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RESEARCH ARTICLE

Electromagnetic Interference From Natural Lightning on 4G Communication Links

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ABSTRACT In this study, microwave radiation pulses emitted from natural lightning have been found to interfere with the Fourth Generation Long Term Evolution (4G LTE) mobile communication data transmission. Two sets of measurement instruments have been synchronized where lightning electric field sensor together with 4G LTE network were evaluated its performance under two conditions namely fair-weather (four cases) and storm (four lightning cases). The microwave radiation emitted from lightning was directly measured without the use of a mixer and down-convertor to ensure the preservation of information such as the number of pulses and amplitude. A client-server architecture has been set up for data transmission utilizing User Datagram Protocol (UDP) where the packets have been generated by using Internet Performance Working Group Third Version (Iperf3) platform. Under fair-weather conditions, the 4G LTE connection at both the client and server nodes demonstrated stability and experienced minimal impact. On the other hand, natural lightning electromagnetic interference disrupted the 4G LTE communication links. Among the four reported storms, three storms have affected the 4G LTE data transmission. The first and fourth storms resulted in a complete connection drop to zero, lasting for 4 minutes and 2 seconds and for 44 seconds, respectively. The observation of hundreds microwave radiation pulses, each characterized by individual oscillating features suggests a potential disruption to packet transmission. Moreover, negative could-to-ground (-CG) and intra-cloud (IC) lightning flashes have been identified as the primary sources of interference to the 4G LTE data transmission. This information could be useful for future studies and for developers working on improving the reliability and performance of 4G LTE networks, particularly in areas prone to thunderstorms.

INDEX TERMS Lightning interference, microwave radiation, UDP, 4G mobile network.

I. INTRODUCTION

Electromagnetic fields radiated from natural lightning flashes have been detected over a wide range of frequency spectrum. The topic of microwave radiation (0.3 to 300 GHz) emitted from natural lightning flashes garnered lots of interests for its relation to lightning initiation process. Generally, there are two main types of lightning flashes namely cloud-to-ground (CG) and intra-cloud (IC) flashes [1]. A special type of IC flash known as the narrow bipolar event (NBE) [2] was recently discovered to emit strong very-high frequency (VHF) and microwave radiation pulses. The first encounter of microwave radiation emitted from lightning flashes was observed in [3]. They reported microwave radiation associated with lightning activities at 0.4 and 0.85 GHz. Later, observations at 0.4, 0.7, and 0.9 GHz reported noise-like bursts of radiation that lasted around 10 ms [4]. Microwave radiation observation at 2.2 GHz reported significant bursts

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of impulsive activities during preliminary breakdown pulses (PBPs), stepped leaders, initial return strokes, dart leaders, and K changes [5]. Microwave radiation pulses associated with positive and negative NBEs at 2.4 GHz were reported in [6]. The noise-like bursts appeared a few microseconds earlier before the onset time of the NBE electric field radiation. Moreover, [7] reported the observation of microwave radiation emitted from lightning at 1.63 GHz during CG flashes.

Furthermore, simulations conducted in [8], [9], and [10] have suggested that the sources of microwave radiation emitted by lightning were associated with the breakdown of electron avalanches or corona at the tip of a leader and head-on collisions of streamers. Motivated by the simulation studies, [11] designed a lightning measurement system using a microwave antenna with a center frequency of ~1 GHz (sampled at 2.5 GS/s without a down-converter). They observed microwave radiation associated with stepped leader pulses of ten CG flashes. The detected microwave radiation pulses consistently preceded the stepped leader pulses, and it has been suggested that these microwave radiation pulses were emitted by the electron avalanche/corona process, while VHF radiation pulses were emitted by propagating streamers. Later, [12] reported microwave and VHF radiation pulses associated with positive NBEs in the tropical region. It was discovered that microwave and VHF radiation associated with positive NBE originated from electron avalanches/corona and fast-propagating streamers, respectively.

As the characterization studies of microwave radiation emitted by natural lightning flashes progress very well, a new frontier has been explored to understand the effect of the microwave radiation towards wireless communications link. As many of the wireless communication networks are operating in microwave band region (2.4 GHz, 5.2 GHz, 5.8 GHz, etc.), it is an important issue to be taken seriously. Experimental work has been conducted in [13] by observing the effect of high voltage arc produced in laboratory on a private mobile radio (PMR) communication link. A pair of walkie-talkies operated at 1.6 kHz and 1 kHz were used to transmit audio packets containing 1000 frequency shift-keying (FSK) modulated bits each. They observed the bit loss rate (BLR) at a 5 m line-of-sight (LOS) separation. During the experiment, a total of 25 bits were lost at current values of 440 A, 850 A, and 2 kA, corresponding to a BLR value of 2.5×10^{-2}. Besides, the delay of packet received during high voltage arc and current conditions was higher compared to situations when the spark was not operational.

Furthermore, [14] initiated a study on the effect of lightning interference towards 2.4 GHz wireless communication links. They utilized the received signal strength indicator (RSSI) method and performed evaluations in terms of Signal-to-Interference-Noise Ratio (SINR), Bit Error Rate (BER), and Packet Error Rate (PER) at a 1 m LOS. The finding revealed that lightning flashes resulted in inaccurate transmission signal due to the corrupted packets. On top of that, [15] reported the BER resulting from lightning interference during audio transmission at 2.4 GHz and 5.2 GHz. The measurement compared the readings of BER between conditions under fair-weather and under thunderstorm. Lightning interference significantly increased the BER during thunderstorms, with a maximum recorded BER of 9.9×10^{-1} and average recorded values of 2.07×10^{-2} for BER and 2.44×10^{-2} for PER. In contrast, under the influence of adjacent channel interference (ACI) and co-channel interference (CCI), the average fair weather BER and PER were much lower, at 1.75×10^{-5} and 7.35×10^{-6}, respectively.

Moreover, [16] found that the occurrence of both IC and CG flashes affected the data transmission at 2.4 GHz wireless communication links. It has been found that NBE is the strongest interferer in the 2.4 GHz band. The PBPs together with return stroke pulses interfered with the data transmission at 2.4 GHz quite severely with BER ranging between 1.0×10^{-2} and 2.5×10^{-2}. Two factors have been identified to influence the severity of the interference which were the number of lightning pulses and the amplitude of the radiation waveforms. Driven by the study in [16], a study to examine the impact of lightning interference on the Fourth Generation (4G) mobile communication network was initiated. The research work provides the fundamental groundwork to understand the impact of lightning interference on 4G network operated at 2.3 GHz [17].

