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Effect of VLAN configuration on IEC 61850 sampled values

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ABSTRACT

IEC 61850, the standard for communication in power utility, has solved the interoperability problems between different vendors in substation communication networks (SCNs). However, most studies on SCN that use IEC 61850 were conducted using computer-based simulations or commercial equipment with fixed functions. In this study, an experiment on an SCN was conducted using real equipment such as a network switch, Raspberry Pi, and a mini PC. A cyclic data model was used for the traffic generation of sampled values (SVs) according to IEC 61850. The effect of applying a virtual local area network (VLAN) in the SCN on the transfer time and throughput of the SV frames was measured. In addition, when using IEEE 1588 in the time synchronization process, it was verified that the clock offset remained unaffected irrespective of the use of VLANs or changes in the sampling frequency. The experimental results can serve as guidance for the actual planning and construction process of SCNs.

1. Introduction

Currently, many studies are being conducted to evaluate and enhance the overall performance of substation communication networks (SCNs) through experiments and simulations. However, most of these studies are carried out using computer-based simulations or by conducting experiments using commercial equipment with fixed functions (IEC, 2003; Ingram et al., 2011; Schossig, 2014; Ustun et al., 2019; Zhang et al., 2015). Therefore, the following items should be considered to evaluate the performance of SCNs accurately. First, a mathematical model that can appropriately express various required messages should be applied. Therefore, in this study, sampled value (SV) traffic was generated using the SV cyclic data flow suggested in Zhang et al. (2015). Second, it is necessary to evaluate real-time performance by using actual equipment based on the SV data flow model. Hence, computer-based simulation tools such as OPNET Modeler were not used in this study. Instead, the experiment was conducted using real equipment such as Cisco IE 4000, Raspberry Pi, and mini PC. Finally, the influence of using VLAN and the change in the sampling frequency on the transfer time and throughput of SV frames was measured. Also, the effect on the clock offset of time synchronization in IEEE 1588 was analyzed.

2. Related works

IEC 61850-9-2 standard defines SV protocol as publisher/subscriber type communication. SVs are currently used to deliver instantaneous current and voltage samples from current transformers (CTs) and voltage transformers (VTs) to an SCN. Examples of the sampling frequency for raw data for protection and control in IEC 61850-5 are 480, 960, and 1920 Hz, and examples of the sampling frequency for raw data for metering are 1500, 4000, and 12000 Hz (IEC, 2003).

A local area network (LAN) can be logically divided into different broadcast domains by using virtual local area networks (VLANs). When a VLAN is configured, only the terminals belonging to a specific VLAN can access, transmit, and receive data on that VLAN. Also, unicast, broadcast, and multicast frames can be sent within the same VLAN. In addition, network performance can be enhanced by using VLANs because unnecessary broadcast and multicast packets need not be sent to other VLANs. Furthermore, it makes it easy to configure the network because terminals can be connected logically without relocating them physically.

The size of a typical IEC 61850-9-2 SV frame, including the Ethernet and 802.1Q headers, is 125 octets long. It takes 133 octets to transmit one SV

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frame: 7 octet preamble, 1 octet start frame delimiter, and 125 octet SV frame. When SV frames are transmitted at a sampling frequency of 960Hz, 1,021,440 bits are transmitted per second. The Cisco IE 4000 network switch used in this study operates at 10Mbps, 100Mbps, and 1 Gbps per port. If the experiment is conducted based on 1 Gbps, over 980 sources are needed to generate SV frames at a sampling frequency of 960 Hz to generate SV frames until congestion occurs. However, using more than 980 pieces of equipment creates severe financial and spatial constraints. If the experiment is conducted based on 10Mbps, it only takes nine or more sources to generate SV frames at a sampling frequency of 960 Hz to generate SV frames until congestion occurs. Therefore, in this study, the experiment was conducted by setting the transmission rate per port in the IE 4000 switch to 10Mbps to measure the VLAN effect in the experimental model. Table 1 shows the number of bits transmitted per second according to the sampling frequency.

