Sub-50 µs Sample-Level Synchronization in a Battery-Powered BLE MEMS Accelerometer Node for Industrial Vibration Monitoring

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***Abstract*—Accurate synchronization of data samples is crucial for wireless sensor networks (WSNs) used for vibration monitoring and condition diagnostics. This paper describes two practical methods for achieving sample-level synchronization with better than $50\,\mathrm{microsecond}$ accuracy on battery-powered wireless MEMS accelerometer nodes. The first method uses a hardware-based real-time synchronization approach, where each sensor node has a $1.024\,\mathrm{MHz}$ clock which is synchronized through periodic interrupt pulses. The second method employs a software-based cross-correlation alignment to achieve precise synchronization after data acquisition, which is suitable for cases without accurate hardware clocks. Both methods are implemented using compact Bluetooth Low Energy (BLE) sensor nodes with off-the-shelf components. Experimental results on a shaker test platform confirm that synchronization within $50\,\mu\mathrm{s}$ is reliably achieved with both methods, demonstrating the suitability of these methods for industrial vibration monitoring applications.**

***Index Terms*—wireless sensor networks, synchronized sampling, vibration monitoring, MEMS accelerometers, Bluetooth Low Energy (BLE), sensor skew correction, condition monitoring, industrial sensing**

I. Introduction

In many modern industrial settings, high-speed robotic systems are widely used to automate precise tasks, such as wafer-handling in semiconductor production. These robots often experience vibrations affecting their operation and reducing their lifespan or can be sign of malfunction. Monitoring these vibrations is crucial to ensure efficient, safe, and reliable robot performance. This vibration monitoring typically involves attaching multiple accelerometers to different robot parts, recording motion simultaneously, and analyzing the collected data to identify potential issues.

To accurately analyze these vibrations, data samples from multiple sensors must be captured at almost exactly the same time. The required precision is very high, typically, half of the sampling period. Therefore, for about $1\,\mathrm{kS/s}$ (Kilo Sample per second) synchronization better than $50\,\mu\mathrm{s}$ is required [1]. Traditionally, wired sensors have been used to achieve this level of synchronization; however, this is often impractical, especially in complex moving machines. On the other hand, Wireless sensors are much easier and quicker to deploy, but achieving the necessary precise synchronization remains challenging.

Current research on accurate wireless synchronization splits into two separate lines of work.

- *Hardware-driven Synchronization*: Each sensor node uses a precision clock, which is synchronized with the clocks of other nodes. Due to imperfections in the clock frequencies, the clocks deviate from each other over time. Therefore, periodic synchronization (reset) pulses are needed to force every sensor onto the same time grid. Early modal-analysis studies reported skews of a few tens of microseconds by wiring an external clock or pulse to each accelerometer [2], [3]. These solutions rely on high-quality oscillators to be implemented in a wireless network, and the reset pulses need to be communicated.
- *Software-based Synchronization*: Each sample is stamped locally, and later the streams are aligned using correlation or resampling algorithms, an approach common in recent bridge and building deployments [4]–[8]. These works avoid extra hardware. However, their accuracy depends on post-processing assumptions, and they are typically validated only in offline analysis.

To the best of our knowledge, no prior study evaluates both hardware and software Synchronization methods *experimentally on the same platform*; the literature, therefore, lacks a clear, side-by-side comparison based on accuracy, power efficiency, and data-loss trade-offs, especially for small, battery-powered BLE sensor nodes intended for fast industrial robots.

This paper addresses this gap. We implement both hardware and software synchronization methods using the same device, introduced in [9] and [1] to maintain synchronization within $50\,\mu\mathrm{s}$ limit at $1\,\mathrm{kSa/s}$ and compare the performance side-by-side. The node combines a low-noise ADXL355 accelerometer, a Bluetooth-enabled microcontroller (CC2640R2F), and an efficient data logging memory (FRAM).

In our hardware-driven synchronization approach, we call *Real-time-reset*; each sensor's internal filter is reset simultaneously by an external synchronization pulse, ensuring immedi-

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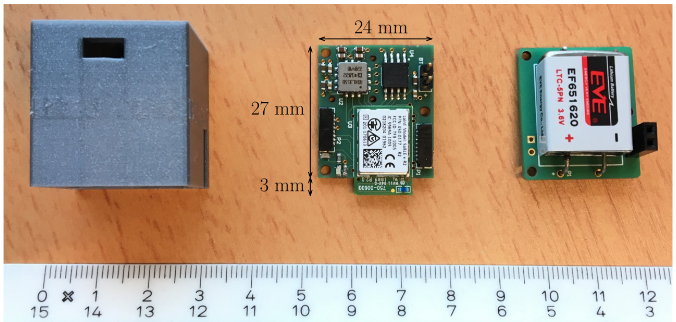

Fig. 1. Housing, sensor board, and battery [9].