Motivated by the studies in [15], [16], and [17] we are driven to understand the effect of adverse weather conditions on Fourth Generation Long Term Evolution (4G LTE) network. This study was stimulated by the distinctive approach of directly measuring the microwave radiation emitted from lightning, bypassing the use of down-converters and mixers to ensure that information such as the number of pulses and amplitude were preserved [11], [12], [18], [19]. Besides, this study expands the examination of temporal characteristics related to microwave radiation from stepped leader pulses, NBEs and initial breakdown, by integrating directly measured hundreds of microwave radiation pulses with the 4G LTE performance analysis. This integration aims to assess performance over 4G LTE, addressing a gap in the existing literature. Notably, while [16] focused on evaluating the performance of data transmission over 2.4 GHz, this study focuses on 2.3 GHz. Moreover, the 2.4 GHz band in [16] operated using wireless fidelity (Wi-Fi) technology, while this study employed the 4G LTE technology, which offers broader coverage and higher transmitted power compared to Wi-Fi technology. Therefore, it will be interesting to observe the severity of interference effects on 4G LTE technology operating at 2.3 GHz band.

In this paper, we evaluate the performance of the 4G LTE network by examining transmitted datagram and throughput at the client node as well as packet loss, jitter, and throughput at the server node. Furthermore, we collected data on the flash rates of lightning at 10-minute intervals to establish correlations between the types of lightning flashes and their disruptions at both the client and server nodes. Subsequently, we analyzed the different types of lightning flashes that contribute to disruptions in data transmission to find the most dominant type of lightning flashes. Additionally, a detailed statistical analysis is presented, illuminating the correlation between interference effects and the intricate physics of lightning, with a specific focus on the lightning initiation process and the involvement of the electrical breakdown process.

II. INSTRUMENTATION AND METHODS

The measurement set up in this study was divided into two parts. The first part covers electric field measurement, while the second part involves 4G LTE network performance measurement. Both measurements were conducted at the Faculty of Electronics and Computer Technology and Engineering (FTKEK) (UTeM, 2.314077°N, 102.318282°E).

A. ELECTRIC FIELD MEASUREMENT

The electric field setup comprises systems for measuring fast-varying electric fields, microwave electric fields and background electric fields. The fast-varying electric field measurement involves an air-gap parallel plate antenna made of aluminum. The antenna is connected to a buffer circuit with a decay time constant of 13 ms [11], [12], [18], [19]. In contrast, the microwave radiation detection system utilizes a fiberglass antenna with an omnidirectional radiation pattern, suitable for 4G or LTE systems. The microwave antenna covers frequency from 0.8 GHz to 2.7 GHz, aligning with the specifications of the local telco company operating at 2.3 GHz. The sampling rate for both the fast antenna and microwave systems is 2.5 GS/s with a window size of 200 milliseconds. An electric field mill (EFM) was installed on the rooftop of FTKEK to measure the background electric field of thunderclouds. It can detect the static electric field generated by the thunderclouds within a 30 km radius of the measurement site. The EFM not only detects nearby lightning but can also identify the atmospheric conditions preceding lightning.

B. 4G LTE NETWORK PERFORMANCE

The measurement tools used to collect data on lightning interference to 4G LTE wireless links operated concurrently with the electric field measurement. The 4G LTE telecommunication tower was situated 0.12 km from the lightning sensors [17]. The 4G LTE network performance measurement involved two nodes, each assigned different roles based on the settings of the Internet Performance Working Group Third Version (Iperf3) software installed at the nodes: one as a client and the other as a server. Both nodes were connected to a 4G LTE modem at 2.3 GHz. The client and server nodes were positioned with a LOS separation of 1 m, a design choice aimed at maximizing the bandwidth of the 4G LTE links with a wavelength of 0.13 m.

The application layer at the client node of the transmitting system generated a packet upon receiving command from the Iperf3 software. The data was transmitted using the User Datagram Protocol (UDP), chosen for its connectionless structure. Furthermore, the packet's route involved a round-trip transmission: initially from the client node to the server node, and subsequently from the server node back to the client node. The total time allocated for the round-trip transmission was set to 1 second, facilitating time synchronization with the electric field records. The size of the generated packet was 1 Megabyte (MB). Moreover, the client and the server nodes were equipped with Global Positioning System (GPS) clocks to synchronize timing between the nodes and electric field records.

During the round-trip transmission of the UDP packet, network performance parameters including packet loss, jitter and throughput were measured. Upon completion of the measurement, the data were saved as log files. These log files contained information on packet loss, jitter, transmitted datagram and throughput along with corresponding timestamps. The timing of the log-files was synchronized with the electric field records to observe network performances during lightning flashes (Note that local time is 8 hours ahead of Universal Time Coordinated (UTC+8)). The data resulting from the integration between electric field system and 4G LTE network performance were analyzed and presented in the results to examine the impact of lightning interference on 4G LTE communication links.

Algorithm 2.1 Main

```
STATE: IDLE node is idle and observes the EFM display
if EFM displays high background electric field then
  go to algorithm 2
end if
if UDP packets ready to be sent then
  go to algorithm 3
end if
if receive UDP packets then
  go to algorithm 4
end if
if complete  round-trip then
  go to algorithm 5
end if
```

C. MEASUREMENT CAMPAIGN

The algorithms for the integration between electric field measurement and 4G LTE performance measurement are outlined in Algorithm 2.1 to Algorithm 2.5 as follows:

III. RESULTS AND ANALYSIS

The measurement campaign was conducted from 8 October 2021 until 23 November 2021. The experimentation of the 4G LTE performance was conducted under fair-weather and thunderstorm scenarios. The selection of the specific storms was carefully guided by the static electric field conditions, as observed through EFM records and lightning intensity data from the fast antenna records. Table 1 shows the details of fair-weathers conditions and thunderstorms for

Algorithm 2.2 EFM Sensors

STATE: WAIT check background electric field level
if EFM sensor displays high background electric field activity less than 30 km radius
then
fast electric field changes and microwave electric field are logged in
else
go to **STATE: WAIT**
end if

Algorithm 2.3 Client Node

STATE: TRANSMIT
if command received
then
UDP packets of 1 MB are generated
then
UDP packets are transmitted every 1 second to server node (see Algorithm 2.4)
else
go to **STATE: IDLE**
end if

Algorithm 2.4 Server Node

STATE: RECEIVE
if UDP packets received
then
measure throughput
else
go to **STATE: IDLE**
end if

Algorithm 2.5 Collection

STATE: COLLECTION complete round-trip data transmission
if UDP packets completed round-trip route
then
measure throughput, jitter and packet loss
else
go to **STATE: IDLE**
end if

analysis. Based on the detected waveforms, the flash rate with sampling rate of 10 minutes was characterized with a focus on various lightning flash types, namely +CG, −CG, IC, +NBE, and −NBE.