Table 1: Bits transmitted per second according to sampling frequency

Sampling Frequency	Bits for Transmitting an SV Frame	Bits Transmitted per Second
480 Hz	133 x 8	510,720
960 Hz	133 x 8	1,021,440
1500 Hz	133 x 8	1,596,000
1920 Hz	133 x 8	2,042,880
4000 Hz	133 x 8	4,256,000
12000 Hz	133 x 8	12,768,000

IEC 61850 for substation automation and control recommends using version 2 of the Precision Time Protocol (PTPv2), IEEE Standard 1588-2008, for high accuracy time synchronization in substations. PTPv2 packets are exchanged for time synchronization with SV frames in SCNs. Table 2 shows IEC 61850 Protocols and Requirements and Fig. 1 shows the structure of the SV frame.

Table 2: IEC 61850 protocols and requirements

Function Type/Message		Protocol	Maximum Transfer Time	Priority	Application
1A. Trip	GOOSE	L2 Multicast	< 3 ms	High	Protection
1B. Other	GOOSE	L2 Multicast	< 20 ms	Medium High	Protection
2. Medium Speed	MMS	IP/TCP	< 100 ms	Medium Low	Control
3. Low Speed	MMS	IP/TCP	< 500 ms	Medium Low	Control
4. Raw Data	SV	L2 Multicast	< 3 ms	High	Process Bus
5. File Transfer	MMS	IP/TCP/FTP	< 1000 ms	Low	Management
6. Time Sync	Time Sync	IP (SNTP) L2 (PTP)		Medium-High	General Phasors, SV
7. Command	MMS	IP		Medium Low	Control

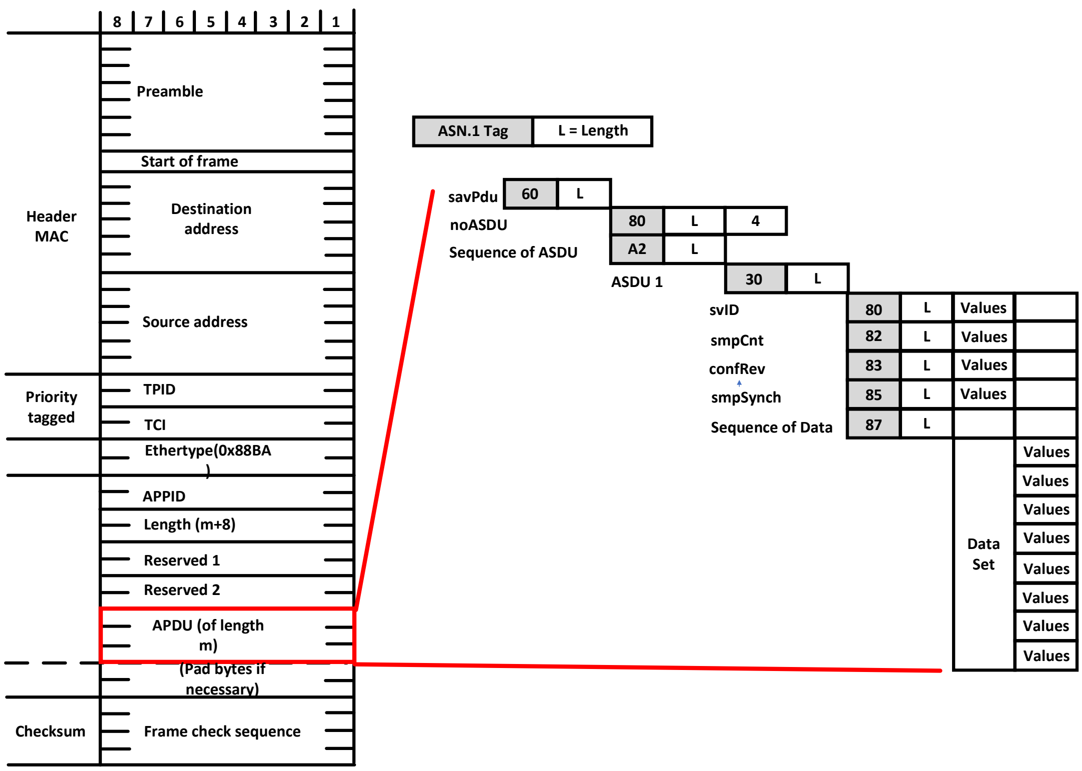

Fig. 1: Structure of the SV frame

3. System design and implementation

According to IEC 61850-5, all messages in a substation can be divided into seven types, as shown in Table 2. The cyclic data flow of SVs, which are raw data, is generated by periodic sampling of the CT and PT.

