In: 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), 1-5 October 2023, Barcelona, Spain
DOI:10.1109/DASC58513.2023.10311277

Design and hardware-in-the-loop evaluation of a time dissemination framework for drone operations in urban environments

1st Sorin Andrei Negru
SATM
Cranfield University
line 4: Cranfield, UK
s.negru.965@cranfield.ac.uk

2nd Ivan Petrunin
SATM
Cranfield University
Cranfield, UK
i.petrunin@cranfield.ac.uk

3rd Weisi Guo
SATM
Cranfield University
Cranfield, UK
weisi.guo@cranfield.ac.uk

4th Antonios Tsourdos
SATM
Cranfield University
Cranfield, UK
a.tsourdos@cranfield.ac.uk

Abstract— **With the advent of UAVs (Unmanned Aerial Vehicles) several companies started to offer services, in urban, semi-urban, and rural regions. Although GNSS (Global Navigation Satellite System) can disseminate time information to different platforms, external factors may degrade the signal quality and lead to erroneous time synchronization. The paper is presenting a resilient time dissemination framework, using a wireless 802.11ax protocol and NTP (Network Time Protocol) for the synchronization aspect. A time server, formed by a rubidium clock, a GNSS receiver, and time information provided by NPL (UK's National Physical Laboratory) traceable to UTC, dictates the time to all the users within the WLAN (Wireless Local Area Network). To evaluate the proposed framework, a lab-based HIL (Hardware in the Loop) simulation is performed using two Jetson Nanos as CC (Companion Computer) and a Pixhawk 2.4 as FCU (Flight Control Unit) representing the end-users in the dissemination framework. In this way, all the communication links are tested and evaluated. Results showed that the two platforms can be synchronized to the time server as an alternative time source, achieving an average RTT (Round Trip Delay) of 8 ms from the Research and Innovation timing node to the FCU, and an average time offset of -0.2 ms.**

Keywords—GNSS, time dissemination, oscillators, drift, urban mobility, UAVs, urban mobility, synchronization

I. INTRODUCTION

Time is one of the most important and valuable data, used by many industries worldwide to keep track of all the data exchanged between services and devices. With the advent of urban air mobility and the constant increase in the number of autonomous platforms, a common time source is needed for better synchronization and coordination in time and space, avoiding possible collisions and conflicts between other aerial vehicles. Thus, time can be used for inter-machine synchronization, where sensors from different vehicles are synchronized to each other, but also locally on each platform, known as intra-machine synchronization[1]. Considering that, most drones are equipped with GNSS (Global Navigation Satellite System) receivers, time and position information can be extracted as presented in [2]. Although the receiver can provide accurate data in open-sky conditions, urban[3], semi-urban and indoor environments lead to signal degradation due to multipath[4], NLOS (Non-Line-Of Sight), and signal obscuration, as can be seen in Figure 1. In addition, jamming and spoofing are other potential threats [5] that can decrease the time signal accuracy and affect the control and stability of the UAV (Unmanned Aerial Vehicle).

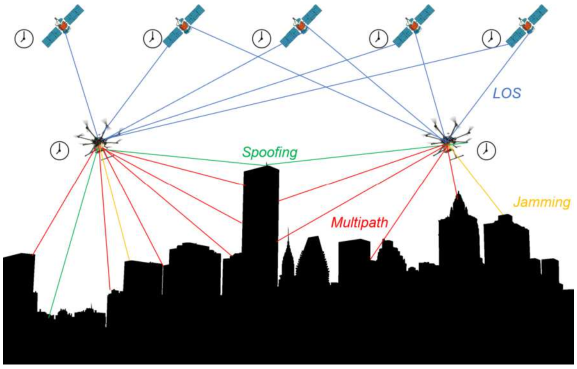

Figure 1 GNSS time signal degradation in urban environments

[3][4][5] Using a TWSTFT (two-way satellite time and frequency transfer) method accurate time can be disseminated between two stations as described in[6]. As a main disadvantage, the TWSTFT method cannot be used by multiple and dynamic platforms, as autonomous systems.

Oscillators with different relative frequency stability, such as XO (Crystal Oscillator), TCXOs (Temperature Compensated Crystal Oscillators), OCXOs (Oven-Controlled Crystal Oscillators), CSACs (Chip Scale Atomic Clocks), and rubidium oscillators, can be used to guide the drone's internal oscillator, reducing the time drift, but only for a limited period, depending on to the selected oscillator. This solution can increase the robustness of the system but does not guarantee accurate time tracking over time, because of all the external weather effects and all the uncertainties introduced by the technology and the raw materials used to manufacture each type of oscillator.

