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Resilient Time Dissemination Fusion Framework for UAVs for Smart Cities †

Sorin Andrei Negru [1,*], Triyan Pal Arora [1], Ivan Petrunin [1], Weisi Guo [1], Antonios Tsourdos [1], David Sweet [2] and George Dunlop [3]

[1] School of Aerospace, Transport, and Manufacturing, Cranfield University, Bedfordshire MK43 0AL, UK; triyanpal.arora@cranfield.ac.uk (T.P.A.); i.petrunin@cranfield.ac.uk (I.P.); weisi.guo@cranfield.ac.uk (W.G.); a.tsourdos@cranfield.ac.uk (A.T.)
[2] iQuila Ltd., Unit 5, Excelsior Business Park, Cardiff CF14 3AY, UK; david.sweet@iquila.com
[3] Quantum Dice, Oxford Centre for Innovation, New Rd, Oxford OX1 1BY, UK; george.dunlop@quantum-dice.com
* Correspondence: s.negru.965@cranfield.ac.uk
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Abstract: Future smart cities will consist of a heterogeneous environment, including UGVs (Unmanned Ground Vehicles) and UAVs (Unmanned Aerial Vehicles), used for different applications such as last mile delivery. Considering the vulnerabilities of GNSS (Global Navigation System Satellite) in urban environments, a resilient PNT (Position, Navigation, Timing) solution is needed. A key research question within the PNT community is the capability to deliver a robust and resilient time solution to multiple devices simultaneously. The paper is proposing an innovative time dissemination framework, based on IQuila's SDN (Software Defined Network) and quantum random key encryption from Quantum Dice to multiple users. The time signal is disseminated using a wireless IEEE 802.11ax, through a wireless AP (Access point) which is received by each user, where a KF (Kalman Filter) is used to enhance the timing resilience of each client into the framework. Each user is equipped with a Jetson Nano board as CC (Companion Computer), a GNSS receiver, an IEEE 802.11ax wireless card, an embedded RTC (Real Time clock) system, and a Pixhawk 2.1 as FCU (Flight Control Unit). The paper is presenting the performance of the fusion framework using the MUEAVI (Multi-user Environment for Autonomous Vehicle Innovation) Cranfield's University facility. Results showed that an alternative timing source can securely be delivered fulfilling last mile delivery requirements for aerial platforms achieving sub millisecond offset.

Keywords: Kalman Filter; time dissemination; time fusion; software-defined-network; quantum encryption; smart cities

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1. Introduction

The emergence of smart cities brings new challenges towards the integration of UAVs in urban environments, where traditional GNSS COTS (Commercial-Off-The-Shelf) receivers, due to urban shadows and adversarial attacks, makes PNT data unreliable, increasing the chance of collisions. Nowadays with the constant increase of radiofrequency interferences especially within the Baltic and in the Black see regions, as reported in [1], all maritime, ground, and aerial GNSS users are severely affected. Considering that GNSS receivers are used as one of the main sources which provides time and position data, to manned and unmanned aviation, alternative PNT sources are required. Time data is critical

to ensure that autonomous vehicles operate safely, especially when in cohabitation with human-operated systems. Small errors in time can lead to a corresponding miscalculation in space between fast-moving vehicles. Accurate timing distribution is critical for autonomous transport, where stable control, collision avoidance, and safety-critical management are all time-sensitive in different ways.

To enhance the time dissemination within each user, a fusion framework is required, as presented in [2,3] where a clock ensemble KF algorithm is used to track the clock errors by using different time sources relative to one reference clock. Each user requires more time sources to enhance the ability to cope with external threats which may degrade the time accuracy of the system time as specified in [4]. Although it is possible to use an ensemble of identical clocks as presented in [5], a combination of different clocks can provide better performance and resilience [6].