A. FAIR-WEATHER CONDITIONS

Figure 1 presents the plot of log files generated by Iperf3 software during FW3 that shows the throughput, jitter, and packet loss at the server node (depicted in orange, blue and magenta). The plot also shows the transmitted datagram and throughput at the client node, represented in green and purple, respectively. Additionally, the red plot shows the reading of the background electric field. The data encompasses a 15-hour measurement period that commenced at 18:42:00 on 26 November 2021, and concluded at 9:42:00 on 27 November 2021. Notably, this period was characterized by fair-weather conditions, with no recorded lightning flashes within 30 km radius of the sensors. Overall, the plot during FW3 illustrates stable connection at both client and server nodes. The transmitted datagram and throughput at the client node show a maximum reading at 42 Bytes and 1570 Kbps, respectively without dropping to zero. Furthermore, the server node exhibited a maximum throughput of 1400 Kbps and jitter of 19 ms. The average packet loss at the server node was $0.7084 \pm 4.6373\%$ but peaked at 78% at 22:03:13.

Similar instances occurred for an 8-hour measurement period during FW1 and FW2, and for 9 hours during FW4. At the client node, the maximum throughput value during FW1 was 1590 Kbps, while both FW2 and FW4 reached maximum throughput value of 1570 Kbps, all while transmitting maximum datagrams with a size of 42 Bytes. Besides, there is no loss of connection to zero at client node. On the server side, the maximum throughput for FW1, FW2, and FW4 was 1400 Kbps, 2140 Kbps and 2420 Kbps, respectively, with corresponding maximum jitter values of 24 ms, 31 ms, and 71 ms. Besides, the packet loss reached maximums of 72%, 94%, and 58% at 15:40:52, 22:04:14 and 12:06:50 for FW1, FW2 and FW4, respectively. On top of that, Table 2 displays the 4G LTE performance during fair weather conditions showing the average values.

TABLE 1. The details of fair-weather and storms selected for the analysis.

Fair-weather (FW)	Date	Time
1	14/11/2021	15:35 – 23:35
2	24/11/2021	18:36 – 02:28
3	26/11/2021	18:42 – 09:42
4	29/11/2021	11:12 – 20:09
Storm	**Date**	**Time**
1	29/10/2021	17:32 – 19:26
2	29 and 30/10/2021	22:54 – 01:27
3	9/11/2021	12:29 – 20:19
4	19/11/2021	16:21 – 23:28

B. NETWORK PERFORMANCE ANALYSIS OF STORM 1 AND STORM 2

Figure 2 shows the throughput, jitter, and packet loss at the server node for Storm 1 and Storm 2 that were plotted in orange, blue and magenta colors, respectively while the transmitted datagram and throughput at the client node were plotted in green and purple colors, respectively. Furthermore, the red plot shows the background electric field from 17:10:00 (29 October 2021) until 01:30:00 (30 October 2021). However, Storm 1 starts at 16:20:00 until 19:30:00 while Storm 2 starts at 21:10:00 until 00:50:00. In addition,

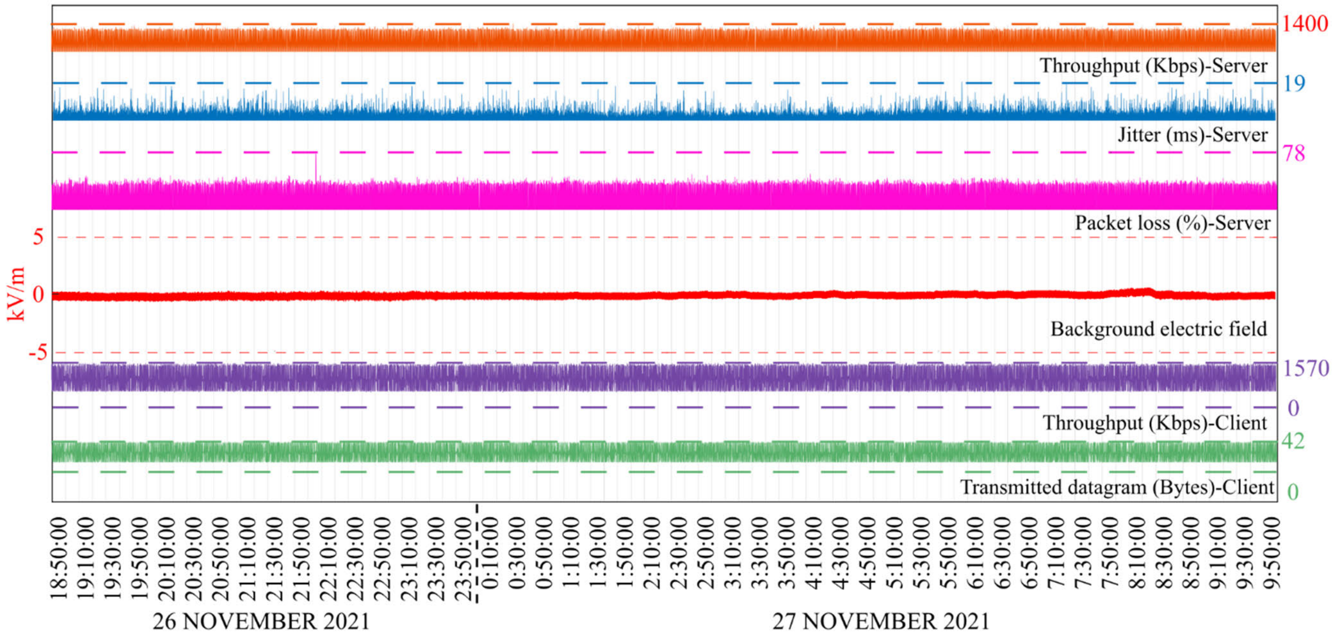

FIGURE 1. **The plots of log files show the data of throughput (Kbps), jitter (ms) and packet loss (%) at the server node in orange, blue and magenta, respectively for 15-hour measurement period from 18:40:00 on 26 November 2021 until 9:50:00 on 27 November 2021. The red plot shows the background electric field in kV/m. The transmitted datagram and throughput (Kbps) at the client node were plotted in green and purple colors, respectively.**

TABLE 2. **The 4G LTE network performance during fair-weathers.**

FW	Transmitted datagram (Bytes)	Throughput-Client (Kbps)	Throughput-Server (Kbps)	Jitter (ms)	Packet loss (%)
1	42 ± 4.6648	1002 ± 176.88	1002 ± 48.8575	2.4833 ± 1.4159	0.6896 ± 3.8650
2	42 ± 4.6648	1002 ± 176.88	352.4395 ± 477.6575	2.6597 ± 1.8328	0.6686 ± 4.1953
3	42 ± 4.6648	1002 ± 176.88	997.5886 ± 44.4722	2.4171 ± 1.3959	0.7084 ± 4.6373
4	42 ± 4.6648	1002 ± 176.88	998.3019 ± 50.5397	2.5991 ± 1.7896	0.7083 ± 4.8544

***mean±standard deviation**

the stacked column bar graphs show the flash rate for Storm 1 and 2, with data sampled every 10 minutes. During Storm 1, a total of 49 lightning flash samples were documented with −CG flash detected the highest, amounting to 30 samples, followed by IC, +CG and +NBE flashes at 14, 3 and 2 samples, respectively. However, a total of 199 lightning flashes were recorded during Storm 2 with −CG flash being the most prevalent, totaling 62 samples, while +NBE, IC, −NBE and +CG flashes followed with 58, 56, 12 and 11 samples, respectively.