Instead, radio time signals such as MSF (Time From NPL) DCF77, and WWVB can represent a good source of time to be disseminated to multiple receivers. Unfortunately, radio time signals are not available in every country, and the continuity of the signal can be interrupted by regular maintenance activities all over the year. In addition, because the signal is operating in the LF (Low Frequency) band, the signal can be disrupted by external factors such as noise and interference from other devices as presented in [7]. Thus, radio time receivers, cannot disseminate continuous time to dynamics platforms.

Better performances are achieved, using NTP (Network Time Protocol) and IEEE 1588 PTP (Precision Time Protocol), widely used across wired networks to disseminate time. These kinds of protocols can be used to synchronize ground stations, and then disseminate time across wireless or cellular protocols such as 5G, 4G, and 3G, to mobile platforms.

Since most of the UAVs are equipped with wireless cards operating within 2.4 GHz and 5 GHz bands, compatible with

Wi-Fi protocols such as 802.11ac and 802.11ax, NTP can be used to synchronize all devices in the same network, as presented in [8], with ROS (Robotic Operation System), being able to achieve milliseconds accuracy.

Although PTP can disseminate more accurately the time, over networks, each device should be equipped with a NIC (Network Interface Card), using hardware timestamps, rather than software timestamps. PTP with hardware timestamps configuration can be implemented only with NICs on static devices, and it is not feasible for autonomous systems.

Time and frequency can be disseminated also using the WR (White Rabbit) time transfer system as described in [9] using a millimeter-wave carrier, operating between 71 GHz, and 76 GHz, achieving sub-nanosecond accuracy, within 500 m. Even though good performances can be achieved using the WR system, expensive infrastructure is required, and the range is limited. Thus, the scalability of such a system is limited and costly for autonomous vehicles.

UAVs require accurate and continuous-time signals, without affecting the overall flying operations, even if the main time dissemination source fails. To decrease the impact of external perturbances, which can affect the accuracy of the delivered time solution, holdover mechanisms can be used. As presented in [10], the authors used a CSAC module as a holdover clock, to improve the recovery time, required by the local system, after GNSS outages.

Considering all the mentioned time dissemination methods, the framework presented in this paper uses time inputs from the Research and Innovation Timing Node located at Cranfield University. The Node, provided under the UK's National Timing Center program, provides an accurate and resilient time and frequency source, traceable to UTC, including holdover clocks. Time data is then disseminated through Wi-Fi 6, which operates in an unlicensed band, to the target devices, in a lab environment using a HIL simulation set-up, and synchronized using the NTP protocol. The two target devices used, represent two UAVs, equipped with an FCU (Flight Control Unit) and a CC (Companion Computer), being the end-users in the dissemination framework.

The paper is divided as follows: in section, I different dissemination methods are presented, in section II the clock error model is defined, in section III the communication latency boundaries, in section IV the proposed solution, in section V the proposed system configuration for the HIL experiment, in section VI the results are discussed, and finally in section VII future work and conclusions are discussed.

II. UAV ERROR MODEL DEFINITION

UAVs operate in a standalone mode during the development phase, but once deployed and introduced in a common air space, time synchronization is essential, to avoid any possible collision with other vehicles. Assuming that different UAVs are operating in the same local airspace, with different clock accuracies, a common time dissemination source is needed, to dictate accurate UTC time. Each UAV in the airspace is equipped with an internal oscillator, represented mostly by a XO, susceptible to external perturbances. From Equation 1 it is possible to define the UAV's clock, defined as $C_{[UAV]i,}$ at the moment t, relative to a reference clock as defined in [11], where cs_i represents, the clock skew, and co_i the clock offset.

$$C_{[UAV]i,}(t) = cs_i t + co_i \qquad (1)$$

In an ideal case, the UAV would be perfectly synchronized to the time reference, if they both have the same rate and an equivalent offset converging to 0. Thus, from equation 2 it is possible to define the perfect clock model.

$$C_{[UAV]i,}(t) = t \qquad (2)$$

Unfortunately, the offset, representing the time difference between two clocks, the skew, representing the frequency difference between two clocks, and its variation in time defined as drift, tend to oscillate in the real world.

