

## TESTBED FOR ONE-WAY IP PACKET DELAY MEASUREMENT IN SMART GRID WAMS APPLICATIONS BASED ON IEEE C37.118

*Martin Ivanov, Technical University of Varna, martinivanov@tu-varna.bg*

*Rozalina Dimova, Technical University of Varna, rdim@tu-varna.bg*

**Abstract:** *With the emergence of Smart Grid technologies, the wide area measurement systems show potential in securing the reliability of the power grids by using real-time centralized data collection over hundreds or thousands of kilometers. The strict requirements for sub-20 ms one-way delay of these systems impose numerous challenges to the process of accurate network delay measurement. In this paper, a testbed for one-way delay measurement in wide area measurement systems is proposed. The testbed is based on system clock synchronization to the Coordinated Universal Time (UTC) via Global Positioning System (GPS) receivers and Network Time Protocol (NTP) servers. In order to evaluate and bound the measurement error, two experiments have been performed in accordance with the IETF RFC 2679 standard. The results show low relative errors and allow accurate reporting of the one-way delay measurements.*

**Keywords:** *one-way packet delay, testbed, wide area measurement systems, synchrophasor communications.*

## ЕКСПЕРИМЕНТАЛНА ПОСТАНОВКА ЗА ИЗМЕРВАНЕ НА ЕДНОПОСОЧНИ ПАКЕТНИ ЗАКЪСНЕНИЯ В SMART GRID ШИРОКООБХВАТНИ СИСТЕМИ ЗА НАБЛЮДЕНИЕ БАЗИРАНИ НА IEEE C37.118

*Мартин Иванов, Технически университет - Варна, martinivanov@tu-varna.bg*

*Розалина Димова, Технически университет - Варна, rdim@tu-varna.bg*

**Резюме:** *С появата на Smart Grid технологиите, широкообхватните системи за наблюдение показват потенциал за осигуряване на надеждността на електроенергийните системи чрез централизирано събиране на данни в реално време на стотици или хиляди километри. Строктните изисквания на тези системи за еднопосочни закъснения в рамките на 20 ms налагат редица предизвикателства пред точното им измерване. В тази статия е предложена експериментална постановка за измерване на еднопосочни пакетни закъснения в широкообхватни системи за наблюдение. Постановката е базирана на синхронизация на системни часовници посредством GPS приемници и NTP сървъри. С цел да бъде оценена и ограничена грешката при измерване са проведени два експеримента в съответствие със стандарта RFC 2679 на IETF. Резултатите показват ниски относителни грешки и позволяват точно докладване на измерените стойности за еднопосочни закъснения.*

**Ключови думи:** *еднопосочни пакетни закъснения, експериментална постановка, широкообхватни системи за наблюдение, синхрофазорни комуникации.*

## I. INTRODUCTION

The IP-based network technologies are rapidly gaining popularity with the power utilities and operators due to the recent advancements in the paradigm shift towards information- and communication-enabled power grids (widely known as Smart Grids, SG). The critical nature of the SG applications imposes stringent requirements toward network delay in order to achieve real-time centralized data collection over hundreds or thousands of kilometers.

The widespread approach for measuring IP packet delay is the round-trip time (RTT) between two network hosts, defined as the sum of the forward and the reverse delay. In the context of SG reference and architectural models [1]-[3], the centralized northbound data collection from end devices (smart meters, phasor measurement units, energy management systems, etc.) is characterized by large network traffic volumes, exceeding numerous times the southbound traffic which consists mainly of configuration messages and polling requests. From this perspective, measuring RTT for network performance evaluation leads to increased uncertainty due to the discrepancy in northbound and southbound traffic volumes, as well as the possibility of using different paths in each direction. Instead, the approach of one-way delay (OWD) measurement is more suitable solution, differentiating both traffic directions and enabling more precise one-way path diagnostics. The motivation for OWD measurement instead of RTT is given in RFC 2679 [4]:

- *Asymmetric paths* – different sequences of routers are used for the forward and reverse paths (RTT measurement actually measure the performance of two distinct paths together).
- *Asymmetric queueing* – even when two paths are symmetric, they may have radically different performance characteristics due to asymmetric queueing policies.
- *Application performance* – the overall application performance may depend mostly on the performance in one direction.
- *Quality of Service (QoS) provisioning* – in QoS-enabled networks, provisioning in one direction may be radically different than provisioning in the reverse direction, and thus the QoS guarantees differ.