The first significant observation is that the transmitted datagram and value of throughput at the client node both experienced a complete drop to zero, spanning the period between 17:50:52 and 17:54:54 within Storm 1. Besides, just 20 ms before the connection starts to drop, the value of throughput was very low which is 29.8 bps with only 1 Bytes transmitted datagram. After this lapse, a retransmission of packet occurred at the client node. The value of transmitted datagram went back to 1 Bytes with throughput value of 95,900 Kbps after 20 ms of retransmission, and both increased to 992 Bytes and 423,000 Kbps, respectively 40 ms later. The value of transmitted datagram and throughput at the client node reached maximum after 60 ms of retransmission with 12,217 Bytes and 440,000 Kbps, respectively. This unequivocally indicates a disconnection lasting approximately 4 minutes and 2 seconds at the client node. Conversely, the value of packet loss at 17:55:10 was 99% at the server node while the values for jitter and throughput stood at 8.749 ms and 2580 Kbps, 16 seconds after the retransmission of packet at the client node. According to the data shown in Fig. 2, approximately 10 minutes prior to the connection dropping to zero at the client node, a total of 14 samples of −CG flashes and 2 samples of IC flashes were detected.

Moreover, Fig. 3 illustrates an instance of a −CG flash detected just 13 seconds before the connection was lost. Both CG and cloud activities have been found to cause the loss of connection for 4 minutes and 2 seconds at the client node during Storm 1. Microwave radiation associated with the fast

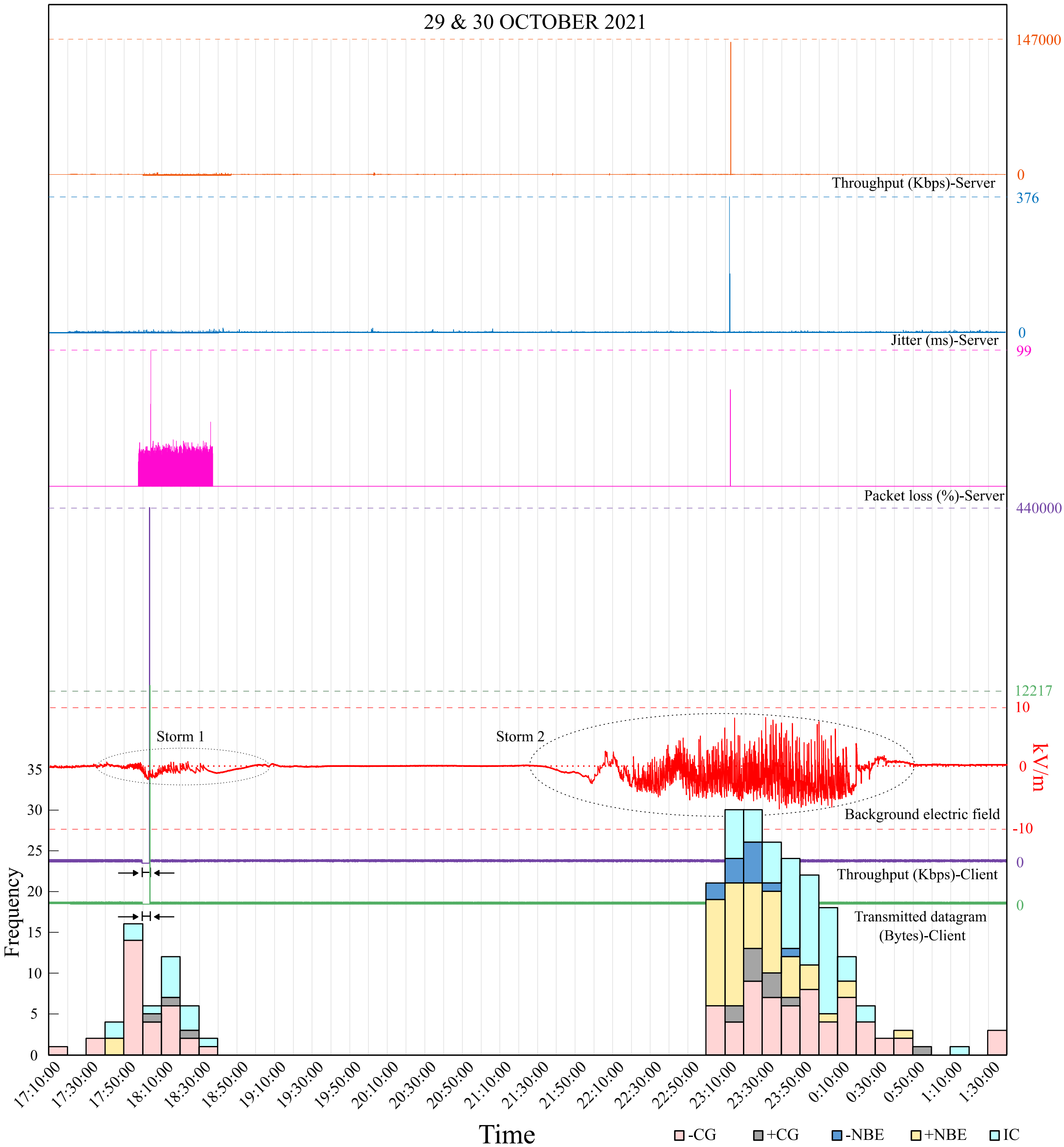

FIGURE 2. **The plots of log files show the data of throughput (Kbps), jitter (ms) and packet loss (%) at the server node in orange, blue and magenta, respectively for 15-hour measurement period from 18:40:00 on 26 November 2021 until 9:50:00 on 27 November 2021. The red plot shows the background electric field in kV/m. The transmitted datagram and throughput (Kbps) at the client node were plotted in green and purple colors, respectively.**

antenna in Fig. 3 was detected at the same band of frequency at 4G LTE band which is 2.3 GHz. Additionally, it could be observed that Storm 1 was accompanied by a notably high background electric field (maximum at 2.33 kV/m).

