Experimental Evaluation of Free Space Optical device performance as a function of weather conditions

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Abstract: - This research focuses on the effects of weather conditions on the performance of the Free Space Optics devices. At the University of Wollongong in Dubai, Free Space Optics (FSO) device was deployed in 2012 providing wireless connection between the three buildings of the University as it is crucial to the entire IT infrastructure. However, the major drawback of Free Space Optics was the data bandwidth limitation. Weather impact on the link visibility was another major problem.

Weather data and Free Space Optics performance were collected throughout the year of 2013. The FSO bandwidth performance is measured in Megabit per second (Mbps). The link visibility translating the availability of the FSO system was also measured. Weather data included temperature, humidity and wind speed. This work highlights the experimental outdoor Free Space Optical (FSO) communication system performance and studies the climatic impact within Dubai, United Arab Emirates.

Key-Words: Free Space Optics, bandwidth, weather interference, regression, Microwave Link

1 Introduction

The objective of this research is to assess the performance of Free Space Optics (FSO) in relation to climatic factors. Weather factors such as temperature, humidity and wind speed limit the maximum data rate of the FSO system since the propagation of optical beam is transmitted in the air. This study needs a thorough understanding of the performance of FSO communication system as a point-to-point wireless communication including understanding how the system works and clarifying its advantages and disadvantages in the daily operation of the network services provided to the University community. This research called for the study of the network design infrastructure using FSO technology and for a comparison with other existing technologies such as Microware Radio Frequency (RF) technology.

Free Space Optics (FSO) is gaining popularity in the telecomunication and network enterprises and is now accepted as a functional, wireless, high-bandwidth access tool for network and telecom engineers. However, as of today, optical fiber cable technology is still preferred by the consumers due to the high data rates and high capacities in connecting data networks. Unfortunately, fiber optic cable based connection is not applicable in all situations, especially for long distance networks, as it needs under cable trenching. The FSO, however, has a lower cost compared to fiber optics technology and has a significantly shorter installation time. FSO is now considered a viable alternative to fiber for short-haul access distances of 4 km or less.

FSO systems can be operated in a point-to-point mode to interconnect two locations or in a point-to-multipoint mode. In the past year, different types of communication system devices were deployed to connect three buildings of a higher education institution. The air-distance between the school buildings and the broadcast station is approximately 200 meters.

To determine the performance of FSO links, Bandwidth and link availability were observed for the entire period of 2013 (Jan 1 to Dec 31). Link availability expressed in percentage in general defines the proportion of time a system is in full operational condition. The results of our investigation reveal that there are some atmospheric disturbances. The results also reveal that fog can have a considerable impact on the reliability of the FSO link.

2 Problem Statement

While fiber-optic cable and FSO technology share many characteristics, they have different challenges due to the way they transmit data. Fiber-optic is subject to outside disturbance. Laying out this optic cable is sometimes not practical as it depends on the structure of the building. FSO technology has an outstanding potential solution for wireless network bridging purposes.

In the case of our University, under-cable trenching is not possible. The connectivity between these buildings is very crucial to the daily operations of the entire network infrastructure. If there is a disconnection from the FSO system, most IT services will not work. These services include internet, emails, finance applications, virtual desktop machines and wireless campus network.

For a wireless point-to-point implementation such as FSO technology, the network must be designed in such as a way to resist the severe changes in weather so that atmospheric conditions do not affect the FSO link performance in both bandwidth capacity and link availability. Since the implementation of the FSO is a line of sight technology, it relies mainly on transmitter and receiver devices as points of interconnection and must be free from physical obstruction in order for the devices to be able to see each other. Climatic factors such as humidity, temperature, wind-speed, sand-storm and fog may attenuate the signal transmitted between the two devices. Such attenuation would then degrade FSO performance in data bandwidth and network availability. Obviously, climatic factors are uncontrollable but still there is an urge to assess the effect of climatic factors on the FSO performance.

3 Historical background and technical feature of FSO

In the 19th century, Alexander Graham Bell invented a new device named *photophone* that transmits sound over an invisible beam light. In the late 60s, Dr. Erhard Kube, a German scientist known as the father of the FSO technology, published a paper which explained the possibility of data transmission through the atmosphere using light beams. FSO was first used in military research providing secure data and voice transmissions in their military defence. The limited ranges of only few kilobits per second transmission provided by FSO technology was a major disadvantage. Furthermore, it witnessed a vulnerability to weather interferences [1]. Today, because of a significant increase in FSO power, the feasible range distance of transmission reaches up to 4 km.