Furthermore, the packet processing delay in the destination host incurs additional uncertainty when using RTT, as it is regarded as computational and not communication delay, and must not be included in the delay analysis [5].

The de facto standard for synchrophasor communications in WAMS is the IEEE C37.118-2011, consisting of IEEE C37.118.1 for synchrophasor measurements description and IEEE C37.118.2 for data transfers [6], [7]. This paper addresses the second part of the standard with an emphasis on OWD measurement. Being a protocol on the application layer, the IEEE C37.118 does not define a complete communication system and thus it is not bounding the network performance parameters, including OWD: “*If delay in data delivery is critical to applications, the designers need to examine all communication aspects they are incorporating to make sure delivery time meets specifications and there are no unexpected delays*”, [7].

Despite the lack of standardization activities for defining maximum allowable end-to-end OWD in WAMS, several studies have already pinpointed the need of achieving sub-20ms packet OWD while monitoring power systems with nominal frequency of 50 Hz [8]-[10]. The ITU-T recommendation Y.1541 defines 6 main QoS classes with each class creating a specific combination of bounds on the network performance values (Table 1). Clearly, the sub-20ms WAMS delay bounds does not match the established values in Y.1541. Under the most stringent Class 0, the packet delay bound exceeds the WAMS requirement five times, thus also introducing quintuple increase in the relative measurement error.

Network performance parameter <sup>1</sup>	QoS Classes					
	Class 0	Class 1	Class 2	Class 3	Class 4	Class 5 (unspecified)
IPTD	100 ms	400 ms	100 ms	400 ms	1 s	U
IPDV	50 ms	50 ms	U	U	U	U
IPLR	$1 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$	U
IPER	$1 \times 10^{-4}$					U

Table 1. IP network QoS class definitions as in Y.1541 [11]

The main contribution of the current paper is the development of an experimental OWD measurement testbed for IP-enabled WAMS applications, based on system clock time synchronization between source and destination end nodes. The paper is organized as follows. Section II offers a description of the testbed, discussing the proposed setup, system time sources and clock synchronization as well as the used notions of clock uncertainty. Evaluations of the synchronization and the difference between “host” time and “wire” time are presented in Section III. The work is concluded in Section IV.

## II. EXPERIMENTAL TESTBED OUTLINE

In order to achieve system clock time synchronization and reduce the OWD measurement errors, both source and destination end node network segments are equipped with NTP version 4 compliant servers [12]. Each NTP server is connected to a GPS receiver, enabling accurate time tagging with UTC timestamps. Figure 1 depicts the structure of the proposed testbed.