However, it could be noticed that transmitted datagram and throughput values at the client node exhibit stabilization after the packet retransmission event. Furthermore, such cases involving the connection dropping to zero for transmitted datagram and throughput at the client node did not manifest during Storm 2 despite the presence higher intensity of lightning flashes that occurred. Notably, the background electric field reached its peak at 8.36 kV/m during Storm 2. Moreover, it could be observed that the values of jitter, packet loss and throughput at the server node recorded at 23:04:44

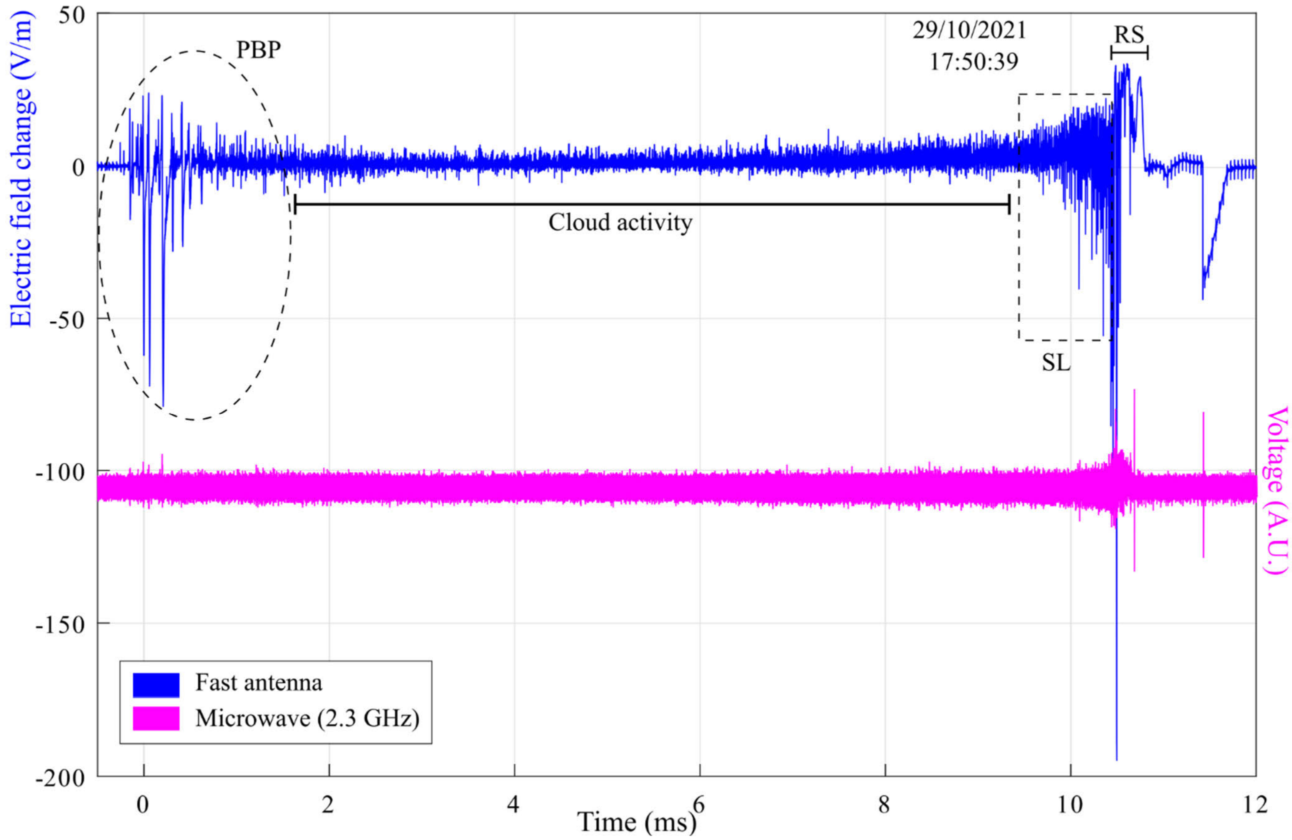

FIGURE 3. An example of −CG detected on 29 October 2021 at 17:50:39, 13 seconds prior to the connection dropping to zero at the client node during Storm 1. Blue waveform shows the fast electric field (V/m) record of the −CG flash that starts with preliminary breakdown pulse (PBP), stepped leader (SL) process and return stroke (RS), while the magenta shows the microwave radiation (2.3 GHz) associated with the −CG flash in arbitrary unit (A.U.).

were 164 ms, 71% and 147,000 Kbps, respectively. It is worth noting that the values of jitter peaked at 376 ms for 5 seconds prior to the sudden increase in throughput to maximum at the server node. Markedly, preceding this occurrence, a +NBE flash and two IC flashes were detected 42, 25 and 9 seconds earlier, respectively. Furthermore, 10 minutes before the heightened throughput, jitter and packet loss observed at the server node, a total sample of 9 −CG flashes, 19 +NBE flashes, 5 −NBE flashes and a +CG flash, were recorded.

C. NETWORK PERFORMANCE ANALYSIS OF STORM 3 AND STORM 4

Figure 4 and Fig. 5 show the performance analysis plot for 4G LTE during Storm 3 and Storm 4, respectively. The duration of lightning flashes rate for Storm 3 and Storm 4 were between 15:00:00 and 20:30:00 on 9 November 2021 and between 16:20:00 and 23:50:00 on 19 November 2021, respectively. There was a total of 286 lightning flashes recorded with +NBE detected the highest with 121 samples, followed by IC, −CG, +CG and −NBE with 57, 50, 50 and 8 samples respectively during Storm 3. From Fig. 4, the value of transmitted datagram and throughput at the client node show a stable connection even though the flash rate could peak with 74 samples per 10 minutes. In the meantime, at 15:34:25 at the server node, the value of jitter peaked at 149 ms with 93% of packet loss and 634 Kbps of throughput. It was found that a −NBE was recorded on 15:33:03 which is 1 minute and 22 seconds earlier. Furthermore, the maximum value of background electric field was 12.45 kV/m during Storm 3.