Another approach to improve the local system time stability and accuracy is presented in [7], where a deep coupled integration is implemented using a CSAC (Chip Scale Atomic Clock) and a COTS GNSS receiver. CSAC are characterized of a better long term-stability, against other oscillators equipped on most of GNSS COTS receivers, which can improve the PNT solution. As result, less satellites are needed to compute the receiver position [8]. Although, a CSAC can provided superior performances against local XO (Crystal Oscillators), the relatively high cost does not allow the scalability of such solution to multiple devices on a large-scale scenario.

Hence, the secure deployment of UAVs in smart cities requires alternative PNT sources, and an adequate fusion framework capable to cope with potential time disruptions, thereby preventing any possible conflict with other manned and unmanned systems. To disseminate alternative time data to multiple users, United Kingdom's NPL (National Physical Laboratory), with the NTC (National Timing Center) program, aims to deliver precise time data to multiple users, through four time innovation nodes in the UK. Cranfield University is one of the hosts of the timing nodes, and joint academic partner in the NTC program, contributing to the building of RETSI (Resilient Enhanced Time Scale Infrastructure).

To address the need of an adequate time fusion framework the authors extended the work presented previously in [9] by combining time data from a GPS receiver and the Research and Innovation timing node, in an outdoor environment, using a KF algorithm, to predict the time offset and skew of the system time. Time data is disseminated using the IEEE 802.11ax protocol and iQuila's SDN coupled with Quantum Dice QRNG (Quantum Random Number Generator) keys.

The rest of the paper is divided as follows: in Section 2 the sensor fusion time requirements for autonomous systems are defined, in Section 3 the proposed fusion framework is described, in Section 4 the system configuration framework, in Section 5 the results are presented and in Section 6 the conclusions.

2. Time Synchronization Requirements

Considering that each vehicle does have very specific dynamics, and each user is equipped with sensors with different noises and timestamping accuracies, it is important to outline the impact of time synchronization in sensor fusion frameworks. Sensor synchronization can be classified as intra-machine synchronization, which consist of the synchronization of all the sensors within a specific user, and inter-machine synchronization which consist in the synchronization of all the sensors of all the users within a common network, as specified in [10]. This factor can significantly influence the safety of shared airspace, between manned and unmanned aerial vehicles. Aerial vehicles such as UAVs and aircraft are characterized by fast dynamics, and the main factor, which is limiting the accuracy of sensor fusion frameworks, is dictated by the synchronization precision and

the used sensors accuracy as presented in [11]. From Table 1 it is possible to observe the minimum synchronization error, which is required by three platforms, a car, a multi rotor and fixed wing UAV, each characterized by a specific dynamic, and all users which will be encountered in urban environments. Time synchronization is critical also for ground infrastructures which can be used to track UAVs in urban dense environments. In [12] the authors analyzed the impact of the time synchronization on tracking a UAV within a predefined airspace showing a consistent degradation in performance when the synchronization error exceeded 100 ms. Hence, urban environments require stringent time synchronization requirements to avoid any air collision.

Table 1. Minimum synchronization error requirements for different platforms [11].

Sensor Category	Sensor Model	Platform Type		
		Car	**Multi Rotor**	**Fixed Wing**
GNSS	Ublox F9P PVT	86 ms	520 ms	123 ms
	Ublox F9P RTK	0.577 ms	3 ms	0.824 ms
IMU	SBG Ellipse	4 ms	0.663 ms	2 ms
	Kongsberg MRU5	0.067 ms	0.009 ms	0.038 ms
Lidar	Velodyne Apha Prime	5 ms	2 ms	3 ms

3. Fusion Framework

Most UAVs are equipped with low-cost XOs which are responsible to keep the system time as accurate as possible. Unfortunately, external weather conditions, and crystal aging factors, are deteriorating substantially the accuracy of the system time or 'kernel time' as presented previously in [9]. Considering, that most of the XOs have a frequency tolerance of ±20 ppm (Parts Per Million) at 25 °C, as it can be seen from Equation (1), the kernel clock will drift 100 ms in approximately 83 min, considering a constant frequency accuracy of 20 ppm.

