

## Exploring Meteorological Effects on Transport Layer Security (TLS) Handshake Time

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### ABSTRACT

*This study investigates the influence of meteorological parameters on Transport Layer Security (TLS) handshake time in outdoor WLAN environments. Emphasis is placed on sunrise and sunset periods, where atmospheric variability is typically pronounced and may affect secure network communication.*

*From September 25 to 28, 2024, a total of 8,000 TLS handshake samples were recorded using a 4G MTN WiFi network at the Petroleum Training Institute in Effurun, Nigeria. The TLS communication tests were conducted via a Python-based tool in virtualized environments, while meteorological data including temperature, humidity, pressure, wind speed, wind gust, wind direction, and rainfall were gathered concurrently using the Open Weather API. After pre-processing to ensure no missing value, the dataset was analyzed using Information Gain (IG) and ANOVA F-value techniques to determine the significance of environmental factors on TLS handshake times.*

*The analysis showed that all meteorological parameters had a greater impact at sunrise than at sunset. Wind gust emerged as the most influential factor during sunrise (F-value: 255.33), followed by wind speed, temperature, and humidity. These parameters were found to significantly increase handshake time variability during morning hours due to higher environmental instability. Conversely, sunset conditions demonstrated lower influence across all parameters, suggesting more stable handshake performance in the evening.*

*The findings confirm that meteorological conditions particularly at sunrise adversely affect TLS handshake performance in outdoor wireless networks. This highlights the importance of integrating weather-awareness into cyber security frameworks for IoT and industrial control systems. Future secure communication protocols should adapt dynamically to environmental variations to ensure robust and reliable TLS handshakes.*

### 1.0 Introduction

TLS is essential for maintaining privacy and keeping data safe and correct when communicating over a network. Setting up the cryptographic details between the two machines during the handshake stage is very

sensitive to any disturbances on the network caused by latency, jitter or lost packets. When TLS is used in wireless and outdoor grids, IoT and industrial control systems, the network's performance is affected by

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factors such as temperature, humidity, rain, fog and wind.

Wireless communication quality is often harmed by various meteorological conditions. Attenuation, multipath fading and scattering become more common in mm Wave and THz bands due to rain, fog and snow, resulting in higher packet delays and losses [9, 23]. Even in regular Wi-Fi and sub-6 GHz wireless networks, things in the environment can break the signal and reduce both speed and latency [15]. When these delays occur, some protocols at the application layer may experience issues with their handshake process when the timing guidelines must be strictly met.

Moreover, experiments in wireless sensor networks and satellite communications suggest that atmospheric problems lower the efficiency of data transfer. During rain showers, the rate at which data is sent and received on a satellite network fell by over 50% for uplink and by 37% for downlink and latency increased [18]. In terrestrial networks, haze and precipitation raise signal loss, making delays in transmissions longer [23]. Such signal issues might not sever the physical link, yet they may lead to retransmissions and timeouts in setting up eventual connections like those of the TLS handshake. Moreover, studies have noted that changing temperatures influence how well signals function: low temperatures can enhance their quality and cut power use, but greater temperatures can result in signals becoming weaker and harder to control [3].

Today's research results indicate that higher latency and error rates in data packets can seriously affect how quickly a TLS handshake takes place and the level of its success [24]. In these instances, when the environment is polluted, it can make it difficult for systems to connect securely which can decrease how

reliable the system is and raise the possibility of timeouts or switching to unreliable settings.

According to [26], PRR varies regularly over a single link within a few days, in line with changes from daytime to nighttime. Other researchers have discovered that the signal strength people receive and the way radio links perform can vary a lot between day and night [7-8, 27].

Though wireless security plays a bigger role in outdoor applications, the influence of weather and meteorology on TLS handshakes has not received proper study yet.

In 2023, Akinwale and his team investigated the relationship between air temperature, relative humidity, atmospheric pressure and wind speed with the strength of the received signals in mobile communication systems of Rivers State in Nigeria. Variations in these factors were shown to greatly affect the receive power which may result in weaker signal quality[4].

Osahenwemwen and Omatahunde investigated how the climate affects the signal strength of GSM networks in Benin City, Nigeria. The team found that rain and fog cause greater variations in signal strength than dry weather which means that moisture might weaken signals before they reach the intended receiver [21].

