MTSFB TR 015:2023

TECHNICAL REPORT

LIGHTNING INTERFERENCE IN 4G WIRELESS COMMUNICATION LINKS

Preface

Malaysian Technical Standards Forum Bhd (MTSFB) has awarded Universiti Teknikal Malaysia Melaka (UTeM) the Industry Promotion and Development Grant (IPDG) to implement the Proof of Concept (PoC) of the Lightning Interference in 4G Wireless Communication Links. The duration of this PoC is for 12 months starting April 2021. The PoC is carried out in *Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer* (FKEKK), UTeM, Jalan Hang Tuah Jaya, 76100 Durian Tunggal, Melaka.

This Technical Report outlines the objectives, benefits, scope of work, methodology and result analysis.

Prepared by:

Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer
Universiti Teknikal Malaysia Melaka
Jalan Hang Tuah Jaya
76100 Durian Tunggal
Melaka, Malaysia

In collaboration with:

U Mobile Sdn. Bhd.
Berjaya Times Square
No 1 G17, Ground Floor East Wing
55100 Kuala Lumpur
Malaysia

Published by:

Malaysian Technical Standards Forum Bhd (MTSFB) 200401016865 (655368-P)
Level 3A, MCMC Tower 2
Jalan Impact, Cyber 6
63000 Cyberjaya
Selangor Darul Ehsan

Tel : (+603) 8680 9950
Fax : (+603) 8680 9940
Email : support@mtsfb.org.my
Website : www.mtsfb.org.my

mtsfbcyberjaya

Contents

Page

Abbreviations

For the purpose of this Technical Report, the following abbreviations apply.

4G	Fourth Generation
BER	Bit Error Rate
CG	Cloud-to-Ground
CLD	Consecutive Lost Datagram
CPU	Central Process Unit
EFM	Electric Field Mill
EM	Electromagnetic
FA	Fast Antenna
GPS	Global Positioning System
IC	Intra-Cloud
ITU-R	International Telecommunication Union Radiocommunications
LTE	Long-Term Evolution
MDF	Magnetic Direction Finder
NBPs	Narrow Bipolar Pulses
PC	Personal Computer
PER	Packet Error Rate
RTP	Real Time Protocol
SA	Slow Antenna
SINR	Signal to Interference & Noise Ratio
TCP	Transmission control protocol
UDP	User datagram protocol
VPN	Virtual Private Network

LIGHTNING INTERFERENCE IN 4G WIRELESS COMMUNICATION LINKS

Executive summary

This project aims to quantify and analyse the effect of lightning electromagnetic interference to 4G wireless communication links. Comprehensive experimentation has been conducted to measure low frequency and microwave electric field radiations together with User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) packets transmission over Fourth Generation (4G) wireless communication link during storm events.

A storm event is an event when lightning activity detected. In contrary, an event without detection of lightning activity is known as Fair-Weather (FW) event. It has been found that throughputs of data transmission over 4G wireless communication link have dropped below than 10 kbps for seven storm events. For other storm events, the throughputs dropped significantly (106-626 kbps) when compared to FW events (713-814 kbps).

Furthermore, the jitter and packet loss have been observed to drop significantly during storm events when compared to FW events. The maximum jitters during severe storm events were between 26.3 and 473.5 ms compared to FW events between 4.7 and 12.6 ms. The maximum packet losses during storm events were between 36% and 99% compared to FW events between 0% and 23%. Therefore, it can be concluded that lightning electromagnetic waves do interfere with 4G wireless links. The interference severity depends on the intensity of lightning activity.

Based on this study, a significant contribution to the understanding of lightning interference severity to 4G wireless communication links has been made. A quasi-empirical Throughput-Signal to Interference and Noise Ratio (SINR) model would be very useful for 4G network planning. The Throughput-SINR models can be used to reduce lightning interference, boost network speed, and very useful for low-latency applications of Industrial Revolution 4.0.

1. Background

Tropical regions are mostly characterised by heavy precipitation that causes deep signal fades on wireless communication links operating at frequencies approximately 10 GHz and above. One obvious example in Malaysia is signal losses experienced by satellite television operator. There are two specific standards associated with rain attenuation problem, namely International Telecommunication Union-Radio (ITU-R) P.530 and ITU-R P.618. The ITU-R P.530 standard provides detail recommendation on the planning and design of terrestrial digital line-of-sight systems considering several propagation effects including attenuation due to precipitation or solid particles in atmosphere. On the other hand, ITU-R P.618 standard provides detail recommendation on the planning and design of Earth-space communication links considering several propagation effects including absorption and attenuation due to hydrometeors in clouds (water and ice droplets).

On top of that, a new study reveals that electromagnetic (EM) radiation from lightning might be a potential candidate as one of interference sources to wireless communication links. The experimental study was conducted in Sweden focused on wireless communication links at 2.4 GHz and 5.8 GHz. Seven measurement campaigns had been conducted between year 2010 and 2011 and the analysis was done based on Bit Error Rate (BER) and Packet Error Rate (PER) records. The transmitted packet was arranged in a way that application layer at the server of the transmitting system emulated a RealAudio application broadcasting audio content from a multimedia compact disc-read-only memory or CD-ROM. The average sending data rate was 80 kbps. The size of the audio data was 1 MB. This data was transmitted using Real Time Protocol (RTP) over User Datagram Protocol/Internet Protocol (UDP/IP). The payload type of the RTP was G.729.

Lightning can be categorised into three types, namely Cloud-to-Ground (CG), Intra-Cloud (IC) and Narrow Bipolar Pulses (NBPs). Both IC and NBP are in-cloud events. The CGs are the most common lightning striking Earth. The study found that all lightning events (CG. IC, and NBP) interfered with the transmission of bits in wireless communication systems. The severity of the interference depends mainly on two factors namely the number of pulses and the amplitude intensity of the lightning. The NBPs are found to be the strongest source of lightning interference to multiple antennas wireless communication network operating at 2.4 GHz.

There is a wide misconception that lightning involves low frequency radiations only and therefore it does not interfere with microwave communication links. In contrary, lightning emits significant radiation components in microwave and even millimetre wave region. The research study on microwave radiation from lightning has been started decades ago with the first complete experimental works at 420 MHz and 850 MHz reported by Brook and Kitagawa in 1964. Kosarev et al. recorded microwave radiations at 400 MHz, 700 MHz, 900 MHz and 1300 MHz emitted by natural lightning at Lenin Hills of Moscow during the summer of 1968. Rust et al. reported measurement results of microwave radiations at 2.2 GHz captured from CG and IC flashes close to Kennedy Space Center (KSC) in Florida in July 1977. In 2001, Fedorov et al. set up a measurement system (included radiometer) to measure millimetre wave radiations at 37.5 GHz from CG lightning located 5 km from the radiometer. In 2013, Petersen and Beasley used a 1.63 GHz ceramic patch antenna to capture and analyse microwave radiations associated with CG flashes. Table 1 summarizes previous studies related to microwave radiation emitted by lightning.

In addition to studies on lightning microwave physics, studied the severity level of interference caused by natural lightning to wireless communication link at 2.4 GHz for audio streaming application. It was found that all types of lightning (CG, IC, and NBP) interfered with audio streaming transmission. Figure 1 shows statistical correlation analysis between BER, maximum Consecutive Lost Datagram (CLD) and all types of lightning. The interference level became worse when the number of pulses (return stroke) in a lightning flash increased and the amplitude intensity of pulses in a flash intensified. As can be seen from the correlation analysis plotted in Figure 1, all lightning events recorded BER values lower than 0.1 (and all above 0.001) except for the NBP event with peak value at 0.154. The acceptable BER value is below than 0.001 where very minimum errors occur.

Table 1. List of related studies on microwave radiation emitted by lightning

No	Year	Author	Frequency	Instruments	Lightning events
1	1964	Brook and Kitagawa	0.42 GHz and 0.85 GHz	Helical antennas (BW=200kHz)	CG and IC flashes
2	1970	Kosarev at al.	0.4 GHz, 0.7 GHz, and 0.9 GHz	Vertically polarizes omnidirectional dipole antennas (BW=1 MHz)	Observed noise-like bursts of radiation with the durations from a few hundreds of microseconds up to 10 ms.
3	1979	Rust et al.	2.2GHz	High gain parabolic antenna (BW=500 kHz)	Preliminary breakdown process (PBP), stepped leaders, initial return strokes, dart leaders, and K changes.
4	2001	Fedorov et al.	37.5 GHz	8-mm-wavelenght radiometer	Return stroke of CG flash.
5	2013	Peterson and Beasley	1.63 GHz	Ceramic patch antenna (BW=2 MHz)	Preliminary breakdown, negative stepped leader breakdown, negative dart leader breakdown and return stroke

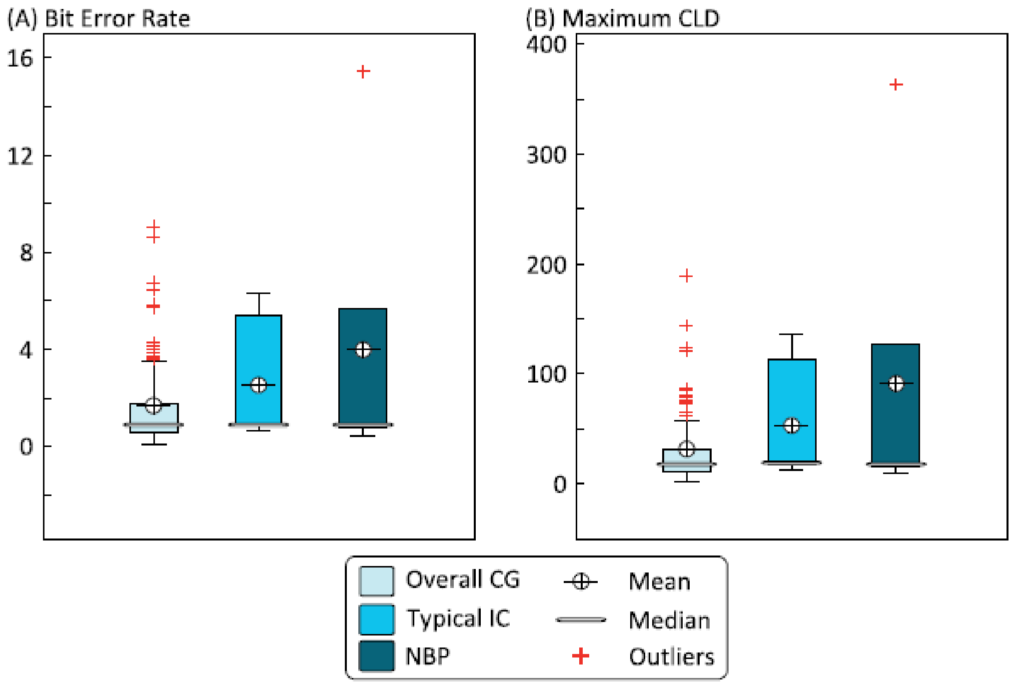


Figure 1. BER and max CLD vs. lightning types

Therefore, it can be concluded that during thunderstorms, the wireless communication network experienced mostly intermittent interference due to burst errors. Occasionally, in the presence of a very intense NBP event, the wireless communication network could experience total communication loss. The NBP is the strongest interferer to the bits transmission than other processes of lightning flashes such as CG and IC flashes (see Figure 2). Despite the fact that NBP consists of only a single bipolar pulse, it has been observed to interfere with the bits transmission more severely than typical IC and CG flashes. The typical IC and CG flashes consist of tens of individual bipolar pulses compared to the NBP with only a single bipolar pulse. Moreover, NBPs are most likely to occur more frequent in the tropics relative to high latitudes. Furthermore, NBP has been discovered to initiate both CG and IC flashes. These facts make lightning particularly microwave radiations of NBPs as a potentially severe large-scale interference source to 4G wireless communication links.

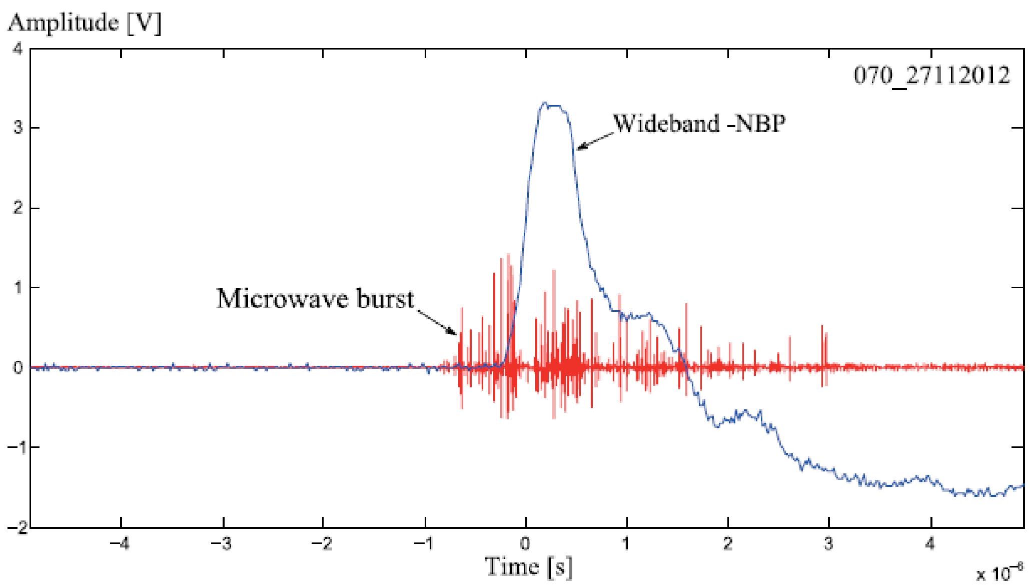


Figure 2. Microwave burst associated with low frequency NBP

2. Objective

The objectives of this PoC are as follows:

a) To design, develop and conduct experimentation of end-to-end traffic transmissions (TCP and UDP services) at 4G telecommunication sites provided by U Mobile synchronised with GPS-based lightning sensor.

b) To evaluate statistical correlation analysis of collected BER, PER and CLD records for all TCP and UDP services and remodel SINR and throughput existing models.

c) To propose a recommendation for new technical code or standard in Malaysia based on lightning factor as large-scale interference source in revised SINR and throughput models and possibly to submit for ITU-R recommendation.

3. Target groups and benefits

No	Target groups	Benefits
1	Community	Provide **awareness** and **information** about the interference from lightning to wireless communication systems particularly 4G as thunderstorms are very common in Malaysia.
2	Telecommunication operators	The target end users of the proposed standard to be used by telecommunication operators involved in design and planning of 4G wireless communication links. The proposed standard would provide detail recommendation in mitigating interference issues from lightning during thunderstorms events in Malaysia. Telecommunication operators will get a clear and detailed information about the interference from lightning to their cellular communication systems. Therefore, the telecommunication operators can plan and avoid negative impact of thunderstorms to their cellular communication systems.
3	Regulatory bodies	The regulatory bodies can use the outputs of this project as the inputs to formulate standards to be used as guide or manuals for telecommunication operators to ensure that the lightning interference is taken into consideration during the network planning for site-specific deployment. Moreover, the outcomes of this project in terms of lightning interference instrumentation can be used by the regulatory bodies or telecommunication operators for future drive tests for propagation study considering the lightning interference effect.

4. Scope of work

The site selected for this project was Postgraduate Laboratory 1, *Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer*, UTeM. This site is selected because it was near to a telecommunication tower that hosted U Mobile’s equipment. The duration of this PoC is for 12 months starting April 2021.

Validation exercise was conducted here as well.

The scope of work includes:

a) Experimental work

This project is an experimental work. The project involves software and hardware that is integrated to measure the interference of lightning to 4G LTE wireless communication links. The analysis of the measured performance parameters has been conducted using MATLAB software. The experiments have been conducted by students and the project leader.

b) Point-to-point topology

The network connection used in this project was point-to-point topology which only involved the client-server architecture. The point-to-point topology is easier to be monitored when compared to other topology that has multiple network nodes.

c) Limited area of setup

The whole setup of the project is conducted at Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer, UTeM. The area of setup is a suitable place for the project as the U Mobile's tower is located less than 500 m from the control room and lightning sensors located at the rooftop of the site.

d) U Mobile 4G network

The type of 4G wireless network that was used in this project is the P38 postpaid plans service provided by U Mobile. Other telecommunication services were not considered for this project. The postpaid plan used in this project was chosen because it provides broadband and unlimited data access and has been provided free of charge based on joint collaboration work between UTeM and U Mobile.

e) TCP and UDP protocols

The usage of TCP and UDP for this PoC is due to their popularity. The TCP and UDP are now dominating the internet protocols and the future will be based on TCP and UDP. This justifies the importance of the usage of these two protocols for this PoC.

f) Analysis software

The software used for this project were mostly open-source software that are available online. The software used for the experimentation were iPerf3, Wireshark, SoftEther VPN, and PicoScope. For the data analysis, they are processed using Microsoft Excel and MATLAB to generate the graphs and charts.

