Demonstration of a decimeter-level accurate hybrid optical-wireless terrestrial positioning system

Diouf, Cherif; Dun, Han; Kazaz, Tarik; Janssen, Gerard; Tiberius, Christiaan

DOI
10.33012/2020.17528

Publication date
2020

Document Version
Accepted author manuscript

Published in
Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)

Citation (APA)
Diouf, C., Dun, H., Kazaz, T., Janssen, G., & Tiberius, C. (2020). Demonstration of a decimeter-level accurate hybrid optical-wireless terrestrial positioning system. In *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020)* (pp. 2220-2228). (Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+ 2020). Institute of Navigation. https://doi.org/10.33012/2020.17528

Demonstration of a decimeter-level accurate hybrid optical-wireless terrestrial positioning system

Cherif Diouf[1], Han Dun[1], Tarik Kazaz[2], Gerard Janssen[2], Christian Tiberius[1]

[1]*Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands*
[2]*Circuits and Systems, Delft University of Technology, Delft, The Netherlands*

BIOGRAPHIES

Cherif Diouf received a PhD degree in system modeling of electronic circuits from the Université de Bretagne Occidentale (France) in 2014. He later carried out research on optical communication and seabed power-over-fiber systems. More recently, he was an embedded systems engineer on deep-sea autonomous floats at the French oceanographic institute. He is currently working in the department of Geoscience and Remote Sensing, Delft University of Technology on the development of an accurate optical-wireless terrestrial positioning system demonstrator.

Han Dun received his BSc degree in Communication Engineering and MSc degree in Communication and Information Engineering from Shanghai University, China, in 2013 and 2016, respectively. From 2013 to 2016, he also worked at the key laboratory of specialty fiber optics and optical access network in Shanghai University, where he contributed to the real-time optical OFDM-PON. He is currently pursuing his PhD degree in the department of Geoscience and Remote Sensing, Delft University of Technology, the Netherlands. His research interests include wireless localization, and statistical signal processing.

Gerard J.M. Janssen received an M.Sc. E.E. degree from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1986 and a Ph.D.degree from Delft University of Technology, Delft, The Netherlands, in 1998. He is currently an Associate Professor with the Circuits and Systems Group, Delft University of Technology. His research interests include wireless communication, particularly narrowband multiuser detection, digital modulation techniques, channel modeling, diversity techniques, and ultra wideband communications and positioning.

Tarik Kazaz received his M.Sc. degree in Electrical Engineering, Department for Telecommunications, from the University of Sarajevo, in 2012, cum laude. In 2013 he joined BH Mobile, where he was a Radio Access Network Engineer, while at the same time he was a part time teaching assistant at the Faculty of Electrical Engineering, University of Sarajevo. In 2015, he joined Ghent University, Department of Information Technology, as a PhD researcher. Currently, he is pursuing his PhD research within the Circuits and Systems research group at Delft University of Technology (TU Delft). He was active in several national and international research projects including EU H2020 ORCA, WiSHFUL, iMinds' IoT Strategic Research Program and NWO SuperGPS. His main research interests are wireless networks, signal processing for communications, software defined radio and cognitive radio, hardware-software co-design.

Christian C.J.M. Tiberius received his PhD degree in 1998 from the Delft University of Technology, Delft, The Netherlands, on recursive data processing for kinematic GPS surveying. He is currently an Associate Professor with the Geoscience and Remote Sensing (GRS) department, Delft University of Technology. His research interest lies in navigation, with GNSS and high-accuracy terrestrial radio positioning.

ABSTRACT

Global Navigation Satellite Systems (GNSS) are nowadays the most common solutions used to cope with Positioning-Navigation-Timing (PNT) applications demands. GNSS are relied on in very diverse contexts and domains, yet the interest in systems such as GPS, GALILEO and Beidou is continuously increasing. However, and in particular for safety critical applications, GNSS are very vulnerable to unintentional interference and to intentional attacks such as spoofing or jamming. GNSS also provide degraded accuracy in dense multipath environments such as in urban canyons. Thus, solutions that could augment, back-up, complement, or surrogate GNSS, are actively sought after. In this paper, we introduce the concept of a hybrid optical wireless positioning system and present the initial experimental positioning results. The system uses optically distributed time and frequency reference signals

for synchronization, and wideband radio signals for ranging. Initial results show that decimeter-level accuracy is obtained in urban-like surroundings.

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have enabled a widespread use of location based services. From transportation applications, military use to precision agriculture, GNSS have nowadays such a significance that they have become a vital technology. While GNSS provide valuable positioning information for a wide range of applications, they also have limitations and vulnerabilities. For instance, due to the low received power level on Earth, GNSS signals can be easily spoofed [1] or disrupted, disabling any reliable positioning or navigation service. Moreover, in dense urban environments, positioning accuracy is very much degraded due to reception of reflected signal components (multipath) by surrounding objects and buildings. Alternative solutions are actively sought after to compensate these GNSS limitations.

