift factor discussed before, the clock pulse is also used to correct the frequency of the oscillator in slaves. Techniques like phase-lock allow the variable oscillator on the slave to be frequency and phase-aligned with the master which ensures minimum time drift between synchronization events.

Measurement Method: The two devices involved in the synchronization, one which is master(Scanning device) and the other which is a slave(Advertising device) are programmed such that at a fixed interval a new connection is established. White-listing of the MAC addresses is done beforehand to ensure that connection is established between the intended device only. A relay is activated as soon as connection event is fired and it is turned off when devices disconnect. These relay outputs are connected to a microcontroller to measure the time difference between the start of two relay events. The microcontroller is configured to run at 25MHz which logs the measured time difference using the UART interface. Figure 4a depicts the block diagram of the measurement circuit.
The target BLE modules used in this approach were Bluegiga BLE121LR and the time difference between the connection event was measured using 3039 samples. The shortest duration of the connection event was 48.5μs. and the longest was 1.39ms. The average was 563.36μs with a standard deviation of 150μs. If the offset correction is considered as 563.36μs, the extremum case occurs with the error of -514.85μs and 739.47μs. Therefore an accuracy of $\pm$750μs can be achieved.

3.2 Time Synchronization Based on Current Measurement [12]:

During the BLE connection establishment procedure when the master receives an advertising packet, the master sends a connection request to the slave on the specific channel. In this packet, the master mentions a set of parameters that the slave has to accept. The parameters are as follows:

1. Frequency channel and frequency hop pattern that will be maintained throughout the lifetime of the connection.
2. Connection interval between the two consecutive connection events, i.e, the time interval between the master's transmission.



(a) Block diagram of measurement circuit[2]

(b) Circuit diagram to measure the current consumption pattern[12].

(c) Circuit for current measurement and detecting post processing state[10]

Fig. 4: Block and circuit diagram of various time synchronization approaches for BLE

3. Slave latency, i.e, how many connection events the slave can skip without responding to the master. If the slave does not respond to the master even after the skip count exceeds the value set in the slave latency parameter, then the master assumes that the connection is lost.

To measure the current consumption profile of the device a simple circuit is built as shown in the figure 4b. It has a 3-Ohm precision shunt register which is in series with the BLE module. Then the voltage drop across the register is measured using instrumentation amplifier with a gain of ten(10). The relationship between the voltage of the instrumentation amplifier and the BLE module is shown in the equation 1.

$$V_{out} = 30 \times I_{sense} + 30 \tag{1}$$

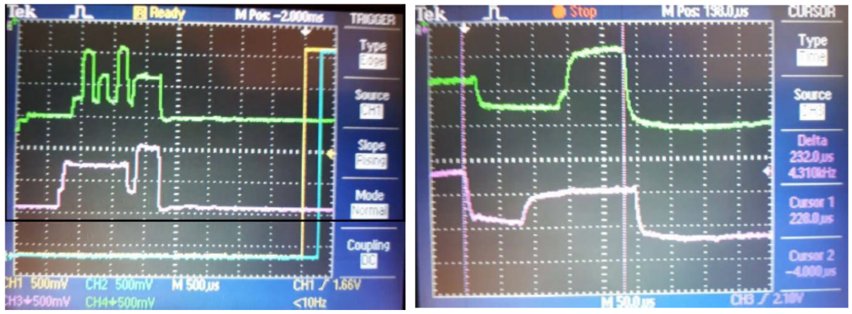
Figure 5a shows the current consumption profile during the connection establishment process. The first peak(39mA) in the top signal corresponds to transmission. After each peak, the current drops to 33mA indicating the device has gone in the scanning mode. Once the slave receives the connection request the current drop to the lowest indicating the device has gone into the idle mode. These jumps indicate the scanning, transmitting and idle mode and relative current consumption profile. Figure 5b shows the time difference between the time the slave ends transmitting of its data packets and the time the master ends scanning/receiving.
The current consumption pattern is similar across all the BLE modules. During the experiment, 15 samples were taken corresponding to the time interval when the master and slave send the end of data packet request and the time difference was found to be 231μs with the standard deviation of 4μs.