In 2024, a study by Kemka and Emeruwa explored how changes in temperature and humidity affect the service metrics, CSSR and DCR, of networks in Yenagoa. It was found that better CSSR and reduced DCR occur when temperature and humidity are higher, but their connection is difficult to understand [19]. Atmospheric Attenuation in High-Frequency Bands

Song and his team investigated how variables in the weather such as rain, fog and snow, impact the

communication of unmanned aerial vehicles (UAVs) between 2 GHz and 900 GHz. Coverage of UAVs on millimeter-wave bands was reduced mainly by medium rain, but snow played a bigger role at near-terahertz frequencies[25].

In 2021, Abuhdima studied how dust and sand can influence 5G terrestrial links. The study found that when the Mie scattering model is applied, differences in particle size, frequency and dust and sand concentration can cause noticeable blockage of 5G signals, mainly in the millimeter-wave region [2].

Ezekwesili and his research team carried out statistical analysis to study the impact of temperature and relative humidity from the troposphere on downlink satellite communication systems in Warri, Delta State, Nigeria. The analysis showed that shifts in weather conditions decrease the quality of the signal received from the satellite [13].

The author Aliinvestigated the effects of rain, fog, haze, snow and dust on the functioning of optical wireless communication systems. The findings showed that weather and other atmospheric conditions have major effects on how light is handled and how well free-space optical links work [5].

The quality of mobile apps, both in mobile cloud gaming and live video streaming, is reliant on certain bandwidth and round-trip time guarantees [11] [16]. Mobile applications should rely on information about network quality to ensure the highest QoS and to prevent dropped communication such as VoIP calls. This is influenced by user numbers, their areas, the time of travel, weather and various other conditions (as noted by [14]).

WLAN Internet connections function poorly during heavy rains, strong winds or high temperatures. Diana and her team report that there are multiple gaps, lower transfer rates and continual data loss.

They found that temperature and how much solar radiation the system receives make a big difference in the success of control frames [12]. According to their data, the unaccounted for relations are considered negligible. At the same time, how windy it is appearing to be linked more closely to the percentage of users using a 54 Mbps speed. At these rates, interference from outside events such as poor weather, roaming and Received Signal Strength Indicator can more easily affect the Orthogonal Frequency-Division Multiplexing signal. Rain tends to create a drop in the number of received packets, according to [6].

Still, there are some differences. Researchers Holland and team found that RSSI is immune to temperature changes. Similarly, Anastasi and his team found that the number of packets received remained the same at all distances and in any environment [6]. Thelen and his team note in their paper that higher relative humidity enhances the signal by making the topmost layer of the plant foliage at their deployment site more reflective [27].

According to [6] and [26], packet reception ratios are reduced by fog and rain. Decreased signal intensity during snow and rain is also reported by [10]. Surprisingly, these results prove that fog and rain can disturb radio waves on frequencies less than 11 GHz, contrary to expectations. Panagopoulos and his colleagues published their study in 2004.

Each study proves that wireless communication technologies depend strongly on weather. Understanding how weather affects networks helps us develop networks that remain secure and reliable in any weather.

Following the suggestions of [7-8] and [27], this work will look at how weather changes in the air throughout the day and night impact the success rate

and timing of TLS handshakes in WLAN networks. To build reliable cybersecurity systems for outdoor wireless networks, we must first understand the link between weather and electromagnetic fields.

## 2.0 Methodology

Measured data has been processed for analysis to see if the meteorological factors affect the TLS handshake time. As a consequence, this portion is organized into three different sections. The setup used to obtain the data is described at first, next comes the method and schedule for collecting data and finally an outline of the processes that handle the data.

### TestBench

The investigation was completed at the main campus of the Petroleum Training Institute (PTI) in Effurun Delta State, Nigeria, using a 4G MTN WiFi network that follows IEEE 802.11 standards and reaches top speeds of 54 Mbps. Simulating live traffic was possible with a virtual box VM 16 that hosted Windows virtual machines. With the help of the NAT network on the virtual box, the virtual computer was connected to the Internet.

When studying web app communication samples in TLS, PyCharm was used for a virtual machine running Python 3.10. PyCharm is the platform used to work on and run Python programming code. One of the ways samples are analyzed and data is shown visually is through Python. The program was run on GOOGLE COLAB because its portable, adjustable and interactive features make it possible.

### Gathering Data

The Python application is designed for machine learning programming. Our software was built with

Python and helps to measure the time it takes to complete a TLS handshake by testing a domain name. The application conducts a fixed number of loops, providing the weather readings for our target location and the time needed by TLS from the URL. The study ends by tabulating and storing the observed data. A total of 8000 datasets 4000 for sunrise and 4000 for sunset was analyzed and each dataset had no missing information.