5. Methodology

5.1 Lightning interference experimentation and correlation analysis

This project has been conducted in 4 phases as illustrated in Figure 3:

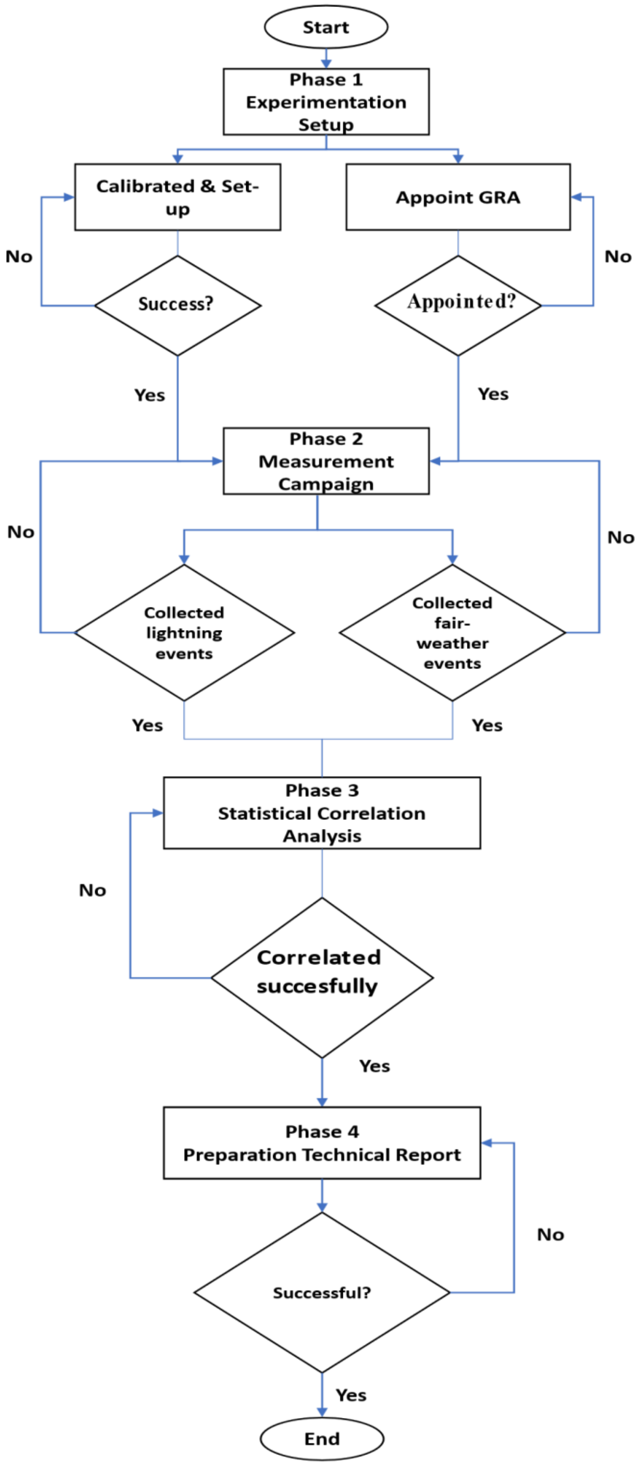


Figure 3. Flow chart of overall phases involved in this project

Phase 1: Experimentation setup

a) Duration: 3 months started on 1 April 2021 until 30 June 2021.

b) Tools used for this phase are a picoscope (digitizer), a high-accuracy GPS, two laptops (as server client pair) and lightning sensors (fabrication in UTeM).

c) Pilot experimentation conducted with traffic transmissions server client pair at 4G telecommunication sites provided by U Mobile. Figure 4 describes the overall architecture of measurement setup.

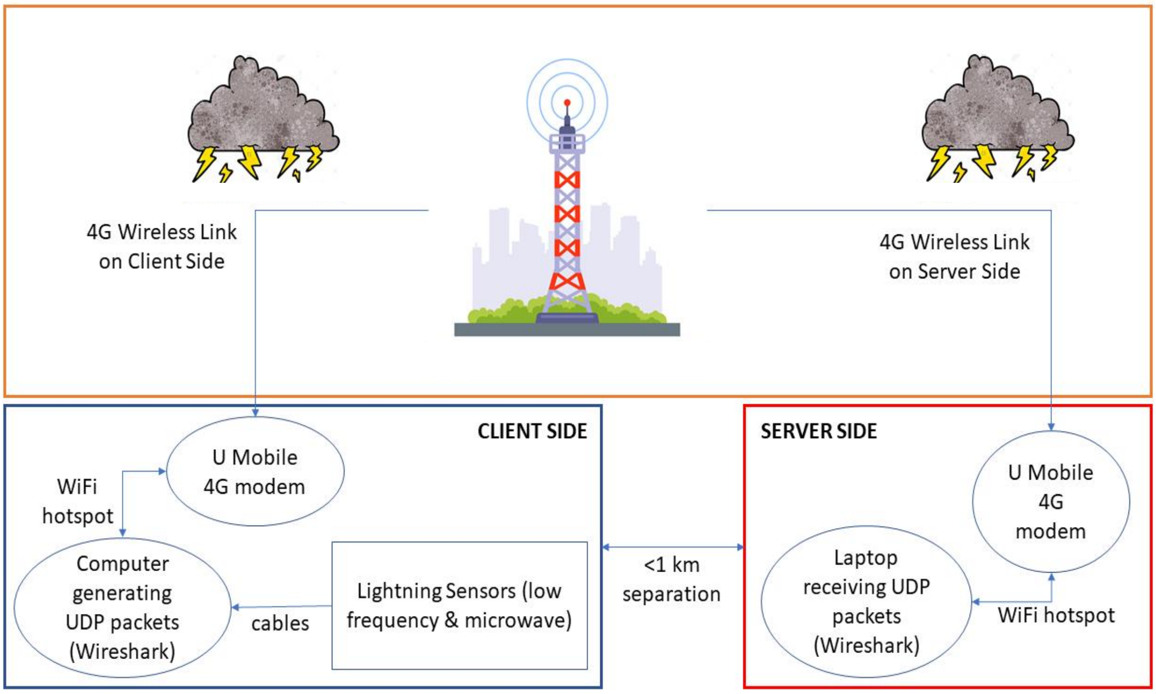


Figure 4. Visual diagram of the measurement setup

Phase 2: Measurement campaign and data collection

a) Duration: 5 months period between July 2021 and November 2021.

b) Measurement campaign and data collection have been conducted between October 2021 and November 2021.

c) A 4G network performance tools (Iperf, Wireshark) have been operated in synchronous with lightning sensor (low frequency and microwave sensors) where both systems were GPS time-stamped.

Experimental setup

The visual diagram of the measurement setup is shown in Figure 4. It consisted of electric field measurement for low and microwave frequency components and data transfer performance measurements. The full measurement campaign consists of five (5) measurement tools:

a) iPerf is used to quantify 4G wireless link performance in terms of throughput, packet loss, and jitter.

b) Wireshark is used to make sure the packet transmissions are correct. Figure 5 shows an example of monitoring UDP datagrams transmission using Wireshark.

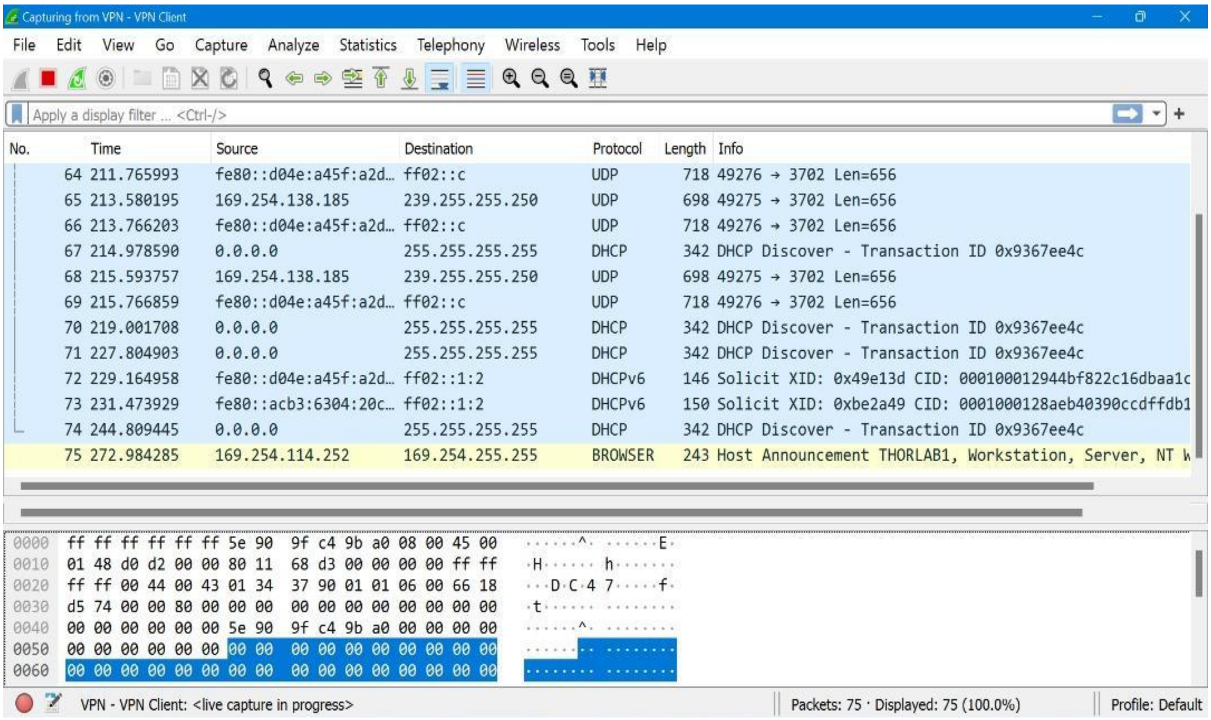


Figure 5. An example of how Wireshark was used to monitor UDP and TCP datagrams transmission

c) PicoScope as shown in Figure 6 is used to digitize electric fields of lightning radiations at 4G microwave band within 20 to 30 km from the lightning sensors. The specifications of the PicoScope that was used is as follow:

Figure 6. PicoScope 6404C

d) CAPPI radar which also known as 'Radio Detection and Ranging' consists of a transmitter that generate a high frequency signal where the signal sent from an antenna and the target will reflect the echo to the receiver (it receives back the echo from the target). Constant Altitude Plan Position Indicator (CAPPI) radar image shows the intensity of water droplet in illustration that can be observed from Malaysian Meteorology Department's (MET) official website. Figure 7 shows an example of CAPPI radar format at 2 km altitude for peninsular Malaysia for analysed storm on 12 November 2019 at 16:20:08 Malaysia Time (MYT) where the circle is the lightning sensor in Malacca (adapted from MET). The measurement of water droplet intensity (precipitation) by the weather radar at 2 km altitude for peninsular Malaysia (Figure 7) is based on how much radiant energy radar reflected by the grains of water in the cloud and is represented by the Reflectivity product which has dBZ (decibel). When the reflected radar energy increase, the dBZ also increases while the greater the dBZ reflectivity value, the greater the rain intensity. Moreover, the dBZ value is an indication to the intensity of the rainfall rate. Thus, if the area of region in Peninsula Malaysia fills with yellow to orange, it can be observed that lightning is intense in that region during that time (refer Figure 7). Meanwhile, blue and green indicate that the region covered happen to occur rain without the lightning activities detected. Usually, the use of CAPPI radar is to identify or to see the evolution of thundercloud and the intensity of thundercloud. Normally data provided by Malaysian Meteorology Department (MMD) covers 2 km altitude for peninsular Malaysia and the sampling time is every 10 minutes.

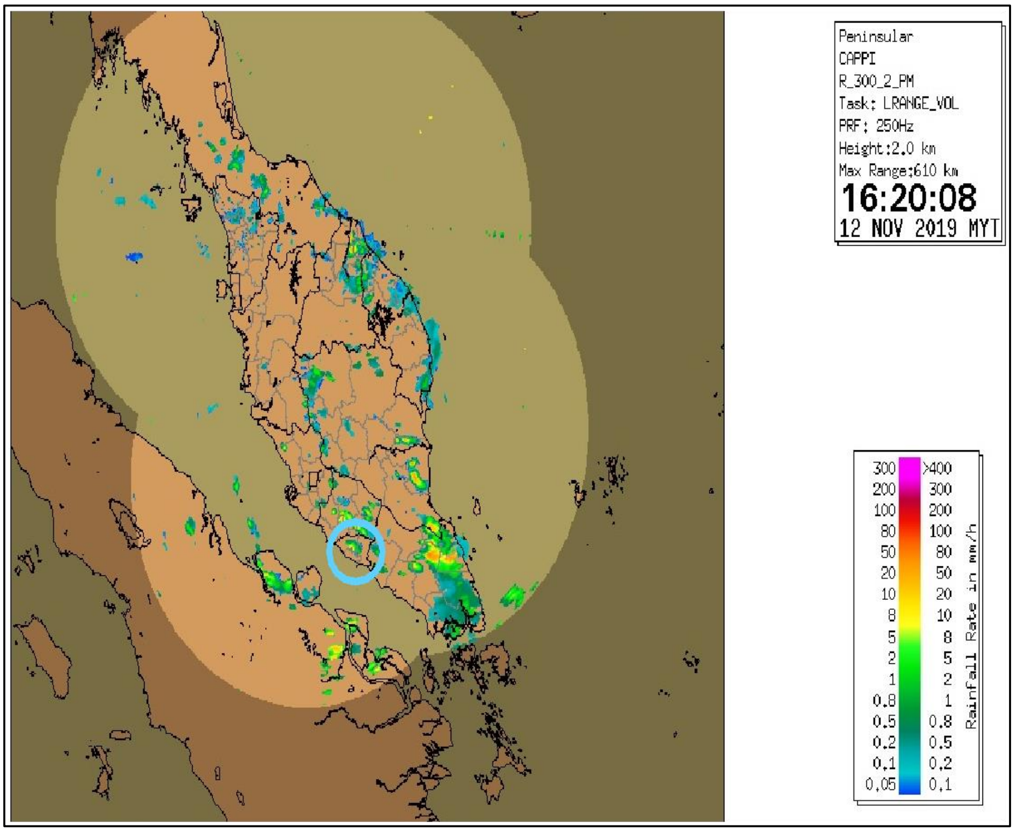


Figure 7. Example of CAPPI radar provided by Met Malaysia on 12 November 2019

e) Electric Field Mill (EFM) is used to monitor approaching thunderclouds. Measuring the static electric field generated by thunderclouds, the Boltek EFM-100 not only detects nearby lightning but can detect the atmospheric conditions which precede lightning. The electric charge contained in a thundercloud also generates an electric field. This field can be measured on the ground. Electric fields develop wherever there is a difference in electric potential. Electric field is measured in Volts per meter (3.3 feet) The electric fields which accompany thunderstorms normally measure in the thousands of Volts per meter, usually abbreviated to kVpm. Lightning is detected as a sudden change in the static electric field.

Figure 8. Electric field mill Boltek EFM-100

Verification of storm and lightning events

The measurement campaigns were carried out on three different weather situations namely fair weather, mild storm, and severe storm to verify the existence of lightning from thunderstorm that interfered with the 4G wireless communication links. The methods of thunderstorm validation were done by using CAPPI radar data, EFM data, lightning mapping using magnetic direction finder (MDF) and lightning intensity (from fast antenna records). From Figure 10, Storms 1, 2, and 3 happened on 29 and 30 October 2021 (Storm 1 – loss for around 4 minutes (282 seconds), Storm 4 happened on 1 of November 2021 (Storm 4 – loss for 43 seconds) while Storm 9 happened on 19 of November 2021 (Storm 9 – loss for 45 seconds). Before Storm 1, the intensity of the EFM record was almost zero and could be identified as fair-weather (FW) condition.

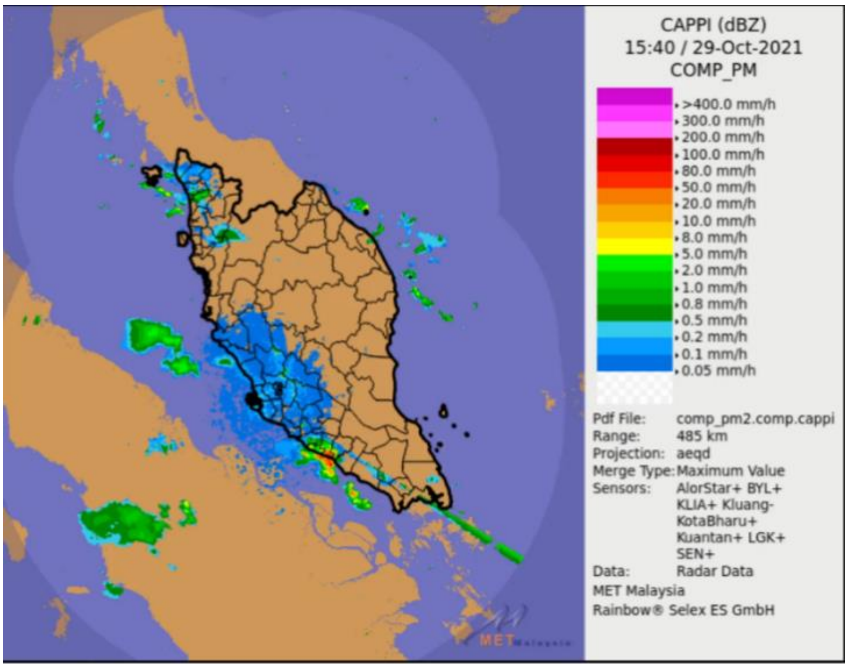


Figure 9. Radar image shows intense storm in Malacca

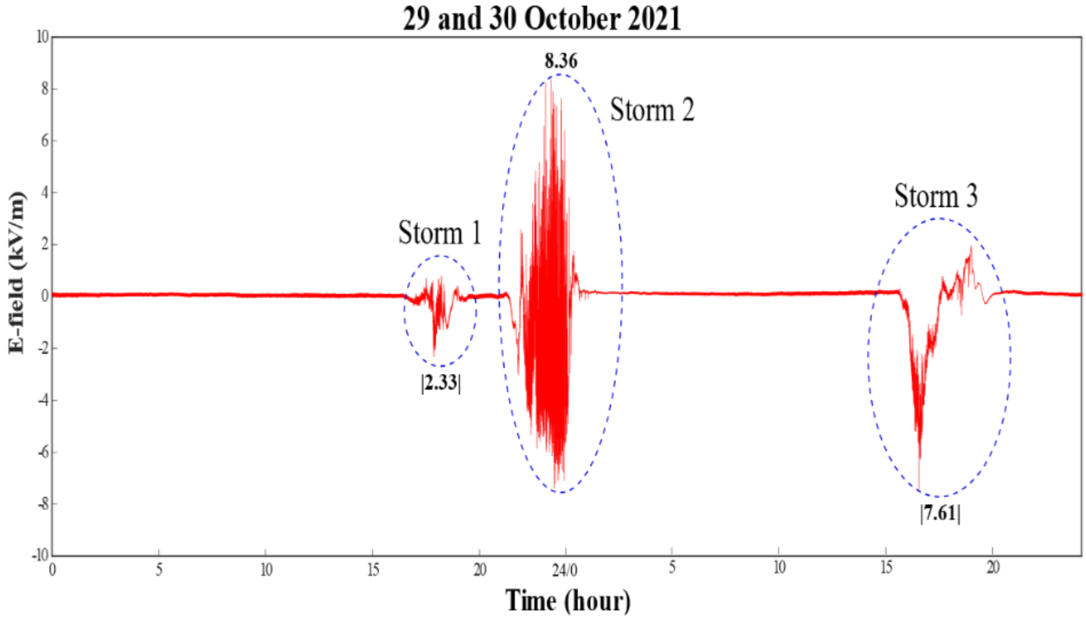


Figure 10. Background electric field measured by using EFM sensor

Low frequency and microwave electric fields radiated by lightning

Lightning flashes emit electromagnetic fields across wide band of frequencies. To characterise the type of lightning flash based on the emitted electromagnetic fields, a buffer circuit for electric field system has been designed. An example of electric field waveform can be seen in Figure 13 (Blue). The buffer circuit used to filter the range of frequency emits by the lightning flashes for frequency between 10 Hz up to 10 MHz. The system consists of air-gap parallel plate antenna made of aluminium or FR4 copper plate connected to a filter circuit by using BNC connector. The filter circuit is connected to Picoscope 6824E by using 20-meter RG58 cable.