After the 70s, the introduction and the deployment of the fiber optic cable in the telecommunication industry became widely popular due to its advantages of performance, such as its high bandwidth, reliability and high securities. In the 80s, by addressing the principal challenges and issues, scientists and researchers began to produce an improved FSO system until it became commercially available in the market. Today, the FSO is one of the options for most of the telecommunication industries because of its similar performance of the fiber optic cable.

3.1 Key drivers of Free Space Optics in Enterprise level

3.1.1 Bandwidth Market Demands

The Middle East is one of the fastest growing regions in the world creating an ever growing demand for bandwidth. Regional telecoms are urged to provide more bandwidth to meet this demand and sustain the growth. According to [2], United Arab Emirates is becoming a world leader in terms to Fiber to the home (FTTH) with a penetration at 65% of households at the end of 2012. UAE is ahead of South Korea, the previous FTTH worldwide leader (57% of households as of December 2012). UAE is sitting in the middle of the world and hence acting as a hub. But it is far behind other hubs like London or New York. It is therefore very important to be connected to the fastest form of traffic growth and it is important to have as much bandwidth as possible.

In 2013, *Optics.org* forecasted that the demand trend will continue to rise in the future and the market for FSO device system will increase. The global market for this technology grew by 13% from the previous year. In the EMEA (Europe, Middle East and Africa*)* region it will grow at merely 4.6%. United Arab Emirates has a huge demand for high bandwidth to support their current infrastructures because of its technological advancement.

3.1.2 Cost and Convenience

Southwell (2013) stated that “When deployed in urban areas, free space optics can act as a low-cost yet high-speed link for last mile connectivity”. In addition, *Malek Charles Akilie*, director of sales for the Middle East at LightPointe explains that the multitude of benefits offered by FSO is also helping establish its enterprise credentials. It has a relatively low acquisition cost compared to leased line connectivity. *Lightpointe Middle-East*, an FSO provider, uses a return on investment (ROI) model that is based on either a European Format (E1) or the digital subscriber line (DSL) that amortizes its costs within six months to one year. Southwell (2013) mentions that currently “FSO technology is also license free, which means that end users wishing to implement the technology do not have to wait for official permission, nor invest in the license itself. Organizations do not need to pay for frequency license to Country regulatory authorities. The author adds that legal advantages of FSO could be overturned if local operators see it as a threat to their leased line business and start lobbying governments, which is the case in the UAE.

3.1.3 Security

Terabema, an FSO vendor, proposes a uni-directional optical stream with a small diameter in order to ensure high security, and only Terabeam’s site equipment can receive data sent from the Terabeam network [3].

In addition, the *OPTera Metro2400* is laser-based and is much more secure than other wireless solutions. Its narrow laser beam is not accessible unless viewed directly on the transmission path. Therefore, it is virtually impossible to intercept its signal without being detected.

3.2 Basic Overview of Free Space Optics

3.2.1 FSO Components

FSO is composed of a transmitter, an FSO channel, and a receiver. FSO uses either LED or diode semiconductor lasers transmitting at wavelengths of 750-785- nm or 1500-1550 nm. The laser can be either directly modulated or it uses an external modulator. Receivers can have light detectors based on either PIN diode or avalanche photodiode (APD).

Free Space Optic propagation Aspect

FSO signal propagates through space as formulated by the *Friis free space propagation antenna equation*

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

This equation describes in terms of the received power P_r, the relationship when a transmitter at point A makes a transmission to a receiver at point B with a distance R between them. The equation indicates that a lower frequency and higher antenna gain will improve transmission rate. It also indicates that the received power P_r depends on the transmit power P_t, the wavelength (λ) and the gains of transmitting and receiving antennas G_t, G_r, respectively in an ideal free space environment. Received power will decrease over distance, although in real world situations the decay rate is also affected by *reflection*, *diffraction*, *scattering* due to obstacles and *atmospheric conditions*.