$$\Delta_{20\text{ppm}}^{25\ ^\circ\text{C}} = \frac{\gamma^{100\text{ ms}}}{|\varepsilon_{20\text{ ppm}}|} \cdot \frac{1}{60} = \frac{0.1}{|20 \cdot 10^{-6}|} \cdot \frac{1}{60} = 83.33\text{ min} \tag{1}$$

To adjust the kernel clock time drift over long periods of time when the board is not powered, the authors implement a RTC (Real Time Clock) mechanism or 'hardware clock'. In addition, to enhance the system time accuracy without getting any corrections over internet with synchronization protocols, such as NTP (Network Time Protocol) or IEEE 1588 PTP (Precision Time Protocol) a time fusion protocol is presented and implemented. To cope with the kernel time instabilities the authors proposed a linear KF, which is fusing time offset and skew from a GPS receiver and SDN, estimating the system time offset, as it can be observed from Figure 1. The fusion algorithm starts once the board is powered, and RTC corrections are applied, as presented in Figure 1 at step 1 and 2. The XO can be described by a two-state equation as follows [13]:

$$\begin{cases} \theta[t] = \theta[t-1] + \alpha[t-1]\Delta t + \omega_\theta[t-1] \\ \alpha[t] = \alpha[t-1] + \omega_\alpha[t-1] \end{cases} \tag{2}$$

where θ is the time offset between the kernel time and the reference clock, while α is defined as skew, which can be described as the difference between the frequency of the kernel time and the reference clock. Instead ω_θ and ω_α are defined as white Gaussian random noise processes, and Δt as the time interval between each reference time data. To gather data from GPS, the gpsd (8) library is used to extract the GPS time offset while GPS skew is calculated

considering the timestamps T_t of each offset value, as described in Equation (3). Instead SDN time offset and skew, which are disseminated using the IEEE 802.11ax protocol and an AP, are gathered and decrypted using iQuila's VEN (Virtual Extended Network) client as illustrated in Figure 1 at step 3 and 4.

