Low-Power Synchronization for Multi-IMU WSNs

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Abstract—**Wireless time synchronization is one of the most important services in a Wireless Sensor Network (WSN). Inertial Measurement Units (IMUs) are often used in these WSNs in healthcare-related treatments. We present a low-power, wirelessly synchronized multi-IMU platform. The proposed approach synchronously captures packets from different IMUs and transmits the data over Bluetooth Low Energy (BLE) to a central Data Capturing Unit (DCU). The contribution of this work is, rather than focussing on the highest possible accuracy, to provide a low-power accurate enough solution for use in a multi-IMU WSN. We examine key factors affecting synchronization accuracy and elaborate on the implementation challenges. An accuracy of sub 1 μs can be achieved with the approach using 74.8 Jh^{-1} of energy, while a power-optimized implementation is presented with an accuracy of 200 μs and an energy consumption of only 198 mJh^{-1}. This approach suits the required accuracy and low-power requirements for a multi-IMU system.**

Index Terms—**Wireless synchronization, Bluetooth, Wireless sensor networks, Inertial sensors, Smart healthcare**

W IRELESS synchronization is becoming an essential service in Wireless Sensor Networks (WSNs). In particular, in Wireless Body Area Networks (WBANs), an increasing amount of sensors is being used to conduct simultaneous synchronized measurements on different parts of the body. For physiotherapists, it can be beneficial to use Inertial Measurement Units (IMUs), instead of high-tech and expensive equipment, to study the long-term evolution of certain symptoms. One wants samples from all IMU to be synchronized, enabling the direct comparison of samples at various locations on the body. Essentially all measured body movements are contained within frequency components below 20 Hz [1]. According to the Nyquist theorem, a sampling frequency of at least 40 Hz should be sufficient. We consider the WBAN case requiring synchronized sampling and design a system with a sampling frequency of 100 Hz. To guarantee packet-level synchronization accuracy, a maximum error of half a sampling period, i.e., 5 ms, is admitted.

Existing solutions for wireless synchronization have been proposed. Network Time Protocol (NTP) [2] is broadly known for keeping a synchronized time on the internet, and can guarantee an accuracy within a few milliseconds. In Reference Broadcast Synchronization (RBS) [3] the master sends broadcast reference messages, the peripheral informs in turn other peripherals about time change. Receivers here use the arrival time as a means to adjust their local clocks. Compared to NTP, RBS eliminates the non-deterministic delays associated with the master, resulting in microsecond level time accuracy. In Timing-sync Protocol for Sensor Networks (TPSN) [4], synchronization is based on a handshake, using 2-way communication. Timestamp generation is done at the Medium Access Control (MAC) layer. Therefore, it achieves an accuracy twice that of RBS. The Flooding Time Synchronization Protocol (FTSP) [5] reduces communication overhead by synchronizing nodes based on a single radio message. To further reduce the synchronization error, FTSP adds drift compensation, combined with MAC-layer timestamping. Accuracies of around 1 µs are feasible.

In Bluetooth Low Energy (BLE), using the connection-based event to synchronize multiple wireless sensor nodes is not very accurate. Since an application-level event is used to trigger a timestamp capture, an accuracy of ± 750 µs is achieved [6]. In [7], a combination of RBS and FTSP is used. The timestamp generation is based on a Real-Time Clock (RTC) timer. With no attention given to hardware timestamping, an accuracy of 30 µs was achieved. Authors in [8] use broadcasting packets to transmit the current timestamp value and the aggregate delay incurred during the transmission of the previous packet. A minimum of 2 broadcast packets needs to be sent to synchronize clocks. While also applying clock drift correction, an accuracy of 10 µs was achieved. In [9] specific current consumption patterns are used as a means of hardware timestamping. Results show an accuracy of 17 µs, however, requiring additional hardware components. BlueSync is presented in [10], featuring average errors as low as 330 ns per 60 sec (single hop). This system, while providing very accurate synchronization, is relatively complex. In conclusion, solutions have been proposed that achieve the required accuracy, yet are not specifically fit for BLE or require a complex integration. In a multi-IMU system, a lot of data will be transmitted anyway. The added complexity of a more advanced synchronization method does not outweigh the limited overhead of sending an extra sync packet. Complementary, e.g., NTP and the connection-based event have been proposed, which are much less accurate.

