13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-104

eNodes: GNSS Time-Synchronised Wireless Accelerometer Measurement Nodes capable of operating indoors

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ABSTRACT: This paper presents time-synchronized wireless acceleration measurement nodes, named eNodes, capable of operating indoors by preserving timing information with a temperature-controlled crystal oscillator (TCXO). While GNSS-based time synchronization is commonly effective for outdoor measurements with available GNSS signals, it does not work indoors, such as inside high-rise buildings or box-girder bridges. To extend GNSS-based time synchronization to indoor applications, timing information is acquired outdoors both before and after the indoor deployment. The TCXO maintains this timing information accurately ensuring a stable and accurate frequency. Each eNode is equipped with an Epson M352 MEMS accelerometer, which offers extremely low noise of 0.2 μg/√Hz, and an ESP32 microprocessor unit. Real-time data transmission is enabled by a Wi-Fi mesh network. A series of experiments were conducted to evaluate the time-synchronization accuracy of the eNodes.

KEY WORDS: Structural Health Monitoring, Wireless Sensor, Accelerometer.

1 INTRODUCTION

It is a challenging task to measure acceleration responses of large infrastructures such as long-span bridges, or high-raise buildings, due to long easy-to-tangle many wires between sensors and a DAQ system, up to several km's. As an alternative to the conventional wired DAQ system, the idea of wireless sensors emerged a few decades ago, but it has brought a side-effect, the time-synchronisation problem between the nodes for a proper identification of mode-shapes.

There have been a few wireless sensors developed and available commercially or academically. To the best knowledge of the authors, they were either not providing the accuracy of time-synchronisation, or not readily available to buy. Recently a few manufacturers emerged to provide time-synch'ed wireless nodes (from Sensquake, or Guralp), however their main application was not perfectly aligned with the task of campaign-type ambient vibration measurement of infrastructures.

This paper presents a realisation of wireless accelerometer nodes focusing on campaign type field measurement applications on civil infrastructures or high-raise buildings. The GNSS based time-synchronisation [1] method was used and extended to indoor measurements by combining the GNSS method with a stable clock source.

2 WIRELESS ACCELEROMETER NODES

2.1 Accelerometer

The accelerometer node, as shown in Figure 1, consists of a M5Stack Core2 based on esp32, a GNSS module (M5Stack GPS V2), an accelerometer module for an Epson M-A352 sensor, a battery module (M5Stack Battery 13.2), and battery charging module (M5Stack M5Go). The company M5Stack provides a convenient modular structure for their MPU and modules, so that a user can easily add a feature by added another layer of module stacked below the M5Stack Core2. The Core2 MPU provides a 320x240 pixels LCD and a touchpad, enabling a convenient control and operation of the sensor node.

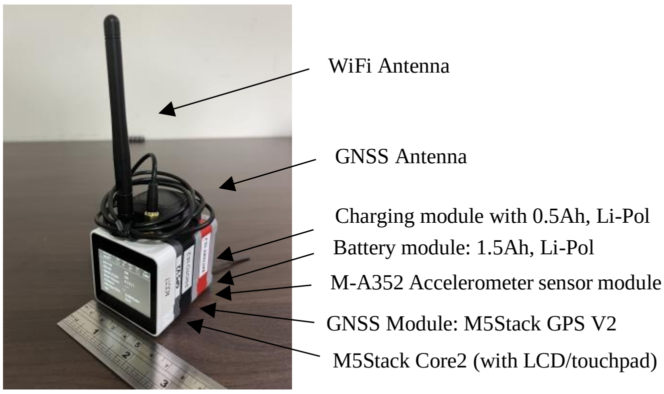

Figure 1. Accelerometer node eNode

Figure 2 shows Epson M-A352 sensor module, which is interconnected to Core2 MPU with 30 GPIO pins as well as the modules stacked together. Epson M-A352 provides the noise floor of 0.2 ug/√Hz, which is extremely low, hence out-performing for low-vibration measurement of civil infrastructures. M-A352 is a digital sensor with a built-in ADC and output data rates range from 50 Hz to 1000 Hz.