Fig. 1 shows the ISO/IEC 8802-3 frame format for an SV and the ASN.1 coded APDU frame structure. The ASDU dataset comprises four voltages and four currents (three phases and neutral for each).

SVs generated by the merging unit (MU) IEDs at the substation process level are delivered to the IEDs at the substation bay level, and the SVs contain time-critical information. Cyclic data are generated with a frame size of fixed length and same time intervals.

Cyclic data are modeled as shown in the following equations (Zhang et al., 2015).

$$M_c = f(L_c, N_c, D_c) \quad (1)$$
$$N_c = f_0 \quad (2)$$
$$D_c = S_c + E_c + R_c \quad (3)$$

where, L_c is the size of the cyclic data containing the frame header, address field, payload, and cyclic redundancy check field. N_c is the number of cyclic data arrived per unit time which numerically equals to the sampling frequency f_0 of IEDs. D_c is the time delay of a message from end to end, representing the sum of Ethernet delay E_c, pretreatment time of the sender S_c, and post-proceeding time of the receiver R_c. According to IEC 61850-5, an SV frame needs to be delivered within $D_s = 3ms$. SV frames are transmitted through a broadcast method without filtering. SVs are a typical cyclic data flow with a fixed frame size.

In IEC 61850, SV frames are delivered using specific VLANs. A port of a network switch is connected to a specific VLAN. SV frames are exchanged between switch ports that are used for the same specific VLAN. Switches using VLANs use the corresponding ports in the trunk mode, and IEEE 802.1Q is used as the trunk protocol. Since VLANs segregate traffic, multicast and broadcast SV frames are segregated by the VLANs. SV frames and PTPv2 packets can be delivered together or separately, depending on the VLAN configuration.

Using a unique time reference within an SCN is very important for properly managing complex tasks and monitoring the behavior of substations. IEEE 1588 can synchronize all IEC 61850 levels (Station, Bay, and Process) within an error range of 1 µs or less. Such accuracy is needed for synchrophasor measurements and the implementation of IEC 61850-9, in which the currents and voltages are digitalized.

Fig. 2 shows the functional diagram of the laboratory setup, which consists of SV publisher, SV subscriber, background traffic sources, PTP master, and network switch. A mini PC is used to configure the SV publisher, which transmits SV frames, and the SV subscriber, which receives SV frames. Background traffics cause traffic loads according to the sampling frequency and the number of sources. The SV publisher, SV subscriber, and background traffic sources perform synchronization when the PTP master sends time synchronization messages. The network switch is used to configure the VLAN and exchange SV frames and PTPv2 packets.