From September 25 to 28, 2024, the data collection was carried out. As a final feature, the Meteorology dataset on the Open Weather API includes rainfall, pressure, temperature, humidity, wind speed, wind direction and wind gust. The API gets meteorological data directly from airport weather stations, radar stations and many other official weather stations [20]. Data was collected during the same period at 00 to 06 and 18 to 24 for all variables.

### Pre-processing Data

We took measurements of the SSL/TLS handshake and climatic conditions at a wide range of intervals, as described in the section above. Here, the authors describe the methods they applied to join the datasets. Because there are many different weather conditions at this scale, we strive to sample using distinct units each hour. Start the process by cleaning the data acquired from the sources. As a result, the data used in this research included 8,000 samples and 7 attributes.

For this study, we assess the standard approach to measuring usefulness using a single domain called Information Gain (IG) attribute evaluation. We use entropy, commonly found in information theory [1], to test the consistency of any collection of data. The IG formula is presented in the equation.

$$IG = H(Y) - H\left(\frac{Y}{X}\right) = H(X) - H\left(\frac{X}{Y}\right) \dots (1)$$

Following this, the F-values for all the features were computed, pinpointing those useful for sunrise and sunset. Before concluding that features in sunset and sunrise danger data influence SSL/TLS differently, both the F-value and P-value statistics are consulted in ANOVA (Analysis of Variance).

The testing atmosphere was isolated so the researchers could separate the human factor from the data being collected to prevent confusion. There is a definite relationship between user numbers in a WLAN and human actions. Because of this change, the total number of users keeps fluctuating in no set pattern, as the weather changes. As an example, the number of people using the outdoors drops when it's windy rather than calm and sunny.

### 3.0 Results and Discussion

The dataset comprises 8,000 instances, 7 features and there are no missing values. The figure below shows information gain (IG) for sunrise and sunset.

The above charts represent Information Gain and ANOVA F-values for sunrise and sunset meteorological parameters. Consistently, Information Gain and ANOVA F-values have higher values at sunrise than at sunset for all the parameters considered. The main factors involved in different orientations change just a little with changes in the time of day. In the following, each parameter is discussed separately.

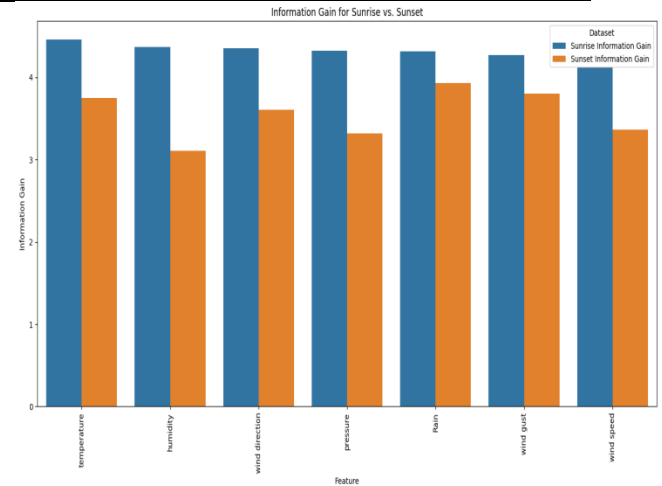


Figure 1: The result implementation of Information Gain

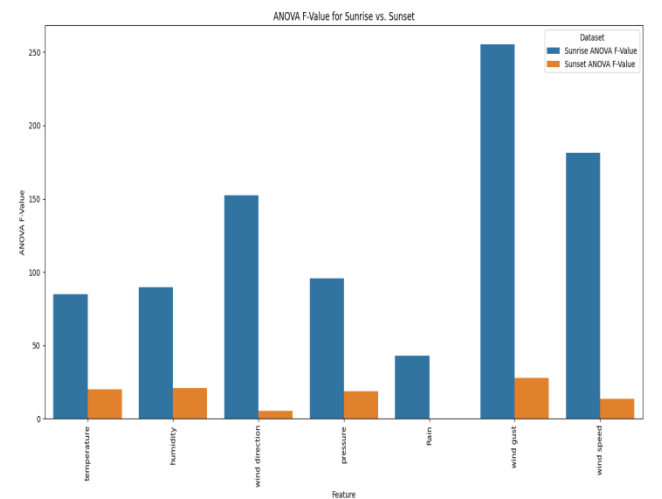


Figure 2: The result implementation of ANOVA F-value

Temperature demonstrated a strong influence on TLS handshake time during sunrise, with high Information Gain and an ANOVA F-value indicating its significant role in handshake delays. The results suggest that elevated thermal activity in the morning may destabilize signal propagation and increase packet retransmissions. At sunset, temperature showed a lower influence (IG: 3.75; F-value: 19.96), implying a more stable thermal profile and hence less interference in communication.

