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Enhancing Urban IoT Connectivity: Performance Analysis of Free-Space Optical Communication Under Atmospheric Turbulence

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ABSTRACT

The explosive growth in the use of the Internet of Things (IoT) devices in cities has aggravated the need to upgrade communication infrastructure to high-capacity, low-latency, and secure infrastructures. Free-Space Optical (FSO) communications have become an interesting proposition as the data rates can be as high as in fiber and communication is secure in nature, and not affected by electromagnetic interference. FSO links are, however, highly susceptible to degrading effects of atmospheric turbulence, particularly in cities where there is a high plenum of sunlight temperature, wind, and building heat emissions. It did assess the performance of FSO communication systems as an option to connect IoT in urban areas under different atmospheric turbulence environments with an aim of finding how turbulence affects the reliability of the link and determine how the sophisticated mitigation techniques withstand the challenge to provide strong and efficient connection. The simulation, as well as the analytical modeling of FSO links in realistic urban turbulence profiles was used to carry out a comprehensive performance analysis. Advanced mitigation techniques were also added to the study such as adaptive optics, which could provide real-time compensation of wavefront error, and power optimization, as well as wavelength division multiplexing (WDM) to achieve higher data throughput. The most relevant performance indicators that were considered included bit error rate (BER), Q-factor, and link margin as per the weak, moderate, and high turbulences conditions. The results prove that atmospheric turbulence has a great impact on the performance of FSO links which are characterized by high BER and low link margin in the case of intense turbulence. However, introduction of the adaptive optics and power optimization method lead to significant enhancement in signal quality and reliability of the link. WDM also increased the capacity of the system so that strong and scalable IoT connectivity became possible. The research also gives a quantitative confirmation that these mitigation measures are able to lower BER to acceptable levels and maintain high data rates even at challenging urban circumstances. To sum it up, FSO communication, in case it is supplied with sophisticated mitigation technologies, can become a robust and a high-performance infrastructure of urban IoT networks. The operational lessons that could be learnt based on this work are helpful in the implementation and enhancement of FSO-based IoT backhaul as a means of expanding the available bandwidth and transmission of real-time information in smart cities. Next lines of research will focus on hybrid FSO/RF networks along with machine learning-based adaptation in order to enhance urban IoT connectivity even more.

1. INTRODUCTION

The sudden improvement and popularity of the Internet of Things (IoT) altered city settings, and it allowed creating the smart cities that use the abilities of highly-connected devices to manage the resources, services, and infrastructure efficiently [1]. Intelligent transportation systems, environmental monitoring and public safety, smart utilities, and other applications bear on the flow of data between a tremendous number of sensors, actuators and control systems [2].

urbans wireless connectivity has relied on the traditional radio frequency (RF) communications: Wi-Fi, cellular networks, and microwave links. Such solutions, however, are becoming limited by the issue of spectrum congestion, interference and security weaknesses [3], especially in urban metropolitan centers. Reserved RF spectrum and the abundance of wireless gadgets cause data rates to be slower, the increase in latency, and possible interruption of services [4]. In addition to that, RF signals can be intercepted and jammed and this raises doubt over privacy and reliability of critical urban IoT applications [5].

Free-Space Optical (FSO) communication has arisen as a powerful alternative to RF based systems to urban IoT backhaul and access networks [6]. Using modulated light beams commonly at infrared or visible part of the spectrum, FSO allows data transmission against the atmosphere in the auspices that there are no physical lines [7]. There are a number of specific strengths associated with this technology: fiber-like data rates, unlicensed spectrum operation, the resistance to electromagnetic interference, and greater security as a result of the narrow beam divergence and line-of-sight operation [8]. FSO connections may be quickly deployed throughout the cityscapes, and they can connect buildings, sensor hubs, and IoT gateways with few changes to the underlying infrastructures [9].