3.3 Comparison Free Space Optics (FSO) vs. Radio Frequency Microwave Link

Radio Frequency (RF) and FSO are two common wireless technologies that are used for last mile solution. According to [4], there is no direct competition between the two technologies.

FSO is just starting to be applied for solving Internet last-mile interconnectivity problem [5]. Some believe that it may be the unlimited bandwidth solution for the metro-urban core of downtown building-to-building communication, as well as the optimal technology for home-to-home and office-to-office connectivity. FSO systems have been shown to be reliable (99.9% to 99.999%) communication channels with fast bandwidth. They are easy to set up and provide cost-effective solutions. However, the industry still does not know how to properly deploy them in telecom networks. To address these concerns, the FSO community recently launched the Free Space Optics Alliance to educate the communication industry as a whole. It is believed that such industry-wide education will enable standards to emerge and growth of FSO technology to occur. Finally, it should be noted that to better quantify the technical and scientific aspects of FSO, there is still a need for research in new laser sources, atmospheric spectroscopy, multi-beam and active alignment techniques and multi-detector averaging.

3.4 Major Challenges of FSO

3.4.1 Technical Challenges

Maintaining the Line of Sight (LOS) between the end-points, i.e. the sender and receiver during the transmission is one of the major challenges facing FSO. This problem is called “Pointing Acquisition Tracking” process. Several researchers have developed adequate solutions to this problem using different techniques. The use of a hierarchical point, or the acquisition and tracking PAT system as a vision-based system to maintain LOS had been proposed [6][7]. The system assumes prior knowledge regarding the initial position of each FSO node and its partner and receiver. The alignment process is carried out using feedback from a high zoom camera system. In contrast, omnidirectional spherical FSO transceivers to maintain the line of sight (LOS) of the FSO system is proposed [8]. The LOS transceiver is a promising approach to the alignment problem in mobile environments. However, the current hardware implementations are not fast enough to switch the beam to another FSO channel without significant breaks of the connectivity.

A different proposed framework using a dynamic RF/FSO staged acquisition technique. This approach also seems a promising solution to the point, acquisition and tracking system (PAT) problem but there has been no implementation or field test to this proposal until now [9 nichol].

3.4.2 Routing and Path protection in FSO

Another challenge facing FSO is the disparate and time varying nature of the FSO channel making routing difficult within FSO network. A concept known as “critically index” was introduced determines the fraction of each traffic profile entry [10]. This means that the path is implemented as an extension of the Open Shorted Path First (OSPF) routing protocols.

3.4.3 Environmental Challenges

A further serious challenge to FSO technology is due to environmental and climatic factors. One of the main limitations of FSO technology is due to fog and severe weather conditions which can have a detrimental impact on the performance of the Free Space Optic systems [11]. In this article entitled “Wireless optical transmission of Fast Ethernet, FDDI, ATM, and ESCON protocol data using the TerraLink laser communication system” have studied in deep the effect of climatic factors on the FSO performance.

It is found that atmospheric conditions such as temperature and wind speed have a significant impact on limiting the distance of the connections: as the beam goes through small pockets of differing variations in air temperature and wind speed the light can be refracted [12]. Since the variations in these factors are very small, most vendors will use multiple lasers in parallel on the Free Space Optic system to compensate, especially on units designed for longer distances. Signal attenuation caused by scintillation depends on the time of day and can vary by orders of magnitude during a hot day. Rain though it causes attenuation of visible radiation on the other hand, also attenuates visible radiation but the optical link can be engineered such that, for a large fraction of time, an acceptable power can be received even in the presence of heavy rain.

4. FSO deployment System

4.1 School Campus Network Architecture

The internet backbone connection between various buildings of the University was deployed by a telecom service provider with a bandwidth speed of 100 Mbps. The school campus has three segregated buildings connected to a LAN network with the use of optical wireless link system with a speed of 1.25 Gbps. The University implemented various solutions to link these separated buildings by implementing the leased line from ISP and Microwave Radio frequency based transmission. As the property management guidelines do not allow cable trenching, the University was seeking other solutions. In the past, the IT department implemented a Microwave RF wireless bridge with a 100 Mbps bandwidth speed connections.

Due to the technological advancement and change in the requirements of the University computing needs, Microwave RF became expensive to maintain and most of all, the Microwave RF was no longer coping up with the growing need of a larger bandwidth.