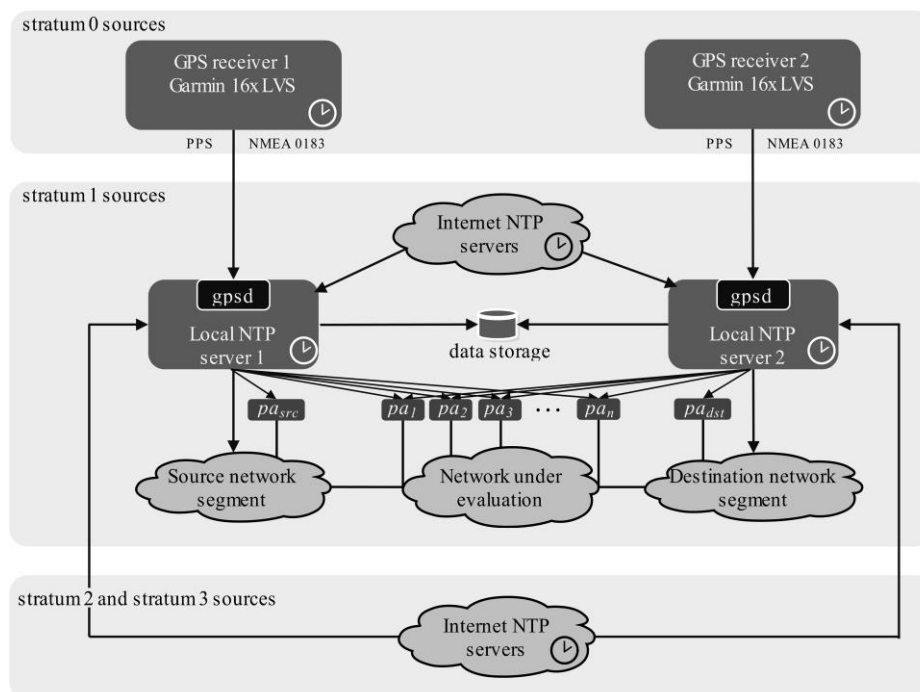


Fig.1. Time sources

<sup>1</sup> Network performance parameters as defined by ITU-T: IPTD – IP packet delay; IPDV – IP packet delay variation; IPLR – IP packet loss ratio; IPER – IP packet error ratio.

The shown stratum 1, 2 and 3 internet NTP servers are only used as secondary (backup) time sources due to the additional uncertainty from the increased hop count and asymmetric delays that NTP assumes to be symmetric. Both source and destination segments are equipped with protocol analyzers,  $pa_{src}$  and  $pa_{dst}$  respectively, in order to document packet generation time and packet reception time. The optional protocol analyzers  $pa_1, pa_2, \dots, pa_n$  are used when packet arrival/departure time measurement is required on the intermediate network nodes. If the operating system of a given device does not support packet capture, the analyzer is connected to that device using a mirrored switch interface. The data storage server consists of MySQL databases and FTP server which are used for the purpose of logging the reference clocks' accuracy.

### **A. Used notions of clock uncertainty**

The testbed evaluation is performed in accordance to the sources of uncertainty as defined by IETF. Both RFC 2679 and RFC 2681 define four distinct but related notions of clock uncertainty [4], [13]:

- *Synchronization* ( $T_s$ ) – measures the extent to which two clocks agree on what time it is.
- *Accuracy* ( $T_a$ ) – measures the extent to which a given clock agrees with UTC.
- *Resolution* ( $r_{clk}$ ) – measures the precision of a given clock.
- *Skew* ( $\varphi(t)$ ) – measures the change of accuracy, or of synchronization, with time.

RFC 2679 provides general guidance for accounting and analysis of various sources of error or uncertainty. The standard also notes the following specifics related to OWD metrics [4]:

- Errors or uncertainties due to uncertainties in the clocks of the source and destination hosts.
- Errors or uncertainties due to the difference between “wire time” and “host time”.

In order to gain an insight on the particularities of the two types of errors or uncertainties in the proposed testbed, both are separately evaluated in section III.

### **B. UTC time sources**

Two Garmin 16x LVS receivers are used as stratum 0 UTC reference clocks in both source and destination network segments. The format of the sentences is based on the NMEA 0183 standard [14]. The model selection is based on the support of additional output for Pulse Per Second (PPS) synchronization signal with  $T_{a,GPS} = \pm 1 \mu s$  on the rising edge [15]. The receivers are connected to the NTP servers via RS-232 serial interfaces with data rate of 9600 bps.