Table 1 Oscillator accuracy [11][12]

Oscillator type	Accuracy [ppm]	Aging in 10 years [ppm]	Temperature drift, ppm/°C (0…50°C)	Cost [$]
Relaxation Oscillator	>1000	-	-	<1
XO	10 ÷ 50	10 - 20	±5 ÷ ±20	~ 1
TCXO	±2 ÷ ±10	10 - 20	±0.2 ÷ ±2	~ 5
OCXO	±0.2 ÷ ±2	0.01	$\pm10^{-3}\div$ ±0.1	~ 50
Rubidium clock	10^{-6}	0.005	-	~ 1000
Cesium Beam	10^{-7}	-	-	~ 3000

As can be seen from Table 1, there are different types of oscillators, that affect the accuracy of the clock over time. Unfortunately, UAVs are not commonly equipped with a Cesium beam or rubidium oscillator, because of their weight, dimension, and high cost.

III. UAV COMMUNICATION LATENCY REQUIREMENNTS

To highlight the importance of latency, into a network used by UAVs, the ITU (International Telecommunication Union) has defined the 'NPC (Non-Payload Communication)'[13], divided into three communication links: the command-and-control link, the communication with the UTM (Unmanned Aircraft Systems Traffic Management), and the capability of the UAV to detect and avoid any collision with other flying vehicles. The UP (Uplink) defines the data exchanged between the UAV to the network, while the DL (Downlink), the data exchanged between the network to the UAV. From the table below it can be observed that for the command-and-control, the latency constraints, increases considerably from 40 ms to 1 s if a video source is added to the communication link.

Table 2 UAV latency requirements for different UAS operations [14]

Non-Payload Communication	Message Interval (UP/DL)	Max UAV Speed (km/h)	End-To-End Latency (UP/DL)
Command and control with video	1s / ≥1s	300	1s / 1s
Command and control without video	40ms / 40ms	60	40 ms / 40 ms

Communication with UTM or ATC	1s / 1s	300	5s / 5s
Detect and Collision Avoidance with other UAVs	500 ms / 500 ms	50	140 ms / 10 ms

On the other hand, sub-second accuracy is not required for the communication with the UTM, while tighter requirements are set for the communication link responsible for the collision and avoidance system, where 140 ms should not be exceeded for the UP (Uplink), and 10 ms for the DL (Downlink).

IV. PROPOSED SOLUTION

Considering, the frequency instability of system's oscillators, that affects the UAV performances, in time, as described in section II, and the latency requirements from section III, the paper analyzes the performances of a time dissemination framework using an IEEE (Institute of Electrical and Electronics Engineers) 802.11ax and an NTP protocol to synchronize all the UAVs in the same network, to a common UTC time.

In comparison, to the previous Wi-Fi protocol, identified as 802.11ac, the Wi-Fi 6 protocol does offer better latency performances and limits the impact of interference using a BSS (Basic Service Set) coloring mark. Basically, if more 802.11ax APs (Access Points), are deployed, each client is not affected by other APs operating in the same frequency band, making the 802.11ax scalable for UAVs operations.

While the 802.11ax is used to disseminate the time data to all the users within the same network, the NTP protocol is responsible to synchronize the UAVs to UTC time. The UAV platform is defined in the paper, by a FCU and an CC.

The FCU is the core part of a UAV, formed by different MEMS (Micro-electromechanical systems) IMUs (Inertial Measurements Units), barometers, GNSS receivers, and other types of sensors used for the navigation, control, and stability. Instead, the CC is usually responsible for all the high-computational cost algorithms, such as computer vision and AI (Artificial Intelligence) based algorithms, that can be used by the UAV's FCU. Thus, the CC is used as a time dissemination interface between the WLAN network and the FCU, using a MAVLINK protocol. The synchronization process between the CC and FCU starts with a TIMESYNC message which sends a time request, with the FCU's current time, identified as the client, and defined as t_{s1}, followed then by a response from the server, with the CC's time and the timestamp sent previously by the FCU, as it can be seen in Figure 2.

Most embedded boards also allow the possibility to add RTC (Real Time Clock) modules to keep track of the time, even when the embedded device is not powered and used. The RTC module is equipped with an alternative power source, that keeps the board oscillator powered, avoiding major time offsets in time. Thus, each CC is equipped with such a device to increase the robustness of the time dissemination framework.