To construct a buffer circuit as shown in Figure 11, there are several components that need to be considered in the circuit. The IC OPA 633 KP has been chosen as the buffer amplifier for the fast and slow electric field systems. This operational amplifier (op-amp) is categorised as high-speed buffer amplifier and it managed to isolate the high input impedance of the antenna. It also provides enough power to drive the signal from antenna to the oscilloscope. This IC OPA 633 KP is a monolithic unity gain high speed buffer amplifier which has a very wide bandwidth and high slew rate. The high output current capability will allow this IC to drive 50 Ω lines.

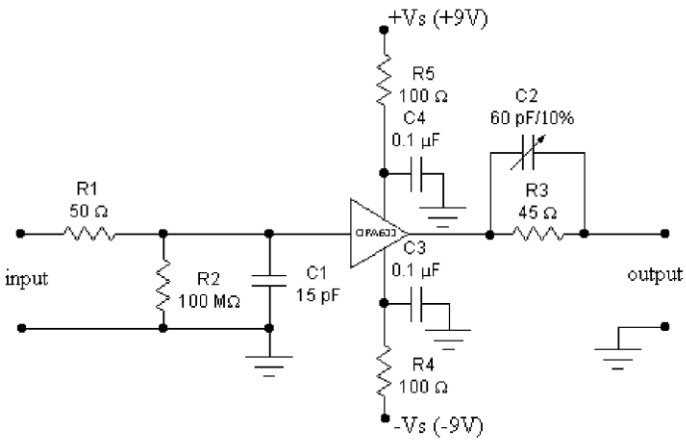


Figure 11. Circuit diagram of high-speed buffer amplifier circuit.

The antenna used is a fiberglass antenna as shown in Figure 12. This 4G omnidirectional antenna is designed for worldwide use. Suitable applications including GSM/LTE systems, machine-to-machine, and industrial systems. The ANT-GROD8-NSMA features N-type fixings and comes with brackets for optional wall mounting. This antenna also comes supplied with a 2-meter coaxial cable featuring a male SMA connector. The omnidirectional antenna has a frequency of 806 MHz to a max of 2700 MHz. The specification fits well with the required frequency range of U Mobile 4G band. The needed range is from 1800 MHz to 2100 MHz for band 1 and band 3 of U Mobile 4G network. An example of digitised microwave electric field radiation waveforms captured by this antenna can be seen in Figure 13 (magenta coloured waveform).

Figure 12. ANT-GROD8-NSMA omnidirectional antenna

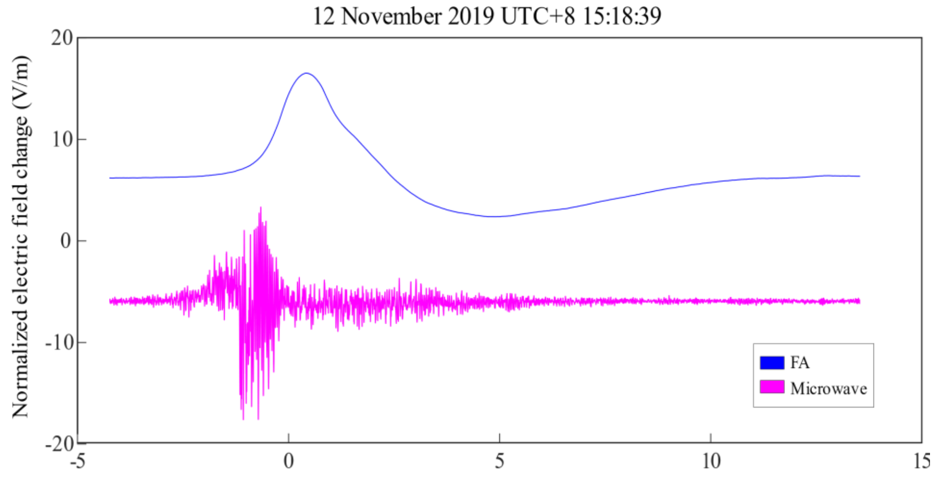


Figure 13. Example of fast antenna (low frequency) and microwave waveforms

The low and upper frequency components radiated from lightning flashes were digitised by using the PicoScope and stored in the laptop. From Figure 13, the blue is the low frequency electric field while the magenta is the upper frequency electric field. The sensors can identify the type of lightning based on the shape of the blue waveforms (FA). This is important to ensure that there was lightning event during the interference of the 4G communication links, and not detected from other electromagnetic sources. As the frequency band of 4G communication links around 2.4 GHz, a monopole antenna with centre frequency around 2.3 GHz was deployed together to record the microwave radiation associated with the lightning flashes. This could help to prove the high energy frequency components from lightning caused the drop in the data transfer communications.

4G network performance measurement

The measurement tools were running in parallel to collect sufficient data of lightning interference to 4G wireless links for statistical analysis. The comprehensive statistical analysis has been conducted in this stage. The full measurement has started on 21 October 2021. A total of 31 storm events data (Iperf, Wireshark, Picoscope, CAPPI Radar, and EFM) have been collected between 21 October and 23 November 2021. In addition to storm event data, baseline data (no lightning occasions or known as fair weather (FW)) have been collected for comparative study. The flowchart of the design and development of data transfer system is shown in Figure 14. The data transfer system consists of two main software that were essential to connect as well as measure the U-mobile data transmission. The software used are Iperf3 and SoftEther VPN. Two laptops were set up as client-server as transmission and reception of data packets between 4G communication links as shown in Figures 15 to 17.

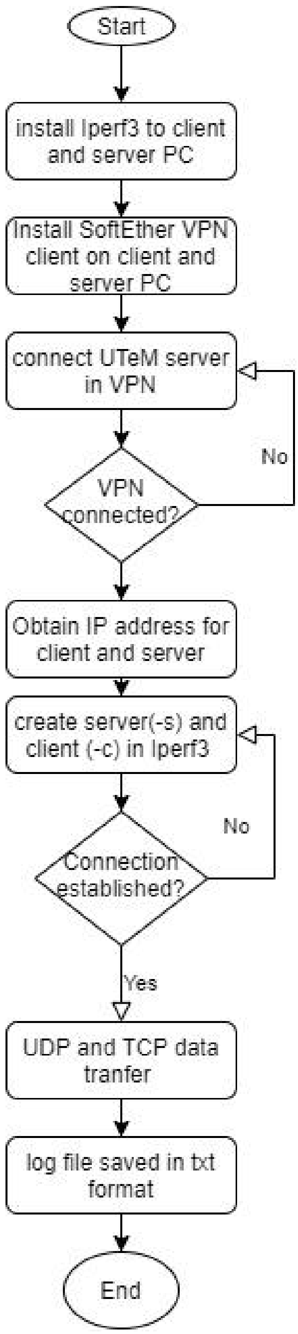


Figure 14. Flow chart for network performance measurement

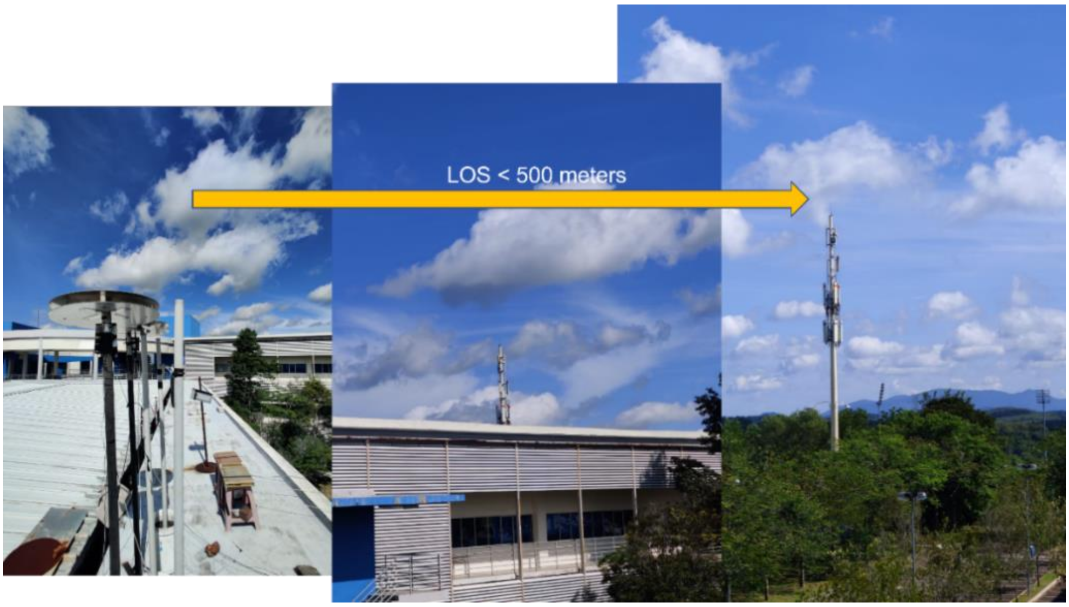


Figure 15. The telecommunication tower hosted U Mobile 4G equipment located less than 1 km from the lightning sensors

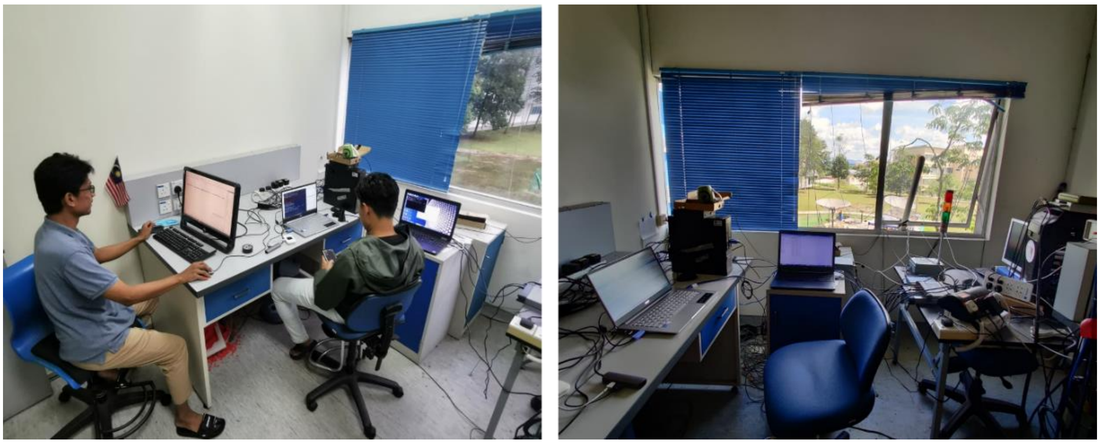


Figure 16. Measurement system monitoring and maintenance room

Figure 17. Client (left) and server (right) laptops

iPerf3 configuration

iPerf3 is a software tool that is used for network performance measurement and tuning. It can measure the maximum achievable bandwidth on IP networks. It is a cross-platform tool that can produce standardised performance measurements for any network type such as TCP, UDP, SCTP with variation of IPv4 and IPv6. For each on the network test, iPerf3 reports the bandwidth, loss, and other parameters. iPerf3 has client and server functionality and can create data streams to measure the throughput between the two ends in one or both directions. This is perfect to be used as well since it is an open-source software, and it met the requirement of the project which is to measure the TCP and UDP data transmission.

The configuration of the iPerf3 is detailed in **Annex A**.

Phase 3: Statistical correlation analysis

a) Duration: 2 months, December 2021 to January 2022.

b) Based on collected data, thorough analysis has been conducted focusing on throughput, jitter, packet loss, and CLD parameters with high resolution timing (down to 1 ps) comparison with lightning data. The processes related with the correlation analysis are provided in **Annex B**.

Phase 4: Preparation of technical report

a) Duration: 2 months, February to March 2022.

b) The first white paper has been presented at MyHVNet colloquium on 14 February 2022. The second white paper is in preparation to be submitted as journal paper.

c) A technical report has been written and submitted to MTSFB.

5.2 The rationale of the method

The most suitable method to measure the real interference effect from electromagnetic waves radiated by lightning is by using experimental technique rather than simulation or analytical. By conducting the experimentation:

a) Electromagnetic waves radiated by natural lightning can be detected and analysed. The lightning electromagnetic waves are the real contributor to the interference effect to wireless communication links.

b) To quantify the interference level, lightning electromagnetic fields are measured. These can only be done through experimentation.

c) The 4G network performance are synchronised with the lightning sensors by using GPS clock. The packets transmissions (UDP and TCP) are every 1 second. As lightning is impulsive event, 1 second packet transmission is the optimal duration to observe any interference effect to the packet transmission.

d) By performing real UDP and TCP packets transmission over 4G wireless links, the results are real and not from controlled simulation. The conclusion can be drawn strongly from experimentation results rather than simulation.

5.3 Method of analysis

This section covers the method to analyse the collected data. The overall flow chart of the analysis work is shown in Figure 18.

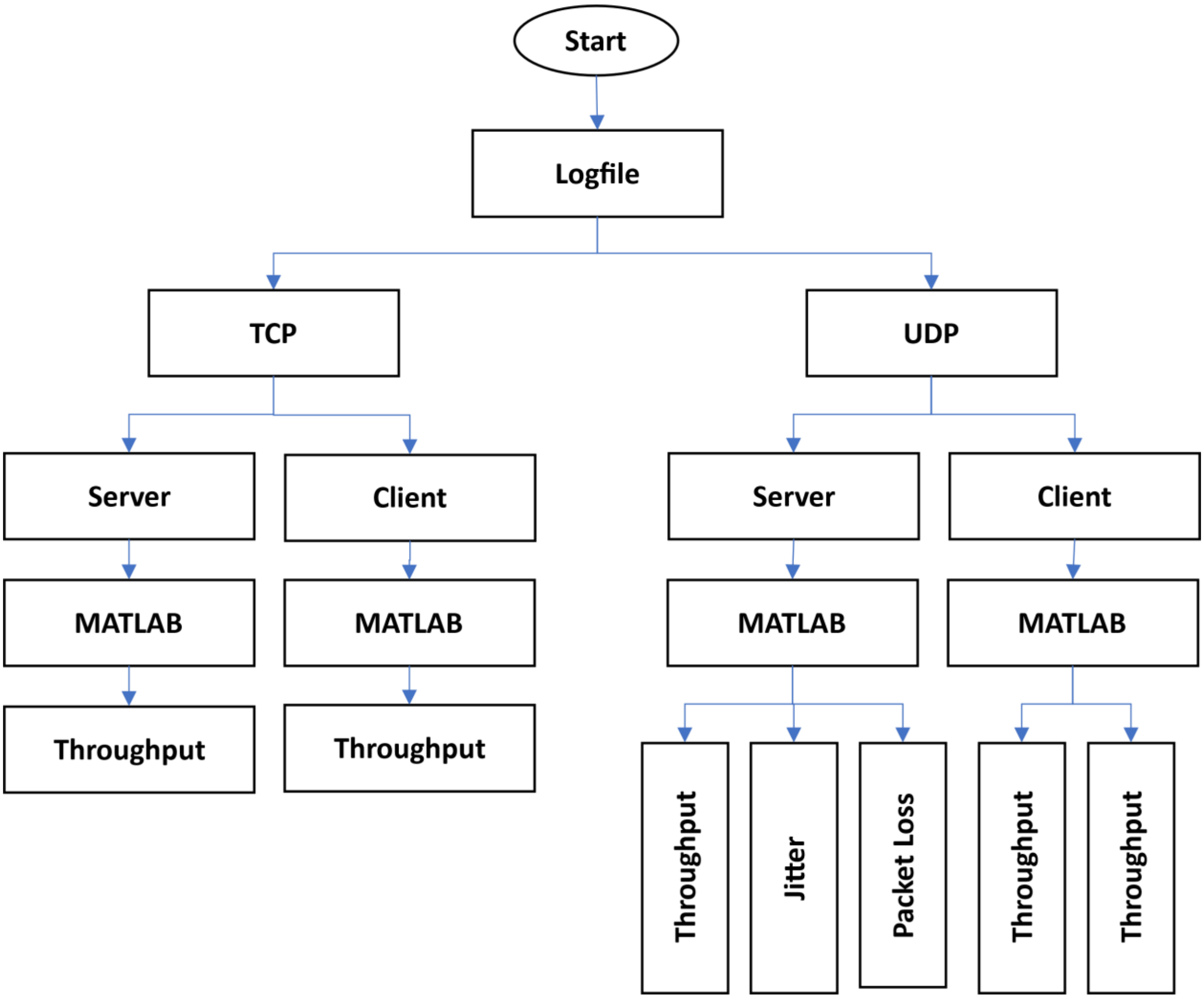


Figure 18. Overall flow chart of the method of analysis

5.4 Research tools and materials

This section listed the tools and materials used throughout the experimentation period. The tools are combination of self-made tools and commercial tools. The key equipment used are as follows:

Equipment	Specification
Electric Field Change Sensor (low frequency lightning sensor)	• Measure lightning waveforms for frequency between 10 Hz up to 10 MHz • Designed and fabricated in UTeM • Consists of air-gap parallel plate antenna made of aluminium or FR4 copper plate connected to a filter circuit by using BNC connector • The filter circuit is connected to Picoscope 6824E by using 20-meter RG58 cable
Broadband Microwave Receiver System (microwave lightning sensor)	• Measure lightning waveforms for 4G system frequency band • Designed and fabricated in UTeM. We have anechoic chamber and other facilities to design microwave radio system • Consists of an antenna, a low noise amplifier and a bandpass filter, all connected by using SubMiniature version A (SMA) connectors • The bandpass filter is connected to Picoscope 6824E by using 10-meter RG58 cable
Picoscope 6824E (digitiser)	• USB based digitiser where the display and data are stored directly in the laptop • The picoscope is connected to the laptop at the receiving side of 4G communication link • Bandwidth 500 MHz with sampling rate 5 Giga samples per second (GS/s), 12-bit vertical resolution and 4GB internal memory • 3 inputs are utilised where channel 1 is for electric field change sensor, channel 2 is for microwave sensor and channel 3 is for a Pulse per Second (1PPS) signal of GPS
High accuracy GPS receiver	• The output from GPS will be used to synchronise the time of the laptop at the receiving side of 4G communication link • The target accuracy is 1 ps • 1PPS signal from the GPS receiver will be recorded by Picoscope at channel 3
Laptops or CPUs	• 2 laptops or CPUs are set up as client-server at transmitting tower and at receiving side between 4G communication link. • At the transmitting laptop or CPU, traffic of various services are generated and will be transmitted over 4G wireless link by using U Mobile 4G infrastructure to the receiving laptop or CPU. • The performance of the link will be evaluated at the receiving side.