We present a multi-unit wireless IMU WBAN synchronization approach and platform, and elaborate on synchronization error localization and implementation challenges on off-the-shelf wireless System on Chips (SoCs). The synchronization approach presented suits the accuracy and
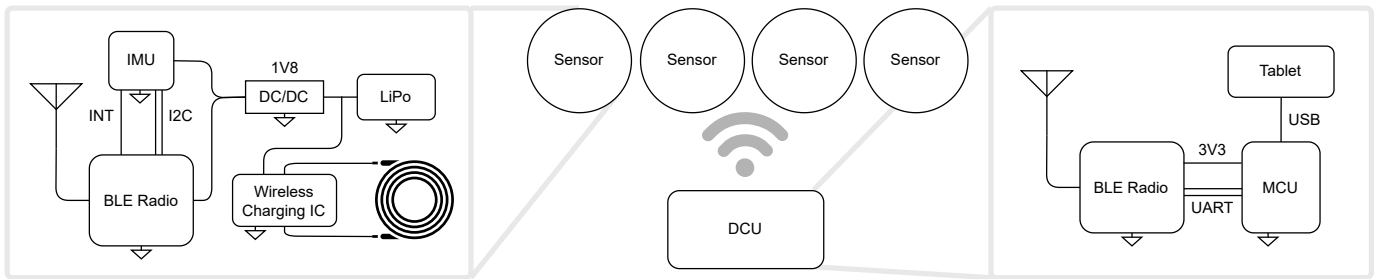
Fig. 1. System overview. A central Data Capturing Unit (DCU) with multiple wireless Inertial Measurement Units (IMUs) sensor modules. In the center: top-down view of system. On the left: block diagram of the sensor node. On the right: simplified block diagram of the DCU.

low-power demands required in WBAN. The embedded software and hardware are shared through GitHub [11]. The remainder of the paper is structured as follows. First, an overview of the system is given. The synchronization analysis and methodology are elaborated on in Section II and III. The results are presented in Section IV, with Section V concluding this work.

I. SYSTEM OVERVIEW

The considered WSN system consists of a central Data Capturing Unit (DCU) (master) and a number of IMU sensors (peripherals), operating in a star network topology. The DCU hosts both a *Nordic nRF52832* BLE SoC and a *STM32H743ZIT6* microcontroller unit (MCU), which in turn communicates with a tablet and is used for further data processing. The peripherals consist of IMU sensor modules with the same BLE SoC, which features an ARM Cortex M4+ processor with Floating Point Unit (FPU) running at 64 MHz. It includes a radio module for wireless communications at 2.4 GHz and supports BLE, NFC, ANT and proprietary protocols. The *TDK InvenSense ICM20948* [12], despite not having an external clock input, is chosen for its lower power consumption of only 2.5 mW. The DCU processes the received IMU packets and acts as the synchronization master. Up to 8 sensor nodes (peripherals) can be wirelessly connected and synchronized. BLE is chosen as the most suited communication technology for its rather high data throughput while still maintaining a low power consumption. Fig. 1 gives an overview of the system, Fig. 2 depicts the hardware implementation.

II. SYNCHRONIZATION ANALYSIS

Working with low-cost components, one may expect the accuracy and stability of their clocks not to be high. Low cost components do not always have the necessary inputs, i.e. a clock input, to accommodate optimal synchronization. We performed the following experiment to illustrate the impact and consequent need to perform a dedicated synchronization. When observing two identical IMUs sampling at 100 Hz during 30 minutes and measuring their sampling rate by the interrupt pin (set to toggle when a sample is available), two problems can be identified: A **frequency mismatch**: 103.5 Hz and 104.4 Hz instead of the expected 100 Hz. A **frequency instability/drift**: a clear spread on the clock frequency of $\pm$ 2 Hz. We propose

Fig. 2. Realized hardware: IMU sensor node with BLE connectivity, powered by a small LiPo battery, and wirelessly rechargeable (Top). Battery powered DCU for tablet communication, including a BLE radio, an MCU for processing, and Qi wireless charger (bottom).

a synchronization approach to address the two problems by a combination of measures:

1) **Oversampling the IMU** at 225 Hz. With each IMU interrupt, the First In First Out (FIFO) buffer is read, and the last available value is saved on the microcontroller in Random Access Memory (RAM). Only the last stored sample is read at a frequency determined by the user. By doing so, a small error (max. 4.4 ms) is introduced between actual sampling time and buffered data, which is quasi-random but does not increase over time.