Figure 2. Epson M-A352 Accelerometer module: (left) Top View, and (right) Bottom View

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Figure 3. M5Stack GPS V2 module: (left) Top View, and (right) Bottom View

Figure 3 shows the M5Stack GPS V2 module, which plays the critical role for time-synchronisation. This outputs NMEA sentences and PPS (Pulse-Per-Second) signals to the Core2 MPU, which combines these outputs to get a highly accurate timestamping on each measured acceleration. Details method is shown in [1].

Espressif IoT Development Framework (ESP-IDF) was used, rather than the Arduino platform, mainly for the full control on the lower-level timing operations of esp32. In addition, Mesh-Lite was used to utilise a WiFi mesh network, extending maximum allowable distance between nodes, by multi-hops.

3 SYNCHRONISATION ACCURACY

Four different experiments were carried out from the ideal condition (Case #1), to the most realistic condition (Case #4) of the indoor capable eNodes with a temperature variation as shown in Table 1.

Table 1. Experimental Cases of timestamping err measurement

Case #	GNSS signal	Clock-Source	Temp. dev.
1	always	GPTimer (10MHz)	No
2	always	TCXO (32.768kHz) for RTC	No
3	limited	TCXO (32.768kHz) for RTC	No
4	limited	TCXO (32.768kHz) for RTC	Yes

3.1 Case #1: Continous GNSS signals with a GPTimer

Accuracy of time synchronisation for the hardware of the Core2 and the GNSS module was measured using the setup shown in Figure 4. This setup assumed that GNSS signals were always available with a high-frequency General Purpose Timer (GPTimer) of 10 MHz as the basis of the ideal time-sync performance for a comparison with the following Cases #2-4.

A common 10 Hz trigger signal was generated by a function generator, fed to the two identical nodes of Core2 and M5Stack GPS module. Each node was programmed to timestamp each trigger signal. GNSS signal was available all times during the experiment. In theory both nodes should produce the exactly same timestamps, but in reality they differ slightly. Their difference was measured and shown in Figures 5 and 6.

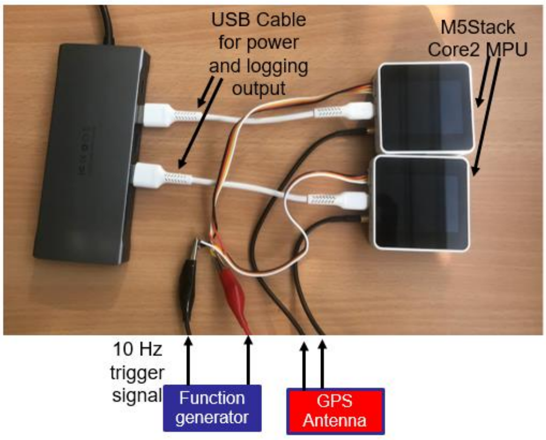

Figure 4. Experimental setup for measuring time-sync accuracy for eNode

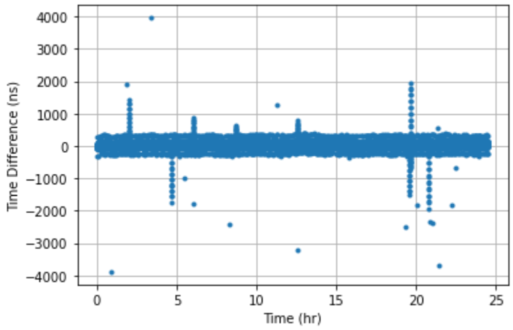

Figure 5. Case #1: Difference in timestamps by two identical nodes

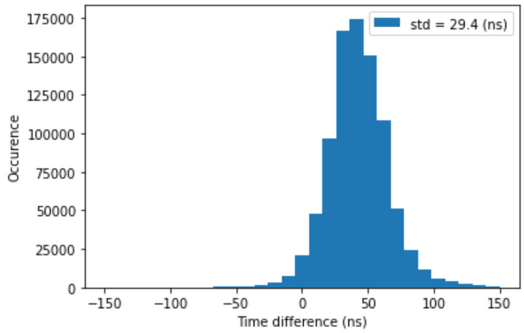

Figure 6. Case #1: Histogram of difference in the timestamps

3.2 Case #2: Continuous GNSS signals with a TCXO

Frequency of General Purpose Timer used in Case #1 is influenced by temperature variation, which drastically reduces timestamping accuracy during the period without GNSS signals. There are different ways to improve this using OCXO (Oven Controller Crystal Oscillator) or TCXO. In this study, a TCXO with 32.768 kHz was used as the clock-source for the Real-Time Clock of ESP32 to replace GPTimer of Case #1.