Solutions may vary from GNSS augmented systems relying on 3D mapping [2], LiDAR [3], radar, computer vision, wireless networks, to completely independent replacements such as terrestrial positioning systems [4], [5]. In this paper, we present initial positioning results of a resilient optical-wireless terrestrial positioning system which is able to back-up or complement GNSS and provides positioning, navigation and timing services. Synchronization being a key issue, a time and frequency reference provided by a UTC-disciplined atomic master clock is shared through an optical infrastructure or telecommunication network. In this topology, timing devices are essential in keeping a 100 ps-level synchronization accuracy between the nodes of the optical infrastructure.

The positioning system particularly targets multipath-rich environments such as urban and built-up environments, where classic positioning systems, such as GNSS, provide poor accuracy. To that aim wideband radio ranging signals are used to facilitate discrimination between the Line-of-Sight (LOS) component and reflections in a multipath channel. Hence, these higher bandwidth signals allow for a better time resolution and ranging accuracy. The current contribution will present the first experimental demonstration and the validation results of such a terrestrial positioning system concept.

The rest of the paper is organized as follows. In section II, we first introduce the full system architecture. Clock generation and time and frequency transfer are detailed. Wideband radio signal transmission and formats are discussed in section III. The so-called pseudolites (radio transmitting devices), Software Defined Radio (SDR) based, are introduced, and the data acquisition scheme for the purpose of the demonstration is discussed. In section III, the outdoor test site, the test configurations and conditions, are introduced. The experimental results, which show a decimeter level accuracy obtained in 2D positioning, are presented in section IV. Finally, in section V, we will conclude the paper and open the scope towards future works.

II. SYSTEM ARCHITECTURE

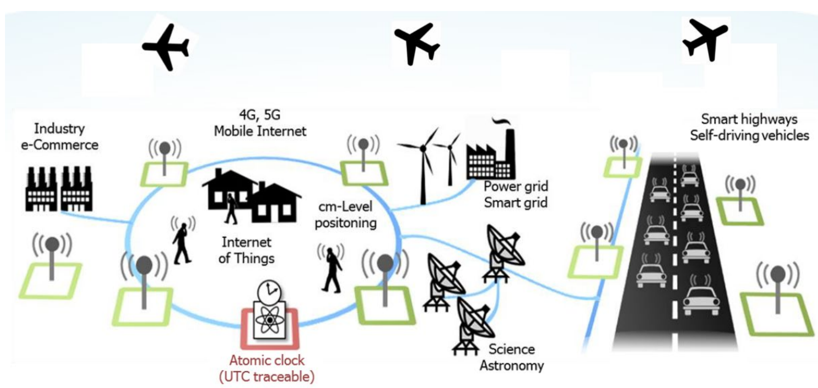

Figure 1: The hybrid optical-wireless positioning system. In red, an atomic clock is connected to an optical telecommunication network (blue). Time and frequency references are transferred, through the network to the terrestrial radio-transmitters, also referred to as pseudolites (green squares). Receivers, carried by mobile users and vehicles, acquire the incoming radio signals in order to determine their positions.

The positioning system has been developed in the scope of the SuperGPS project, funded by the Dutch Research Council (NWO, project 13970). The project's main objective is to demonstrate a hybrid optical-wireless positioning system with decimeter-level accuracy. In the positioning concept, the central time-frequency reference of the system, the Master clock, is an atomic clock which signals are accurately distributed through an existing optical telecommunication network (Fig. 1). Time and frequency reference distribution is carried out through optical transport while ranging is performed by wideband transmitters.

a) Time and frequency reference distribution through optical transport

10 MHz and 1 Pulse-Per-Second (1PPS) reference signals are generated by a central atomic clock (Master clock). The reference signals are then distributed to all timing devices within the optical infrastructure. The devices rely on an enhanced White Rabbit protocol to guarantee accurate synchronization with respect to the Master clock and with respect to each other. Sub-nanosecond synchronization across 1000 nodes over a distance of 10 kilometers can be achieved. Higher synchronization accuracy may be considered in the future. Hence, in [6], a 4 ps uncertainty delay measurements over a distance of 75 km of fiber has been demonstrated. In the context of this demonstration the timing devices in the experimental set-up will, however, allow for a fairer 100-ps level of timing uncertainty between the nodes and the pseudolites. One should note that 100 ps corresponds to a distance of about 3 cm in free space propagation. Such a distance causes a tolerable offset for the decimeter-level accuracy targeted by our system. These uncertainty values are still well below the microsecond accuracy provided by precision network timing protocols (PTP) and nanosecond accuracy of GNSS receivers.