6. Findings

In this report, the analyses of 12 storm data and six fair-weather data are discussed. The correlation analysis has been conducted in terms of:

a) average or maximum or minimum throughput;

b) average or maximum jitter; and

c) average or maximum packet loss

2 scenarios have been observed:

a) 12 Storm data (validated with EFM sensor, radar, and lightning data) – severe and mild (duration of storms: 1 to 5 hours). (Refer Table 2).
b) 6 Fair-weather data (validated with EFM and radar data) – baselines with duration FW between 1 and 4 hours. (Refer Table 3).

Table 2. Details of 12 storm data

Date	Time	Scenarios
29-Oct-21	17:32-19:26	Very severe
29&30-Oct-21	22:54-23:59 00:00-01:27	Severe
30-Oct-21	14:35-23:58	Not severe
1-Nov-21	15:00 - 19:42	Very severe
9-Nov-21	12:29 - 20:19	Severe
10-Nov-21	16:41 - 23:14	Medium
12-Nov-21	12:47 - 15:52	Severe
16-Nov-21	12:33 - 18:32	Medium
19-Nov-21	16:21 - 23:28	Very severe
21-Nov-21	16:18 - 18:55	Medium
22-Nov-21	00:00 - 03:47	Medium
23-Nov-21	12:58 - 13:34	Severe

Table 3. Details of 6 fair-weather events

Date	Time	Scenarios
27-Oct-21	8:19-12:19	Fair-weather
27-Oct-21	13:05-13:21	Fair-weather
27-Oct-21	14:15-18:15	Fair-weather
28-Oct-21	17:43-17:47	Fair-weather
12-Nov-21	13:33-15:43	Fair-weather
14-Nov-21	15:35-23:35	Fair-weather

Figures 19 to 21 show the background electric field (EFM record) of 3 storms on 29 October 2021, 1 November 2021, and 19 November 2021, respectively (Storms 1, 4, and 9, respectively), when the throughputs dropped to 0 kbps. In total, seven storm events have been observed to be severe storms with throughputs dropped below 10 kbps.

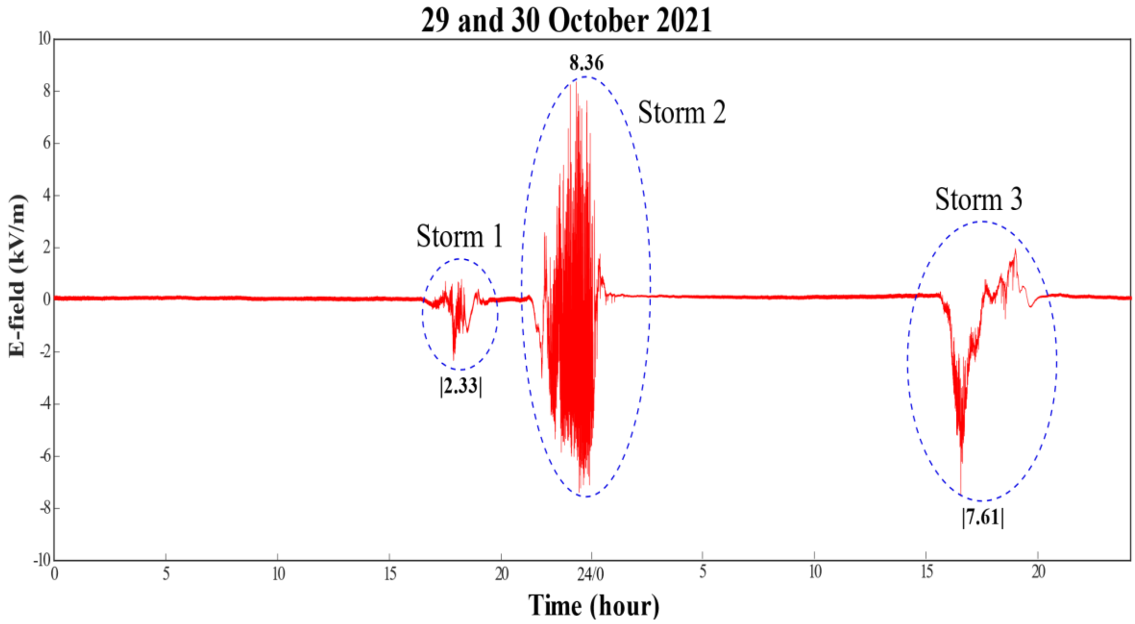


Figure 19. The background electric field records of Storms 1, 2, and 3 happened on 29 October 2021 and 30 October 2021.

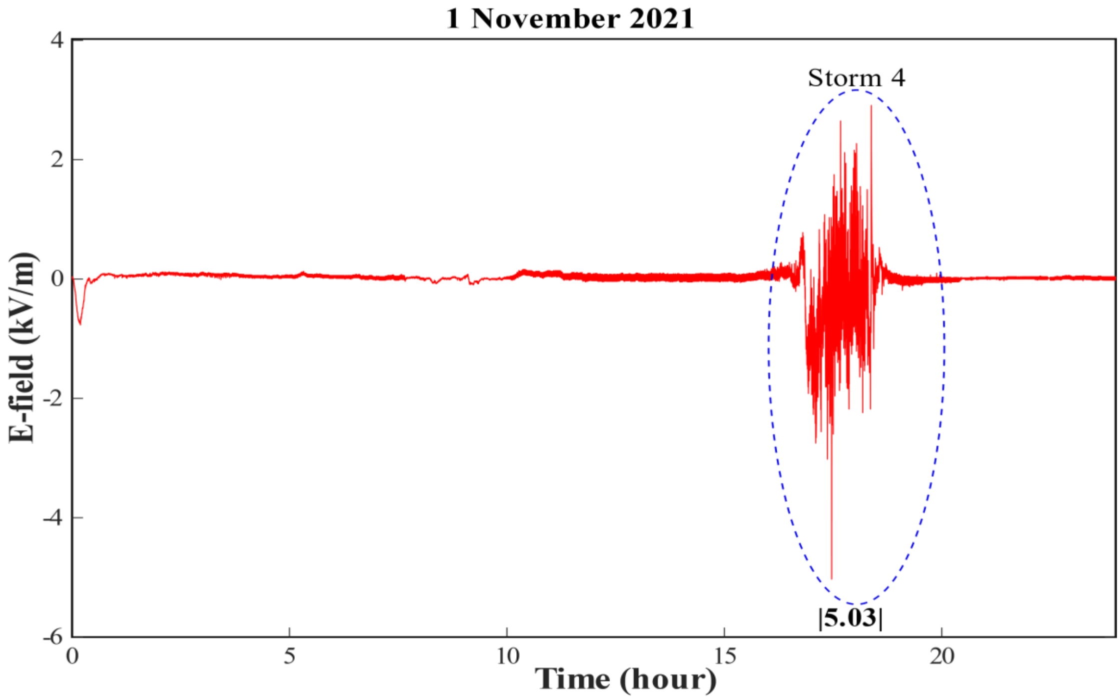


Figure 20. The background electric field records of Storm 4 happened on 1 November 2021

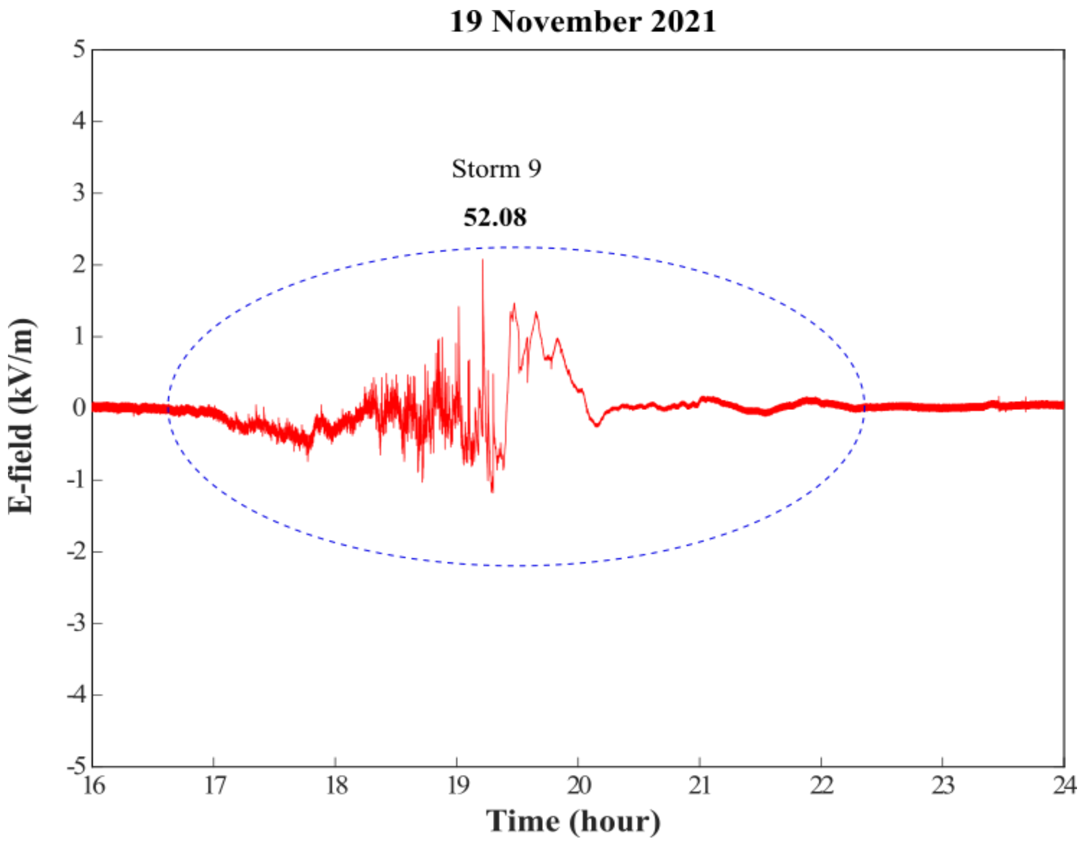


Figure 21. The background electric field records of Storm 9 happened on 19 November 2021

7. Results analysis

Based on the findings, a statistical correlation analysis between throughput, jitter, packet loss and storm and FW events have been formulated.

It has been found that interference effect from lightning events can be categorised into 2 scenarios:

a) When throughput drops to below than 10 kbps (0 to 10).

b) When throughput drops below than FW throughput but over 10 kbps.

Figures 22 and 23 show the relationship formulation of correlation analysis between lightning events and minimum or maximum throughput of 4G network. The throughput dropped significantly as lightning events became more severe. The index of lightning events was sorted from less severe to most severe. The throughputs of data transmission over 4G wireless link have dropped below than 10 kbps for seven storm events. For other storm events, the throughputs dropped significantly (106-626 kbps) when compared to FW events (713-814 kbps).

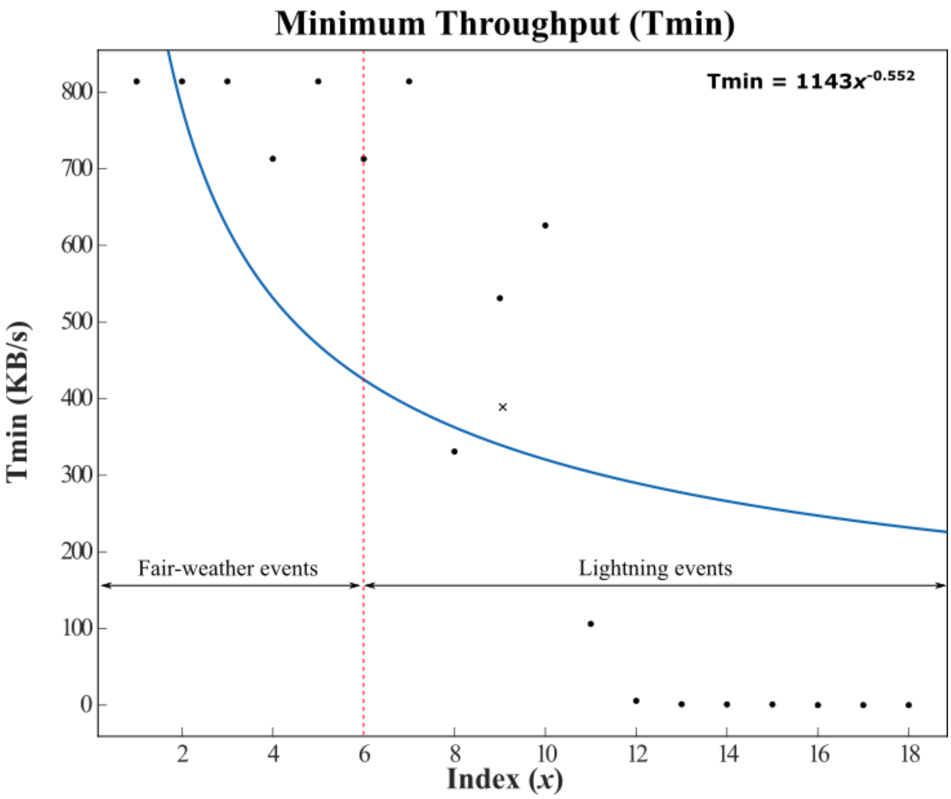


Figure 22. The relationship formulation of correlation analysis between lightning events and minimum throughput of 4G network

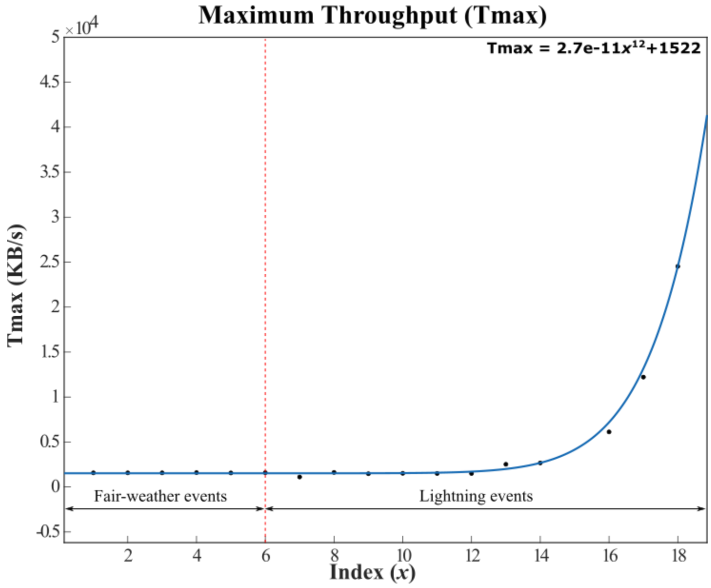


Figure 23. The relationship formulation of correlation analysis between lightning events and maximum throughput of 4G network

It can be observed that the minimum throughput (Tmin) of index 16 to 18 (Storms 1, 4, and 9) are 0. This means that no data transmission has occurred due to severe interference impact. When the result is compared to maximum throughout (Tmax in Figure 23), the throughput increased dramatically in order to re-transmit UDP datagrams. The re-transmission process of UDP datagrams happened because of lost connections due to severe interference impact.

Figure 24 shows the relationship formulation of correlation analysis between lightning events and maximum jitter experienced by 4G network. The jitter increased significantly as lightning events became more severe. The maximum jitters during severe storm events were between 26.3 ms and 473.5 ms compared to FW events which were between 4.7 ms and 12.6 ms. The jitter during the lightning events were higher compared to during FW events.

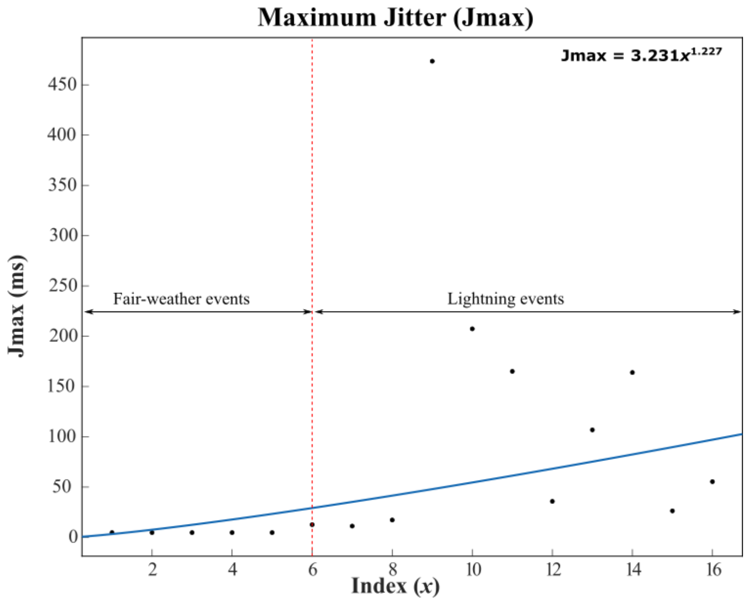


Figure 24. The relationship formulation of correlation analysis between lightning events and maximum jitter experienced by 4G network

Figure 25 shows the relationship formulation of correlation analysis between lightning events and maximum packet losses of 4G network. The packet losses increased steadily as lightning events became more severe. The maximum packet losses during storm events were between 36 % and 99 % compared to FW events which were between 0 % and 23 %.