### **C. Clock resolution**

The precision of the periodic system clock corrections, issued by NTP, is limited by the time resolution  $r_{clk}$ . Therefore, in order to reduce  $r_{clk}$ , the operating system used for both NTP

servers is Ubuntu Linux 14.04.3 with kernel version 3.16. The compliance with RFC 2783 by using PPSkit allows achieving of  $r_{clk}$  values under  $1 \mu s$  [16], [17]. In comparison, Microsoft Windows offers  $r_{clk} \in [0.5ms, 15.6ms]$  and for most applications, the available resolution is 1 ms. Values of such order result in high instrument errors leading to inaccurate OWD measurement.

#### D. Local NTP servers

As synchronization via remote NTP servers is considered unsuitable for primary time source in the current testbed, the local NTP servers are directly connected to the status 0 GPS receivers. The presence of two separate GPS receivers aims at excluding the possibility of transmitting NTP packets through the OWD-evaluated network segments in order to reduce the systematic and random errors and allow the testbed deployment over geographically remote locations, i.e. between substations and control centers.

The NTP servers are unable to establish a direct interface with GPS receivers, but have a numerous interfaces for accessing synchronization data through the use of additional system services for processing and placing the NMEA 0183 sentences and PPS in a shared memory segment. Figure 2 shows the data processing procedure of the used GPS service daemon [18].

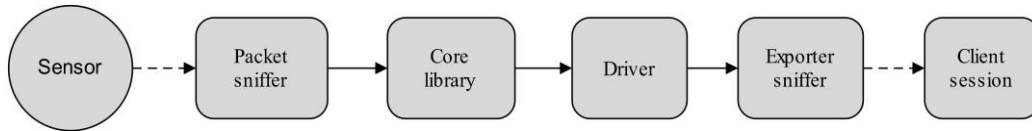


Fig.2. Dataflow architecture between GPS receiver and NTP server

### III. EXPERIMENTAL TESTBED EVALUATION AND RESULTS

RFC 2679 states the error in OWD measurements could be bounded by determining all the individual uncertainties, and adding them together to form the budget [4]:

$$U_{\max} = E_{\text{synch}}(t) + r_{\text{clk},\text{src}} + r_{\text{clk},\text{dst}} + H_{\text{src}} + H_{\text{dst}}, \quad (1)$$

where:

- $E_{\text{synch}}(t) \geq |\varphi(t)|$  denotes the upper bound on the uncertainty in synchronization (or accuracy).
- $r_{\text{clk},\text{src}}$  and  $r_{\text{clk},\text{dst}}$  denote the resolution of the source and destination clocks, respectively.
- $H_{\text{src}}$  and  $H_{\text{dst}}$  denote the upper bounds on the host-related uncertainties due to the differences between “wire time” and “host time”.

As  $r_{\text{clk},\text{src}}$  and  $r_{\text{clk},\text{dst}}$  are known, the main uncertainty sources considered in this paper are synchronization and differences between “wire time” and “host time”. Their evaluation is conducted in sections III.A and III.B respectively.

#### A. Synchronization evaluation

The testbed design is aimed for OWD measurement in IP-based WAMS that are inherently digital communication networks and allow differentiation of random and

systematic errors. Let  $d_m^{[p]}$  be the OWD of Type-P IP packet “ $p$ ”, defined in RFC 2330 [5], that is measured between two endpoint network devices  $\kappa_i$  and  $\kappa_j$  that are being synchronized by the NTP servers. Assuming that the GPS receivers and NTP servers operate in a stable state and system clocks of the respective devices are synchronized to UTC, the measured value of OWD is given by:

$$d_m^{[p]} = T_{ij,dst}^{[p]} - T_{ij,src}^{[p]}, \quad (2)$$

where  $T_{ij,src}^{[p]}$  and  $T_{ij,dst}^{[p]}$  are the timestamps of sending  $p$  by  $\kappa_i$  and receiving  $p$  by  $\kappa_j$ . Let  $d_{ete}^{[p]}$  be the true OWD value that cannot be directly determined due to the presence of systematic  $e_s$  and random  $e_r$  errors [19]:

$$d_m^{[p]} = e_s^{[p]} + e_r^{[p]} + d_{ete}^{[p]} \quad (3)$$

When multiple OWD measurements are performed (packet flow  $p_1 \dots p_n$ ), the changes in  $e_s$  and  $e_r$  in time must be bounded, as they characterize the skew  $\varphi(t)$  of the time sources. The systematic errors remain constant or vary in predictable matter [19]. The known or estimated systematic error can be compensated by the correction  $c_s = -e_s$ , with the corrected value of a single measurement being  $d_c^{[p]} = d_m^{[p]} + c_s^{[p]}$ . In the proposed testbed, the known systematic errors are considered to be instrumental, the bounds of which can be determined by a large number of measurements under the same conditions.

In terms of deploying the testbed over geographically distant locations, the most appropriate approach is to evaluate the accuracy  $T_a$  instead of synchronization  $T_s$  for the determination of  $\varphi(t)$ , avoiding the need for further exchange of synchronization data over long distances. The degree of synchronization can be determined by the accuracy of the NTP servers at each time point using  $T_s = |T_{a,NTP1}| + |T_{a,NTP2}|$ .

When performing multiple measurements, the random error  $e_r$  varies in an unpredictable manner [19]. As the number of measurements increase, the mean value approaches the probability density function of  $e_r$  and can be eliminated by performing large number of measurements under the same conditions.

In order to evaluate  $\varphi(t)$ , an experimental measurement of  $T_a$  with 1800 measured samples for each NTP server is conducted under the same conditions. The duration is 8 hours (28800 seconds). Given in UTC format, it represents the period 25200 – 54000 seconds. The input of the GPS service daemon is used for reference timing data acquisition which is accessed by gpspipe application [20]. The results are depicted on figure 3 and figure 4.

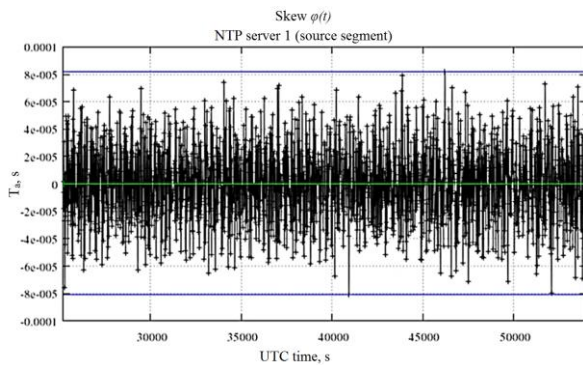


Fig.3. Skew  $\varphi(t)$  of NTP server 1

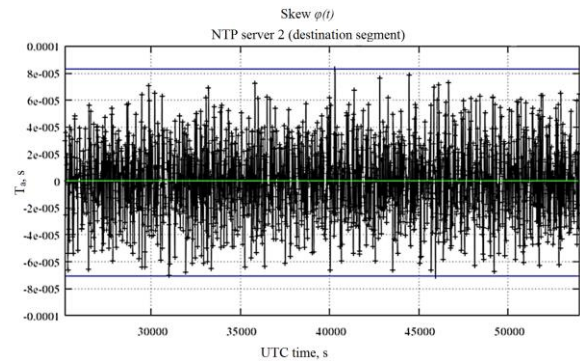


Fig.4. Skew  $\varphi(t)$  of NTP server 2

The results show similar characteristics in the change of  $T_a$  over the evaluation period. A statistical summary is shown in table 2.