3.3 Time Synchronization Based on Current Consumption Pattern [10]:

This method of establishing the time synchronization between master and slave is similar to that of the previous method [12] but with a very few modifications in the circuitry as shown in the figure 4c. The relationship between the instrumentation amplifier and the BLE is device is as per the equation 2.

$$V_{out} = -30 \times I_{sense} \tag{2}$$

The ad-on to the circuitry is a comparator that compares the reference voltage to the output of the instrumentation amplifier. This circuitry generates a pulse when the device enters into the post-processing mode. This pulse is generated when the reference voltage is set to a value that is between the receive/transmit state and post-processing state. The modes that the device enters is very clearly depicted in figure 6a and 6b. The output of this circuit is then connected to the microcontroller and

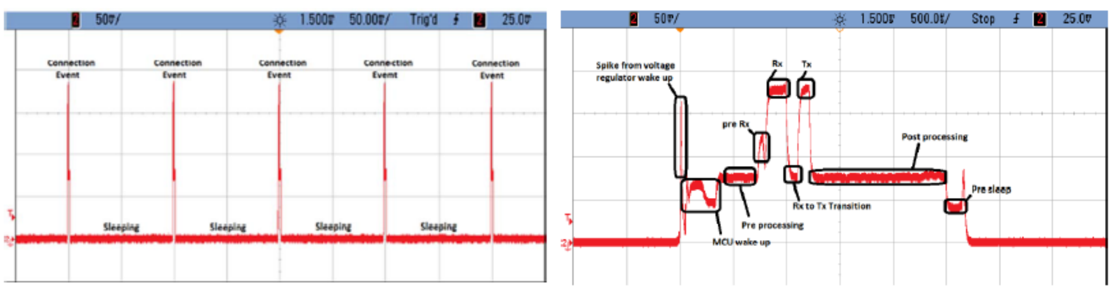


(a) Current Consumption during connection establishment(Master below, Slave Above).

(b) Current consumption profile during packet exchange(Master below, Slave Above).

Fig. 5: Current consumption measurements on oscilloscope[12].

is tied to edge detect hardware interrupt in the firmware. In this way, a timestamp is put to fulfil the task of synchronization.



(a) Typical current pattern when the device is connection mode.

(b) Typical current pattern when the device is connection interval.

Fig. 6: Typical current consumption pattern[10].

During the procedure, a series of test were performed using the circuitry to measure the effect of Device dependency, Temperature and Transmitter power. All test cases were run for 15minutes and 6000 samples were collected. Three(3) separate BLE modules were used to measure the effect of device dependency. To measure the effect the temperature the devices were first tested at room temperature and then a frozen cold pack was kept on BLE modules with an interval of 30 minutes. Transmitter power was varied from -10dBm to +8dBm in the steps of 6dBm. It was noted that average the accuracy is $\leq 19\mu$s and a standard deviation is $<1\mu$s.

3.4 Time-Sync free NFMI devices:

The inherent nature of BLE facilitates Central(Single Master) and Peripheral(Multiple Slaves) based communication which introduces buffering and queuing. This directly implies non-deterministic processing time and delay. But a peer-to-peer protocol of NFMI is a very streamlined protocol stack and the NFMI is meant for only short-range communication. Thus there is no effect of propagation delay which eliminates buffering or queuing and processing time delay which is a root cause for

time synchronization. Experimental results [11] have shown that as the receiver coils sensitivity is increased the transmitter coil power is reduced and the range of data transfer is also increased. To reduce the noise picked up the NFMI antenna it mandatory that the antennas are co-axially aligned and avoid placing them orthogonal to each other.
Using the NFMI based devices, experimental results have shown that with Rx sensitivity of 50μV [+0dB] we can attain a range of 25cm with Tx power of 400μW and when the Rx sensitivity is increased to 100μV [+ 6dB] the range is also increased to 31.5cm with Tx power of only 100μ which is only 25% of what was originally required.

4 Conclusion

As a part of this study, we analysed the importance of time synchronization in BLE device. Then we understood why the existing protocols like NTP and SNTP are not applicable for wireless networks due to their high energy requirements and complexity. Later in section 3.1, we learnt about an approach which takes into account the events generated by the BLE master and slave during connection establishment in the application program. The difference between receiving time of the event through a relay is measured using an oscilloscope and also automated by connecting it to the microcontroller. This approach resulted in an accuracy of $\pm$750μs. Since the events are generated in the application program there is a non-deterministic time delay, i.e, we cannot accurately tell when the packet is actually transmitted. To make the synchronization more accurate, section 3.2 and 3.3 details about current consumption pattern as a means of time synchronization among BLE devices in a network. Both the methods utilize additional hardware circuitry which is capable of detecting the current consumption pattern. The accuracy of the system when the current consumption pattern was taken into consideration was $\leq$19μs. The only drawback of this method is the involvement of additional hardware circuitry. Not all BLE devices are provided with a module that facilitates the reading of the current waveform. Also, the very nature of electromagnetic signals emitted by the radio of BLE devices is prone to attenuation due to conductive body tissues and the application of this network of BLE devices is rooted in Body Area Network. To overcome this issue of signal attenuation and additional hardware for time synchronization, NFMI based devices come into play. With the advent in the field of magnetic induction based devices for near field communication scheme, the non-determinism involved in processing time is eliminated and hence the need of time synchronization is also purged. Since these devices are meant for only short-range applications with co-axially aligned antennas and also have a peer-to-peer protocol, they are convenient and desirable property for any Body Sensor Network application.

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