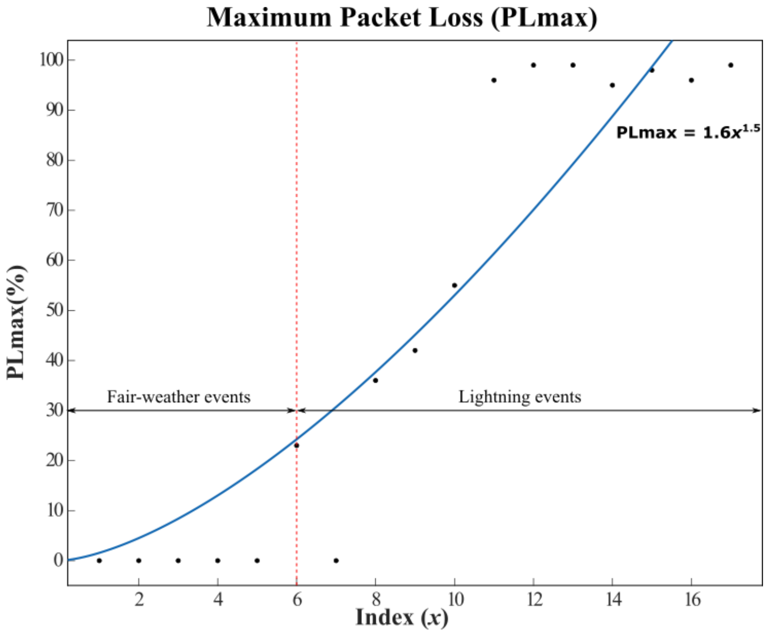


Figure 25. The relationship formulation of correlation analysis between lightning events and maximum packet losses of 4G network

Through numerical method analysis, the relationships between throughput of 4G network and lightning events are formulated as the following equations:

$$Tmax(x) = 27x10^{-12}x^{12} + 1522(kbps)$$
$$Tmin(x) = 1143x^{-0.552}(kbps)$$

Subsequently, the analyses of jitters and packet losses reveal statistical relationships between lightning events and 4G network performances (see Figures 24 and 25) can be formulated as the following equations:

$$Maximum\ Jitter = Jmax(x) = 3.23x^{1.23}(ms)$$
$$Maximum\ Packet\ Loss = PLmax(x) = 1.6x^{1.5}(\%)$$

8. Conclusion

In summary, it can be concluded that lightning electromagnetic waves do interfere with 4G wireless links. The interference severity depends on the intensity of lightning activity. Experimentation design and measurement campaign have been successfully conducted. Based on collected data from measurement campaign, the statistical correlation analysis has been formulated successfully for throughput, jitter, and packet loss performances. As this finding is novel, a proposal on lightning factor as large-scale interference source for technical code or standard is prepared.

Based on this PoC, a significant contribution to the understanding of lightning interference severity to 4G wireless communication links has been made. A quasi-empirical Throughput-SINR model would be very useful for 4G network planning. A recommendation for Technical Code (TC) is significant to be delivered to telecommunication industries. Throughput-SINR model can be used by telecommunication operators to reduce lightning interference. SINR mapped with the throughput during thunderstorm is a measure of interference strength. This can be used to estimate adaptive transmitted power or other suitable mechanism to reduce the effect of lightning interference. This PoC has a good prospect to be expanded to understand how lightning electromagnetic waves interfere with 5G wireless links at much higher frequency bands.

ANNEX A

(Normative)

iPerf3 installation guide

The iPerf3 installation guide is as below.

1. Download iperf3 for windows at https://iperf.fr/iperf-download.php.
2. Extract the files and copy it into C:\Windows\System32.
3. Open Command Prompt.
4. Type ipconfig to determine IP address of clients. Look at the VPN-VPN Client IPv4 Address.
5. Remember and record each IP address for clients. Run the Iperf3 codes as below to test the connectivity.
6. Assign one PC as server with these codes. [iperf3 -s]. The output should display 'server is listening on 5201'.
7. On another PC will act as client, run this code to send the data packets to server.
8. [iperf3 -c (server's IP address) -t(how many seconds)]
9. Then, the data packets will keep sending according to the time set.
10. To do a test while saving a log file. Use this code instead of in step 8. [iperf3 -c (server's IP address) -t(time in seconds) >> c:\iperf3\(name of the file).txt]. While running a test, command prompt will not show any display. After the test is done then we can see the data packets sent in the log file created. Go to C:\iperf3 folder to see the log file generated.

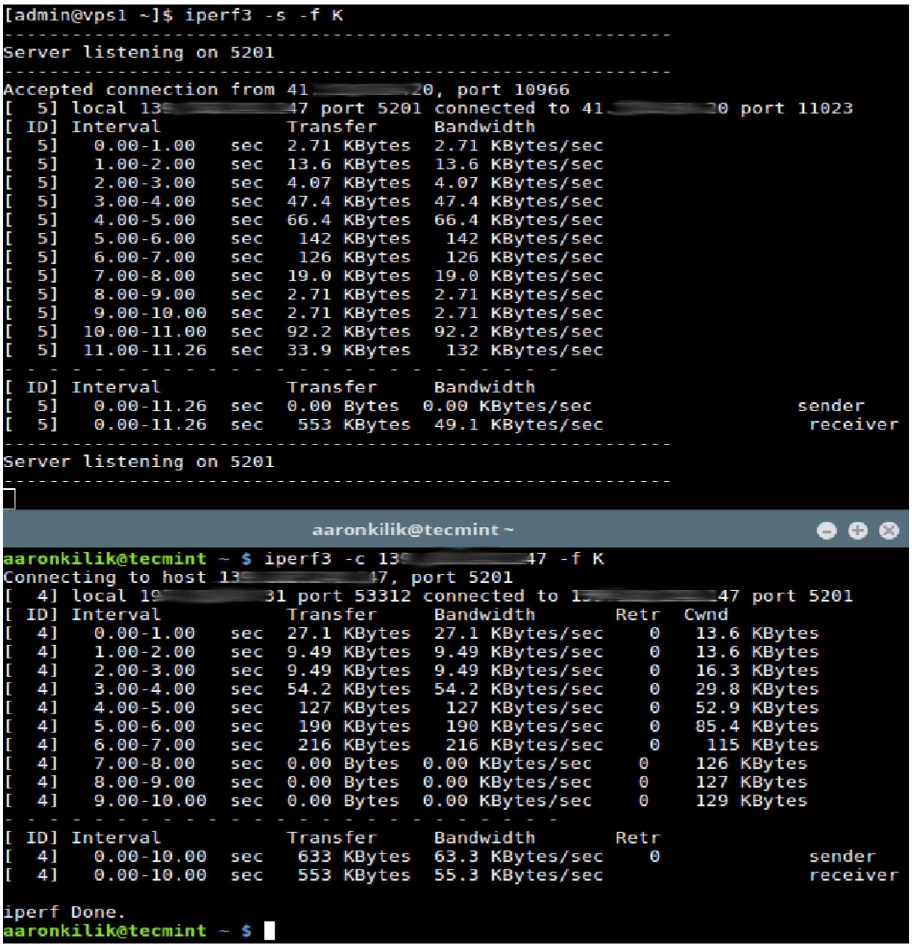


Figure A1. iPerf3 interface in window command prompt.

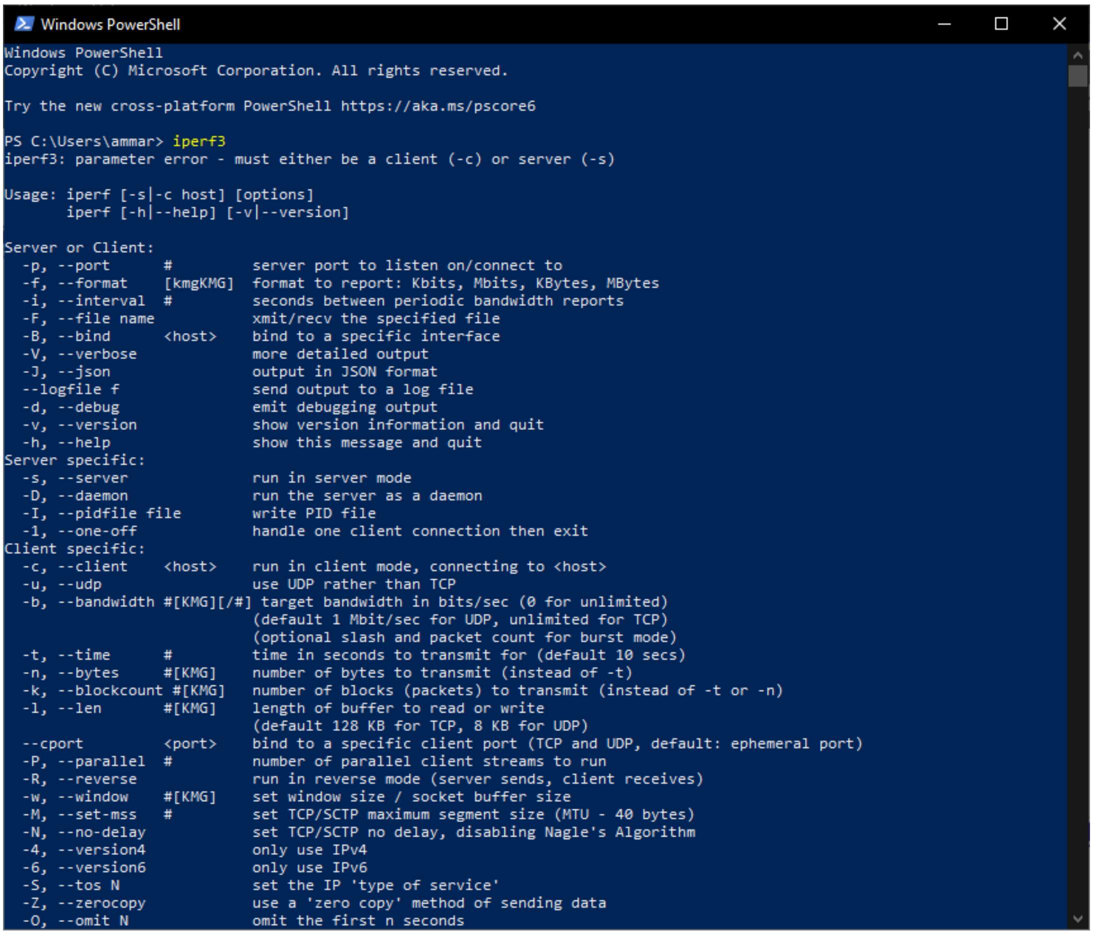


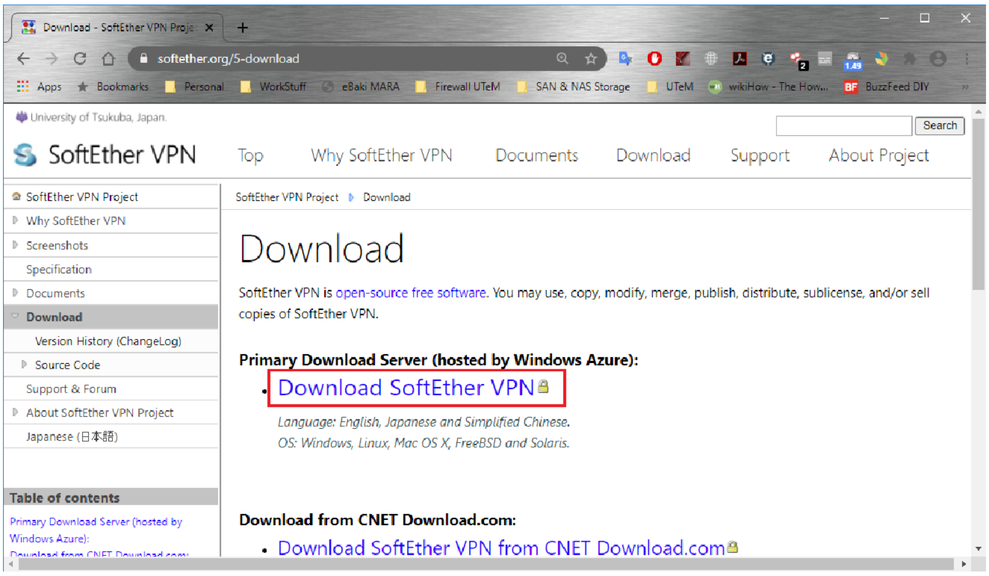
Figure A2. iPerf3 interface in Window PowerShell.

Softether VPN installation

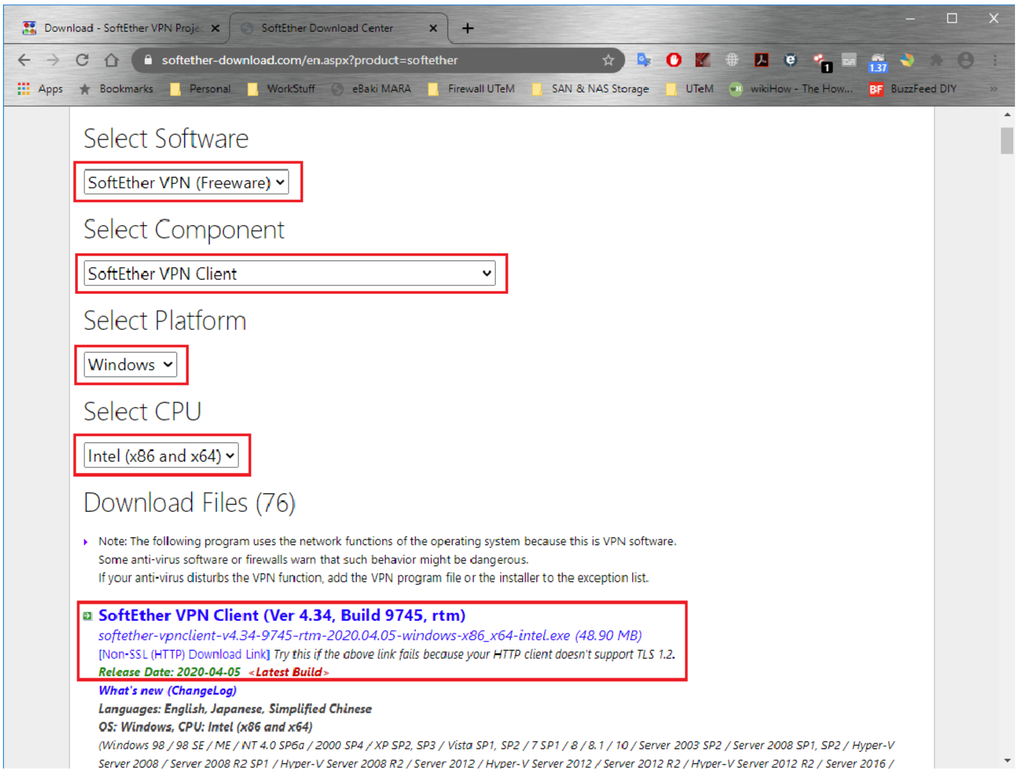
Install the software on both client and server laptops:

1. Click https://www.softether-download.com/en.aspx?product=softether

2. Select component SoftEther VPN client



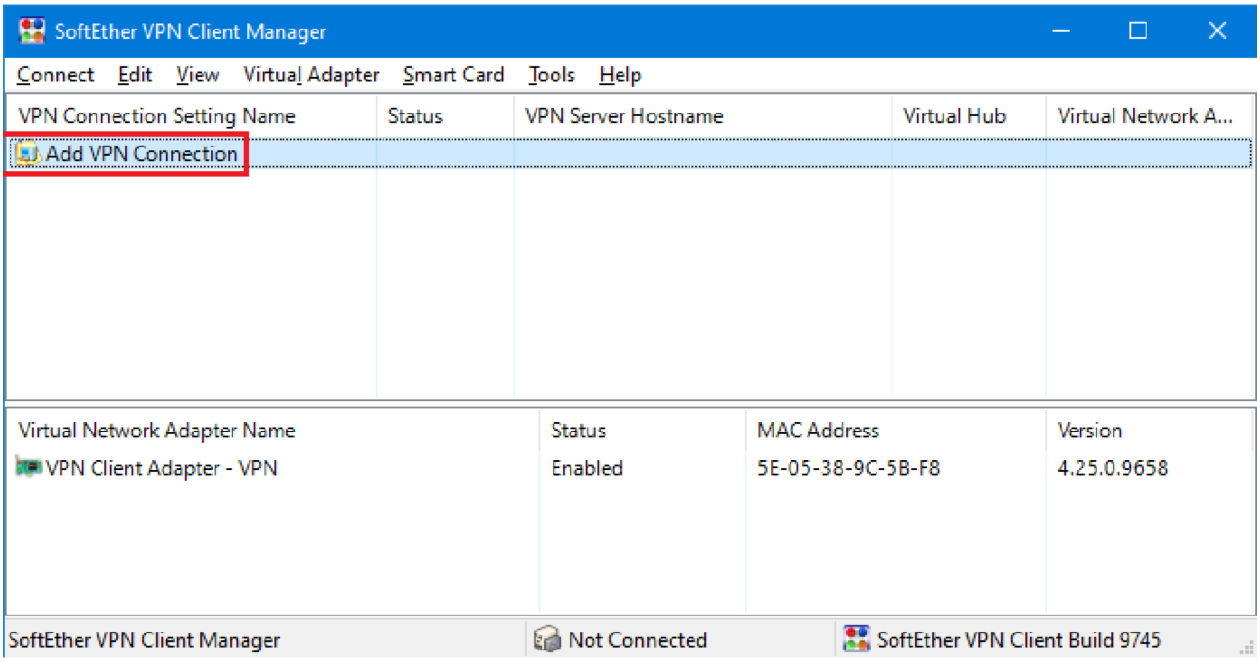
3. Select platform



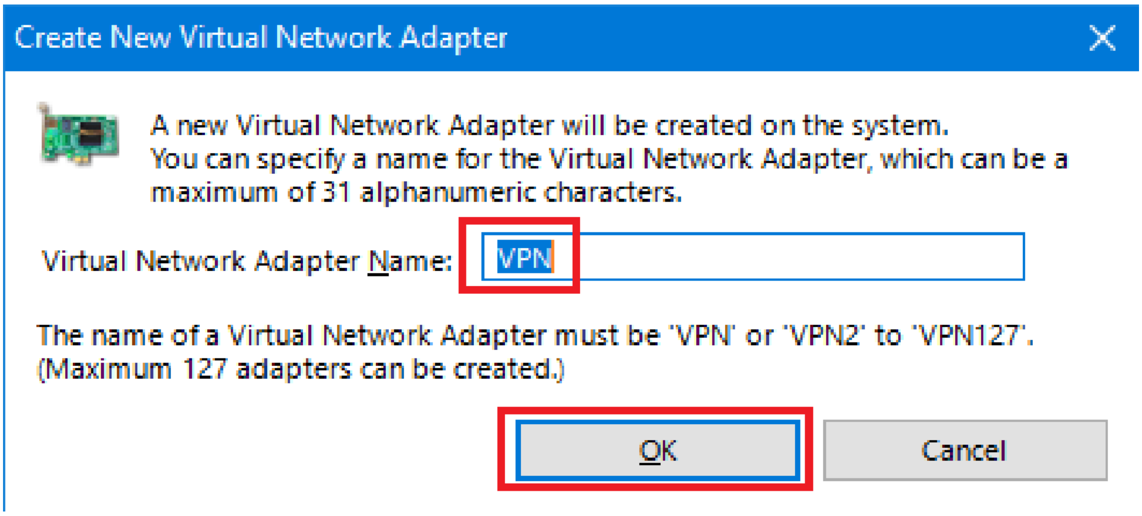
4. Click on SoftEther VPN Client (Ver 4.34, Build 9745, rtm)