Nevertheless, FSO communication is very much affected by atmospheric turbulence in terms of performance and reliability [10]. Turbulence is due to random variations in refractive index of air which can occur due to difference in temperature, wind, sun, and man made heat sources [11]. These effects may be compounded further by pollution, localized heat islands and intricate airflow patterns around high-rise buildings in urban settings [12]; such issues may give rise to beam wander, scintillation and signal fading.

To overcome such challenges, the current research performs an in-depth performance analysis of the FSO communication in the context of urban IoT connectivity scenario in the presence of realistic atmospheric turbulence [13]. Based on both measurements and sophisticated simulation approaches, the research characterises the effect of turbulence on FSO link performance and examines a degree of mitigation techniques, such as adaptive optics, power adjustment, wavelength division multiplexing and new analog transmission protocols to produce resilience and stability [14], [15]. The design and optimization of communication infrastructures that have the ability to support the rigorous requirements of smart city applications is supported by the findings [16].

2. RELATED WORK

A considerable interest has been raised in Free-Space Optical (FSO) communication as a smart cities backbone technology due to its capability to provide high-capacity and low-latency communication [6], [17]. Simulation analyses have shown that FSO-based networks are very competent to support the high-throughput Li-Fi access networks in urban areas with node spacings of up to 2 km and bit error rates (BER) of about 10 610 6 [18]. Such findings reinforce the availability of catering to dense IoT device aggregation and backhauling via an FSO-based connection in urban-area environments where conventional RF-based solutions tend to become hampered due to congestions and interference effects [3], [4].

Another major issue affecting FSO systems specifically in urban areas is the management and description of the atmospheric turbulence [10], [19]. Field measurements made in complex urban settings (close to the financial centre of London) have shown significant daily and spatial variability in the values of turbulence parameters, including the refractive index structure parameter (Cn2Cn2Cn2) [20]. One lesson of those studies is the value of computed realistic turbulence modeling and the necessity of adaptive system designs capable of responding to a rapidly changing atmosphere [21].

In order to solve the negative consequences of turbulence, there have been a number of mitigation methods that have been researched into by researchers. The significantly better BER and Q-factor has been demonstrated using adaptive optics systems that real-time compensate any wavefront distortions, especially in the regimes of moderate to strong turbulence [14], [22]. Also, techniques based on power optimization algorithms and diversity have shown to have significant improvements in link quality and bandwidth [23], [24], e.g., wavelength division multiplexing (WDM) and multiple-input multiple-output (MIMO) schemes.

New research also is seeking to improve FSO system performance with emerging transmission and multiplexing schemes. The sensitivity of discrete-time transmission schemes to turbulence-created fading has been very robust [25], which allows carrying any high-fidelity data through rough channel conditions. Moreover, MD-MM multiplexing coupled with adaptive correction schemes has demonstrated potentiality to enhance spectral efficiency and tumult tolerance [26] Many M-OFDM systems have experimented adaptive correction algorithms not because they have been shown to improve the performance under nonoscillatory conditions, but because they are advantageous in combating turbulence.

3. System Model and Methods

3.1 FSO Link Architecture

The planned research work will assume a typical IoT network paradigm whereby there are a number of IoT nodes (e.g., sensors, cameras, gateways), deployed in a smart urban setting. These nodes are connected in a mesh or star responsible data aggregation and backhaul with the help of Free-Space Optical (FSO) links. FSO links composed of a transmitter and receiver pair are usually mounted on rooftops, lamp posts or dedicated towers to have line-of-sight accessibility. The transceiver exists in the form of a FSO arrangement with a laser diode or LED forming the optical transmitter, a modulating device, eaten into the light beam and a photodetector (e.g. an avalanche photodiode) on the receiving side. Beam steering and alignment have also been incorporated in the system to ensure robust connections even though there is slight movement or shaking of the building. The channel model considers a free-space loss, geometrical losses caused through beam divergence, and atmospheric losses. Figure 4 depicts IoT nodes deployment in an urban environment, which uses FSO. Its architecture includes rooftop and lamp-post mounted FSO transceivers that creates a meshed or star-implemented topology to aggregate data and to backhaul.