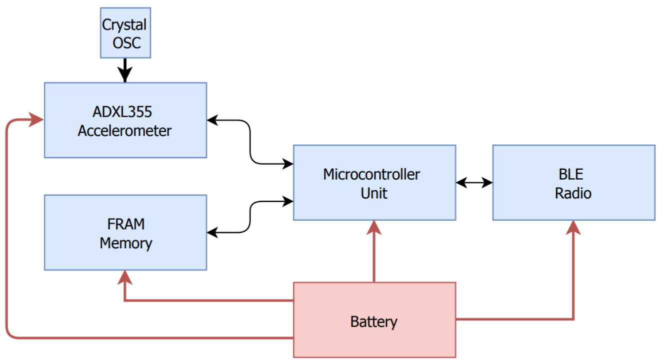

Fig. 2. Architecture of the wireless sensor node [1].

ate alignment of samples. In the software-based synchronization *Post-hoc alignment*, Sensors record precise local timestamps, and the data streams are synchronized later through a simple cross-correlation method during post-processing.

The rest of this paper is organized as follows: Section II outlines the wireless sensor node architecture and synchronization methods. Section III describes the experimental setup used to evaluate the techniques. Section IV presents the results, comparing timing accuracy, data integrity, and power consumption. It also discusses the findings and offers guidance on method selection. Finally, Section V concludes the paper and outlines future works.

II. Node Architecture & Synchronization

Fig. 1 depicts the sensor node hardware, which is a compact ($30\,\mathrm{mm} \times 35\,\mathrm{mm}$) device designed specifically for wireless vibration monitoring. In addition to the battery, the sensor node consists of four primary components (see Fig. 2).

- **ADXL355 MEMS Accelerometer:** A three-axis, low-noise accelerometer capable of external clock input and synchronous digital filter reset. This device operates synchronously from a $1.024\,\mathrm{MHz}$ reference clock.
- **CC2640R2F BLE Microcontroller:** Incorporates a Cortex-M3 CPU, performs sensor data acquisition, storage, and transmission via Bluetooth Low-Energy (BLE).
- **4-Mbit FRAM Memory:** Provides rapid, non-volatile buffering, ensuring data continuity in case of radio transmission interruptions.
- **Clock Source:** Either a precision $0.3\,\mathrm{ppm}$ oven-controlled crystal oscillator for high accuracy or the integrated MCU $40\,\mathrm{ppm}$ RC oscillator as a low-cost alternative.

Operating at a sampling rate of $1\,\mathrm{kSa/s}$, the node consumes approximately $2.6\,\mathrm{mW}$ when utilizing the precision crystal oscillator and around $2.3\,\mathrm{mW}$ when using the lower-precision RC oscillator. Both values remain well below $10\,\mathrm{mW}$, a level that can be considered non-intrusive and safe for coexisting systems in industrial environments [9].

A. Synchronization Methods

Two methods were implemented to achieve sample-level synchronization:

1) Real-time-Reset: In this method, a periodic Reset-Pulse-Event (RPE) signal simultaneously resets the digital filters within each ADXL355 sensor. By leveraging the internal high-quality clock source with precision P (in ppm), the maximum expected skew between nodes is described by:

$$\Delta t_{\max} = \frac{P \times T_{\mathrm{RPE}}}{10^6}$$

Using the oscillator of the microcontroller with $40\,\mathrm{ppm}$ precision and the maximum timing skew of $20\,\mu\mathrm{s}$ (to be safely within $50\,\mu\mathrm{s}$) a reset pulse interval of $0.5\,\mathrm{s}$ is required. However, using the ADXL355 internal clock, this interval should be much shorter. Each RPE event results in losing at least one sensor sample due to the distortion in the dissimilation filters.

2) Post-processing Alignment: When using the lower-cost RC clock, sensor samples are timestamped locally by the microcontroller's internal timer. After data collection, a host processor performs alignment through cross-correlation and resampling techniques over four-second windows. This approach effectively reduces initial clock drifts without loss of samples. However, this method requires additional radio bandwidth for timestamp transmission and modest host-side computational resources.

III. Experimental Setup

Two wireless sensor nodes were securely mounted on a rigid aluminum plate ($20\,\mathrm{cm} \times 12\,\mathrm{cm}$), which was attached to an electrodynamic shaker (*LDS V406*), as illustrated in Fig. 3. The shaker was programmed to generate a controlled sine sweep vibration ranging from $10\,\mathrm{Hz}$ to $1\,\mathrm{kHz}$, ensuring identical vibrational input for each node. A reference measurement was simultaneously obtained using a calibrated piezoelectric accelerometer (PCB 356B18, sensitivity: $10\,\mathrm{mV/g}$) located at the center of the plate, sampled at $51.2\,\mathrm{kSa/s}$ via an NI-9234 data acquisition module.