5. Click install

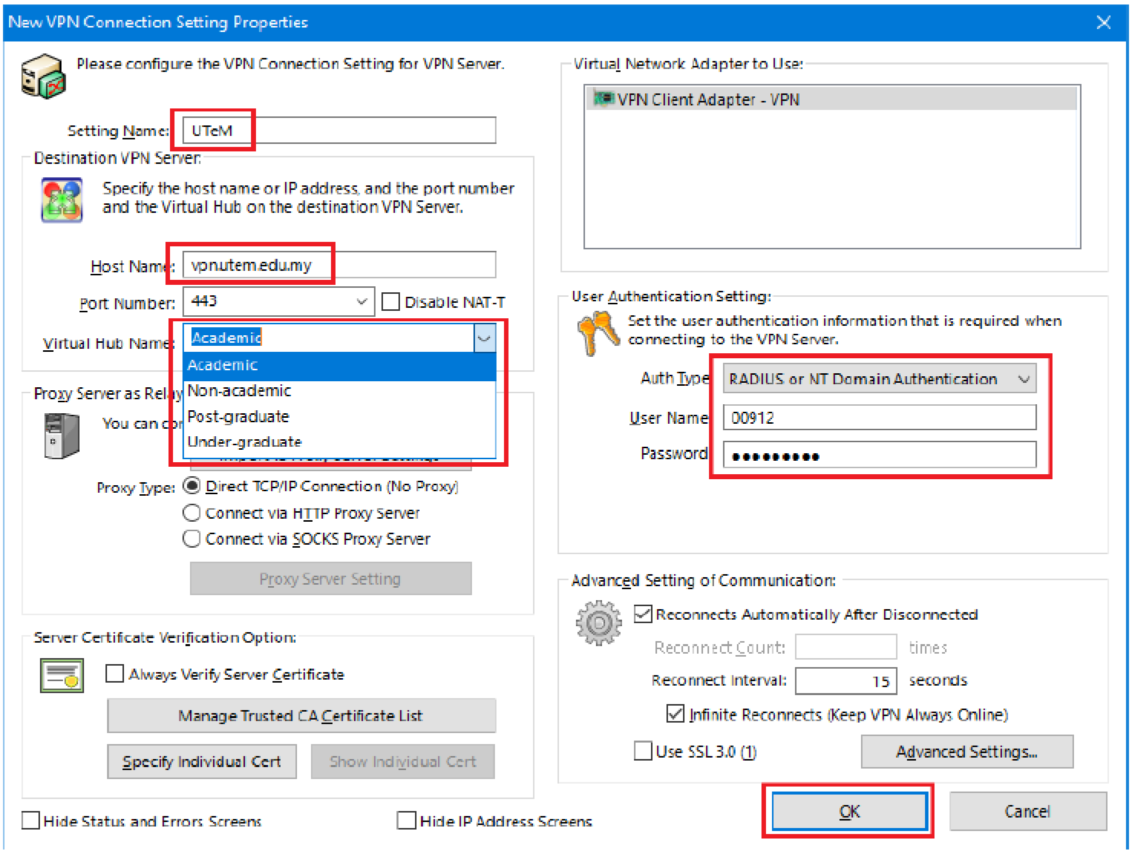
6. Click on “Add VPN Connection” and click yes



7. set the name as VPN



8. Right click and click on “new VPN connection settings” and insert the credentials as below



Username 1(client): B021810141

Password: 1(client); UTeM@PPPK

Username 2(server): b021810074

Password: 2(server); UTeM@PPPK

The command for the Iperf3 is used to send data to the server according to the data set. Different command is used to send either UDP or TCP data type.

For the server, the same process is used for the installation of the software. The SoftEther VPN client was installed as well as the Iperf3 software. The PC for the client is then connected to the network using the UTeM VPN server. Then the server is setup in Iperf3 using the command prompt.

```
iperf3 -s
```

SERVER

```
iperf3 -s -V | Foreach{"{0}-{1}" -f (get-date -Format "yyyy/MM/dd T HH:mm:ss:ffff") ,$_} | tee "C:\Users\Acer_User\OneDrive - Universiti Teknikal Malaysia Melaka\Shared with Everyone\server data\MARCH_25_R1_S.txt"
```

CLIENT

```
iperf3 -c 169.254.138.185 -t54000 -i 0.2 -V  -b 1M -l 900 | Foreach{"{0}-{1}" -f (get-date -Format "yyyy/MM/dd ") ,$_} | tee "C:\Users\acer\OneDrive - Universiti Teknikal Malaysia Melaka\Shared with Everyone\client data\MARCH_28_R1_C.txt"
```

ANNEX B

(Normative)

UDP data results and analysis

```
reading_2_29_Oct.txt - Notepad
File  Edit  Format  View  Help
2021/10/29 -iperf 3.1.3
2021/10/29 -CYGWIN_NT-10.0 ThorLab1 2.5.1(0.297/5/3) 2016-04-21 22:14 x86_64
2021/10/29 -Time: Fri, 29 Oct 2021 09:47:12 GMT
2021/10/29 -Connecting to host 172.26.2.183, port 5201
2021/10/29 -      Cookie: ThorLab1.1635500832.008508.0b54f72b7
2021/10/29 -[  4] local 172.26.3.182 port 54118 connected to 172.26.2.183 port 5201
2021/10/29 -Starting Test: protocol: UDP, 1 streams, 900 byte blocks, omitting 0 seconds, 43200 second test
2021/10/29 -[ ID] Interval           Transfer     Bandwidth       Total Datagrams
2021/10/29 -[  4]   0.00-0.21   sec  14.9 KBytes   591 Kbits/sec  17
2021/10/29 -[  4]   0.21-0.41   sec  22.9 KBytes   923 Kbits/sec  26
2021/10/29 -[  4]   0.41-0.61   sec  25.5 KBytes  1.03 Mbits/sec  29
2021/10/29 -[  4]   0.61-0.80   sec  24.6 KBytes  1.08 Mbits/sec  28
2021/10/29 -[  4]   0.80-1.00   sec  24.6 KBytes   994 Kbits/sec  28
2021/10/29 -[  4]   1.00-1.21   sec  24.6 KBytes   981 Kbits/sec  28
2021/10/29 -[  4]   1.21-1.41   sec  24.6 KBytes  1.02 Mbits/sec  28
2021/10/29 -[  4]   1.41-1.61   sec  22.9 KBytes   922 Kbits/sec  26
2021/10/29 -[  4]   1.61-1.81   sec  24.6 KBytes   993 Kbits/sec  28
2021/10/29 -[  4]   1.81-2.00   sec  31.6 KBytes  1.38 Mbits/sec  36
2021/10/29 -[  4]   2.00-2.20   sec  17.6 KBytes   711 Kbits/sec  20
2021/10/29 -[  4]   2.20-2.41   sec  25.5 KBytes  1.03 Mbits/sec  29
2021/10/29 -[  4]   2.41-2.61   sec  24.6 KBytes   992 Kbits/sec  28
2021/10/29 -[  4]   2.61-2.81   sec  22.9 KBytes   922 Kbits/sec  26
2021/10/29 -[  4]   2.81-3.00   sec  31.6 KBytes  1.38 Mbits/sec  36
2021/10/29 -[  4]   3.00-3.20   sec  17.6 KBytes   713 Kbits/sec  20
2021/10/29 -[  4]   3.20-3.41   sec  25.5 KBytes  1.03 Mbits/sec  29
2021/10/29 -[  4]   3.41-3.61   sec  24.6 KBytes   992 Kbits/sec  28
2021/10/29 -[  4]   3.61-3.80   sec  23.7 KBytes  1000 Kbits/sec  27
2021/10/29 -[  4]   3.80-4.01   sec  24.6 KBytes   993 Kbits/sec  28
2021/10/29 -[  4]   4.01-4.21   sec  22.9 KBytes   922 Kbits/sec  26
2021/10/29 -[  4]   4.21-4.41   sec  24.6 KBytes   993 Kbits/sec  28
2021/10/29 -[  4]   4.41-4.62   sec  36.0 KBytes  1.45 Mbits/sec  41
2021/10/29 -[  4]   4.62-4.80   sec  14.1 KBytes   614 Kbits/sec  16
2021/10/29 -[  4]   4.80-5.01   sec  24.6 KBytes   993 Kbits/sec  28
2021/10/29 -[  4]   5.01-5.21   sec  24.6 KBytes   993 Kbits/sec  28
2021/10/29 -[  4]   5.21-5.41   sec  22.9 KBytes   921 Kbits/sec  26
2021/10/29 -[  4]   5.41-5.61   sec  36.0 KBytes  1.46 Mbits/sec  41
2021/10/29 -[  4]   5.61-5.80   sec  13.2 KBytes   576 Kbits/sec  15
2021/10/29 -[  4]   5.80-6.01   sec  25.5 KBytes  1.03 Mbits/sec  29
Ln 1, Col 1    100%    Windows (CRLF)    UTF-16 LE
```

Figure B1. Sample of UDP client iPerf3 logfile (29 October 2021 R2)

```matlab
function [TA DA t start masa statTA statDA statall] = client(year,month,day,hour,minute,second,dt)

filename = 'reading_2_29_Oct.txt';
fileID = fopen(filename,'r');
data = textscan(fileID,'%*s %f %c%[^\n\r]','Delimiter',{'bits/sec','KBytes'});
throughput_client = data{1}.*1000.^(data{2}=='M');
datagram = data{3};
datagram_client = str2double(datagram);
fclose(fileID);

%convert time and plot
dv = [year,month,day,hour,minute,second];
start = datetime(dv,'TimeZone','Asia/Singapore','Format','dd-MMM-uuuu HH:mm:ss z');

dv(1,4) = dv(1,4)+8;
k=1;
saizT = length(throughput_client);
for i=1:saizT
    if dv(1,4) >= 24
    dv(1,4) = dv(1,4)-24;
    else
    end
      t(i,1) = dv(1,6)+(i*dt);
      testsaat = t(i,1)/(60*k);
      if testsaat == 1
          dv(1,5) = dv(1,5)+1;
          k=k+1;
          if dv(1,5) == 60
              dv(1,5) = 0;
              dv(1,4) = dv(1,4) + 1;
          else
          end
      else
      end
```

Figure B2. MATLAB client code for UDP analysis (part 1)

```
        jam(i,1) = dv(1,4);
        minit(i,1) = dv(1,5);
        saat(i,1) = t(i,1)-(60*(k-1));

end
%% analysis part for T,
Tclient = fillmissing(throughput_client,'constant',0);
TA = rmmissing(Tclient);
TA=(TA(10:end-10,:));
Tpurata = mean(TA);
Ttinggi = max(TA);
Trendah = min(TA);
statTA = [Ttinggi, Trendah, Tpurata];

%% analysis part for D
Dclient = fillmissing(datagram_client,'constant',0);
DA = rmmissing(Dclient);
DA=(DA(10:end-10,:));
Dpurata = mean(DA);
Dtinggi = max(DA);
Drendah = min(DA);
statDA = [Dtinggi, Drendah,Dpurata];
statall = [statDA, statTA];

masa = [jam, minit, saat];
masa=(masa(10:end-10,:));
t=(t(10:end-10,:));

clear  Tclient Dclient statD statT Dpurata Dtinggi Drendah Tpurata Ttinggi Trendah  saizP1 saizP2
figure(1);plot(t',TA)
title('Throughput client')
figure(2);plot(t',DA)
title('Datagram client')
end
```

Figure B3. MATLAB client code for UDP analysis (part 2)

```
Command Window
>> [TA DA t start masa statTA statDA statall] = client(year,month,day,hour,minute,second,dt)
```

The code in the command window from MATLAB software.

Instruction to run the MATLAB code for UDP client:

1. Open the code in MATLAB (see Figures B1, B2 and B3).
2. Change the name of the file according at line 3 in the code to the logfile file.

```
1    function [TA DA t start masa statTA statDA statall] = client(year,month,day,hour,minute,second,dt)
2
3 -  filename = 'reading_2_29_Oct.txt';
```

3. In the command window, copy the code below from line 1 and change the (year, month, day, hour, minute, second, dt) according to the details from the logfile.

```
Command Window
>> [TA DA t start masa statTA statDA statall] = client(2021,10,29,5,47,12,0.2);
```