$$\alpha[t] = \frac{\theta[t] - \theta[t-1]}{T_t - T_{t-1}} \tag{3}$$

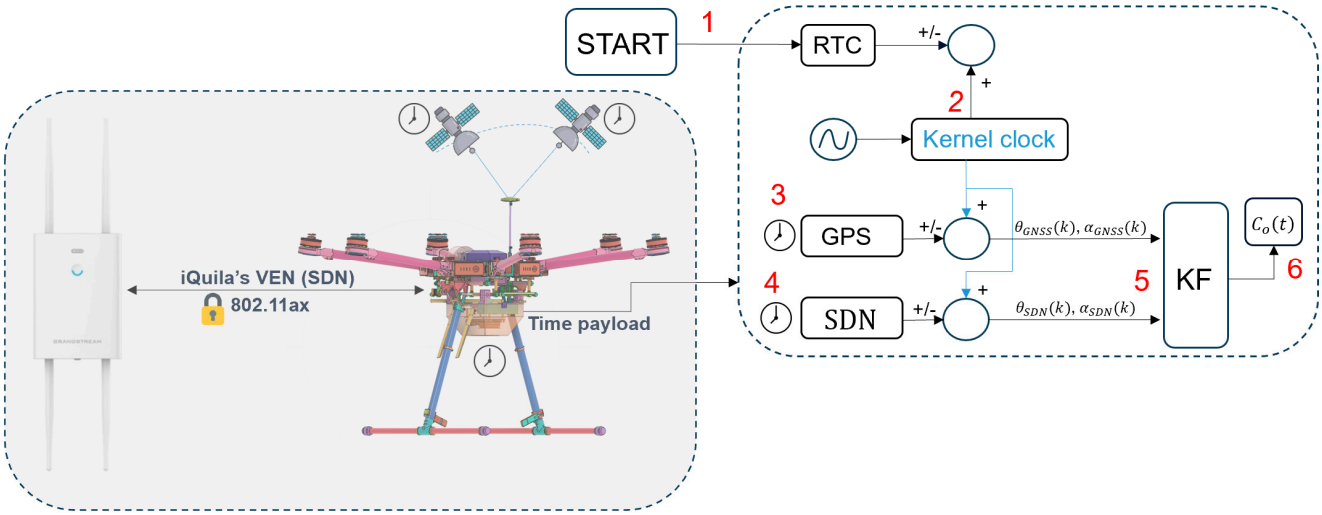


Figure 1. Time fusion framework using GNSS and iQuila's VEN time data as alternative time source. 1—Start the local embedded board; 2—Kernel clock adjusted with the RTC mechanism; 3—GPS time source; 4—SDN time source; 5—KF input data; 6—KF output.

To filter the time data gathered from both sources, a KF is defined by the prediction step as defined in Equations (4) and (5) [14].

$$\hat{x}_{k|k-1} = A_k \hat{x}_{k-1|k-1} + B_k u_k, \begin{cases} \hat{x} = [\theta\ \alpha]^T, u_k = [\theta\ \alpha]^T \\ \hat{x} = [\theta_{GNSS}\ \theta_{SDN}\ \alpha_{GNSS}\ \alpha_{SDN}]^T \\ u_k = [\theta_{GNSS}\ \theta_{SDN}\ \alpha_{GNSS}\ \alpha_{SDN}]^T \end{cases}$$
$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}, B = \begin{bmatrix} -1 & -\Delta t \\ 0 & -1 \end{bmatrix} \tag{4}$$

$$P_{k|k-1} = A_k P_{k-1|k-1} A_k^T + Q_k$$
$$Q_k = \begin{bmatrix} \sigma_\theta^2 & 0 \\ 0 & \sigma_\alpha^2 \end{bmatrix} \tag{5}$$

where σ_θ^2 and σ_α^2 are the variances of the offset and skew of each time source. Instead, the correction step is defined by the following equations:

$$\tilde{y}_k = z_k - H_k \hat{x}_{k|k-1}$$
$$H_k = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{6}$$

$$S_k = H_k P_{k|k-1} H_k^T + R_k \tag{7}$$

$$K_k = P_{k|k-1} H_{k+1}^T S_k^{-1} \tag{8}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k \tag{9}$$

$$P_{k|k} = (I - K_k H_k)\, P_{k|k-1} \tag{10}$$

where $\widetilde{y}_k$ is the innovation residual, z_k the measurement vector, $\hat{x}_{k|k-1}$ the predicted state vector, S_k the innovation covariance, while K_k is the Kalman gain along the $\hat{x}_{k|k}$ and $P_{k|k}$ being respectively the corrected state estimate and corrected estimate covariance. The measurement noise covariance matrix R_k is defined in Equation (11) [15] where σ_t^2 and $\sigma_{C(t)}^2$ are timestamping uncertainty variances of the master and respectively of the slave, while σ_d^2 the variance of the propagation delay asymmetry, and σ_θ^2 and respectively σ_α^2 the variance of the offset and skew.

$$R_k = \begin{bmatrix} \sigma_\theta^2 & \frac{\sigma_\theta^2}{\Delta t} \\ \frac{\sigma_\theta^2}{\Delta t} & 2\left(\frac{\sigma_\theta}{\Delta t}\right)^2 \end{bmatrix}, \begin{cases} \sigma_\theta^2 = \frac{1}{2}\left(\sigma_{C(t)}^2 + \sigma_t^2 + \sigma_d^2\right) \\ \sigma_\alpha^2 = 2\left(\frac{\sigma_\theta}{\Delta t}\right)^2 \end{cases} \tag{11}$$