2) **Triggering packet transmission using a synchronized clock.** Compared to using the free-running IMU clock to trigger packet transmission, we trigger packet transmission based on an accurate synchronized clock (depicted in Fig. 4), generated by the BLE SoC.
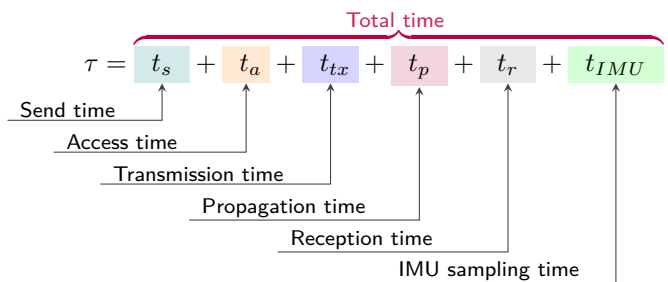

Fig. 3. Causes of error in time synchronization

The total error rate on the synchronization is denoted as τ. Several parameters contribute to this time error,

depicted in Fig. 3. For an accurate synchronization, τ has to be minimized. The send time, i.e., the time to construct the message at the sending node, is deterministic. The access time, i.e., the time between sending the message and the message actually being transmitted, can vary significantly in BLE networks. In a connection-based event with reliable data transfer, this varies from 7.5 ms to 4 s, while with advertising packets it can be in the order of microseconds. The transmission time, i.e., the time to send a packet from sender to receiver, is dependent on the data rate, the packet length, and the channel conditions. The wireless propagation time, e.g., 30 ns for a distance of 10 m, can be neglected. The reception time, i.e., the time needed for the peripheral to receive, decode and process the packet, is dependent on the used SoC.

III. Synchronization Methodology

Following the analysis of causes of synchronization errors and identification of contributing components in the previous section, we here describe the methodology used to minimize these errors. The DCU's main controller receives the accurate UTC time with second-level precision from the tablet. The BLE chip on the DCU replicates this time and establishes a relative synchronization between itself and the IMUs in a star network topology. The relative synchronization is implemented using a simplified version of the FTSP with MAC-layer time stamping, excluding clock drift compensation. The master periodically sends synchronization packets to the slaves in a star network topology. Advertising packets are here used to decrease the access time as much as possible. Since the master is not subject to any energy constraints, optimizing for energy consumption at this side is not necessary or relevant. The slaves can optimize accuracy and energy consumption by intermittently listening for synchronization packets, and adjusting radio receive window lengths. The resulting timestamps at the DCU are calculated using a combination of the UTC time and relative IMU packet timestamps. Since we do not compensate for clock drift, clocks are only updated during the transmission of a synchronization packet. Compared to FTSP, our solution thus requires more transmissions, yet we achieve a sufficient accuracy for the application and incur only a very limited energy overhead at the IMU side. The accuracy is depicted in Fig. 4. Our solution does not interfere with any ongoing BLE communication, as it only requests available time slots in-between the normal BLE communication, i.e., when the channel is free.

A. Timestamp Generation on Master

The received UTC time with second-level accuracy from the tablet is transferred from the microcontroller (*STM32*), in control of tablet communication, to the BLE radio (*nRF*) over UART. The slight delay introduced here is not detrimental, since the synchronization between IMUs is handled by the BLE chips. The central node (BLE radio at the master) has a free-running timer. For timekeeping, a combination of two 16 MHz timers is used, derived from the 32 MHz high-frequency crystal oscillator with an accuracy of ± 10 ppm. The wrap around value of 16 000, in combination with the 62.5 ns resolution, corresponds to a wrap-around time of 1 ms, which is used to accurately trigger transmission of IMU samples at different frequencies. It takes 49.71 days until a timer overflow occurs, i.e., plenty for typical WBAN purposes. For a slightly lower power but less accurate time synchronization (each tick takes $\pm$ 30 µs), a clock derived from the 32.768 kHz crystal, consuming only 0.25 µA, instead of 250 µA [13] could be used. We chose to use the higher accuracy crystal, since this rather small increase in power consumption is negligible compared to the continuous BLE transmission. A Nordic library [14] was used, which implemented already a lot of features, such as the use of Programmable peripheral interconnect (PPI) to set up radio transmission of sync packets, high-accuracy timestamping, and clock corrections. The Nordic Timeslot API allows the library to request time slots in between the normal BLE communication in advance, and herein transmit synchronization packets, i.e., minimizing the fixed access time to a couple of microseconds. The library was adapted to lower the energy consumption by carefully managing the high frequency clock states, radio receive window lengths, and update rates. At the peripheral, the interval between sync updates is managed by a timer, only enabling the receiver sporadically and disabling it after receiving a sync packet. The radio settings used are 2 MBit PHY, +4 dBm output power. The send and transmission time is kept predictable by capturing the timer value at a consistent time delta from the actual transmission. The fixed delay hereby introduced can be easily compensated for at the receiver. At the start of an allocated time slot, i.e., when the radio is ready, the timers will be captured by means of PPI. The PPI channels are synchronized to the 16 MHz clock, meaning 1 clock cycle delay will be introduced here [13]. When the radio is ready, the Central Processing Unit (CPU) copies the PPI sampled values from the timer registers into the transmit packet. The time this operation takes is predictable, depending on the compiler optimization level, and is in our case determined to be 29 µs.