The university has more than 350 faculty and administration staff and 4500 students. The entire campus has nine computer laboratories with a total of 250 workstations, and it has 300 individual workstations. Other services are provided to students such as virtual desktop infrastructure (VDI) consisting of 500 virtual machines. Students’ electronic data such as lecture notes, e-books, class schedules that were previously available only on computer labs, are now accessible from any device at any time, on or off campus. Students and staff have now virtual access to teaching software programs such as Adobe Creative Master Suite, SPSS, NVIVO, Matlab, RobotC, Oracle, visual studio and Arena.

4.2.Technical Specification of FSO System deployed

FSO device has 4 laser beams in order to stabilize the transmission, and to assure the connectivity when some beams are blocked. *Lightpointe Hybrid-FSO* device is designed for 99.999% link availability in all-weather conditions. These links include a multi frequency adaptive rate modulation technology, which automatically adjusts the system throughout [13].

4.3 FSO point-to-point Implementation

Due to the restrictions of laying out fiber cable, the university had to implement an alternative solution for connecting the three buildings. Based on the physical layout of the buildings, the type of network applications needed to implement is the point-to-point network architecture; which means that endpoints need to be connected to each other.

Measuring the distance gap between the buildings with high precision is crucial in order to avoid an unstable link. GPS positioning was used to mark each location at both ends and to work out the exact distance between the laser heads. Heights of the installation requirements are also taken into consideration in order to achieve stable performance and to ensure the use of the correct size unit. FSO system data transmission can be used for a distance up to 1000 meters distance transmitting data through the air

4.4 FSO Installation

FSO system was installed in the rooftop of a building that is 120 feet high; this is to avoid link interruption for the people walking in front of the FSO system. Other factors that need to be considered are for example: the utilization of a special cable for outdoor areas for longer use and durability.

5. Performance Analysis of the FSO system

In analysing the performance of the FSO system, two categories of parameters are considered: internal parameters and external parameters. Internal parameters are related to the design of the FSO system; this includes the optical power, wavelength, transmission bandwidth, optical loss on the transmit side, receiver sensitivity, bit error rate (BER), receiver lens diameter, and the receiver field of view. External parameters or non-system parameters are related to the environment in which the system must operate and includes visibility, atmospheric attenuation, scintillation, deployment distance, window and pointing loss. In this experimental study, two factors have been investigated: The installation and the *climatic factors* as they may have a significant impact on FSO performance.

5.1 Experimental setup and data collection

Data was gathered through the FSO system logs of the device. Along with the logs, server and client machine and installed *Jperf* software [14] are configured to measure the bandwidth performance of the entire network. With the results of bandwidth performance, link availability needs to be looked with the use of *AireManager* from the *Lighpointe* FSO system.

Besides daily network traffic, the bandwidth performance, daily weather data for a year were collected through the *Accuweather* satellite website. The weather data includes the temperature, wind speed, humidity, and precipitation. Every single datum was recorded and tabulated carefully until the end of the day.

5.2 Statistical Analysis

91.69 Mbps total bandwidth average was achieved compared to 8.31 Mbps total average loss of bandwidth. Although there is a loss of bandwidth performance throughout the year, it is obvious that the actual achieved performance is much higher than the loss. The bandwidth performance is higher because the FSO system performed well, despite of having sometimes bad weather conditions. Higher link percentage is translated to availability of the FSO system. Further the higher the link, the higher the bandwidth is achieved from the network. Bandwidth performance is usually related to the performance of the link availability. The loss performance by the FSO link failure is due to weather conditions, such as fog and rain; which attenuate the performance of the FSO link. This happens more in winter time as can be seen in figure 1.