4. System Configuration

To test the KF algorithm, two static users and one dynamic, are deployed. Each user is formed by a Jetson Nano (NVIDIA Corporation, Santa Clara, CA, USA) as CC, an Intel AX200 IEEE 802.11ax (Intel Corporation, Santa Clara, CA, USA) wireless card, a VK-162 GPS receiver (Shenzhen FlyFun Technology, Shenzhen, China), and a Pixhawk 2.1 (Cubepilot, Breakwater, Australia) as FCU. The role of the CC is to gather and fuse all the time data from the GPS, and the IEEE 802.11ax receiver and to run the iQuila's VEN client which is responsible to extract and decrypt time data from the Research and Innovation timing node. In addition, time data is disseminated to each FCU as presented previously in [9]. Time data from the Research and Innovation timing node is disseminated to all the users within the same network through a fiber link, and two Grandstream GWN7664LR (Grandstream Networks, Boston, MA, USA) APs (Access Points) which are covering each a range of approximately 180 m using the MUEAVI Cranfield's University facility as it can be seen from Figure 2.

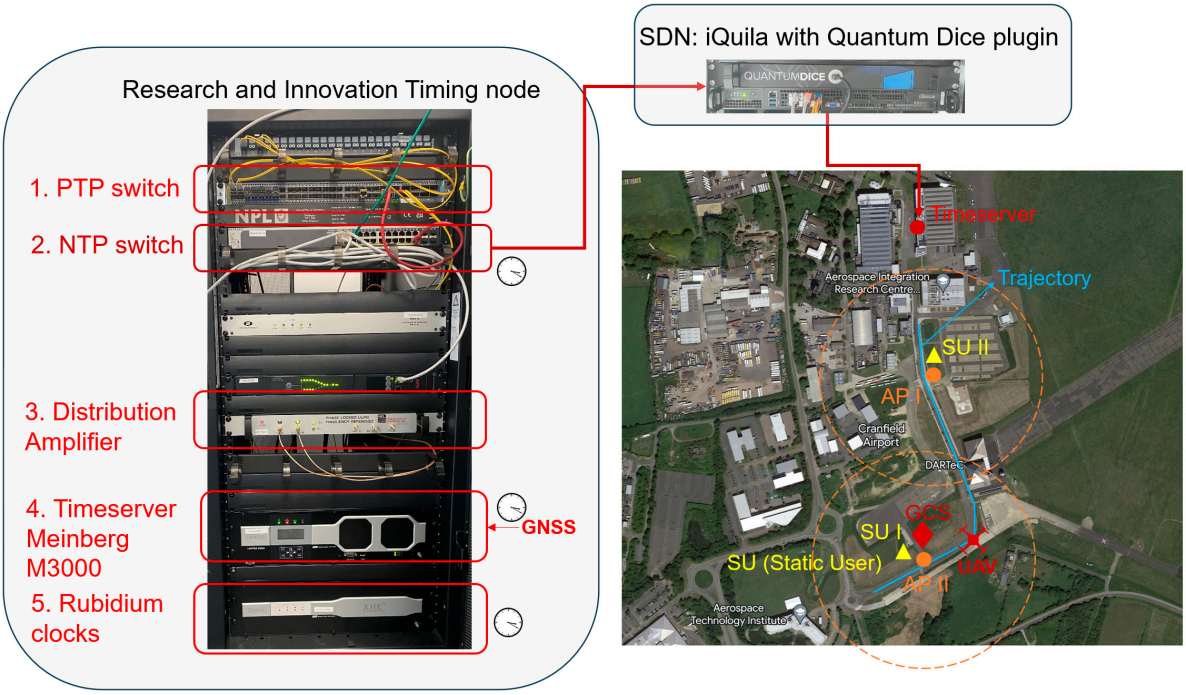


Figure 2. Practical system configuration in an outdoor environment.

Each AP can connect simultaneously up to 750 users, and the range can be extended within the same network up to 50 AP, according to the manufacturer datasheet. Each AP is

configured to operate only within the IEEE 802.11ax 5 GHz band, to avoid any possible interference of the command-and-control link which is responsible for the control and stability of the UAV, which operates in the 2.4 GHz band. Furthermore, a GCS (Ground Control Station) is used to monitor the connectivity and the performance of all the users within the same network. As it can be seen from Figure 2, AP I and AP II, represents the location of the two access points, SU and SU II the static users location, while the UAV is identified as the dynamic user.