An additional dedicated optical infrastructure/network is not required to implement the time frequency reference distribution. The synchronization ensemble can be inserted in existing telecommunication networks using allocated wavelengths. The timing devices acting as hosts, can then seamlessly operate by using the data going through the optical network in order to enable synchronization between devices located kilometers apart. No synchronization data is thus injected in the existing telecommunication infrastructure. Finally, to synchronize the pseudolites (radio transmitters), reference optical signals are converted by the timing devices to the electrical domain. The electrical synchronization signals, in the form of 1PPS and 10 MHz references, are then provided to the pseudolites through (short) RF cables. The synchronization accuracy between the pseudolites can be assumed to be at the same order as the synchronization accuracy of the timing devices, i.e. at 100 ps level. For the demonstration, the pseudolites are based on Software Defined Radio (SDR) systems.

b) Wideband Radio Ranging Signals

Wideband radio ranging signals are transmitted by the pseudolites (SDR based). Knowing that the ranging accuracy is inversely proportional to the signal bandwidth, better ranging estimates and positioning solutions can be obtained by employing larger bandwidth signals. The pseudolites will, for the current demonstration, stream Pseudo-Random-Noise (PRN) sequences, and the receiver, which generally has no access to the time and frequency reference signals over the optical infrastructrure, will sample the incoming ranging PRN signals. Then, Time-Difference-Of-Arrival (TDoA) estimates between the received signals of different transmitters will be computed offline and used for positioning.

The transmitters are associated in a Time-Division-Multiplexing (TDM) way, in which the transmitters are streaming ranging signals successively, each one occupying a 30 µs transmission slot. In the initial experiments, the receiver unit is used in a coherent mode, meaning that it is also synchronized to the optical reference signals and to the pseudolites. However, for more realistic experiments, the receiver could also operate in a standalone asynchronous mode. The device will then rely on cross-correlation techniques to detect incoming ranging signals from background noise. To enable the different operating conditions and schemes, the pseudolites and receiver units are based on SDR systems in which we have been implemented custom logic. Commercially available, ultra-wide-band antennas (from 700 MHz to 6 GHz), are connected to the SDRs for wireless signals' transmission and receiving. For the actual test, transmitters and receivers will operate at a center frequency of 3.96 GHz with a bandwidth of 160 MHz. In a dense multipath environment, such bandwidth allows for a better time resolution and help in distinguishing the LOS component from reflections due to surroundings objects (Fig. 2). An experimental license was obtained from the Dutch Telecom Agency (Agentschap Telecom) to operate at such center frequency and with such a bandwidth.

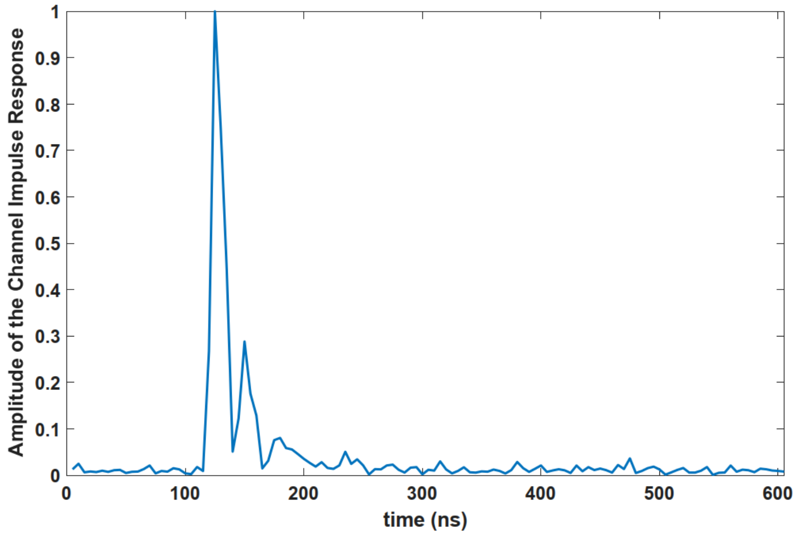

Figure 2: Normalized amplitude of a channel response between an SDR-based pseudolite and an SDR-based receiver, measured at the experimental validation site and sampled at 200 MSPS (5 ns sampling period). The signal bandwidth is 160 MHz. In the figure, a multipath component (MPC, with an amplitude of about 0.3) can be observed, following the first peak (the LoS component). Higher bandwidth allows for easier discrimination of close-in MPCs and better ranging accuracy.

c) SDR based pseudolites and receiver units

X310 Universal Software Radio Peripheral (USRP) devices from Ettus are used as pseudolites. These devices are high-end SDR systems capable of wideband operation. Each X310 has two wireless channels that can be either in transmitting or receiving radio mode. The central frequency can be tuned between 10 MHz and 6 GHz. Each channel has a 160 MHz maximum bandwidth. When both channels are associated, a contiguous 320 MHz bandwidth can be obtained. Using sub-band techniques an even higher transmitting and receiving virtual bandwidth can be achieved [7]. In that way, a ranging system can be implemented which to a very large extent is resilient to multipath. The X310 USRPs maximum sampling rate is 200 MSPS. The sample values are represented in a 32 bits format: 16 bits-I (in phase) and 16 bits-Q (quadrature phase).