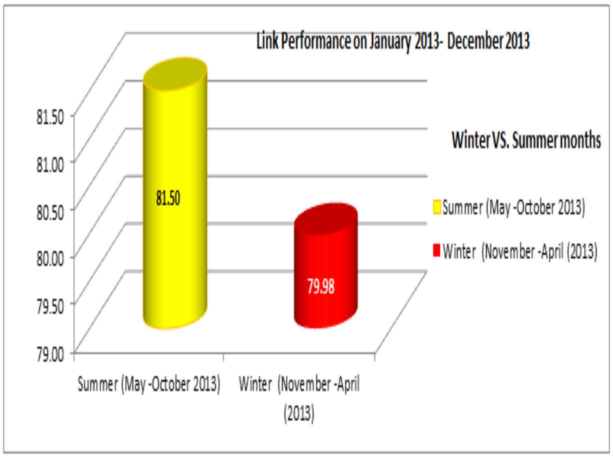

Figure 1 Link Performance Summer vs. Winter

Figure 1 shows the link performance over the period of 12 months within the campus. Throughout the summer months (May to August), the implemented FSO system had link performances as high as 81.5%. On the other hand, throughout the winter months (November to April) link performances reached as high as 79.98%. This decrease in performance mainly happened because of external factors such as the weather conditions discussed above. This instability in the weather conditions is mainly what hinders the link performance during the winter months. Still, the hindered performance was not that important as the performance only decreased by 1.52%. Despite of some bad weather conditions, FSO system still performed better than expected. In addition, having a good base of installation of FSO system helps maintain the alignment of the beams despite of any unstable weather conditions.

The total link performance reached 81.5%, and only 19.5% total performance loss. Some external factors, such as weather conditions, have great effects over the link availability and performance of the FSO system. Diverse atmospheric and weather conditions like rainfall, direct sunlight, snow or fog can cause some disturbances to the connection of the FSO system.

The performance measures include the average network bandwidth and link availability. Climatic factors include the average monthly temperature of the city in degree Celsius, and the average monthly wind speed in km/h. The lowest total link availability was in January, while the highest was in May. The lowest network bandwidth was in April, whereas the highest was in June. The highest performance in both the link availability and the network bandwidth were during summer mainly in May and in June. The lowest performances were during winter mainly in January to April. This illustrates and proves that the downturn of the FSO system is linked to some extent to climatic weather conditions.

5.2 Descriptive Statistics of the Data Collected

Table 1 presents Descriptive statistic of the data collected throughput the year (365 days) mainly the four climatic factors, link availability and bandwidth. The results reveal that the link availability is 80.46% with a coefficient of variations of 6.92%. The network bandwidth reached on average 91693.31 (kbps) with only 3.46% variation. Whereas, temperature, wind and humidity and have larger variations' coefficients of 18.69%, 29.42% and 23.43% respectively over the 365 days. Initially, these results may reveal that there only a minor effect of the weather conditions on FSO performance measures as the later parameters are more stable. Only 8 days out of 365 days, rain precipitation was observed with a total of 36 ml.

5.3 Frequency distribution of FSO Performance

The variation in link visibility performance and FSO Bandwidth throughout the 365 days are presented as distribution histograms and shown in figure 2.

TABLE 1. Descriptive Statistics of the data collected

	Temperature (Celsius)	Wind (km/h)	Humidity (%)	Precipitation (ml)	Availability 100%	Bandwidth Achieved
Average	33.57	11.42	52.19	0.10	80.44	91693.31
Median	34.00	11.00	53.00	0.00	81.00	92000.00
Min	21.00	5.00	19.00	0.00	63.00	70705.00
Max	49.00	27.00	79.00	13.00	92.00	99193.00
Std	6.27	3.37	12.23	0.94	5.57	3172.81
Coef- of Variation %	18.69	29.52	23.43	948.33	6.93	3.46

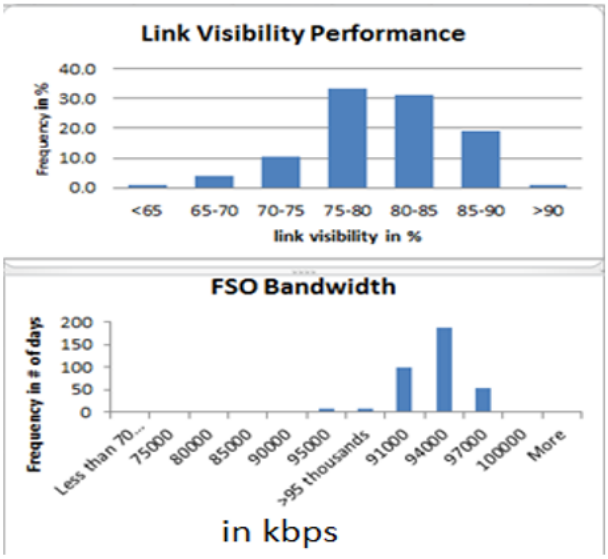

Figure 2. Frequency distributions of the FSO Performance measures (N=365 days)

5.4 FSO Performance as a function of weather conditions

Further, the weather was categorized as being either Thunderstorm, Hazy fog, cloudy, rainy or sunny day and for each category the average FSO performance was calculated. The results are presented as a bar graph for comparison in figure 3. During Sunny days both performance measures are much higher than other days. The difference is estimated to be around 20% for link availability and around 8% for bandwidth.