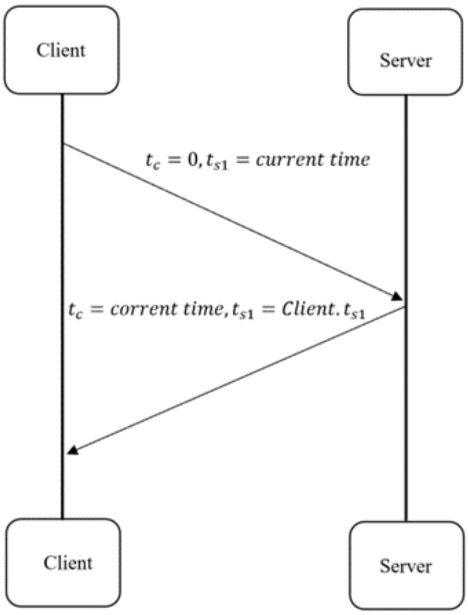

Figure 2 Time synchronization between the client and the server using a MAVLINK protocol

V. HIL SYSTEM ARCHITECTURE

To evaluate the performances of the IEEE 802.11ax and the NTP protocol, a HIL simulation is performed. The HIL framework presented in the paper integrates the Research and Innovation timing node provided by NPL at Cranfield University, as can be seen in Figure 3. An active hydrogen maser, atomic clock, generates 1 PPS (Pulse per Second) and sends the signal to a PTP grandmaster, used then to distribute the time signal over an optical fiber to Telehouse Docklands. From Telehouse Docklands the PTP signal is sent then again over a fiber link to Cranfield University as can be seen from Figure 4. To increase the resilience of the network, a cesium beam PTP holdover clock at Telehouse Docklands is used to act as a backup, if the optical fiber link from Teddington fails. In this way, the PTP signal at Cranfield University can be used continuously. The PTP link is then fed into the time server using a PTP switch, as can be seen in Figure 3 and Figure 5. The Research and Innovation timing node, located at Cranfield University, incorporates a LANTIME M3000 time server, which gets PTP signals from NPL Teddington, and GNSS signals from a Meinberg GPSANTv2 antenna, installed on the roof of the building, where the time server is located. The GNSS antenna can receive GPS signals in the L1 band and GALILEO signals in the E1 frequency band. As a holdover clock, the time server is equipped with a PRS10 rubidium clock, capable of keeping accurate time for 72 hours, at stratum 1 level.

The time signal from the LANTIME M3000 is sent then to an AX1800 Dual Band Wi-Fi 6 Router and synchronized using the time server IP address, using the NTP switch. Once the router is synchronized, the time signal is disseminated to two Jetson Nanos, representing the CC of the UAV, using an 802.11ax protocol. Two Jetson boards were used, to observe if major perturbances are introduced into the WLAN network. Each CC has installed chrony, being an implementation of NTP, and used to define the time server IP address, from where it is synchronized.

Instead, the FCU used in the paper is a Pixhawk 2.4 board. The internal oscillator of the FCU is usually disciplined by GNSS time signals, gathered during the flight mission.