The USRPs are compatible with the GNU Radio / RFNoC software environments, which allow the development of both software and hardware DSP units to build up a coherent communication system. Hence for on-device processing operations, each device embeds a mid-end Xilinx Kintex7 FPGA system. An X310 SDR will be also used as a receiver. For the actual demonstration, the receiving SDR will only acquire the ranging samples and forward them to a connected host-PC. After the acquisition is completed, positioning solutions will be computed in post-processing at a later stage using a scientific software environment (Matlab or Python/Numpy).

Offline data processing enables us to compare performance of different positioning techniques while avoiding specialized, time-consuming implementation of embedded signal processing algorithms on the FPGA. However, one should consider here that transferring data sampled at high rate from the receiver to the host-PC poses a real challenge. Operating at a 200 MSPS sampling rate generates an enormous data throughput. At a rate of 200 MSPS, the data throughput is 800 MB/s for a single channel configuration. And accordingly, for one minute of experiment, a data file of 48 GB is created. To be able to carry out our experiments, hardware development on the X310 Kintex7 FPGA was nevertheless required in order to transmit and receive low duty cycle ranging signals with a reasonable throughput and data file size [8]. Experiments of several hours could be run. For the receiver, a custom logic unit was implemented to save incoming samples, taken from the ADC unit for a short duration τ, over a period T. These samples are in fact saved in a RAM memory acting as a buffer before being forwarded to the host-PC.

Given a repetition period T, the pseudolites will stream radio ranging signals for a short fraction, τ, of this transmission period T .The duty cycle $d = \tau / T$ (Fig. 3) is chosen so that a sustainable offloading throughput can be maintained. For instance, for $d = 0.1$ and $T = 1\ ms$, ranging signals are transmitted only for 100 µs every 1 ms. The related throughput becomes 80 MB/s for a single channel configuration. If needed, the throughput can be reduced further by choosing an even lower duty cycle. For the pseudolites, custom logic, implemented in the X310, has been developed in order to load ranging samples from a connected host-PC and then to transmit the samples periodically in the presented low duty cycle scheme (Fig. 3).

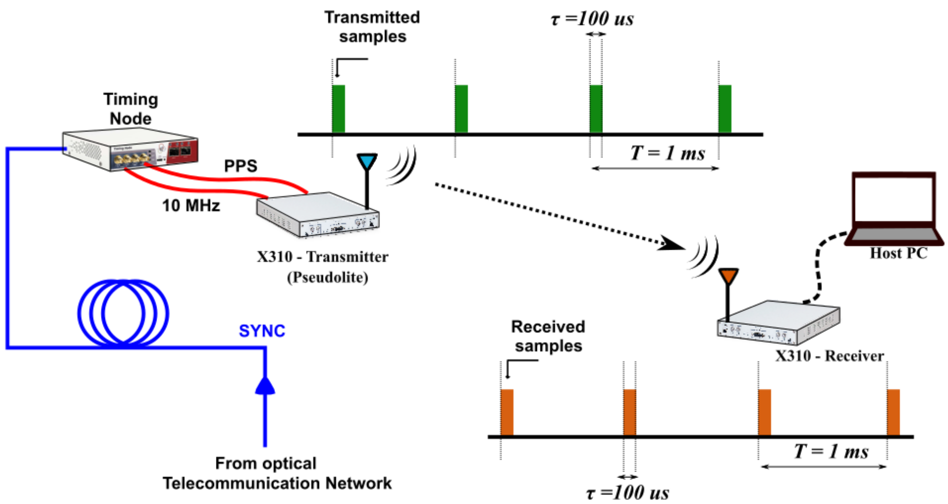

Figure 3: 1 TX – 1 RX configuration, in which the time-frequency reference is provided to the timing node through the optical telecommunication network (in blue). The timing node delivers 1PPS and 10 MHz electrical signals (red cables) to the X310 pseudo-lite. The transmitter is streaming wireless ranging signals in a low duty cycle scheme with $d=0.1$ for every $T = 1$ *ms*. The receiver samples the incoming ranging signals and forwards the data to the host-PC. Ranging samples are finally available for offline TDoA estimation on the connected PC. These TDoA estimates are used for positioning.

III. EXPERIMENTAL SETUP AT THE GREEN VILLAGE

The experimental validation was carried out at The Green Village [9], a living outdoor lab located at the TU Delft campus. The aim of The Green Village is to accelerate development and implementation of innovations for a sustainable future. An area of 1 ha is available for performing technology experiments and demonstrations. In The Green Village, the surroundings are close to an urban configuration with buildings and objects that could create effects such as multipath (Fig. 2) and blockage.