On the other hand, Storm 4 recorded 173 total samples of lightning flashes with −CG and IC flashes detected the most with 65 samples each, followed by +NBE, +CG and −NBE with 22, 15 and 6 samples, respectively. Figure 5 shows that the transmitted datagram and value of throughput at the client node drop to zero from 19:59:03 to 19:59:47 for about 44 seconds. It was worth noting that 20 ms before the connection drops to zero, the value of throughput at the client node was very low with only 164 bps and 1 Byte transmitted datagram. After that, a retransmission of packet took place as the transmitted datagram and value of throughput at the client node spiked to 6121 Bytes and 218,000 Kbps, respectively. On the other hand, in between that lapse at server node, the values of packet loss recorded the highest with 96% at 19:59:25 with throughput and jitter stood at 2960 Kbps and 10 ms, respectively. Meanwhile, the maximum value of throughput at server node was 5090 Kbps with jitter and packet loss values of 0.7 ms and 54%, respectively at 19:59:23

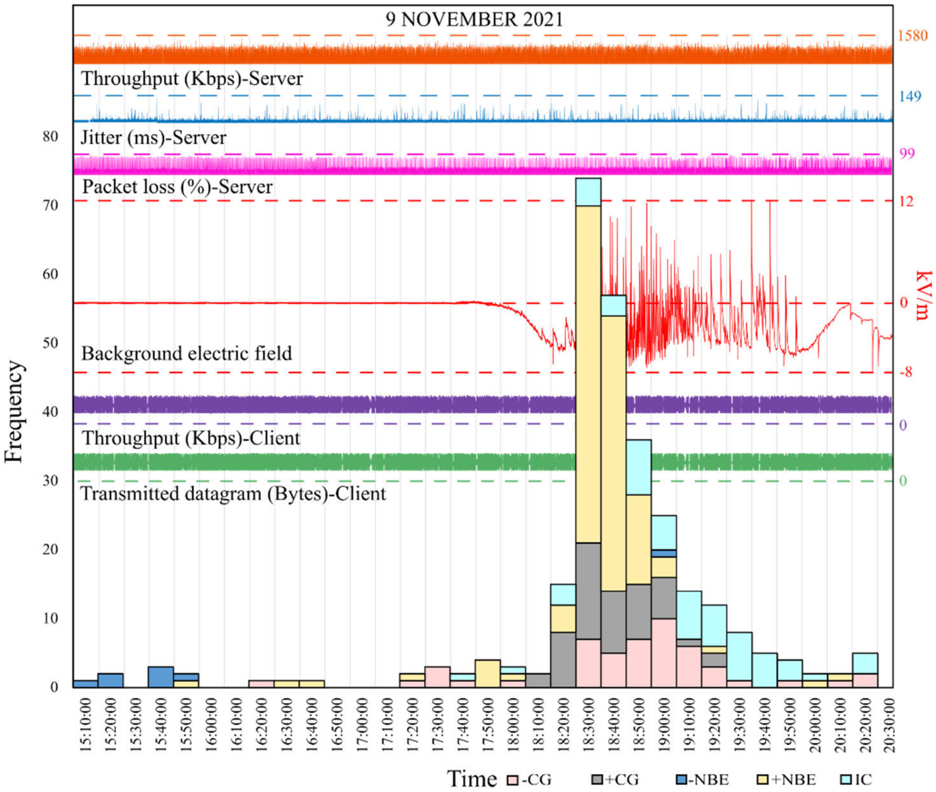

FIGURE 4. The stacked column bar graphs show the flash rate on 9 November 2021 from 15:00:00 to 20:30:00 with data sampled every 10 minutes. The throughput, jitter and packet loss at the server node were plotted in orange, blue and magenta, respectively. The red plot shows the background electric field in kV/m. The transmitted datagram and throughput at the client node were plotted in green and purple colors, respectively.

which is 2 seconds earlier. Notably, the maximum value of background electric field was 2.08 kV/m during Storm 4.

IV. DISCUSSION

A. PART 1

In this paper, a performance analysis of 4G LTE network has been conducted to observe the effects of lightning interference on the 4G LTE connection under both fair-weather and stormy conditions. Two nodes were assigned different roles using Iperf3 software, one as the client and the other as the server with a 1 m LOS. It was found that during fair-weather conditions, the connection of 4G LTE at both the client and server nodes exhibited stability and experienced minimal impact. On the other hand, lightning electromagnetic interference disrupted the 4G LTE communication links. However, out of the four analyzed storms, three exhibited effects on client or server nodes. Furthermore, Storm 1 and Storm 4 show connection at the client node that dropped to zero for 4 minutes and 2 seconds and for 44 seconds, respectively. Such an occurrence did not take place during the four reported fair-weather conditions in this paper. Additionally, [15] and [16] conducted similar comparisons between fair-weather and thunderstorm conditions, but their studies focused on Wi-fi technology operated at 2.4 GHz band.

During Storm 1, the throughput dropped by approximately 100%, going from 1110 Kbps to 29.8 bps, and the transmitted datagram decreased by approximately 96%, reducing from 28 Bytes to 1 Byte at the client node. These drops occurred just 20 ms before the connections reached 0 Kbps of throughput and 0 Byte of transmitted datagram that lasted for 4 minutes and 2 seconds. After that, a packet retransmission occurred, resulting in a significant increase in both throughput, which surged by 396.4 times to 440,000 Kbps, and transmitted datagram, which saw an increase of 436.32 times to 12,217 Bytes. After 16 seconds of the initial drop, the server node reported a staggering 99% packet loss. On the other hand, the value of throughput at the server node during Storm 2 exhibited a remarkable increase of approximately 137.85 times to 147,000 Kbps with high jitter value of 376 ms for 5 seconds beforehand. However, Storm 3 did not significantly affect the 4G LTE connection at both the client and server nodes although the total lightning flashes recorded were the highest with 286 samples. Meanwhile, during Storm 4, the connection at the client node abruptly dropped to zero for a duration of 44 seconds, despite the absence of any reported lightning flashes in the preceding 10 minutes. Remarkably after the retransmission of packet, the throughput value surged by a factor of 219.35, reaching 218,000 Kbps, while the