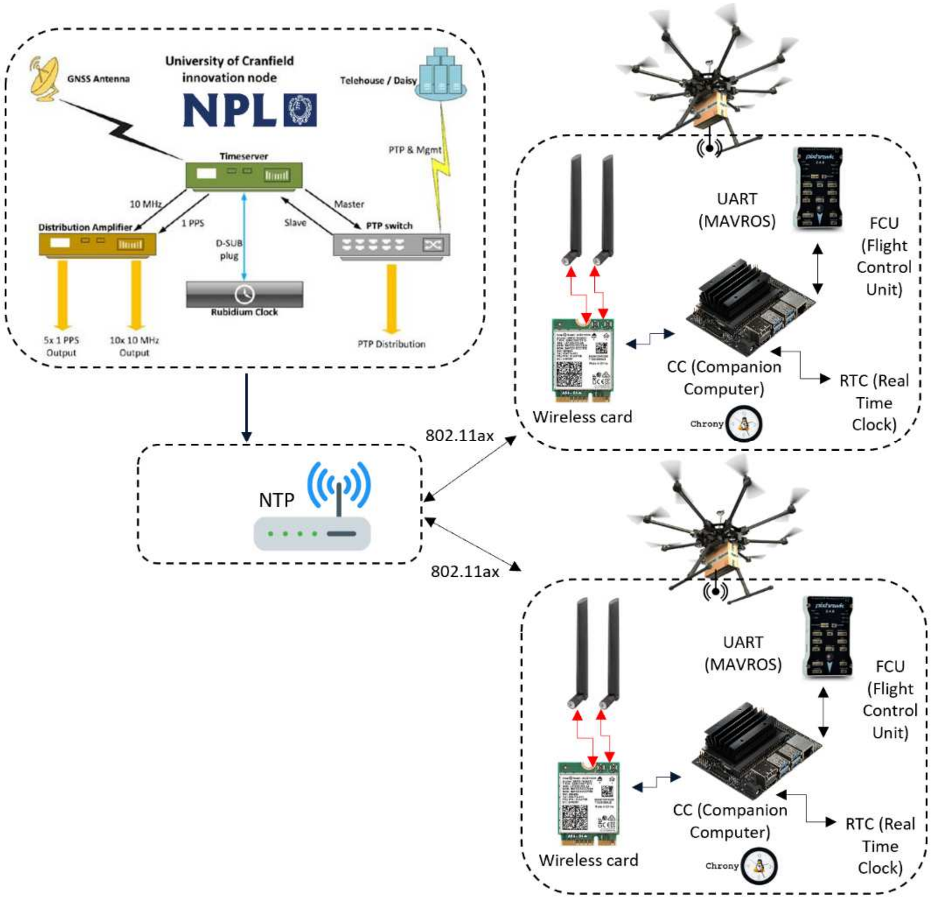

Figure 3 HIL System architecture

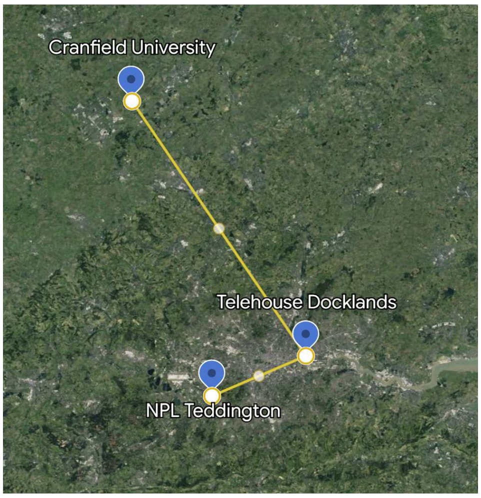

Figure 4 PTP link to Cranfield University

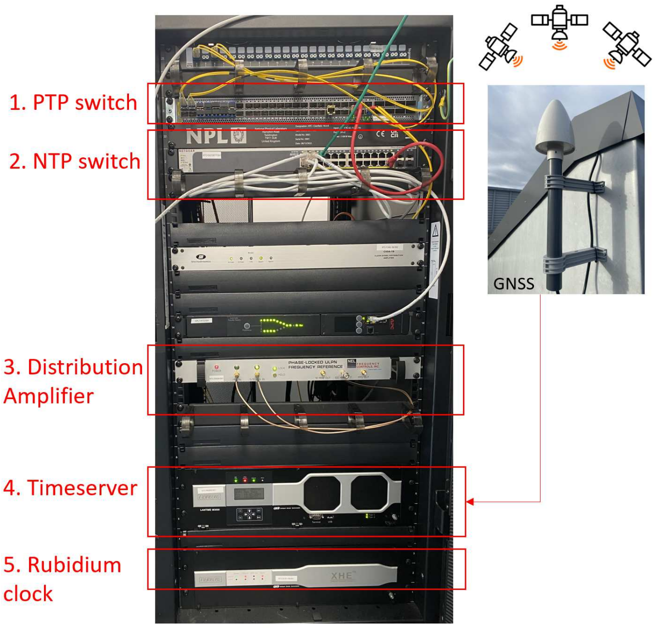

Figure 5 Research and Innovation timing node at Cranfield University

Three possible bits can be selected from FCU settings, each representing a time source option, as follows: Bit 0 (GPS), Bit 1 (MAVLINK_SYTEMS_TIME), and Bit 2 (HW). Bit 0 allows to synchronize of the FCU to time signals from the on-board GNSS receiver, Bit 1 uses the onboard oscillator as a time source, and Bit 2 uses the CC's time. Thus, by selecting the second bit, the Pixhawk board can synchronize its time, to the CC, which is synchronized to the UTC via the Research and Innovation timing Node.