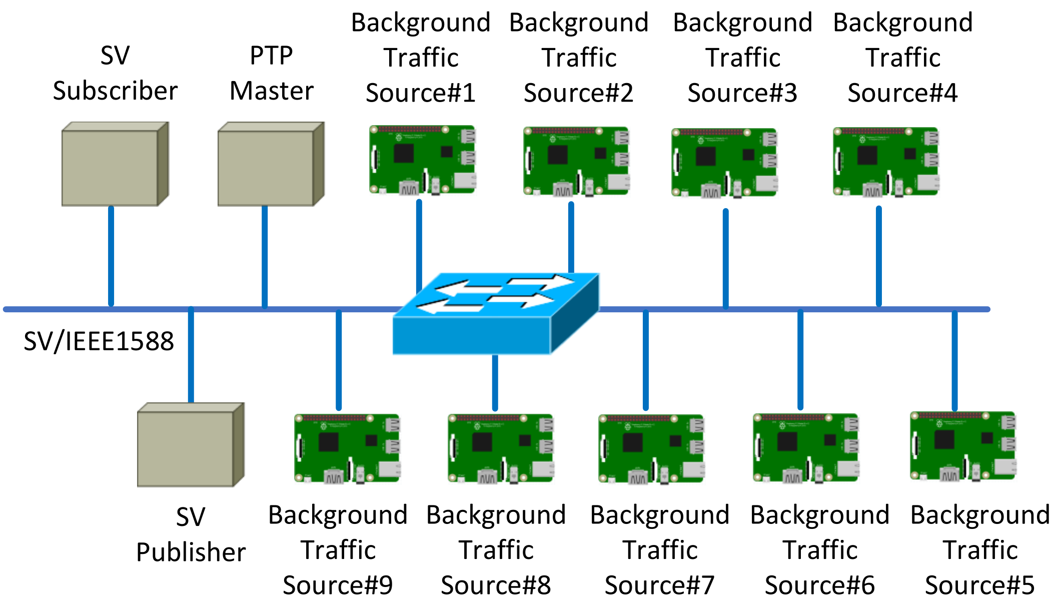

Fig. 2: Functional diagram of laboratory setup

4. Performance evaluation

Fig. 3 shows the hardware system used in this study. One mini PC is used for the SV publisher; one mini PC is used for the SV subscriber, and nine Raspberry Pi's are used to generate background traffic. One mini PC is used for the IEEE 1588 PTP Master to provide accurate time synchronization. One Cisco IE4000 switch is used as the network switch, and TShark is used to perform protocol analysis of SV frames.

Table 3 shows information about messages. The SV publisher delivers messages regularly according to the sampling frequency. The SV subscriber receives the SV frames transmitted by the SV publisher. The PTP master sends time synchronization packets once every second, and background traffic sources send SV frames according to the sampling frequency.

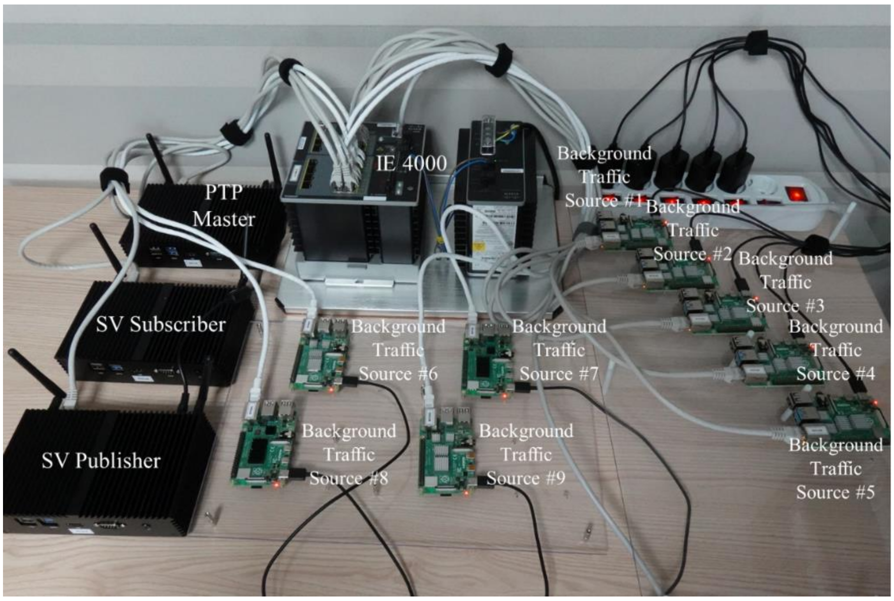

Fig. 3: Hardware system

Table 3: Detail information on messages

Device	Message Type	Sampling Frequency	Interval Period of Frame or Packet
SV Publisher	SV	480 Hz	2083333 ns
		960 Hz	1041667 ns
		1500 Hz	666667 ns
		1920 Hz	520833 ns
		4000 Hz	250000 ns
		12000 Hz	83333 ns
PTP Master	IEEE 1588	1 Hz	1 s
Background Traffic Source	SV	480 Hz	2083333 ns
		960 Hz	1041667 ns
		1500 Hz	666667 ns
		1920 Hz	520833 ns
		4000 Hz	250000 ns
		12000 Hz	83333 ns

Fig. 4 shows the diagram of the IEC 61850 SV frames generated cyclically. It can be seen that SV frames of fixed length are generated at fixed inter-arrival time intervals.

The mean transfer times were measured by transmitting 10,000SV frames, and Fig. 5 shows the measurement results.

When VLANs were not used, the mean transfer time increased rapidly as the total background traffic approached 10Mbps at each sampling frequency. However, when VLANs were used, all mean transfer times were below the reference value of 3ms regardless of the sampling frequency.