5. Results

As described in the previous section, three users were used during the outdoor tests, one dynamic and two static users. To the evaluate the latency performance of the IEEE 802.11ax link, between the AP and the connected users, against the results presented previously in [9], similar performances were obtained, in an outdoor environment, along the IMEC road, with an average RTT (Round Trip Delay) of 4 ms for both cases.

Considering the system configuration presented in Section 4, in Figure 3 it can be observed, the offset and skew performances achieved over time, considering all three users. It can be observed that although GNSS offset values against the system time are better, in comparison to SDN data, GNSS values are characterized by a higher skew, representing a more unstable time source. Instead, the SDN source, because of the air link, is characterized of a higher offset, and a lower skew. The SDN skew, in this case does have better performance, because of the Research and Innovation timing node, which is traceable to UTC (Coordinated Universal Time). Furthermore, it can be observed based on the SDN offset and skew performance, that the dynamic user, is affected by the change in dynamics over time. This is due the change in direction of the dynamic user antenna, which is mounted on a UAV, towards the used AP, during the tests.

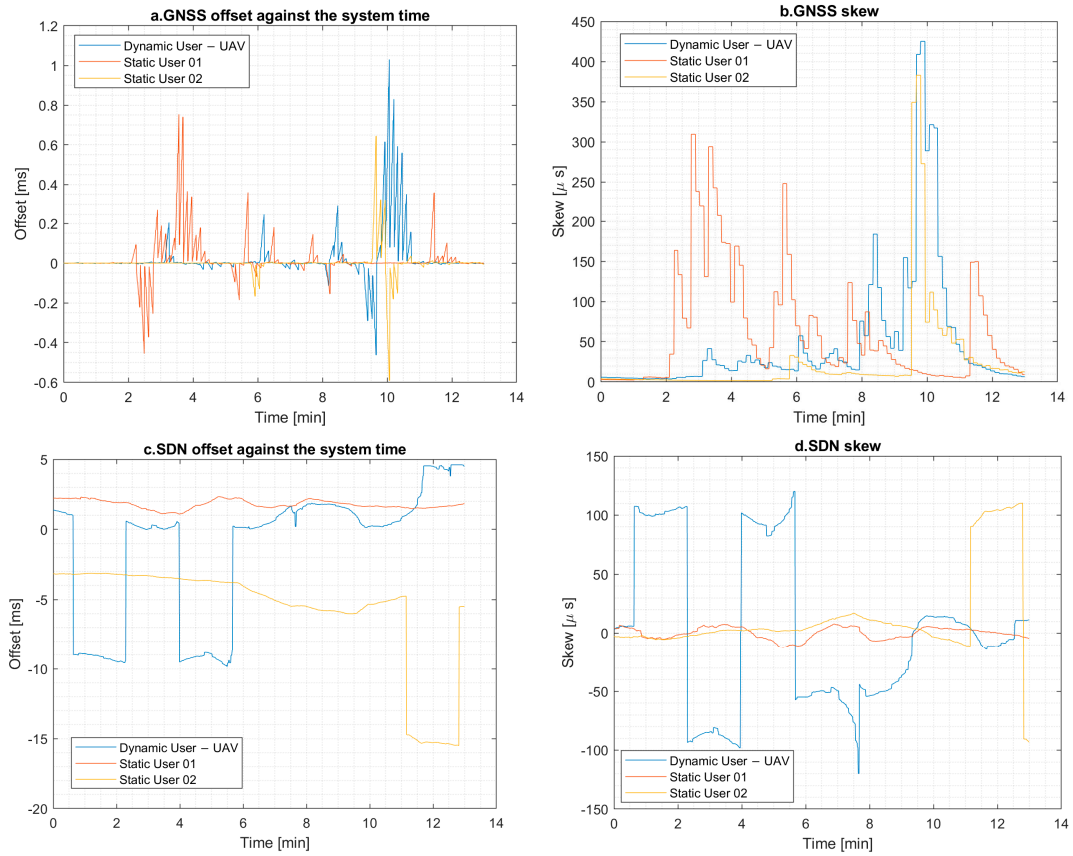


Figure 3. GNSS and SDN performance for two static and dynamic users within the same network.