	NTP server 1	NTP server 2
Minimum ( $\mu\text{s}$ )	-80.9	-70.9
Maximum ( $\mu\text{s}$ )	82.2	83.2
Range ( $\mu\text{s}$ )	163.1	154.1
Median ( $\mu\text{s}$ )	0.101	0.088
Mean $\bar{T}_a$ ( $\mu\text{s}$ )	-0.029	0.042
Standard deviation $\sigma$ ( $\mu\text{s}$ )	28.55	28.61
Skewness	0.0196	0.0467
Kurtosis	-0.48	-0.50

Table 2. Statistical summary of the experimental results

The skewness and kurtosis are close to 0, suggesting the normal distribution of the measured samples. With confidence level of 95%, the true mean value of NTP server 1 falls within the range between  $-1.35 \mu\text{s}$  and  $1.29 \mu\text{s}$  (with confidence interval of  $\pm 1.32 \mu\text{s}$ ). For NTP server 2, the true mean falls between  $-1.28 \mu\text{s}$  and  $1.36 \mu\text{s}$  (with the same confidence interval). The results indicate very small systematic errors due to the high resolution of the system clocks. However, the random errors remain as a main source of synchronization uncertainty. This is confirmed by the conformity of the sample data with the three sigma-rule (table 3) and the histogram distributions for the two data sets (figure 5). The lack of large variations from the true value of  $\bar{T}_a$  exclude the presence of errors due to loss of system clock synchronization.

	$[\bar{T}_a - \sigma ; \bar{T}_a + \sigma]$	$[\bar{T}_a - 2\sigma ; \bar{T}_a + 2\sigma]$	$[\bar{T}_a - 3\sigma ; \bar{T}_a + 3\sigma]$
NTP server 1	67.45%	96.95%	100%
NTP server 2	66.89%	95.94%	100%

Table 3. Conformity of the sample data with the three-sigma rule

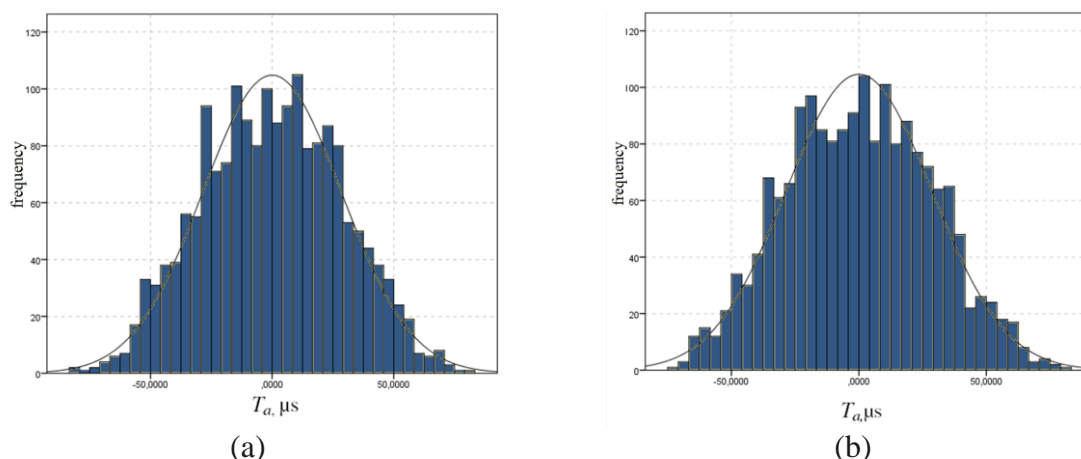


Fig.5. Histogram distribution for NTP server 1 (a) NTP server 2 (b)

The total uncertainty from the synchronization process can be defined as the maximum measured deviation from UTC for both servers and the uncertainty introduced by the GPS receivers:

$$E_{synch}(t) = |T_{a,max,NTP1}| + |T_{a,max,NTP2}| + T_{a,GPS} = 166.4\mu s \quad (4)$$

The notion  $E_{synch}(t)$  represents the upper bound on the uncertainty in the system clock synchronization.