In this paper, the TELEM 2 port is used to link the CC to the FCU with an equivalent baud rate of 115000 bits/s. Further, each CC is equipped with a RTC module.

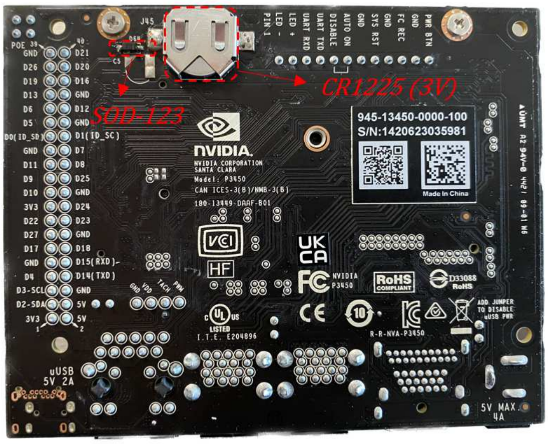

Figure 6 RTC module installation

The embedded RTC configuration for the Jetson Nano is formed by a CR1225 3V battery, its equivalent holder, and additionally a SOD-123 Schottky diode as can be seen from Figure 6.

VI. EXPERIMENTAL RESULTS

To evaluate the HIL framework, presented in the previous section, the experiment was conducted over a period of almost 5 hours, in order to be able to observe and evaluate the synchronization accuracy between the Research and Innovation timing node and the two Jetson Nano boards, and their equivalent FCU while Chrony is used to extract all the presented data.

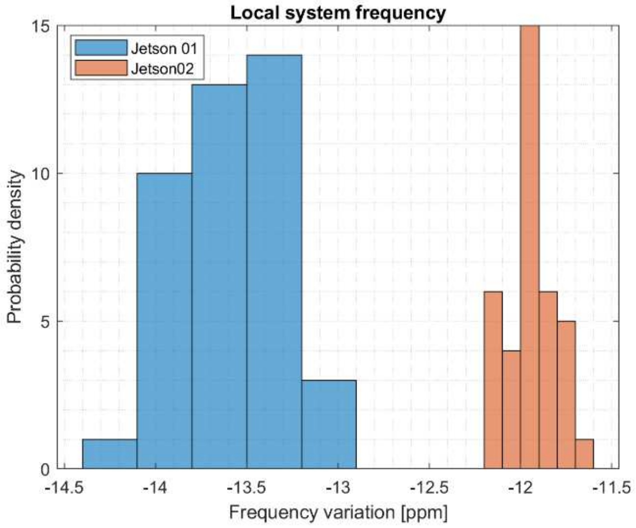

Figure 7 Local system frequency variation for the two Jetson Nano boards

From Figure 7, it can be observed the negative frequency variation of the CC, denoting that the CC's local system is running slower than the Research and Innovation timing node. The first Jetson Nano has an equivalent frequency of almost -13.5 ppm, and the second board has an equivalent system frequency of almost -12 ppm. Considering, that the Jetson Nano board has a frequency tolerance between -20 ppm and +20 ppm, it can be observed that the XO is easily susceptible to external factors, even if both CCs are equipped with a cooling system, represented by an attached cooling fan, on the unit board. From Figure 8 it can be observed the time offset variation in time of both CCs, relative to the Research and Innovation timing node, changing between positive and negative values with an average of -0.2 ms. Positive values denote that the CC system clock is ahead of the Research and Innovation timing node, while negative values denote that the time is behind the Research an Innovation timing node.