The microcontroller's internal RC oscillator rated at $40\,\mathrm{ppm}$, frequency-divided by a factor of 47, is employed to clock the accelerometer. A Reset-Pulse-Event (RPE) synchronization signal with the interval of $500\,\mathrm{ms}$ was distributed to each sensor node via a logic buffer with negligible delay ($<2\,\mathrm{ns}$). The interrupt signals (INT1) generated by each sensor, along with the RPE synchronization pulse, were recorded

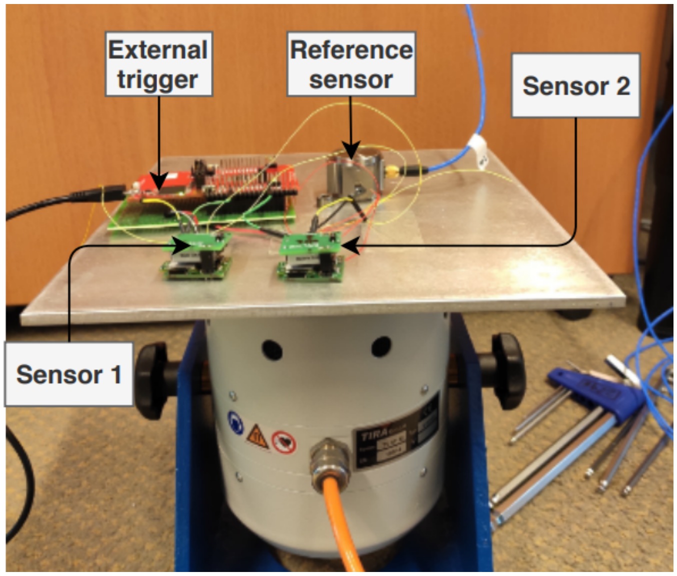

Fig. 3. Sensor nodes and reference sensor on the shaker [1].

TABLE I
SYNCHRONIZATION ERROR AND POWER CONSUMPTION COMPARISON BETWEEN HARDWARE AND SOFTWARE METHODS

Synchronization Method	Mean Skew (µs)	St.Dev. (µs)	Power (mW)
Periodic Reset (Hardware)	22	4.8	2.3
Post Processing (Software)	37	7.1	2.6

using a $500\,\mathrm{MHz}$ oscilloscope (Keysight DSOX3054T) to measure inter-node sample timing differences precisely. Additionally, the power consumption of each node was continuously logged at a rate of $100\,\mathrm{kSa/s}$ using a Keysight N6705B power analyzer.

Each experimental run had a duration of $30\,\mathrm{minutes}$ at a fixed sampling rate of $1\,\mathrm{kSa/s}$, resulting in approximately $1\,800\,000$ data points per node.

IV. RESULTS AND DISCUSSION

A. Timing accuracy

In the real-time-reset synchronization method, the timing differences between INT1 pulses across all sensor nodes throughout the entire $30\,\mathrm{minute}$ measurement period achieved mean skew of $22\,\mathrm{\mu s}$, with standard deviation $4.8\,\mathrm{\mu s}$, and maximum $41\,\mathrm{\mu s}$. In contrast, without real-time-reset, the accumulated timing deviations reaching approximately $850\,\mathrm{\mu s}$. However, applying the post-processing alignment approach effectively reduced this drift to a residual mean skew of $37\,\mathrm{\mu s}$, with standard deviation: $7.1\,\mathrm{\mu s}$ (see Table I).

B. Data Integrity

The real-time-reset method inherently causes the loss of at least sensor samples per periodic reset event, corresponding to an overall data loss of approximately $0.2\,\%$. In comparison, the post-processing alignment method preserves all samples but requires transmission of additional timestamp data, amounting to roughly $6\,\mathrm{kB/s}$ extra payload. This additional overhead remained within the BLE bandwidth capabilities at the tested sampling rate but increased the power consumption.

C. Energy Consumption

The power consumption analysis (as summarized in Table I) indicates that the real-time reset method, relying on the external precision crystal, achieves an average power draw of approximately $2.3\,\mathrm{mW}$. Conversely, due to the additional radio transmission and computational overhead, the post-processing alignment method results in a slightly higher average power consumption of about $2.6\,\mathrm{mW}$.

D. Guidance for Method Selection

The real-time-reset approach is recommended when achieving minimal skew, and low energy consumption is critical. A precision periodic reset clock can be feasibly provided (e.g. via wired, wireless, light, or other channels). In contrast, post-processing alignment offers greater flexibility, as it leverages existing MCU resources and avoids data loss, making it preferable for larger-scale or budget-sensitive implementations.

V. CONCLUSION

Two synchronization methods were successfully evaluated by implementation on compact BLE-enabled sensor nodes posesing MEMS accelerometers capable of sampling at rate of $1\,\mathrm{kSa/s}$. The first method, using a precise external periodic reset signal, achieved an average timing skew of approximately $22\,\mathrm{\mu s}$ at a low power consumption of $2.3\,\mathrm{mW}$, however, at lease 1 sample is lost per resynchronization on each 500 ms due to distortion of sensor's decimation filter. The second, a software-based method uses timestamp-based post-processing alignment, reached an average skew of approximately $37\,\mathrm{\mu s}$, consuming slightly more power at $2.6\,\mathrm{mW}$ but without any data loss.

Future research directions include integrating the high-precision oscillator into a PCB, expanding the test network to ten nodes, and evaluating robust BLE-mesh data streaming performance in realistic industrial environments.

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