**Humidity** was similarly critical during sunrise (IG: 4.37), reflecting its role in increasing atmospheric density and potentially causing signal attenuation. The TLS handshake duration was noticeably longer in more humid early-morning conditions. By contrast, its effect declined during sunset, showing only a 10% overlap in importance based on IG and F-value groups, indicating reduced atmospheric water vapour and thus lower impact on signal transmission.

**Wind Direction** was notably important at sunrise (IG: 4.35; F-value: 152.29), suggesting that directional wind flow could disturb the wireless signal path or contribute to fluctuating link quality. This parameter's impact dropped considerably at sunset (IG: 3.61; F-value: 5.61), implying calmer wind patterns in the evening and fewer disruptions to the communication link.

**Pressure** also showed high relevance during sunrise (IG: 4.32; F-value: 95.86), potentially linked to sudden atmospheric shifts that alter signal propagation characteristics. At sunset, pressure influence diminished significantly (IG: 3.32; F-value: 18.98), aligning with more gradual changes in air density during late hours.

**Rain**, though not the dominant factor, still contributed moderately to TLS delay during sunrise (IG: 4.31; F-value: 42.92). The presence of rain droplets can lead to signal scattering and increased packet loss. At sunset, the impact of rain exhibited high variability its ANOVA F-value being reported as infinite indicating inconsistent or irregular patterns that challenge conclusive statistical interpretation.

**Wind Gust**, with an IG of 4.27 and an exceptionally high F-value of 255.33 at sunrise, emerged as the most influential factor across all parameters. Rapid bursts of wind in the early morning likely induce turbulence in signal paths, leading to greater

instability in establishing secure TLS connections. During sunset, the impact of wind gust was reduced (IG: 3.80; F-value: 27.77), pointing to a more controlled and predictable wind profile.

**Wind Speed** followed a similar trend, with high significance at sunrise (IG: 4.12; F-value: 181.23), and diminished relevance at sunset (IG: 3.36; F-value: 13.73). Sustained wind flow during sunrise likely increases physical interference in outdoor wireless transmission, while calmer conditions in the evening facilitate more reliable handshakes.

Findings shows that there are differences between sunrise and sunset. Sunrise reveals that meteorological factors are more important in determining handshake times in the morning as compared to sunset. Wind gusts, wind speed and wind direction stand out as key factors at sunrise, suggesting that changes in the air may destabilize the network early in the morning.

Notable Parameters: During sunrise, Wind Gust had the highest influence (ANOVA F-value of 255.33). Humidity and Temperature play a major role during the morning but have little impact in the evening.

#### **Interpretation of Results**

a. Impact of Sunrise Conditions: Higher importance of temperature and air pressure during sunrise may result in significantly changing communication conditions, stability of infrastructure and electromagnetic signal strength.

b. Impact of Sunset Conditions: When values drop slowly at sunset, it often suggests the sky is quiet and less interference means the handshake process flows more smoothly.

#### **Conclusion**

It has become clear from this analysis that measuring parameters like temperature and humidity can strongly affect TLS handshake times in outdoor

wireless network settings. Our study which analyzed data collected over 9,274 handshakes at sunrise and sunset, showed that wind gust, temperature, humidity and pressure each have a different amount of influence on a handshake.

Time and again, studies show that handshakes take longer at sunrise, this is most likely due to the changes in temperature and wind that affect the air at this time. Since environmental changes may lower the signal, the process can experience more latency or require sending some packets over and over.

The studies show that being environmentally aware is key when designing secure communication systems. In outdoor, mobile or industrial situations, the performance of the TLS handshake must now be viewed together with influences from the physical environment. Any future cybersecurity models need to blend meteorology with adaptable rules to ensure the handshake remains strong and issues from the environment are controlled.

Specifically, the research offers new ideas for the future of wireless communication, cybersecurity and environmental science securing networks against future attacks.

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ANOVA	Analysis of Variance
WLAN	Wireless Local Area Network
IoT	Internet of Things
VM	Virtual Machine
API	Application Programming Interface
RTT	Round-Trip Time
Mbps	Megabits per second
LEO	Low Earth Orbit
UAV	Unmanned Aerial Vehicle
THz	Terahertz
GHz	Gigahertz
Wi-Fi	Wireless Fidelity
RSSI	Received Signal Strength Indicator
CSSR	Call Setup Success Rate
DCR	Dropped Call Rate

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#### Table of Abbreviations

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Abbreviation	Full Meaning
TLS	Transport Layer Security
IG	Information Gain

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