4. Examples of throughput and consecutive loss datagrams are shown in Figures B4 and B5, respectively.

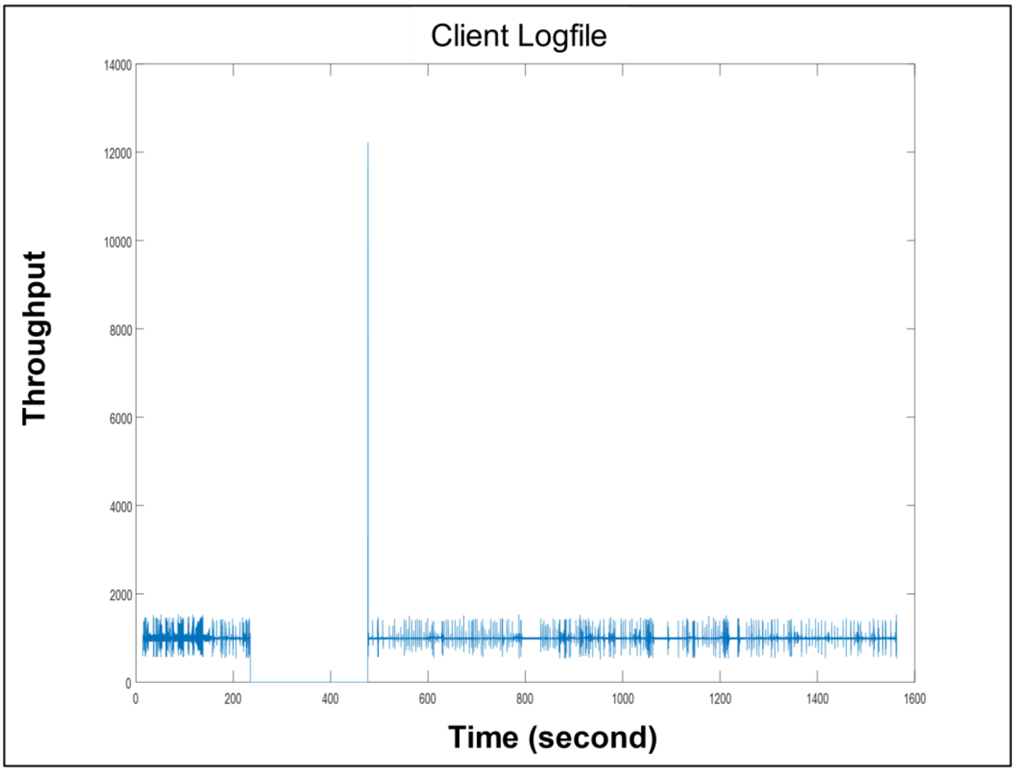


Figure B4. Throughput from client logfile

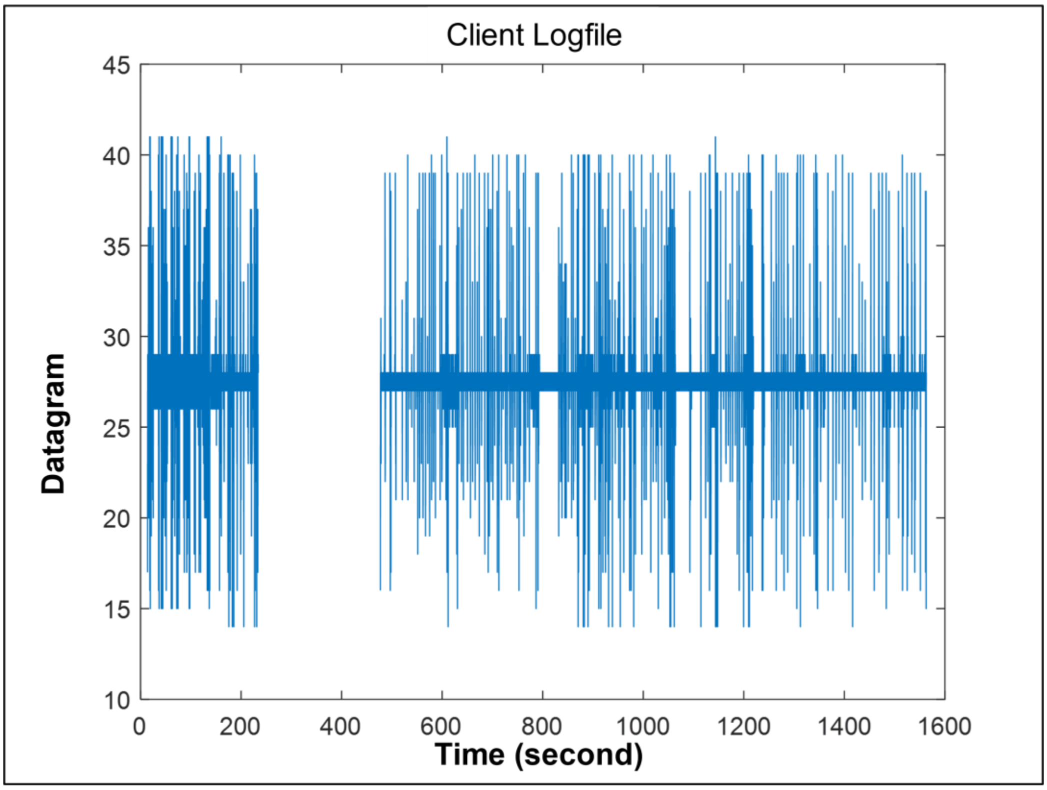


Figure B5. Datagram from client logfile

```
*server_29OCT2021_reading_2.txt - Notepad
File  Edit  Format  View  Help
2021/10/29 T 17:47:42:9861-------------------------------------------------------------
2021/10/29 T 17:47:42:9951-Server listening on 5201
2021/10/29 T 17:47:42:9981-------------------------------------------------------------
2021/10/29 T 17:47:43:0011-Accepted connection from 172.26.3.182, port 64970
2021/10/29 T 17:47:43:0041-[  5] local 172.26.2.183 port 5201 connected to 172.26.3.182 port 54118
2021/10/29 T 17:47:43:0071-iperf3: OUT OF ORDER - incoming packet = 2 and received packet = 3 AND SP = 5
2021/10/29 T 17:47:43:0101-iperf3: OUT OF ORDER - incoming packet = 4 and received packet = 5 AND SP = 5
2021/10/29 T 17:47:43:0131-iperf3: OUT OF ORDER - incoming packet = 18 and received packet = 19 AND SP = 5
2021/10/29 T 17:47:43:0201-iperf3: OUT OF ORDER - incoming packet = 22 and received packet = 24 AND SP = 5
2021/10/29 T 17:47:43:0221-iperf3: OUT OF ORDER - incoming packet = 23 and received packet = 24 AND SP = 5
2021/10/29 T 17:47:43:0241-iperf3: OUT OF ORDER - incoming packet = 28 and received packet = 29 AND SP = 5
2021/10/29 T 17:47:43:0271-iperf3: OUT OF ORDER - incoming packet = 40 and received packet = 41 AND SP = 5
2021/10/29 T 17:47:43:0291-iperf3: OUT OF ORDER - incoming packet = 43 and received packet = 44 AND SP = 5
2021/10/29 T 17:47:43:0331-iperf3: OUT OF ORDER - incoming packet = 46 and received packet = 47 AND SP = 5
2021/10/29 T 17:47:43:0361-iperf3: OUT OF ORDER - incoming packet = 45 and received packet = 47 AND SP = 5
2021/10/29 T 17:47:43:0391-iperf3: OUT OF ORDER - incoming packet = 50 and received packet = 52 AND SP = 5
2021/10/29 T 17:47:43:0411-iperf3: OUT OF ORDER - incoming packet = 51 and received packet = 52 AND SP = 5
2021/10/29 T 17:47:43:0441-iperf3: OUT OF ORDER - incoming packet = 63 and received packet = 64 AND SP = 5
2021/10/29 T 17:47:43:0471-iperf3: OUT OF ORDER - incoming packet = 65 and received packet = 66 AND SP = 5
2021/10/29 T 17:47:43:0501-iperf3: OUT OF ORDER - incoming packet = 81 and received packet = 82 AND SP = 5
2021/10/29 T 17:47:43:0531-iperf3: OUT OF ORDER - incoming packet = 92 and received packet = 93 AND SP = 5
2021/10/29 T 17:47:43:0561-iperf3: OUT OF ORDER - incoming packet = 94 and received packet = 95 AND SP = 5
2021/10/29 T 17:47:43:0581-iperf3: OUT OF ORDER - incoming packet = 101 and received packet = 102 AND SP = 5
2021/10/29 T 17:47:43:0611-iperf3: OUT OF ORDER - incoming packet = 106 and received packet = 109 AND SP = 5
2021/10/29 T 17:47:43:0631-iperf3: OUT OF ORDER - incoming packet = 108 and received packet = 109 AND SP = 5
2021/10/29 T 17:47:43:0661-iperf3: OUT OF ORDER - incoming packet = 111 and received packet = 112 AND SP = 5
2021/10/29 T 17:47:43:0681-[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
2021/10/29 T 17:47:43:0711-[  5]   0.00-1.00   sec  98.4 KBytes   806 Kbits/sec  2.736 ms  21/112 (19%)
2021/10/29 T 17:47:43:0741-iperf3: OUT OF ORDER - incoming packet = 115 and received packet = 116 AND SP = 5
2021/10/29 T 17:47:43:0771-iperf3: OUT OF ORDER - incoming packet = 117 and received packet = 119 AND SP = 5
2021/10/29 T 17:47:43:0801-iperf3: OUT OF ORDER - incoming packet = 118 and received packet = 119 AND SP = 5
2021/10/29 T 17:47:43:0831-iperf3: OUT OF ORDER - incoming packet = 121 and received packet = 122 AND SP = 5
2021/10/29 T 17:47:43:0871-iperf3: OUT OF ORDER - incoming packet = 130 and received packet = 131 AND SP = 5
2021/10/29 T 17:47:43:0901-iperf3: OUT OF ORDER - incoming packet = 132 and received packet = 133 AND SP = 5
2021/10/29 T 17:47:43:0931-iperf3: OUT OF ORDER - incoming packet = 137 and received packet = 139 AND SP = 5
2021/10/29 T 17:47:43:0961-iperf3: OUT OF ORDER - incoming packet = 138 and received packet = 139 AND SP = 5
2021/10/29 T 17:47:43:1011-iperf3: OUT OF ORDER - incoming packet = 143 and received packet = 144 AND SP = 5
2021/10/29 T 17:47:43:1051-iperf3: OUT OF ORDER - incoming packet = 147 and received packet = 148 AND SP = 5
```

Figure B6. Sample of UDP server iPerf3 logfile (29 October 2021 R2).

```matlab
function [masa t start statT statJ statPL ALL statall] = server(year,month,day,hour,minute,second,dt)

filename = '7nov_SerR1.txt';
fileID = fopen(filename,'r');
data = textscan(fileID,'%*s %f %c%[^\n\r]','Delimiter',{'bits/sec','KBytes'});
throughput_server = data{1}.*1000.^(data{2}=='M');
datagram = data{3};
fclose(fileID);

splitcellsJitter = regexp(datagram, '\s+', 'split');
saizJ = length(splitcellsJitter);

for i=1:saizJ
     jitter(i,1) = str2double(splitcellsJitter{i,1}{1,1});
end

splitcellsPL = regexp(datagram, '\d+', 'match');
saizPL = length(splitcellsPL);
     for i=1:saizPL
          saizCellPL = length(splitcellsPL{i,1});
                if saizCellPL == 5
                    packetLoss(i,1) = str2double(splitcellsPL{i,1}{1,5});
                elseif saizCellPL == 3
                     packetLoss(i,1) = str2double(splitcellsPL{i,1}{1,3});
                else
                end
     end

%convert time and plot
dv = [year,month,day,hour,minute,second];
start = datetime(dv,'TimeZone','Asia/Singapore','Format','dd-MMM-uuuu HH:mm:ss z');

dv(1,4) = dv(1,4)+8;
k=1;
```

Figure B7. MATLAB server code for UDP analysis (part 1)

```
saizT = length(throughput_server);
for i=1:saizT
    if dv(1,4) >= 24
    dv(1,4) = dv(1,4)-24;
    else
    end
        t(i,1) = dv(1,6)+(i*dt);
        testsaat = t(i,1)/(60*k);
        if testsaat == 1
            dv(1,5) = dv(1,5)+1;
            k=k+1;
            if dv(1,5) == 60
                dv(1,5) = 0;
                dv(1,4) = dv(1,4) + 1;
            else
            end
        else
        end
    jam(i,1) = dv(1,4);
    minit(i,1) = dv(1,5);
    saat(i,1) = t(i,1)-(60*(k-1));

end
%% throughput
throughput_server = fillmissing(throughput_server,'constant',0);
throughput_server=(throughput_server(10:end-10,:)); %select first 10 data up till last 10 data

maxT = max(throughput_server);
minT = min(throughput_server);
aveT = mean(throughput_server);
statT = [maxT, minT, aveT];
%% jitter
jitter = fillmissing(jitter,'constant',0);
jitter=(jitter(10:end-10,:));
```

Figure B8. MATLAB server code for UDP analysis (part 2)

```
maxJ = max(jitter);
minJ = min(jitter);
aveJ = mean(jitter);
statJ = [maxJ, minJ, aveJ];

%% packet loss
 packetLoss = fillmissing(packetLoss,'constant',0);
packetLoss=(packetLoss(10:end-10,:));
maxPL = max(packetLoss);
minPL = min(packetLoss);
avePL = mean(packetLoss);
statPL = [maxPL, minPL, avePL];

dL = saizJ-length(packetLoss);
if dL~=0
    newV = zeros(dL,1);
    packetLoss = [packetLoss; newV];
else
end
packetLoss=(packetLoss(10:end-10,:));

masa = [jam, minit, saat];
masa=(masa(10:end-10,:));
t=(t(10:end-10,:));

 ALL = [masa, throughput_server, jitter, packetLoss];
 statall=[statT, statJ, statPL];
figure(1);plot(t',throughput_server)
title('throughput')
figure(2);plot(t',jitter)
title('jitter')
figure(3);plot(t',packetLoss)
title('packet loss')
% clear ans fileID filename saizCell i j
end
```

Figure B9. MATLAB server code for UDP analysis (part 3)

```
Command Window
fx >> [masa t start statT statJ statPL ALL statall] = server(year,month,day,hour,minute,second,dt);
```

The code in the command window from MATLAB software.

Instruction to run the MATLAB code for UDP server:

1. Open the code in MATLAB (see Figures B6, B7, B8, and B9).
2. Change the name of the file according at line 3 in the code to the logfile file.

```
1     function [masa t start statT statJ statPL ALL statall] = server(year,month,day,hour,minute,second,dt)
2
3 -   filename = 'server_29OCT2021_reading_2.txt';
4 -   fileID = fopen(filename,'r');
5 -   data = textscan(fileID,'%*s %f %c%[^\n\r]','Delimiter',{'bits/sec','KBytes'});
```

3. In the command window, copy the code below from line 1 and change the (year, month, day, hour, minute, second, dt) according to the details from the logfile

```
Command Window
fx >> [masa t start statT statJ statPL ALL statall] = server(2021,10,29,15,47,12,0.2);
```

Examples of throughput, jitter, and packet loss are shown in Figures B10, B11, and B12, respectively.

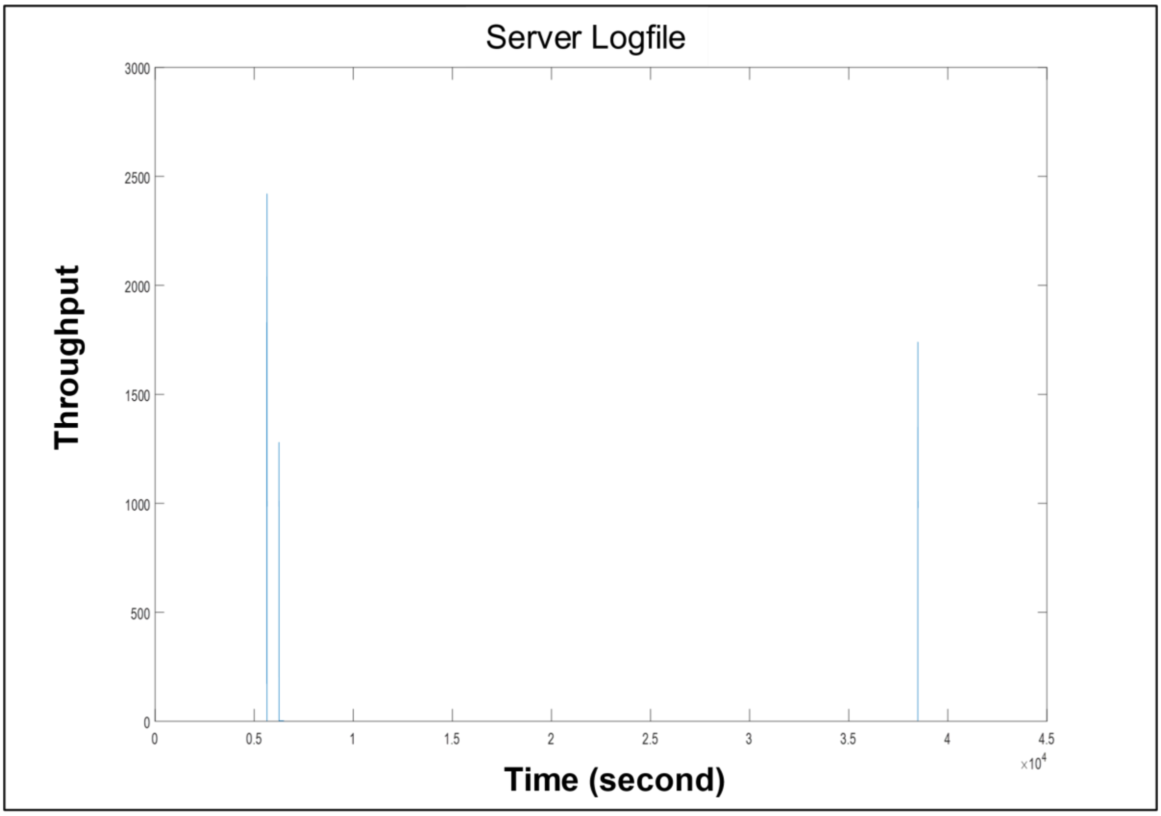


Figure B10. Throughput from server logfile

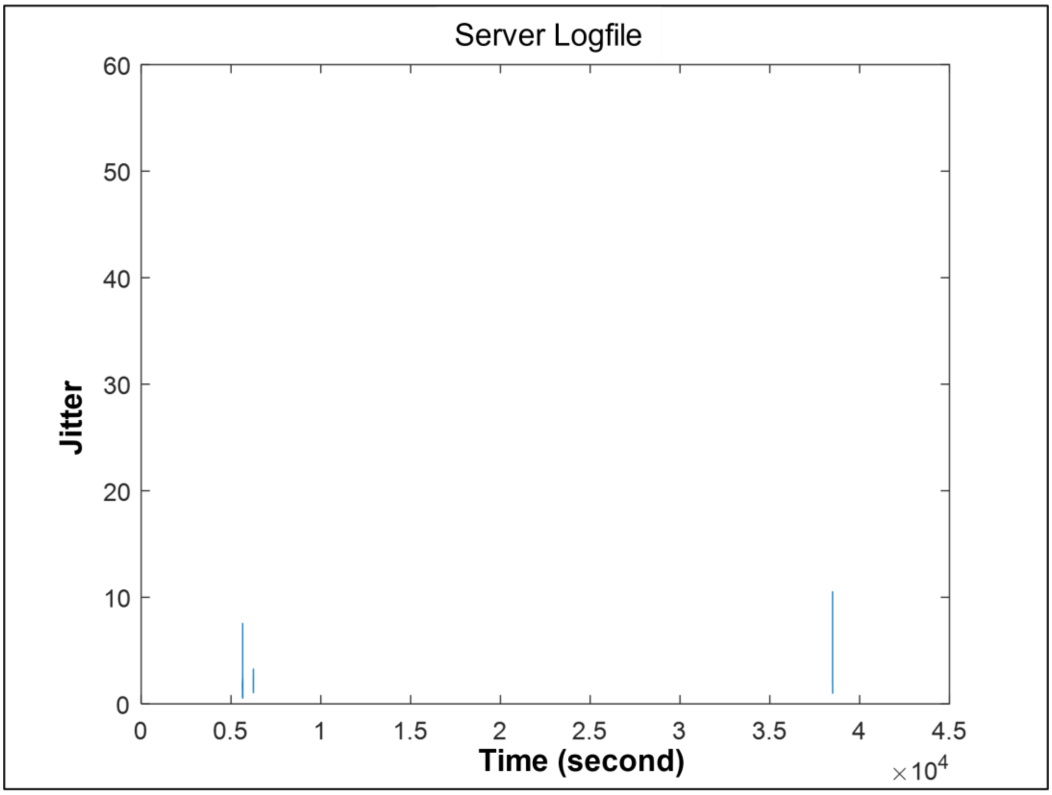


Figure B11. Jitter sample from server logfile

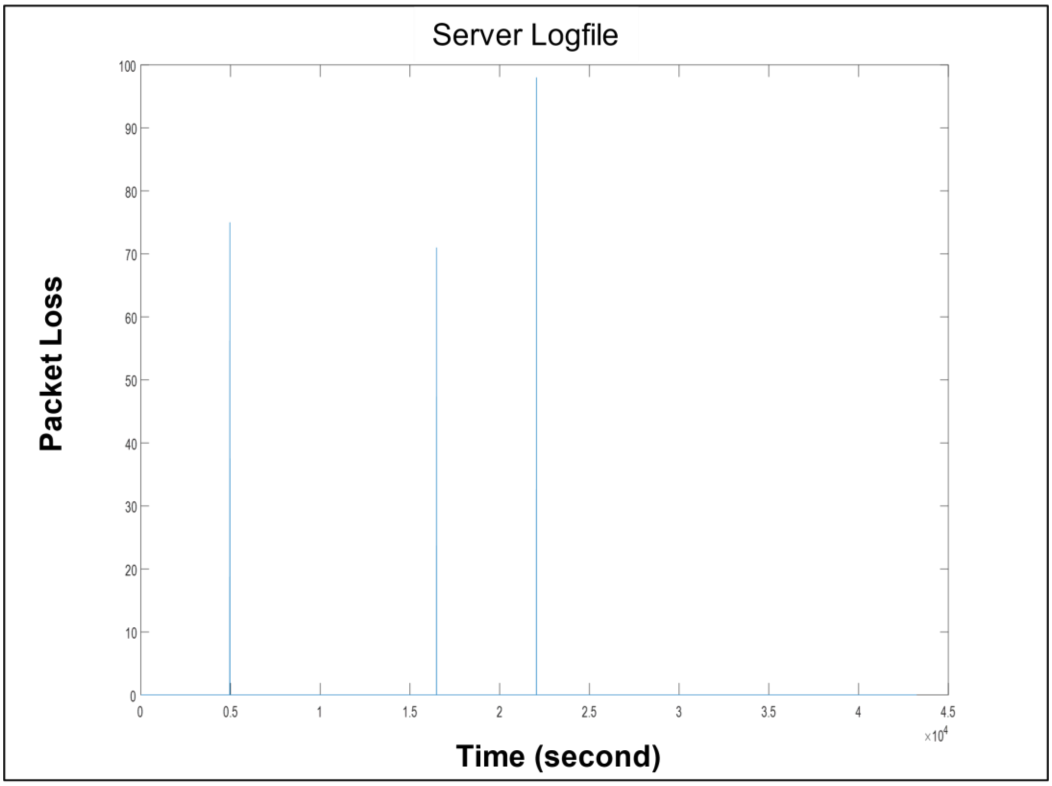


Figure B12. Packet loss sample from server logfile

MARCH_23_R1_C - Notepad

File Edit Format View Help

```
2022/03/23 -iperf 3.1.3
2022/03/23 -CYGWIN_NT-10.0 ThorLab1 2.5.1(0.297/5/3) 2016-04-21 22:14 x86_64
2022/03/23 -Time: Wed, 23 Mar 2022 08:47:43 GMT
2022/03/23 -Connecting to host 169.254.138.185, port 5201
2022/03/23 -      Cookie: ThorLab1.1648025263.050860.5d4cb6b97
2022/03/23 -      TCP MSS: 0 (default)
2022/03/23 -[  4] local 169.254.114.252 port 56559 connected to 169.254.138.185 port 5201
2022/03/23 -Starting Test: protocol: TCP, 1 streams, 900 byte blocks, omitting 0 seconds, 54000 second test
2022/03/23 -[ ID] Interval           Transfer     Bandwidth
2022/03/23 -[  4]   0.00-0.20   sec  21.1 KBytes   862 Kbits/sec
2022/03/23 -[  4]   0.20-0.40   sec  18.5 KBytes   744 Kbits/sec
2022/03/23 -[  4]   0.40-0.61   sec  24.6 KBytes   992 Kbits/sec
2022/03/23 -[  4]   0.61-0.81   sec  22.9 KBytes   922 Kbits/sec
2022/03/23 -[  4]   0.81-1.01   sec  24.6 KBytes   991 Kbits/sec
2022/03/23 -[  4]   1.01-1.20   sec  24.6 KBytes  1.07 Mbits/sec
2022/03/23 -[  4]   1.20-1.41   sec  36.0 KBytes  1.39 Mbits/sec
2022/03/23 -[  4]   1.41-1.60   sec  13.2 KBytes   576 Kbits/sec
2022/03/23 -[  4]   1.60-1.81   sec  25.5 KBytes  1.03 Mbits/sec
2022/03/23 -[  4]   1.81-2.01   sec  22.0 KBytes   886 Kbits/sec
2022/03/23 -[  4]   2.01-2.20   sec  24.6 KBytes  1.03 Mbits/sec
2022/03/23 -[  4]   2.20-2.41   sec  26.4 KBytes  1.06 Mbits/sec
2022/03/23 -[  4]   2.41-2.61   sec  22.9 KBytes   922 Kbits/sec
2022/03/23 -[  4]   2.61-2.80   sec  34.3 KBytes  1.49 Mbits/sec
2022/03/23 -[  4]   2.80-3.00   sec  15.8 KBytes   642 Kbits/sec
2022/03/23 -[  4]   3.00-3.20   sec  24.6 KBytes   994 Kbits/sec
2022/03/23 -[  4]   3.20-3.41   sec  22.9 KBytes   897 Kbits/sec
2022/03/23 -[  4]   3.41-3.60   sec  22.9 KBytes   998 Kbits/sec
2022/03/23 -[  4]   3.60-3.80   sec  12.3 KBytes   499 Kbits/sec
2022/03/23 -[  4]   3.80-4.00   sec  10.5 KBytes   438 Kbits/sec
2022/03/23 -[  4]   4.00-4.20   sec  15.8 KBytes   648 Kbits/sec
2022/03/23 -[  4]   4.20-4.41   sec  7.91 KBytes   304 Kbits/sec
2022/03/23 -[  4]   4.41-4.60   sec  17.6 KBytes   768 Kbits/sec
2022/03/23 -[  4]   4.60-4.80   sec  9.67 KBytes   395 Kbits/sec
2022/03/23 -[  4]   4.80-5.01   sec  15.8 KBytes   630 Kbits/sec
```