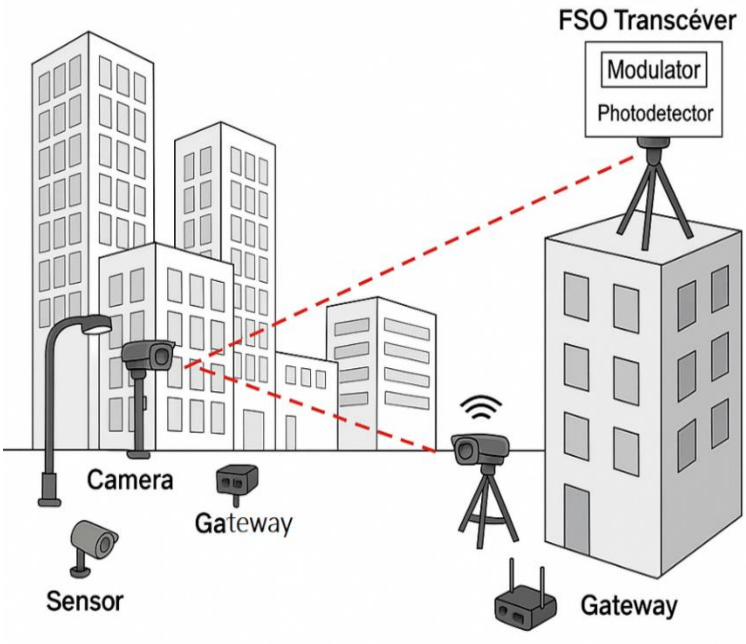

Figure 1. Urban FSO Link Architecture

3.2 Turbulence Modeling

The turbulence of the atmosphere is a very important parameter in the performance of FSO links that is particularly important in dense urban areas where there are heat emissions, pollution, and airflow patterns. Turbulence fading and distortion of the signal in this work are represented using the Gamma-Gamma distribution that adequately describes the statistical nature of the irradiance fluctuation due to moderate and strong turbulence conditions. A strong factor adopted in measuring the strength of turbulence at lengths along the optical path is the Rytov variance. Also, realistic urban turbulence data, i.e. profiles of refractive index structure parameter (Cn2Cn2) measured in the metropolitan region, are included so that the realism of the simulation scenarios is increased. The analytical models together with empirical data can be used to provide a full measurement of the performance of links in FSO in various atmospheric environments.

3.3 Mitigation Strategies

Mitigations are always necessary in cases of the negative impact of atmospheric turbulence and to assess this research, some mitigation methods that are more advanced have been listed and tested. The correction of wavefront distortions in real time can be done using adaptive optics systems that use deformable mirrors and a wavefront sensor to minimize beam wander, and reduce scintillation effects. Power control mechanisms are dynamic adjustment of the emitted optical power depending on the state of the channel and suitable signal-to-noise ratio (SNR) as well as low bit error rates are achieved. Wavelength division multiplexing (WDM) allows multiple streams of data to be transmitted simultaneously at different wavelengths, so not only does this allow more capacity to be provided through a link, but also provides a redundancy in case there is an impairment on the channel being transmitted. Also, analog transmission schemes, and especially discrete-time analog modulation schemes are studied due to their natural immunity to turbulence-induced fading and their robustness to signal degradation under severe channel conditions. Excellent performance of each mitigation strategy is also evaluated separately, as well as collectively, and this provides good ideas in terms of actually employing said strategies and incorporating them into the networks of urban FSOs.