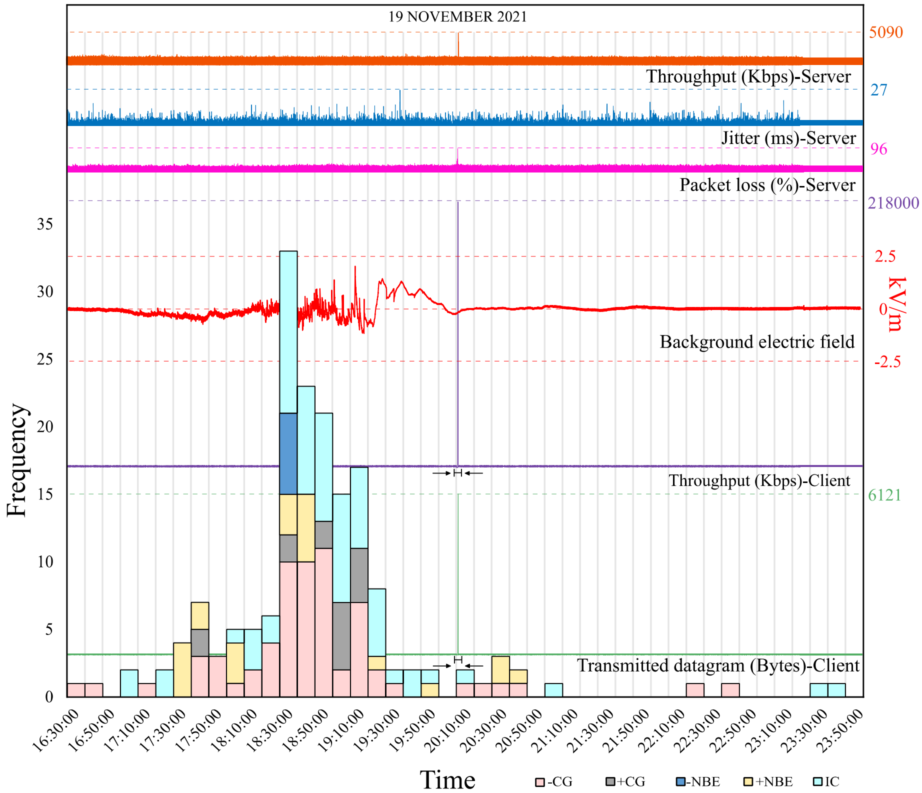

FIGURE 5. The stacked column bar graphs show the flash rate on 19 November 2021 from 16:20:00 to 23:50:00 with data sampled every 10 minutes. The throughput, jitter and packet loss at the server node were plotted in orange, blue and magenta, respectively. The red plot shows the background electric field in kV/m. The transmitted datagram and throughput at the client node were plotted in green and purple colors, respectively.

transmitted datagram size increased by 218.61 times, peaking at a maximum of 6121 Bytes at the client node.

Figure 6 shows the percentage of different types of lightning flashes for the four reported different storms. Notably, −CG lightning flashes were most frequently detected during Storm 1, Storm 2, and Storm 4, with percentages of 61%, 31%, and 37.5%, respectively. However, during Storm 3, the most detected lightning flashes were +NBE with 42% of total lightning occurrences. Additionally, the percentages of IC flashes detected during Storm 4 were tied with −CG with 37.5%, while the percentages of IC flashes detected during Storm 1 and Storm 3 were 20% and 29%, respectively. It could be suggested that −CG and IC lightning flashes have been identified as sources of interference for 4G LTE communications links. This inference is supported by the absence of packet transfer disruptions at client or server nodes during Storm 3, where +NBE lightning flashes were the most prevalent. Previously, [16] reported that both IC and CG flashes significantly disrupted transmitted data over 2.4 GHz wireless communications links.

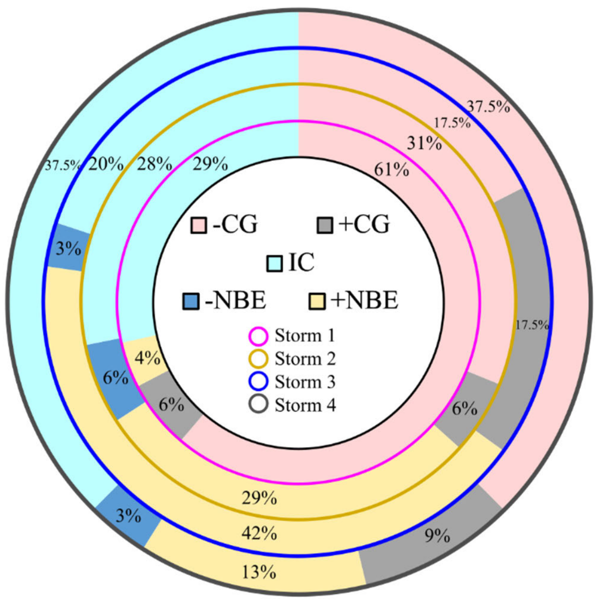

FIGURE 6. The doughnut graph displays the percentages of different types of lightning flashes (−CG, +CG, −NBE, +NBE, IC) for Storms 1, 2, 3, and 4, each represented with a ring in the colors magenta, yellow, blue, and grey, respectively.

B. PART 2

Based on the results, a statistical correlation analysis between throughput, packet loss and jitter and fair-weather and storm events has been formulated. It has been found that interference effect from lightning events can be categorized into 2 scenarios:

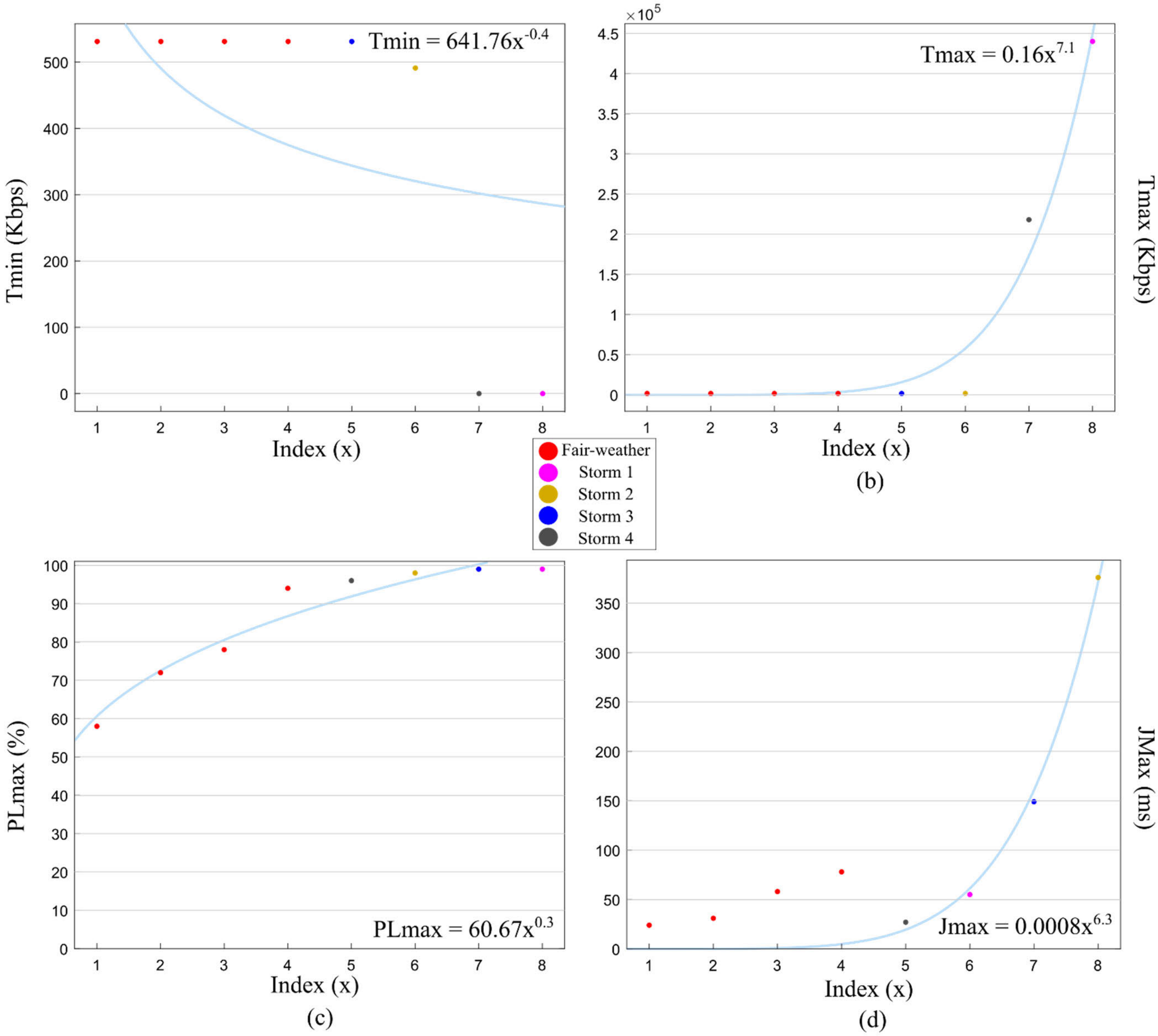

FIGURE 7. **The relationship formulation of correlation analysis between fair-weathers (red dots) and storms and (a) minimum throughput at client node (Tmin/Kbps), (b) maximum throughput at client node (Tmax/Kbps), (c) maximum packet loss (PLmax/%) and (d) maximum jitter (Jmax/ms).**

i) When throughput drops to zero
ii) When throughput drops below than fair-weather but not zero

Figures 7(a) and Fig. 7(b) show the correlation between fair-weather conditions (represented by red dots) and four storms, highlighting the minimum and maximum throughput of the 4G LTE network at the client node. In Fig. 7(a), the throughput of data transmission over 4G LTE wireless link has dropped to zero for Storm 1 (magenta dot) and Storm 4 (grey dot). For the other two storms, the throughputs were similar to fair weather events, with 491 Kbps and 531 Kbps for Storm 2 and Storm 3, respectively, compared to 531 Kbps during fair weather events.

Fig. 7(b) represents the maximum throughput that shows the throughput reaches a maximum of only 1570 Kbps and 1590 Kbps during fair-weather. On the other hand, the maximum throughput increases drastically during Storm 1 and Storm 4. The retransmission of UDP datagrams occurred to restore the connection during periods of connection loss. The longer the connection loss, the higher the throughput value for the retransmitted packets. For instance, during Storm 1, where the connection drops to zero for 4 minutes and 2 seconds, 444,000 Kbps of packets have been retransmitted, compared to a 44-second connection drop to zero with 218,000 Kbps of packets retransmitted. The retransmission of UDP datagrams was a result of the loss of connections due to severe interference effects.

Fig. 7(c) shows the relationship between fair-weather and storm events for maximum packet losses of 4G LTE network. The packet losses increased steadily as lightning events became more severe. The maximum packet losses during storm events were between 96% and 99% compared to fair-weather events which were between 58% and 94%. While there are occurrences of high packet loss during fair-weather, the overall average and mode packet loss, as presented in Table 1, remain relatively small. Furthermore, Fig. 7(d) shows the correlation analysis between fair-weather and storm events for maximum jitter experienced by 4G LTE network which were between 27 ms and 376 ms. Spikes in jitter values were observed during Storm 2 (yellow dot) and Storm 3 (blue dot), even though the throughput at the client node did not experience a complete drop to zero.

Through numerical method analysis, the relationships between minimum, maximum throughput (Tmin, Tmax), maximum packet loss (PLMax) and maximum jitter (JMax) of 4G LTE network and fair-weather and storm events are formulated as the following equations (1) to (4).

$$\text{Tmin}\ (x) = 641.76x^{-0.4} \tag{1}$$

$$\text{Tmax}\ (x) = 0.16x^{7.1} \tag{2}$$

$$\text{PLMax}\ (x) = 60.67x^{0.3} \tag{3}$$

$$\text{JMax}\ (x) = 0.0008x^{6.3} \tag{4}$$

Lightning interference is associated with events that emit radiation across a broad frequency spectrum, including ionizing radiation like X-rays and Gamma rays. However, this study specifically targets the frequency band below ionizing radiation, focusing on the 2.3 GHz range (non-ionizing radiations) emitted from lightning. The microwave radiation from lightning originates from the electron avalanche/corona breakdown at the tip of the leader [8] and head-on collisions of streamers [9], [10]. Meanwhile, the sources of VHF radiation emitted by lightning are propagating streamers [10] and head-on collisions of streamers [9], as later affirmed by [11] and [12] regarding VHF radiation emitted from propagating streamers, based on the onset time difference of microwave and VHF radiation. Moreover, the microwave radiation is characterized as individual oscillating pulses [11] and it was reported that there can be up to 3 microwave radiation pulses associated with each stepped leader pulse and considering the numerous stepped leaders in −CG lightning flashes, the total count of microwave radiation pulses could be in the hundreds.

The microwave receiver at the measurement site directly measures the microwave radiation components without the use of a mixer and down-converter, ensuring the preservation of information such as the number of pulses and amplitudes of the microwave samples. As packets over 4G LTE were configured for transmission every 1 second, the occurrence of hundreds microwave radiation pulses, associated with each stepped leader and return stroke event (refer Fig.2), including subsequent return strokes taking place within a span of 1 to 2 seconds has the potential to interfere with the transmitted packets. Furthermore, the telecommunication tower was located 0.12 km from the measurement site. The stepped leader, return stroke, and subsequent return stroke are components of the −CG process, which is suggested to be a contributing factor to the packet transmission loss based on the predominant types of lightning flashes (refer to Fig. 6) detected during Storm 1 and Storm 4. The stepped leader reported in [11] provides natural lightning measurements that reported the electron avalanche/corona breakdown at the tip of the leader or head-on collisions of streamers contribute to the microwave radiation emitted from lightning. The evidence of lightning interference was substantiated by the lightning initiation process, specifically the electrical breakdown process [18], [19].

V. CONCLUSION

In this paper, we extend the studies in [15], [16], and [17] by observing the impact of lightning interference on 4G LTE communication links operated on 2.3 GHz band under two different conditions which are fair-weather and thunderstorm. The 4G LTE connections demonstrated stability in fair-weather conditions at both client and server nodes. On the other hand, during three out of the four observed storms, the 4G LTE connections were interrupted or completely dropped to zero which is a condition that does not occur in fair-weather scenarios. Furthermore, this study identified that −CG and IC lightning flashes as the main sources of interference in 4G LTE communication, aligning with previous studies reported in [15] that focusing on the Wi-fi technology operated on 2.4 GHz band. The significant fluctuations in transmitted datagram size and overall performance of throughput during storms underscore the vulnerability of these networks to disruptions caused by electromagnetic radiation emitted from lightning flashes. Moreover, the disruptions in packet transmission were linked to the lightning initiation process, which emitted hundreds of individual oscillating microwave radiation pulses.

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