B. Timestamp Decoding at Peripheral

It's important that the peripheral timers can be sampled as close to the packet reception as possible, while the actual time correction is not as time-critical, and can be postponed. Using the implementation of [14], the clocks are adjusted. A PPI is set up to trigger the capture of both timers once the correct address is wirelessly received, generating a very accurate MAC-layer timestamp. In the radio interrupt handler, the synchronization timer offset is calculated and compensated. A fixed delay is added to account for the introduced error at the master when copying the timer value buffers. Timer offset compensation is done using PPI together with timer compare registers. If the

peripheral timer is ahead of the master, the current timer cycle is cut short and the counter timer is incremented. If the peripheral timer is behind the master timer, the current timer cycle is cut short without incrementing the counter, thus delaying the next 1 ms pulse.

IV. RESULTS

Fig. 4 shows the measured synchronization error and theoretical max derivation in clock stability, based on datasheet values. The synchronization error is measured over a period of 30 minutes with a logic analyzer at 24 MSa/s by toggling a General Purpose Input/Output (GPIO) pin by PPI every 10 ms from the synchronized clock at peripheral and master. Table I depicts the measured additional energy consumption for synchronization. The induced random error from oversampling the IMU is one of the biggest contributors to the total error. When sending sync packets very frequently, i.e., at a fixed rate of 30 Hz, it allows the receiver RX-window to be as short as possible. The lowest achievable synchronization error is less than 1 μs. This adds 74.8 J h^{-1} to the peripherals' energy consumption. Note that the theoretical maximal error is greater than the measured error due to lost synchronization packets when the wireless interface is busy transmitting BLE data packets. It is worth noting that temperature variations can impact the frequency deviation of crystals, potentially deteriorating the accuracy. The reception and processing of a single synchronization packet consumes 3.34 mJ. When duty-cycling the receiver, i.e., enabling the receiver only until a sync packet is received, the synchronization error increases but energy consumption decreases. Using a 1 min interval, an accuracy of ± 200 μs with a energy consumption of 198 mJ h^{-1} per hour is achieved. Together with the maximal oversampling error, i.e., 4.4 ms, we achieve a solution with an error of less than the predetermined 5 ms maximal error. The synchronization architecture is designed in a way that new sensors, such as an Electromyography (EMG) sensor can be easily added and synchronized with the same shared clock. The necessary 2 kHz sampling rate can be derived from the synchronous clock, and can be used as a sampling trigger for the EMG. More synchronization packets can be transmitted to achieve sub-packet accuracy.

TABLE I
ADDITIONAL ENERGY CONSUMPTION FOR DIFFERENT RX WINDOWS PER HOUR OF OPERATION

Time [s]	0	1	5	10	20	60	300
Energy [mJ]	74 844	12 016	2 401	1 202	597	198	40

V. CONCLUSION AND FUTURE WORK

We presented a wirelessly synchronized multi-unit IMU platform capable of achieving sub 1 μs time accuracy between nodes. Further, an energy-optimized implementation with an accuracy of 200 μs and an energy consumption of only 198 mJ h^{-1} is achieved. Sources of synchronization error in an IMU system are discussed and minimized. This approach suits the accuracy and low-power requirements
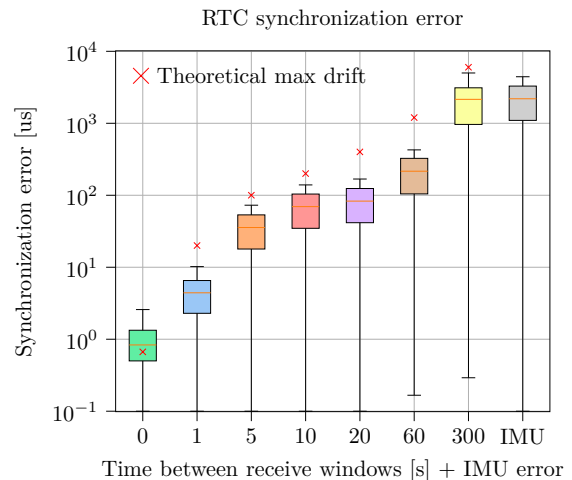

Fig. 4. RTC synchronization accuracy between 2 BLE nodes with different windows for receiving synchronization packets and IMU oversampling error. The 0-second receive window represents continuous reception.

for a multi-IMU system. In future work, the synchronization could be improved, both in terms of accuracy and energy consumption, by actively compensating for the clock drift and using a synchronized wake-up.

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