A. TIME FREQUENCY REFERENCE DISTRIBUTION : FROM THE VSL ATOMIC CLOCK TO THE GREEN VILLAGE

The central atomic clock used in the experiment is located at the Van Swinden Laboratory (VSL), the Dutch national metrology institute. VSL is internationally known for contributing, by providing accurate atomic time, to the realization of UTC (Universal Coordinated Time). VSL has unique facilities for accurate time-frequency reference generation and distribution. In the context of the experiemental validation, VSL's central atomic clock will provide the primary time frequency synchronization signals. These reference signals are then transported to the TU Delft Data Center via an optical link through the SURFnet infrastructure. SURFnet develops and maintains the Dutch national research and education network. From this data center, the synchronization signals are forwarded to The Green Village over the TU Delft optical network. These reference signals are then distributed to the timing nodes on site, which are arranged in a so-called daisy chain setup. An illustration of the signal transport can be seen in Fig. 4.

The timing nodes/devices have been accurately calibrated at the VSL lab prior to the experimental validation setup. Calibration allows to compensate for delay asymmetries, within the two-way propagation path of optical synchronization signals in the timing devices and the small form-factor pluggables (SFPs). The performed calibration has allowed us to decrease the synchronization uncertainties between the timing devices to a level of 100 ps. Five timing nodes will provide electrical synchronization signals (1PPS/10 MHz) to the pseudolites and to the receiver. Four timing nodes are associated to 4 X310 transmitters. The fifth timing node will provide synchronization to the receiving X310 SDR. One X310 transmitter will use its two channels to stream ranging signals, so that we have in total five pseudolites.

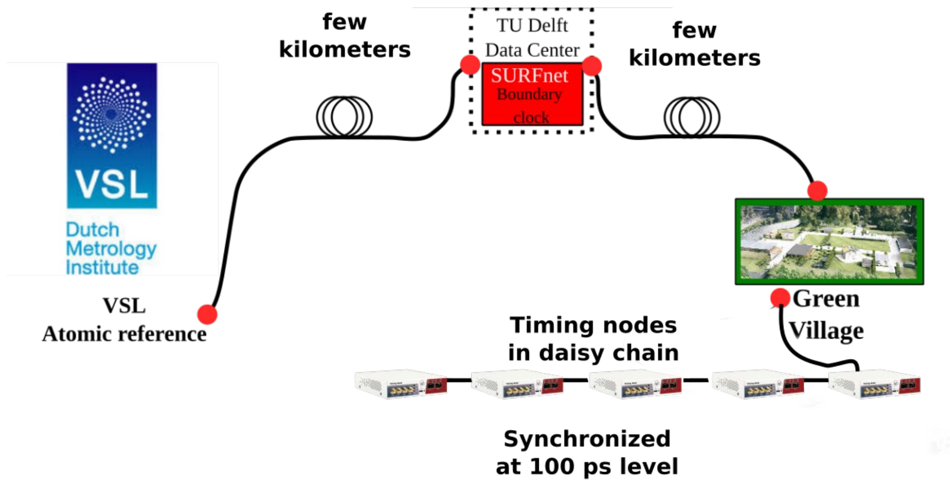

Figure 4: The time-frequency reference signals propagate (bi-directionally over a single fiber) from the atomic clock at VSL to the five timing nodes installed at The Green Village test site. This connection is possible through the SURFnet/TU Delft optical infrastructure.

B. GEOMETRY CONFIGURATION AT THE GREEN VILLAGE

In Fig. 5a, the geometry setup of the pseudolites is shown. Five wideband transmitting antennas, labelled from TX1 to TX5, are connected to 4 X310 SDRs. Antennas TX2 and TX3 are served by the same SDR, which is transmitting on its two channels. The receiver is moved over the road in the area 'covered' by the TX antennas. A professional land-surveying Total Station (Fig. 5b) is used to establish a local 2D positioning coordinate system