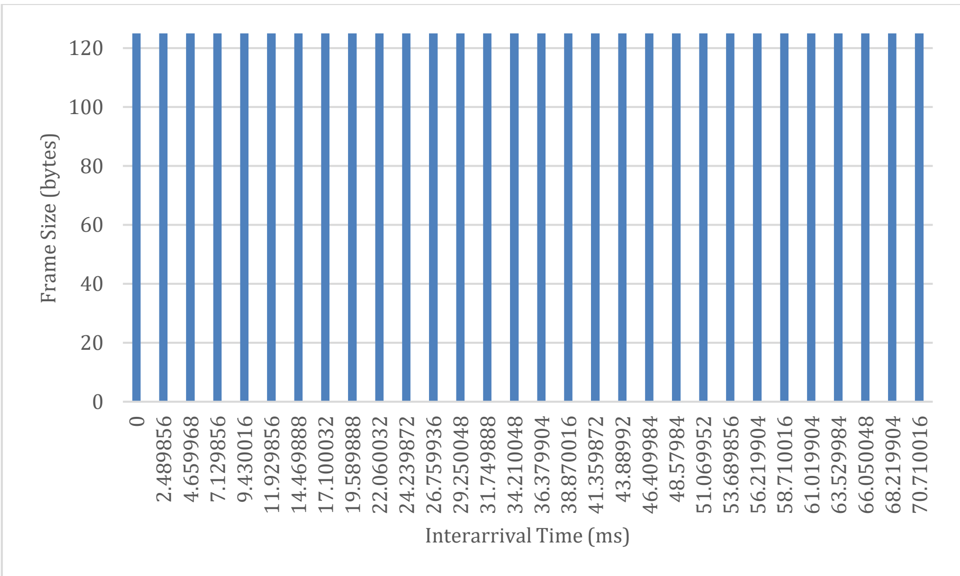

Fig. 4: SV cyclic data flow

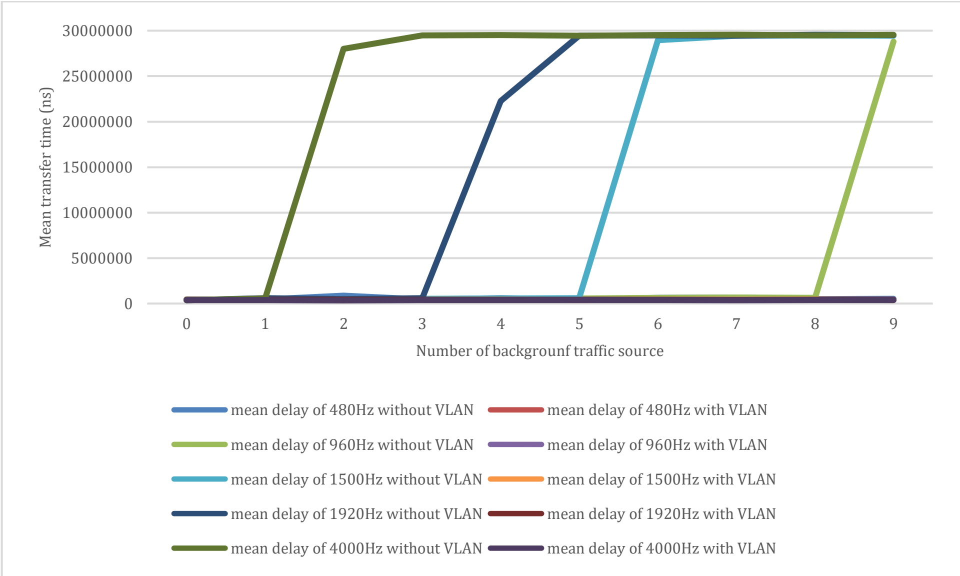

Fig. 5: Mean transfer time of SV frames according to VLAN and sampling frequency

The throughput of the SV frames was measured when 10,000 SV frames were transmitted, and Fig. 6 shows the measurement results. When VLANs were not used separately, it can be seen that throughput decreased rapidly as the total background traffic approached 10 Mbps at each sampling frequency. However, when VLANs were used, all throughput results were 100% regardless of sampling frequency.

When PTPv2 was used, it can be seen that it took approximately 10 s or more to synchronize the clock from the cold start, as shown in Fig. 7. Based on the experimental results of this study, the clock offset was stable within ±1000 ns after 10 s. In this study, SV frames were generated 100 s after a cold boot.