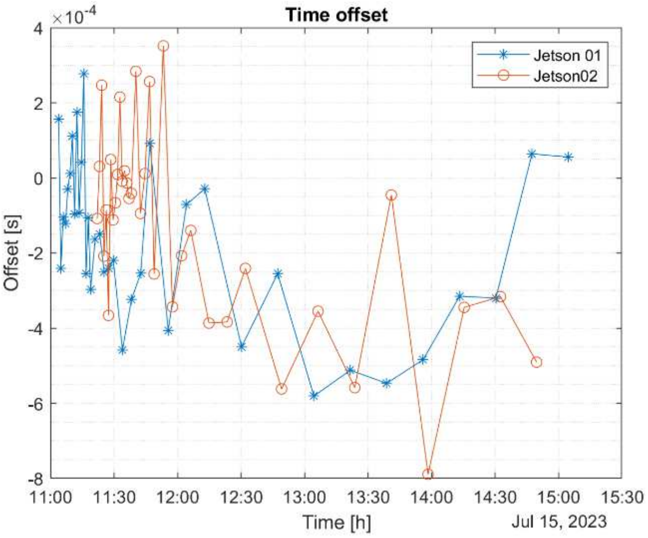

Figure 8 Time offset between each CC and the Research an Innovation timing node

In terms of latency, the RTT (Round Trip Delay) of both CCs, it can be observed in Figure 9, changing between 3 ms and 4.8 ms, with 5 ms peaks.

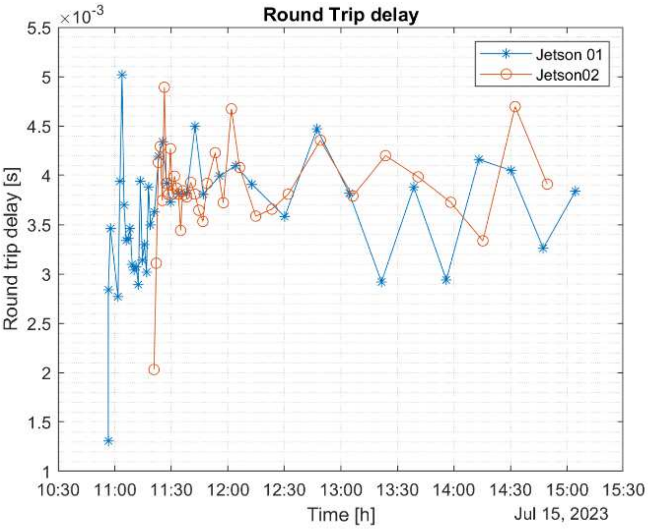

Figure 9 RTT between each CC and the Research an Innovation timing node

Thus, from Figure 8 and 9 it can be observed that even with 2 CCs, similar performances are obtained, without affecting the overall performance.

Instead, as can be seen from the histogram in Figure 10, the main communication latency achieved between the CC and FCU has an average of 2 ms delay, while the RTT is around 4.1 ms.

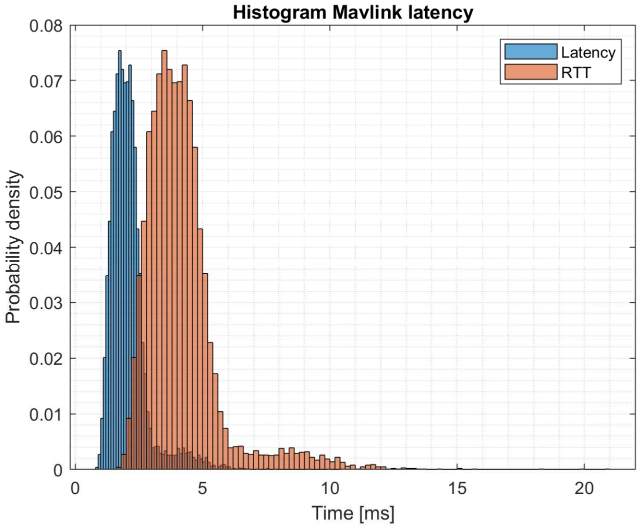

Figure 10 Histogram of the MAVLINK protocol latency and RTT

Thus, considering the total signal dispersions over the air, between the time server and the two Jetson Nano clients, and the RTT between the CC and the FCU, an equivalent RTT of 8 ms is achieved. Considering the latency requirements, for the non-payload communication, defined in section III, the HIL time dissemination framework, presented in the paper, obtained a lower latency. Considering that the UP and the DL for the detect and collision avoidance is around 150 ms, the performance obtained by both CCs is around 8 ms.