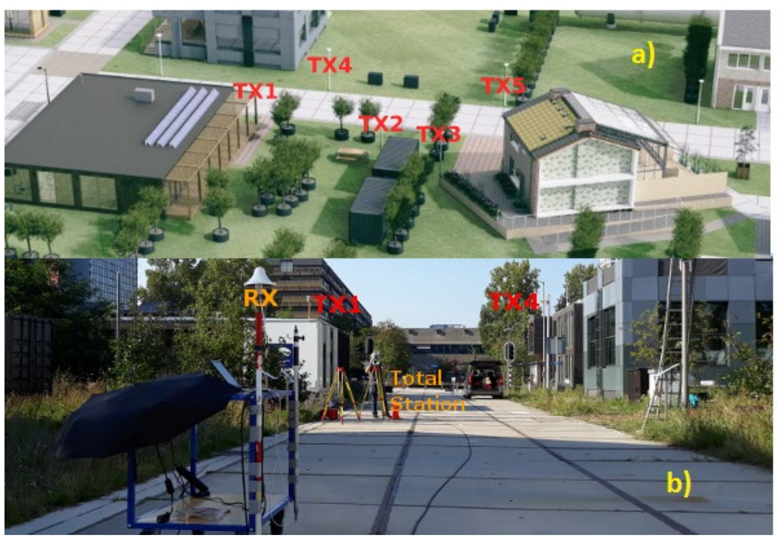

Figure 5: **a)** Geometry configuration of the five pseudolites, labelled in red. Four transmitting SDRs are used to serve 5 transmitting antennas, typically mounted in lampposts. TX2 and TX3 are both linked to a single SDR which is transmitting on its two channels. 1PPS and 10 MHz reference signals are provided by 4 timing nodes connected to the SDR systems. The receiver is moving on the road. The stretch of road covered by the transmitters is about 50 meters long, and 6 meters wide, b) Photo from the experimental test site, the transmitting antennas TX1 and TX4 can be seen. The receiving antenna mounted on a trolley, and the Total Station used to measure its 2D position is shown as well.

The Total Station provides mm-level accurate distances and angle measurements that will be used to compute the ground truths. In a first experiment, 33 locations are surveyed using the Total Station. In parallel the receiver will acquire PRN sequences transmitted, in TDM scheme, by the pseudolites at these 33 locations and forward the data to the host-PC. Based on the computed TDoA estimates, the 2D positioning problem is solved. The position accuracy is assessed by comparing the 2D position solutions obtained from the SuperGPS positioning system to the 2D position references measured by the Total Station. 3D positioning could be considered as well. But in the used configuration the geometric differences in height between the transmitting antennas and the receiver is rather limited which will result in poor estimates of the receiver height coordinate. Therefore, we have restricted ourselves to 2D positioning in this initial setup.

IV. EXPERIMENTAL RESULTS

In this section, initial experimental results obtained from the first real-life demonstration of the SuperGPS positioning concept are presented. The pseudolites at known locations are transmitting PRN sequences in a TDM scheme and the receiver is recording and forwarding sampled ranging signals to the host-PC. In Fig. 6a, we observe the waveforms streamed by the pseudolites. While in Fig. 6b, we can observe that the actual received signals are impaired by the wireless propagation channel. In this paper, we will only present the results when the receiver is synchronized to the transmitters. It can be noted that the ranging sequence from TX1 is slightly longer than the sequences from the other transmitters. The sequence from transmitter TX1 is also embedding a synchronization packet that would allow the receiver to operate in asynchronous mode, using cross/auto-correlation techniques to detect the incoming ranging packets. Nevertheless, the initial results presented in this contribution were obtained in a coherent setup.

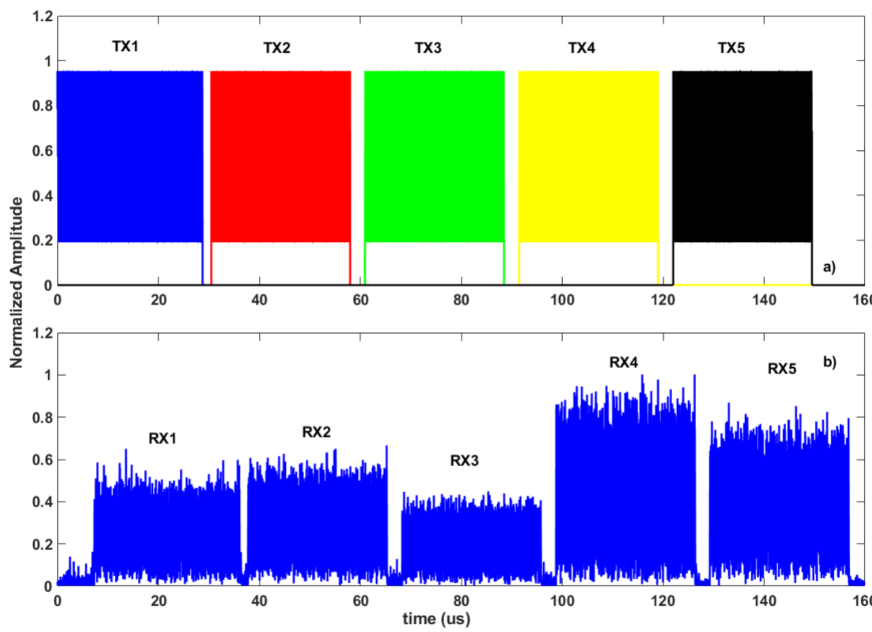

Figure 6: a) Transmitted sequences of the 5 pseudolites associated in Time-Division-Multiplexing, b) an incoming ranging packet at a given location, the packet contains 5 received ranging sequences. The different amplitudes are related to the different propagation distances.