5.5 Influence of the climatic Factors on FSO Performance

In order to assess the dependency of FSO performance (link availability and network bandwidth) on the climatic variables (temperature, wind speed and Humidity), two Regressions were conducted.

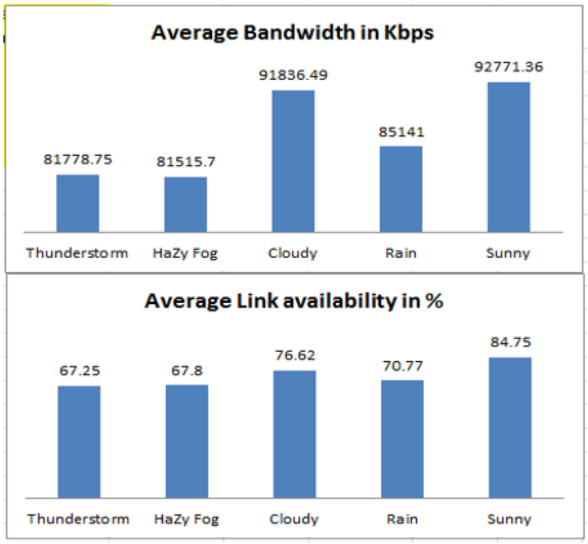

Fig. 3 FSO performance vs. climatic weather conditions

5.5.1 Regression Climatic Factors on FSO Link availability

The first regression is conducted for the *link availability* as a dependent variable; the results presented in table 2 reveal all climatic factors are significant.

Predictor	*Coefficients*	*t Stat*	*P-value*
Intercept	79.767		
Temperature (C)	0.206	4.114	0.000
Wind (km/h)	-0.219	-2.683	0.008
Humidity (%)	-0.070	-2.745	0.006

Table 2. Relationship Link availability versus Climatic Factors R-square 13.1% F(4,364)=13.5 p=0.000

The temperature has positive effect on link availability (coef=+0.206) while both wind and humidity have negative effects Coef.(wind)=-.219 and Coef.(humidity)=-0.70.

5.5.2 Regression Climatic Factors on FSO Bandwidth

The second regression is conducted for the *bandwidth* as a dependent variable; the results presented in table 3 reveal that both the temperature and the wind had no significant effect on Bandwidth. However, Humidity has a significant negative effect on Bandwidth. Further the regression model explains only 8.9% of the variation in the dependent variable.

	Coefficients	*t Stat*	*P-value*
Intercept	92874.5431		
Temperature (C)	42.378	1.455	0.146
Wind (km/h)	21.178	0.444	0.657
Humidity (%)	-53.609	-3.602	0.000

Table 3. Relationship Bandwidth versus Climatic Factors R-square 8.9% F(4,364)=8.8 p=0.000

6. Conclusion

An experimental evaluation of the performance of FSO system has been presented. Two important parameters for evaluating the performance of the FSO system have been analysed and measured in relation to the weather conditions in the university campus. The results show that the FSO system performed well; despite of having some turbulence in weather conditions, it achieved a 91% percent in total in terms of performance during the year 2013. Furth the network bandwidth is significantly stable during the year with less than 4% variation. Similarly, the link availability is also stable with less than 7% variation. This study shows that the FSO system can provide a reliable connection with a total availability of 81.5% over 12 months. Finally, the collected data that was successfully conducted greatly challenged the impact of fogs in the FSO link. The observation of this FSO link performance has shown that the link availability of the FSO system in the summer months obviously performed better than in winter months in Dubai, UAE. All in all, implementing a free-space optics system in order to link connection gaps does face many challenges, but if they are addressed and confronted with careful attention, the FSO performance is effective, efficient, and undoubtable.

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