## B. Evaluation of the difference between “host” and “wire” times

The timestamp  $T_{src}$  represents the sending of the first frame bit from the source interface and  $T_{dst}$  represents the time of receiving the last frame bit in the destination interface – defined in RFC 2679 as “wire” time ( $h_{wire}$ ). In real network conditions, the timestamping of an outgoing network packet is often performed before it is handed to an interface driver. Similarly, the timestamping of an incoming network packet in the destination device is performed after the reception from the interface driver – referred to as “host” time ( $h_{host}$ ). The difference between the two types of timestamping  $H = h_{host} - h_{wire}$  is considered difficult to measure or predict [21]. RFC 2679 states that the difference must be included in the uncertainty analysis but does not provide a methodology to measure it.

The experiment from [22] is reproduced in order to obtain the magnitude of the introduced error  $H$  by the host-related uncertainty. By using Internet Control Message Protocol (ICMP) echo requests between two network hosts in a local area network segment, the authors successfully determine the difference between “host” time and “wire” time.

In the current experiment, an Ethernet frame of 116 bytes carrying the ICMP packets is chosen to comply with the length of the IEEE C37.118 messages, used for evaluation of phasor data bandwidth requirements in [23]. The experiment is based on 1500 ICMP echo requests/replies, generated once every second. The two hosts being evaluated are used in the testbed as source and destination network nodes for measuring  $T_{ij,src}^{[p]}$  and  $T_{ij,dst}^{[p]}$  in order to calculate the OWD values. The hosts can be used for OWD evaluation between substations and control centers by using the iPDC platform [24].

Figure 6 and figure 7 depict the results for the source network segment host and the destination network segment host, respectively.

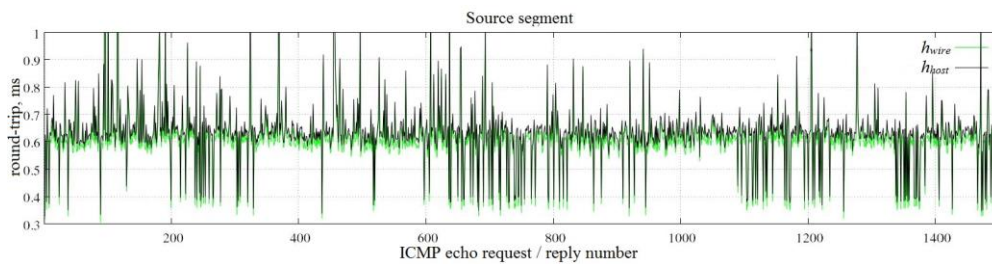


Fig.6. Round-trip measurement results for  $h_{wire}$  and  $h_{host}$  in the source segment

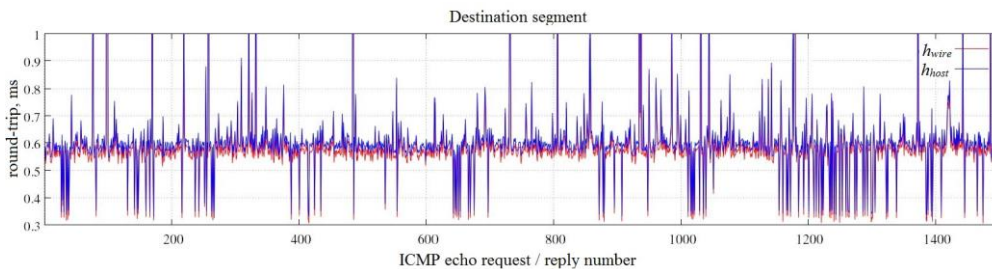


Fig.7. Round-trip measurement results for  $h_{wire}$  and  $h_{host}$  in the destination segment

In both segments, the round-trip values always satisfy  $h_{host} > h_{wire}$  which indicate the correctness of the obtained results. The difference  $H$  for the source segment varies in the range between  $9 \mu\text{s}$  and  $53 \mu\text{s}$ . For the destination segment,  $H \in [8 \mu\text{s}, 36 \mu\text{s}]$ . Table 4 shows a summary of the obtained results during the experiment.