A. POSITIONING PROBLEM USING TDOA ESTIMATES

Based on the received signals (Fig. 6b), we use threshold techniques on the channel responses (between the 5 transmitters and the receiver) in order to compute 4 TDoA estimates: d_j-d_1. Where $j \in \{2..5\}$, d_j being the distance between the transmitter TXj and the receiver RX, and d_1 stands for the distance between the first transmitter TX1 and the receiver RX. TDoA estimation is convenient in this context because it allows to perform ranging without calibration of the hardware delays introduced by the pseudolites and/or the receiver. Once the TDoA pseudoranges have been computed, the 2D position problem is solved using Gauss-Newton iterations. Here, we can also add that the pseudolites are not perfectly phase-aligned. The 5 transmitting frontends and the receiving frontends present different initial phase offsets. These phase offsets are random each time the SDRs are powered on, but then the offsets stay fixed until the next power off/power on cycle.

B. POSITIONING RESULTS AND ACCURACY

In this sub-section, initial positioning solutions obtained from the full optical-wireless demonstrator are presented and compared to the ground-truths values. In Fig.7, a 2D map containing the ground-truth values measured by the Total Station and the computed 2D positions are shown as black crosses and as red circles, respectively. At each static location covered by the receiver, we extract and process one incoming ranging packet (150 µs) to compute the TDoA estimates and the positioning solution. Overall, 33 locations have been surveyed. The 5 antenna locations are presented in black text with yellow background. Comparing the 2D solutions with the ground-truth values shows a decimeter level accuracy. In particular, the Root Mean Square Error (RMSE) error is 24 cm in the X-direction (across road) and 57 cm in the Y-direction (along road direction). From these initial results, the system thus matches the targeted decimeter-level accuracy in terms of RMSE. The results are interesting for a first demonstration. However about 67% of the received ranging packets suffer from degradations due to not yet determined causes. We, however, overcome the issue by reducing the SDR receiver radio frontend gain by 10 dB. Further experiments have been carried out successfully and the data are being processed and analyzed at the time of writing. Tentatively we have also computed the RMS position error over selected packets (from 9 locations), such as the one in Fig. 6b, which were not affected by impairments. For this smaller subset of measurements, the RMSE is 12 cm for the X-direction (across road) and 20 cm for the Y-direction (along road). Similar results are anticipated with the further experiments that have been carried out recently.

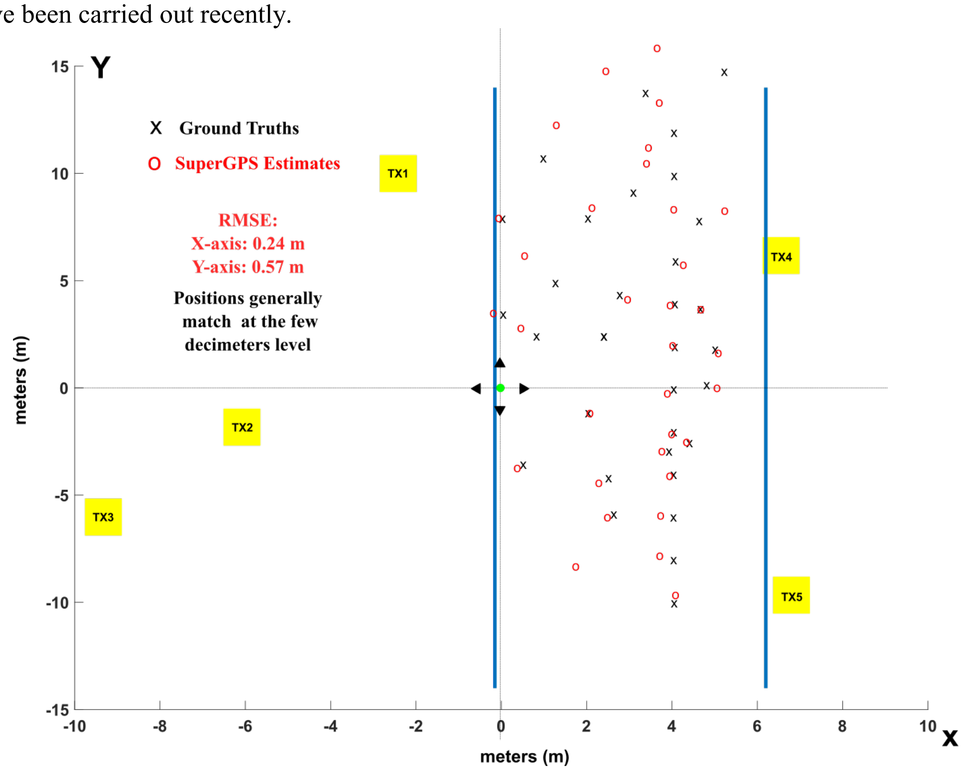

Figure 7: 2D map of the experimental setup. In yellow the 5 transmitter locations, and the blue lines mark the road. The green dot is the map central point (origin). 2D positions determined by the Total Station and 2D positions obtained by the SuperGPS system are presented as black crosses and as red circles, respectively. Positions are generally matching at the decimeter level.