VII. CONCLUSION AND FUTURE WORK

A time dissemination framework in a HIL configuration is presented using as time source the Research and Innovation Timing Node at Cranfield University, as an alternative time source to GNSS, for autonomous systems. With the HIL, this works presents the performances achieved with 2 Jetson Nanos introduced into the local network. Time is disseminated using a local Wi-Fi 6 router, and synchronized using NTP, achieving an average RTT of 3.6 ms for the first Jetson Nano and 3.9 ms for the second CC. A Pixhawk 2.4 is used as FCU, representing the end-user in the framework, achieving an average RTT of 8 ms. On both CCs, an average time offset equivalent to -0.2 ms, relative to the Research and Innovation Timing node, is achieved, denoting that the system clock on both CCs is slightly behind to the Research and Innovation Timing node. In conclusion, the indoor HIL configuration is fulfilling the requirements, presented in Section III.

In future work, the Research and Innovation Timing node will be used to disseminate time in an outdoor environment, with dynamic UAVs at Cranfield University, to evaluate further the performances of the framework.

ACKNOWLEDGMENTS

The work is supported by Innovate UK funding, project number 10038140.

REFERENCES

[1] S. Liu *et al.*, ‘The Matter of Time -- A General and Efficient System for Precise Sensor Synchronization in Robotic Computing’, Mar. 2021, [Online]. Available: http://arxiv.org/abs/2103.16045

[2] S. M. Albrektsen and T. A. Johansen, ‘User-configurable timing and navigation for UAVs’, *Sensors (Switzerland)*, vol. 18, no. 8, Aug. 2018, doi: 10.3390/s18082468.

[3] N. Zhu, J. Marais, D. Betaille, and M. Berbineau, ‘GNSS Position Integrity in Urban Environments: A Review of Literature’, *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 9, pp. 2762–2778, Sep. 2018, doi: 10.1109/TITS.2017.2766768.

[4] M. S. Grewal, L. R. (Lawrence R. Weill, and A. P. Andrews, *Global positioning systems, inertial navigation, and integration*. John Wiley, 2001.

[5] A. Rügamer, ‘Jamming and Spoofing of GNSS Signals- An Underestimated Risk?!’

[6] D. Kirchner, ‘Two-way Time Transfer Via Communication Satellites’.

[7] M. A. Lombardi, ‘How Accurate is a Radio-Controlled Clock?’

[8] N. Mahdoui, V. Frémont, and E. Natalizio, ‘Communicating Multi-UAV System for cooperative SLAM-based Exploration’.

[9] J. E. Gilligan, E. M. Konitzer, E. Siman-Tov, J. W. Zobel, and E. J. Adles, ‘White Rabbit Time and Frequency Transfer over Wireless Millimeter-Wave Carriers’, *IEEE Trans Ultrason Ferroelectr Freq Control*, vol. 67, no. 9, pp. 1946–1952, Sep. 2020, doi: 10.1109/TUFFC.2020.2989667.

[10] D. Calero and E. Fernandez, ‘Characterization of Chip-Scale Atomic Clock for GNSS navigation solutions’, in *2015 International Association of Institutes of Navigation World Congress, IAIN 2015 - Proceedings*, Institute of Electrical and Electronics Engineers Inc., Dec. 2015. doi: 10.1109/IAIN.2015.7352264.

[11] F. Tirado-Andrés and A. Araujo, ‘Performance of clock sources and their influence on time synchronization in wireless sensor networks’, *Int J Distrib Sens Netw*, vol. 15, no. 9, Sep. 2019, doi: 10.1177/1550147719879372.

[12] I. Petrunin and G. Tang, ‘Sensors for aerial, automotive, and robotic applications’, *Advanced Sensor Technology: Biomedical, Environmental, and Construction Applications*, pp. 825–852, Jan. 2023, doi: 10.1016/B978-0-323-90222-9.00022-4.

[13] ‘Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace’, 2009. [Online]. Available: http://www.itu.int/ITU-R/go/patents/en

[14] R. Singh, K. D. Ballal, M. S. Berger, and L. Dittmann, ‘Overview of Drone Communication Requirements in 5G’, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Springer Science and Business Media Deutschland GmbH, 2022, pp. 3–16. doi: 10.1007/978-3-031-20936-9_1.

2023-11-10

Design and hardware-in-the-loop evaluation of a time dissemination framework for drone operations in urban environme

Negru, Sorin Andrei

IEEE

Negru SA, Petrunin I, Guo W, Tsourdos A. (2023) Design and hardware-in-the-loop evaluation of a time dissemination framework for drone operations in urban environments. 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), 1-5 October 2023, Barcelona, Spain

https://doi.org/10.1109/DASC58513.2023.10311277