In terms of KF offset performance, it can be observed from Figure 4, that similar performances are obtained for the static user 01 and the dynamic user, which was mounted on a UAV, while better performances are achieved for the second static user. This factor can be observed also from Figure 3d, where the second user is characterized by a more stable skew in time. In addition, the second user is characterized by negative SDN offset, against the system time, meaning that the time received through the wireless link is behind the local system time. Hence, the stability and accuracy of the used time sources by the KF algorithm have a direct impact, on the estimated offset performance.

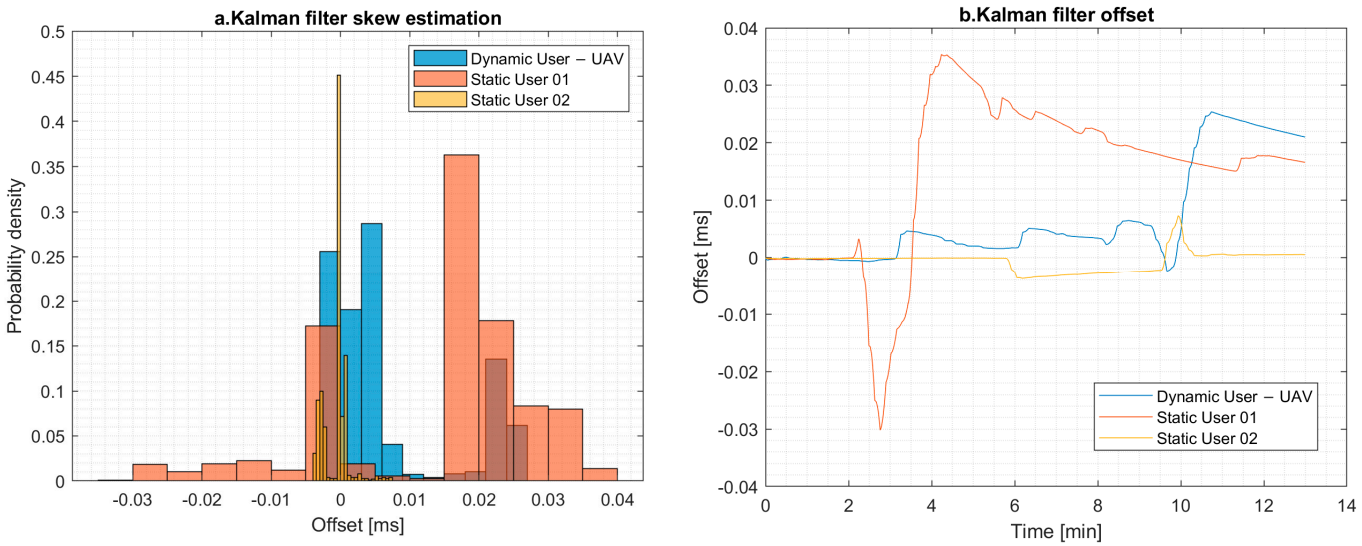


Figure 4. Kalman Filter offset estimation for two static users and one dynamic user.

6. Conclusions

The paper is investigating the performances of a time dissemination framework to different users with different dynamics, in an outdoor environment, enhanced by the implementation of a KF algorithm, which is fusing time data from a GPS receiver and the Research and Innovation Timing node, which is securely disseminated using iQuila's VEN client and Quantum Dice QRNG key, over an IEEE 802.11ax wireless link, through two AP. From the results presented in the previous sections, it can be observed that the KF is improving the time offset, being able to achieve an offset in terms of sub millisecond accuracy, meeting the time requirements from Section 2, considering a multi-rotor platform as reference.

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