Figure B13. Sample of TCP client iPerf3 logfile (23 March 2022 R1)

MARCH_23_R1_S - Notepad

File Edit Format View Help

```
2022/03/23 T 16:46:14:8430-iperf 3.1.3
2022/03/23 T 16:46:14:8470-CYGWIN_NT-10.0 DUEN 2.5.1(0.297/5/3) 2016-04-21 22:14 x86_64
2022/03/23 T 17:03:00:0399-----------------------------------------------------------
2022/03/23 T 17:03:00:0429-Server listening on 5201
2022/03/23 T 17:03:00:0439-----------------------------------------------------------
2022/03/23 T 17:03:00:0449-Time: Wed, 23 Mar 2022 08:47:43 GMT
2022/03/23 T 17:03:00:0449-Accepted connection from 169.254.114.252, port 56558
2022/03/23 T 17:03:00:0459-      Cookie: ThorLab1.1648025263.050860.5d4cb6b97
2022/03/23 T 17:03:00:0459-      TCP MSS: 0 (default)
2022/03/23 T 17:03:00:0469-[  5] local 169.254.138.185 port 5201 connected to 169.254.114.252 port 56559
2022/03/23 T 17:03:00:0469-Starting Test: protocol: TCP, 1 streams, 900 byte blocks, omitting 0 seconds, 54000 second test
2022/03/23 T 17:03:00:0479-[ ID] Interval           Transfer     Bandwidth
2022/03/23 T 17:03:00:0479-[  5]   0.00-1.00   sec  55.4 KBytes   452 Kbits/sec
2022/03/23 T 17:03:00:0479-[  5]   1.00-2.01   sec  60.9 KBytes   494 Kbits/sec
2022/03/23 T 17:03:00:0489-[  5]   2.01-3.00   sec  63.6 KBytes   526 Kbits/sec
2022/03/23 T 17:03:00:0489-[  5]   3.00-4.00   sec  63.0 KBytes   517 Kbits/sec
2022/03/23 T 17:03:00:0489-[  5]   4.00-5.00   sec  66.2 KBytes   543 Kbits/sec
2022/03/23 T 17:03:00:0499-[  5]   5.00-6.01   sec  66.5 KBytes   540 Kbits/sec
2022/03/23 T 17:03:00:0499-[  5]   6.01-7.01   sec  48.6 KBytes   396 Kbits/sec
2022/03/23 T 17:03:00:0499-[  5]   7.01-8.01   sec  76.7 KBytes   633 Kbits/sec
2022/03/23 T 17:03:00:0499-[  5]   8.01-9.00   sec  57.5 KBytes   475 Kbits/sec
2022/03/23 T 17:03:00:0499-[  5]   9.00-10.01  sec  57.1 KBytes   464 Kbits/sec
2022/03/23 T 17:03:00:0509-[  5]  10.01-11.00  sec  57.4 KBytes   474 Kbits/sec
2022/03/23 T 17:03:00:0509-[  5]  11.00-12.01  sec  46.3 KBytes   375 Kbits/sec
2022/03/23 T 17:03:00:0509-[  5]  12.01-13.01  sec  80.5 KBytes   660 Kbits/sec
2022/03/23 T 17:03:00:0509-[  5]  13.01-14.01  sec  81.6 KBytes   667 Kbits/sec
2022/03/23 T 17:03:00:0509-[  5]  14.01-15.00  sec  86.9 KBytes   719 Kbits/sec
2022/03/23 T 17:03:00:0519-[  5]  15.00-16.00  sec  82.3 KBytes   674 Kbits/sec
2022/03/23 T 17:03:00:0519-[  5]  16.00-17.00  sec  86.3 KBytes   706 Kbits/sec
2022/03/23 T 17:03:00:0519-[  5]  17.00-18.00  sec  90.2 KBytes   741 Kbits/sec
2022/03/23 T 17:03:00:0519-[  5]  18.00-19.01  sec  98.2 KBytes   800 Kbits/sec
2022/03/23 T 17:03:00:0519-[  5]  19.01-20.01  sec  84.9 KBytes   695 Kbits/sec
2022/03/23 T 17:03:00:0529-[  5]  20.01-21.00  sec  85.2 KBytes   704 Kbits/sec
2022/03/23 T 17:03:00:0529-[  5]  21.00-22.01  sec  71.1 KBytes   579 Kbits/sec
```

Ln 13, Col 92 | 100% | Windows (CRLF) | UTF-16 LE

Figure B14. Sample of TCP server iPerf3 logfile (23 March 2022 R1)

```
function  [TA  t start masa statTA ] = TCP(year,month,day,hour,minute,second,dt)

filename = 'MARCH_16_R1_S.txt';
fileID = fopen(filename,'r');
data = textscan(fileID,'%*s %f %c%[^\n\r]','Delimiter',{'bits/sec','KBytes'});
throughput_client = data{1}.*1000.^(data{2}=='M');
fclose(fileID);

%convert time and plot
dv = [year,month,day,hour,minute,second];
start = datetime(dv,'TimeZone','Asia/Singapore','Format','dd-MMM-uuuu HH:mm:ss z');

dv(1,4) = dv(1,4)+8;
k=1;
saizT = length(throughput_client);
for i=1:saizT
     if dv(1,4) >= 24
     dv(1,4) = dv(1,4)-24;
     else
     end
        t(i,1) = dv(1,6)+(i*dt);
        testsaat = t(i,1)/(60*k);
        if testsaat == 1
            dv(1,5) = dv(1,5)+1;
            k=k+1;
            if dv(1,5) == 60
                dv(1,5) = 0;
                dv(1,4) = dv(1,4) + 1;
            else
            end
        else
        end
    jam(i,1) = dv(1,4);
    minit(i,1) = dv(1,5);
    saat(i,1) = t(i,1)-(60*(k-1));
```

Figure B15. MATLAB client and server code for TCP analysis (part 1)

```

end
%% analysis part for T,
Tclient = fillmissing(throughput_client,'constant',0);
TA = rmmissing(Tclient);
TA=(TA(10:end-10,:));
Tpurata = mean(TA);
Ttinggi = max(TA);
Trendah = min(TA);
statTA = [Ttinggi, Trendah, Tpurata];

masa = [jam, minit, saat];
masa=(masa(10:end-10,:));
t=(t(10:end-10,:));

clear  Tclient statT Tpurata Ttinggi Trendah  saizP1 saizP2
figure(1);plot(t',TA)
title('Throughput')

end
```

Figure B16. MATLAB client and server code for TCP analysis (part 2)

Instruction to run the MATLAB code for TCP client and server

1. Open the code in MATLAB (see Figures B13, B14, B15, and B16).
2. Change the name of the file according at line 3 in the code to the logfile file name

```
1  function  [TA  t start masa statTA ] = TCP(year,month,day,hour,minute,second,dt)
2
3      filename = 'MARCH_23_R1_S.txt';
4      fileID = fopen(filename,'r');
```

3. In the command window, copy the code below from line 1 and change the (year, month, day, hour, minute, second, dt) according to the details from the logfile

```
Command Window
fx >> [TA  t start masa statTA ] = TCP(year,month,day,hour,minute,second,dt);
```

```
Command Window
fx >> [TA  t start masa statTA ] = TCP(2022,3,23,16,47,43,0.2);
```

Examples of throughput from client and server logfiles are shown in Figures B17 and B18, respectively.

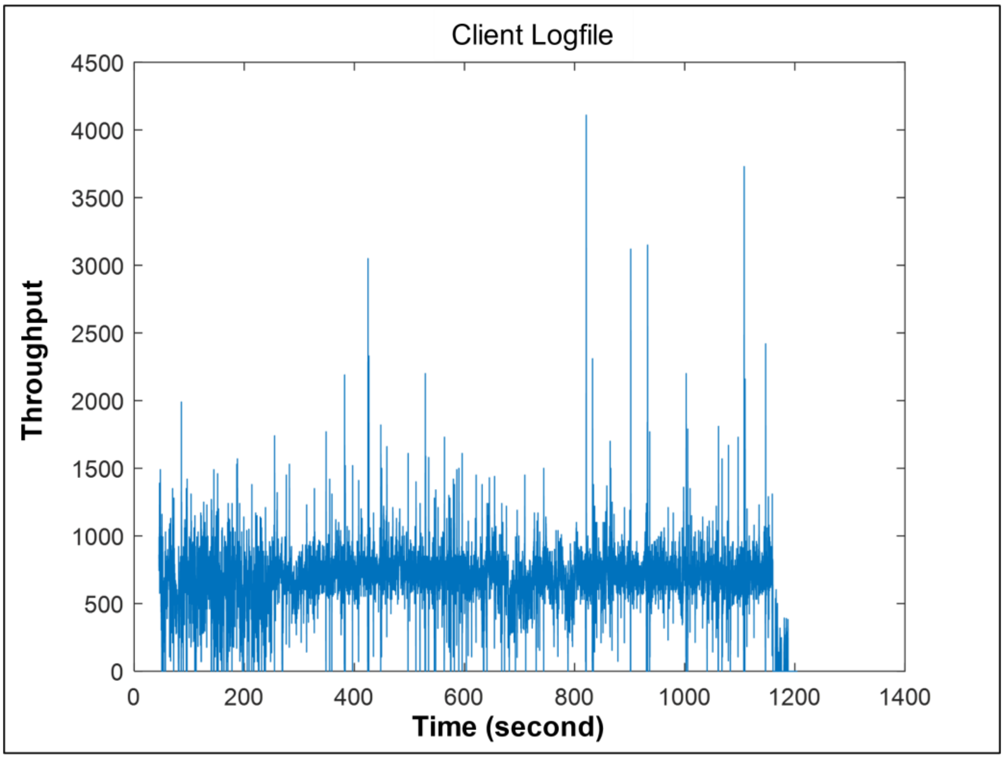


Figure B17. Throughput from client logfile

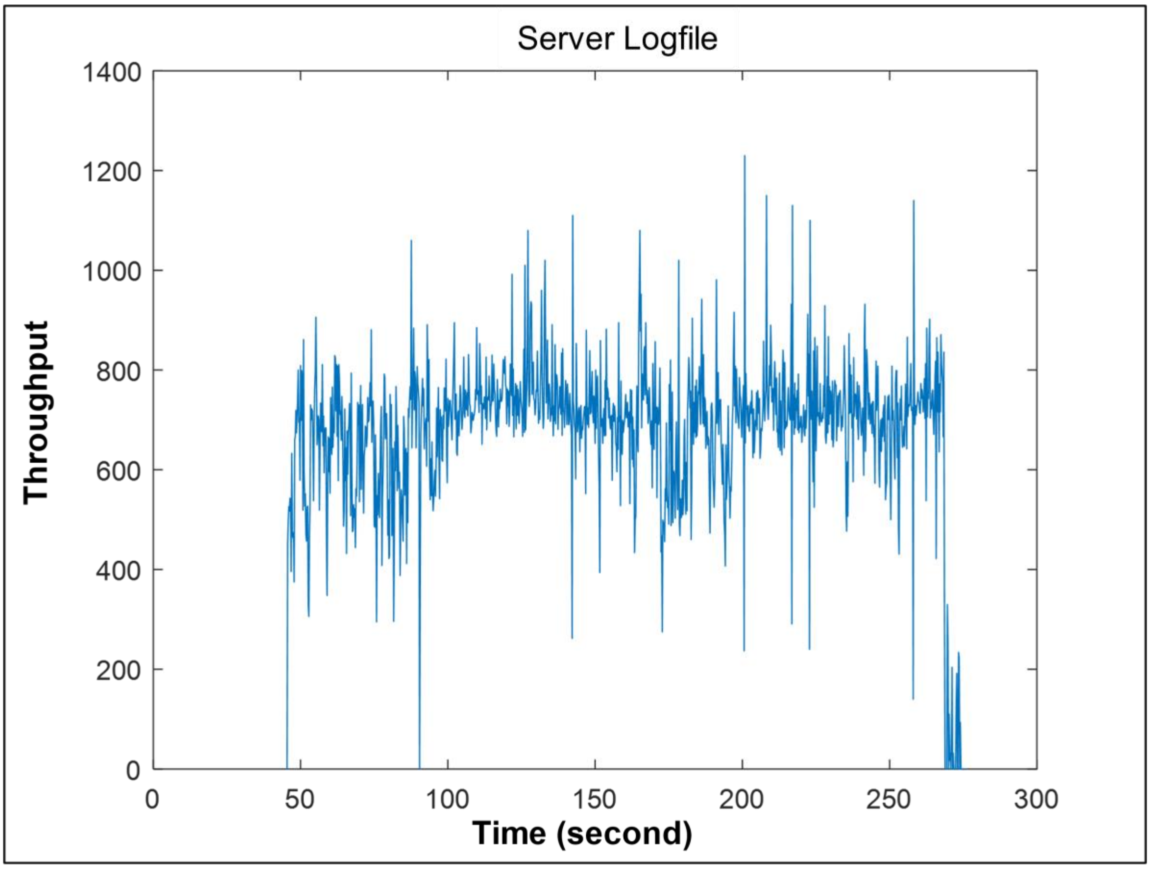


Figure B18. Throughput from server logfile

Bibliography

[1] [Recommendation ITU-R P.530-17, 2017. Propagation data and prediction methods required for the design of terrestrial line-of-sight systems.

[2] Recommendation ITU-R P.618-13, 2017. Propagation data and prediction methods required for the design of Earth-space telecommunication systems.

[3] Ahmad, M.R. 2014. Interaction of Lightning Flashes with Wireless Communication Networks. Special Attention to Narrow Bipolar Pulses. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1188. 70 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9067-6.

[4] Ahmad M.R., Esa M.R.M., Cooray V., Dutkiewicz E., 2014. Interference from cloud-to-ground and cloud flashes in wireless communication system. Electric Power System Research 113: 237–246.

[5] Brook, M. and Kitagawa, N., 1964. Radiation From Lightning Discharges in The Frequency Range 400 to 1000 Mc/s. Journal of Geophysical Research, 69(12), pp.2431-2434.

[6] Kosarev, E.L., Zatsepin, V.G. and Mitrofanov, A.V., 1970. Ultrahigh Frequency Radiation from Lightnings. Journal of Geophysical Research, 75(36), pp.7524-7530.

[7] Rust, W.D., Krehbiel, P.R. and Shlanta, A., 1979. Measurements of Radiation from Lightning at 2200 MHz. Geophysical Research Letters, 6(2), pp.85-88.

[8] Fedorov, V.F., Frolov, Y.A. and Shishkov, P.O., 2001. Millimetric Electromagnetic Radiation of a Lightning Return Stroke. Journal of Applied Mechanics and Technical Physics, 42 (3), pp.392-396.

[9] Petersen, D. and Beasley, W., 2014. Microwave Radio Emissions of Negative Cloud-To-Ground Lightning Flashes. Atmospheric research, 135, pp.314-321.

[10] Ahmad, M.R., Esa, M.R.M., Cooray, V., Baharudin, Z.A., Hettiarachchi, P., 2015. Latitude dependence of narrow bipolar pulse emissions. J. Atmos. Sol. Terr. Phys. 128, 40–45. https://doi.org/10.1016/j.jastp.2015.03.005.

[11] Rison, W., Krehbiel, P.R., Stock, M.G., Edens, H.E., Shao, X.M., Thomas, R.J., Stanley, M.A., and Zhang, Y., 2016. Observations of Narrow Bipolar Events Reveal How Lightning Is Initiated in Thunderstorms. Nature Communications, 7, pp.1–12.

[12] Tilles, J.N., Liu, N., Stanley, M.A., Krehbiel, P.R., Rison, W., Stock, M.G., Dwyer, J.R., Brown, R. and Wilson, J., 2019. Fast Negative Breakdown in Thunderstorms. Nature communications, 10 (1), p.1648.

Publication of:

Malaysian Technical Standards Forum Bhd (MTSFB)
Level 3A, MCMC Tower 2
Jalan Impact, Cyber 6, 63000 Cyberjaya
Selangor Darul Ehsan
Tel: (+603) 8680 9950
Fax: (+603) 8680 9940
Website: www.mtsfb.org.my

In collaboration with

Malaysian Communications and Multimedia Commission (MCMC)
MCMC Tower 1
Jalan Impact, Cyber 6, 63000 Cyberjaya
Selangor Darul Ehsan
Tel: (+603) 8688 8000
Fax: (+603) 8688 1000
Website: www.mcmc.gov.my