The mean, maximum, and minimum values of the clock offset were calculated depending on whether or not VLANs were used. As shown in Fig. 8, the mean is represented by red; maximum is represented by green, and minimum is represented by blue. Fig. 8 shows that the clock offset remains unaffected irrespective of the use of VLANs. Furthermore, the clock offset is not affected by changes in the sampling frequency.

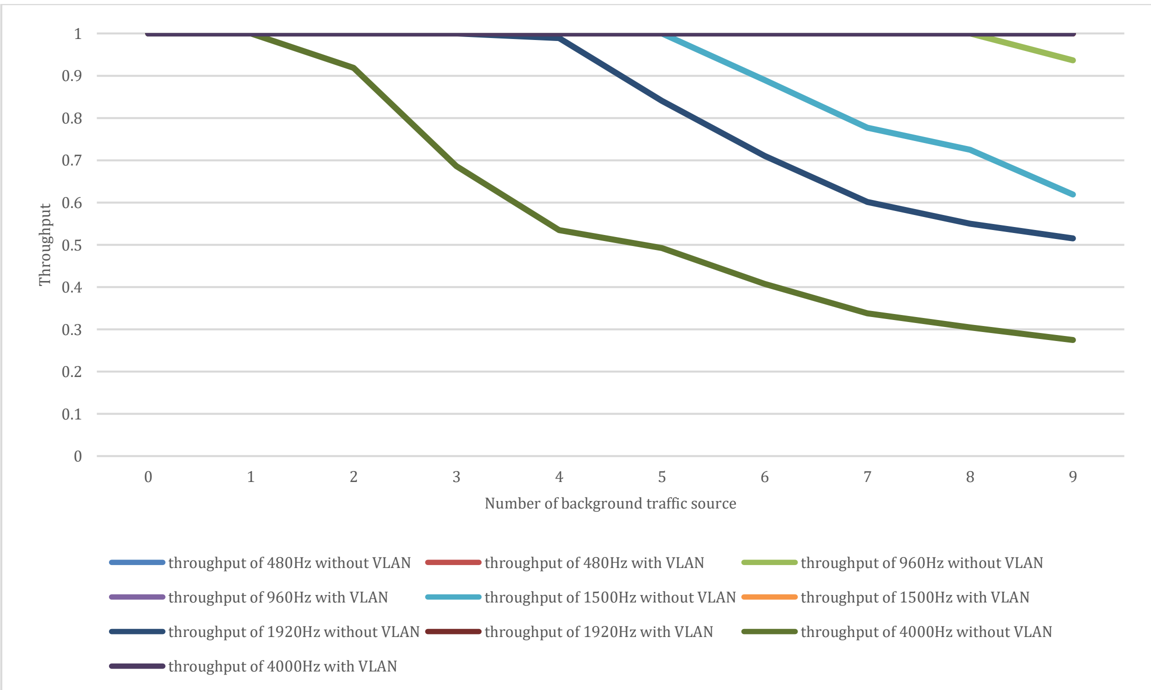

Fig. 6: Throughput of SV frame according to VLAN and sampling frequency

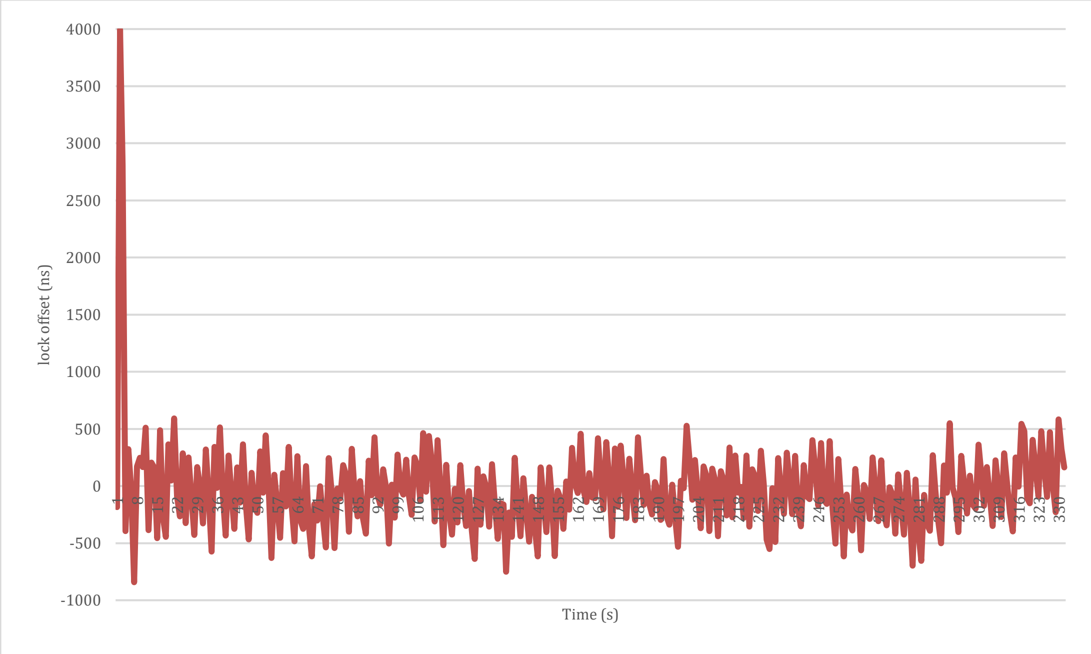

Fig. 7: PTP clock stabilization from cold boot

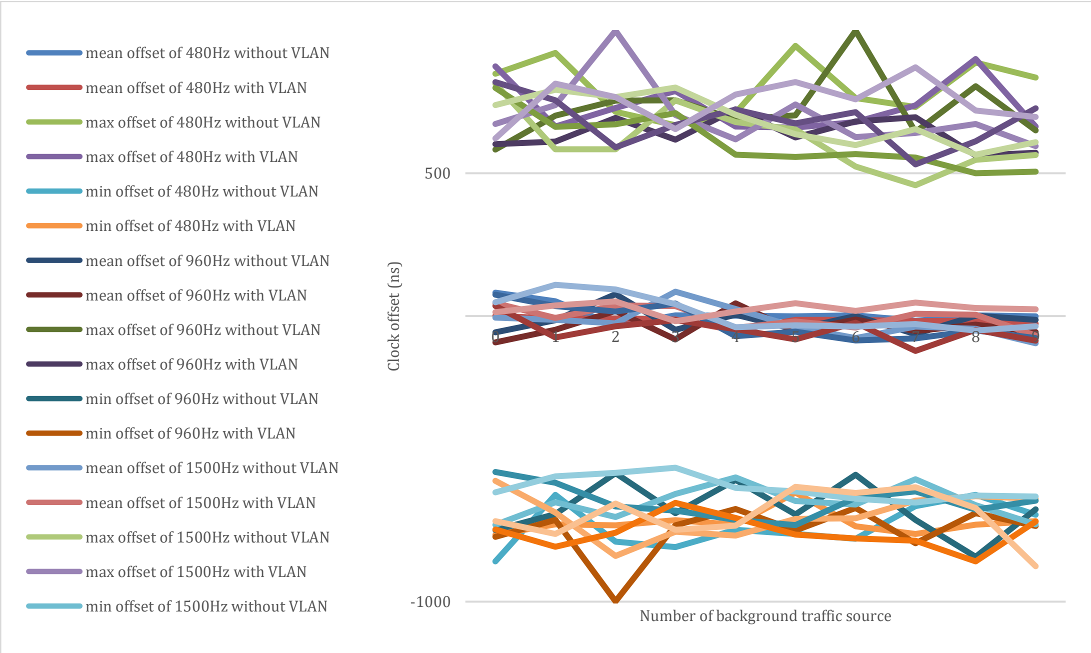

Fig. 8: Clock offset according to VLAN and sampling frequency

5. Conclusion

In this study, SV frames used in IEC 61850 and PTPv2 packets like IEEE 1588 were generated using a mini PC and Raspberry Pi. The protocol of SV frames and PTPv2 packets was analyzed using TShark.

The experimental results show that when VLANs were not used, the mean transfer time increased rapidly, and the throughput decreased drastically as background traffic volume approached 10Mbps. However, when VLANs were configured, the mean transfer time satisfied the reference value of 3ms, and the throughput was 100% as all transmitted frames were delivered. And the important thing is that the clock offset was not affected by sampling frequency or the use of VLANs.

The findings of this study will be useful for developing algorithms, applications, and prototypes in the IEC 61850 environment.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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