Figure 7 shows the timestamping difference over 2 hours period, showing the step-wise errors between ±61 usec. This can be explained two clock-oscillations error in the RTC clock-counter, which only increases by 2. One clock oscillation of a 32.768 kHz clock corresponds to 30.5 usec, and two clock oscillations correspond to 61 usec.

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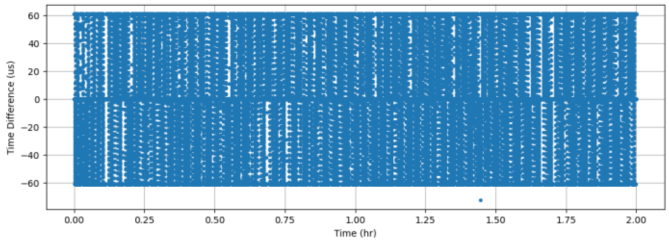

Figure 7. Case #2: Difference in timestamps by two identical nodes with TCXOs

3.3 Case #3: Limited GNSS signals with a TCXO

When eNodes are deployed indoors, GNSS signals becomes unavailable. In this Case #3, it was assumed that GNSS signals were missed for 1 hour in the beginning and becomes available again afterwards. Due to the deviation of TCXO, the two timestamps by the identical nodes differ slightly more than Case #1. Figure 8 shows the measured time-stamping difference in the beginning, followed by the normal pattern observed in Figure 7 in the last half hour.

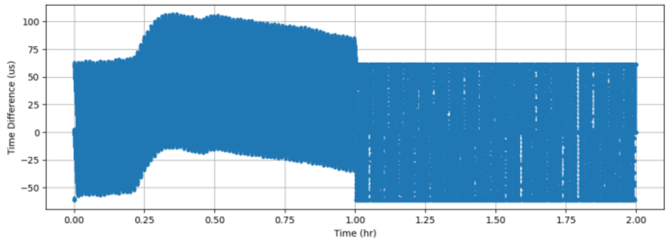

Figure 8. Case #3: Difference in timestamps by two identical nodes with TCXOs

3.4 Case #4: Limited GNSS signals with a TCXO under temperature variation

Temperature variation is a crucial factor to reduce timestamping accuracy in the nodes. TCXOs are designed to compensate the variation, but inevitably capable to do up to a certain degree. In this case, the timestamping difference under temperature variation was investigated.

In this Case #4, a temperature variation was imposed on one node by putting it into a refrigerator whist the other node was kept in room temperature, resulting in 14°C temperature difference. The measured timestamp difference is shown in Figure 9. It was clearly seen that additional error was introduced by temperature variation to the maximum timestamp difference of about 250 usec.

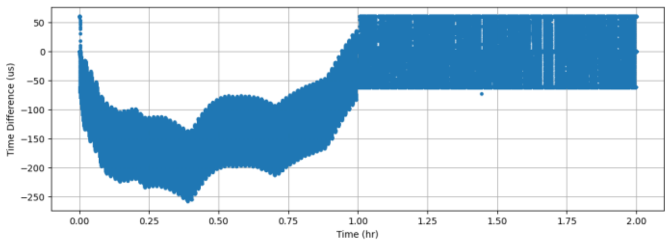

Figure 9. Case #4: Difference in timestamps by two identical nodes with TCXOs

CONCLUSION

In this study, the time-sync accuracy of indoor capable acceleration nodes were measured. With the used hardware of 32.768 kHz TCXO and ESP32, it was found that the maximum of 250 usec timestamping difference was observed for an hour measurement under 14°C ambient temperature difference.

Further study will carry out to validation tests including a laboratory OMA on a shear building frame and a field OMA for a high-rise building.

REFERENCES

[1] K. Koo, D. Hester, S. Kim, time Synchronization for Wireless Sensors Using Low-Cost GPS Module and Arduino 2019 Frontiers of Built Environment, Vol. 4, Article 82.