	Source segment		Destination segment	
	$h_{wire}$	$h_{host}$	$h_{wire}$	$h_{host}$
Minimum (ms)	0.304	0.328	0.305	0.328
Maximum (ms)	3.034	3.06	4.408	4.42
Range (ms)	2.73	2.723	4.103	4.092
Median (ms)	0.606	0.63	0.571	0.592
Mean (ms)	0.606	0.63	0.585	0.606
Std. deviation (ms)	0.130	0.130	0.203	0.202

Table 4. Summary of the experimental round-trip time results

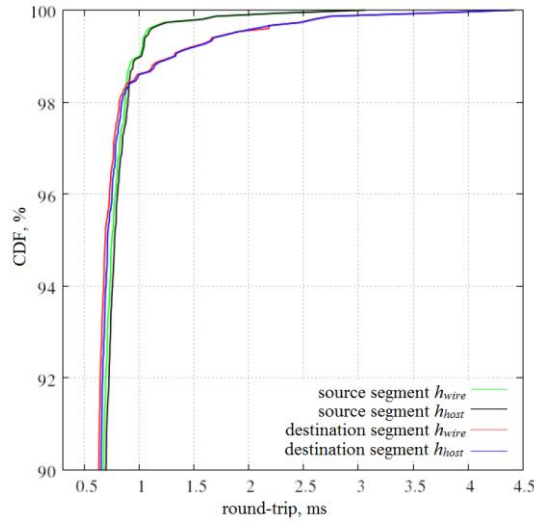


Fig.8. Cumulative distribution function

Figure 8 depicts the cumulative distribution function of  $h_{wire}$  and  $h_{host}$ . The values of  $h_{host}$  closely follow those of  $h_{wire}$  for both segments, showing very low difference variations. The majority of the measured values fall within the range from  $500 \mu\text{s}$  to  $700 \mu\text{s}$ : 83.8% for  $h_{wire}$  and 82.13% for  $h_{host}$  in the source segment, and 88.6% for  $h_{wire}$  and 87.6% for  $h_{host}$  in the destination segment. The sample distributions are characterized by similar standard deviations, as the differences between the mean values for the source and destination segments are  $24 \mu\text{s}$  and  $21 \mu\text{s}$ , respectively. The obtained results show the successful provision of similar host-related conditions in the source and destination segments of the testbed. As the differences  $H$  are accurately known, they can be bounded by  $H_{src} = 53 \mu\text{s}$  and  $H_{dst} = 36 \mu\text{s}$  in accordance with RFC 2679.

### C. Bounded total error in OWD measurements

Based on the obtained results in sections III.A and III.B, the total bounded error in the OWD measurement process with the testbed is calculated using (1). Table 5 gives the values depending on the method used to report the errors and the chosen timestamping procedure in the source and destination segment hosts.

Reporting results	Measuring with $h_{host}, \mu s$	Relative error <sup>2</sup> ( $h_{host}$ ), %	Measuring with $h_{wire}, \mu s$	Relative error <sup>2</sup> ( $h_{wire}$ ), %
Maximum range	$\pm 257.4$	1.287	$\pm 168.4$	0.842
95% confidence (RFC 2679)	$\pm 148.2$	0.741	$\pm 59.2$	0.296

Table 5. Values of errors during OWD measurement with the testbed

#### IV. CONCLUSION

The work presented in the paper addresses the OWD measurement in IEEE C37.118-enabled WAMS. A testbed for measuring sub-20ms packet OWD is presented, based on system clock time synchronization with UTC via GPS receivers and NTP servers. The extensive measurement error evaluation, performed in accordance with RFC 2679, shows very low relative errors and allows accurate results reporting. Future work could explore the possibilities of improving the accuracy of the testbed by using the Precision Time Protocol version 2 (PTPv2), defined in the standard IEEE 1588-2008.

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<sup>2</sup> For  $d_{ete} = 20 \text{ ms}$  ( $f_{AC} = 50 \text{ Hz}$ )

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