V. CONCLUSION

This contribution presents a hybrid optical-wireless positioning concept, and the positioning results of its initial experimental implementation and validation. Accurate synchronization reference signals are provided by an atomic clock at VSL, the Dutch national metrology institute. The reference signals are optically transported to The Green Village, the test site of the demonstration. At the test site, the synchronization reference is optically distributed, over a local glass-fibre network, to 5 timing nodes which synchronize 5 pseudolites at the 100 ps level. A receiver has visited 33 surveyed locations in the area covered by the transmitting antennas. Both the pseudolites and the receiver are SDR based, and able to transmit and receive 160 MHz bandwidth PRN ranging sequences. Such a bandwidth allows for better discrimination of multipath components and thus higher ranging/positioning accuracy.

The pseudolites are associated in TDM, and a 2D positioning system is set up based on TDoA. Position solutions computed by solving the 2D positioning problem are compared to the ground-truth positions of the receiver, which have been measured by a Total Station. These initial results show that the SuperGPS demonstrator setup is achieving decimeter level 2D positioning (in terms of RMSE). More precisely, for the across road direction the RMSE is 24 cm, and for the along road direction the RMSE is 57 cm. While the results are very encouraging for an initial demonstration point, it has to be noted that in this first experiment the majority of the received ranging packets suffered from impairments which cause a degraded accuracy.

Subsequently and following this first demonstration, solutions were found to overcome the initial packet impairment issue, and further experiments have been carried out. These experiments were targeting TDoA, but also Carrier phase based positioning. At the time of writing, we are still processing the data and an accuracy close to one decimeter is expected for TDoA based positioning, and cm-level accuracy for Carrier phase based positioning. Moreover, positioning experiments based on multiband signals [10] are also considered in the future. If these accuracies are confirmed, a further step would be to test the system in even denser multipath environments, such as urban canyons and along high-ways.

ACKNOWLEDGEMENTS

This research is supported by the Netherlands Organization for Scientific Research (NWO) through the SuperGPS project , under Grant 13970. In particular, we would like to thank Erik Dierikx from VSL, Rob Smets from SURF, and Lolke Boonstra and Terence Theijn from TU-Delft ICT-FM, for their expertise and support on the optical infrastructure. We also thank the other project-partners, namely OPNT, FUGRO, and KPN. Furthermore, we would like to thank Agentschap Telecom, and The Green Village for their support in making the SuperGPS demonstrator feasible.

REFERENCES

1. Psiaki, M. L., and Humphreys, T. E. , "GNSS Spoofing and Detection," in Proceedings of the IEEE, vol. 104, no. 6, pp. 1258-1270, June 2016, doi: 10.1109/JPROC.2016.2526658.
2. Groves, PD., Adjrad, M. Performance assessment of 3D-mapping–aided GNSS part 1: Algorithms, user equipment, and review. NAVIGATION. 2019; 66: 341– 362. https://doi.org/10.1002/navi.288
3. Wen, Weisong, Zhang, Guohao, Hsu, Li-Ta, "Correcting GNSS NLOS by 3D LiDAR and Building Height," Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018), Miami, Florida, September 2018, pp. 3156-3168.
4. Barnes, N., Rizos, C., Kanli, M. and Pahwa, A. "A Positioning Technology for Classically Difficult GNSS Environments from Locata," 2006 IEEE/ION Position, Location, And Navigation Symposium, Coronado, CA, 2006, pp. 715-721, doi: 10.1109/PLANS.2006.1650665.
5. Kahe, G., Masoumi Ganjgah, F. “MAKAN: A low-cost low-complexity local positioning system,” NAVIGATION. 2019; 66: 401– 415.
6. Sotiropoulos, N., Okonkwo C.M., Nuijts, R., Koelemeij, J.C.J., “Delivering 10 Gb/s optical data with picosecond timing uncertainty over 75 km distance.”, Optics Express, 2014, 21(26), 32643-32654.
7. Dun, H., Tiberius, C.C.J.M., Janssen, G.J.M., Diouf, C., “Time Delay Estimation Based on Multi-band Multi-carrier Signal in Multipath Environments”, ION GNSS+ 2019, Miami, Florida, September 16-20, 2019, pp. 2299-2313.
8. Diouf, C., Janssen, G. J. M., Kazaz, T., Dun, H., Chamanzadeh, F. and Tiberius, C. C. J. M., "A 400 Msps SDR platform for prototyping accurate wideband ranging techniques," 2019 16th Workshop on Positioning, Navigation and Communications (WPNC), Bremen, Germany, 2019, pp. 1-6, doi: 10.1109/WPNC47567.2019.8970251
9. https://www.thegreenvillage.org/about-us
10. Kazaz, T., Janssen, G. J. M., and Van der Veen, A., "Time Delay Estimation from Multiband Radio Channel Samples in Nonuniform Noise," 2019 53rd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2019, pp. 1237-1241, doi: 10.1109/IEEECONF44664.2019.9049037.