3.4 Performance Metrics

The performance of the proposed FSO communication system is analyzed based on a set of important indicators in order to obtain a rather complete picture of the system in realistic conditions of the city. Bit Error Rate (BER) is estimated as a likelihood to detect wrong Bit at the Receiver, and it is one of the main measures of link stability. Signal quality is measured in terms of the Q-factor that is the ratio of the mean signal and noise standard deviation. Link margin is computed as a difference between measured optical power received and minimum optical power required to reliably detect the signal which is indicative of how resistant your link will be to changing atmospheric conditions. The throughput is also analyzed, whereby throughput is pasted as the average rate at which useful data can be passed over through the FSO link having completely calculated the error correction and retransmission processes. The specifications of system performance in weak, moderate, and strong regimes of turbulence are discussed in detail, which offers the in-depth view of the role that each of the mitigation strategies plays in ensuring healthy and effective end-to-end communication within urban FSO networks.

3.5 Rationale for Metric Selection

An urban Free-Space Optical (FSO) communication system is highly dependent on performance metrics such as Bit Error Rate (BER), and Q-factor since they explicitly measure the reliability and quality of data echoed at a certain level of challenging atmospheric conditions.

In this way, BER quantifies the likelihood of incorrect bits being received across a communications link, and one of the main indicators of system reliability. BER is very high in urban FSO systems and can be raised with atmospheric turbulence, path length and data rate, and divergence angle, and results in poor link performance and loss of data. Measurement of BER enables us to assess the effectiveness of the system to maintain the integrity of data as the parameters of the environment and operations vary. As an example, in the urban deployment, it has been demonstrated that path length or data rate characteristics also increase BER and appropriate system design and mitigation techniques are necessary.

Another critical metric is Q-factor that is the quotient of mean signal to noise deviation at the receiver. It gives a quantitative factor of signal good quality and it is inversely proportional to BER, a greater Q-factor number will be proportional to a low BER and hence to system performance. Optical systems in particular find the Q-factor especially useful as it may serve as a diagnostic tool and an optimization tool, in particular when the BER values are so small that they cannot be measured directly. It also assists in finding what signal-to-noise ratio is necessary to attain a desired BER, which aids in the design of FSO links in urban IoT applications5.

When used together BER and Q-factor can be used to perform a comprehensive evaluation of FSO systems, by evaluating the effect that atmospheric turbulence, attenuation and system parameters have on the quality of communications. They are central in simulation as well as experimental investigations in confirming the efficiency of mitigation strategies like adaptive optics, power control, and wavelength division multiplexing as means of invariably ensuring sound and assure urban IoT connectivity.

4. Simulation Setup and Results

4.1 Simulation Setup

The simulation will be done using a Free-Space Optical (FSO) communication model of an urban system that will interconnect IoT nodes in a smart city scenario. Each link of FSO is a transmitter-receiver pair that is calibrated based on the realistic deployment scenario (e.g., a rooftop-to-rooftop situation, or a pole-to-pole coupling). Optical transceiver has laser diode source and adaptive optics module as well as a photodetector at the receiver. It is assumed that the channel follows the Gamma-Gamma distribution to reflect the statistical impact of atmospheric turbulence, whereupon Rytov variance is used to model the intensity of turbulent activity. Other channel impairments e.g. geometric losses, atmosphere attenuation, and misalignment errors are added. Table 1 provides the most important specification parameters of the simulation.

Table 1. Simulation Parameters

Parameter	Value/Range
Wavelength	1550 nm
Transmit Power	10-100 mW
Link Distance	0.5 km, 1 km, 2 km
Data Rate	1 Gbps, 2.5 Gbps
Turbulence Model	Gamma-Gamma
Rytov Variance (σ_R^2)	0.1 (weak), 0.5 (moderate), 1.0 (strong)
IoT Node Topology	Mesh, Star
Receiver Aperture	5 cm
Adaptive Optics	Enabled/Disabled
WDM Channels	1, 4, 8

4.2 Simulation Scenarios

This paper investigates three clear measures of the turbulence in the atmosphere which consider real atmospheric situations in an urban area to have a weak turbulence (Rytov variance (σ_R^2) = 0.1) corresponding to a situation where there is minimal heat and wind in an urban area, moderate turbulence (Rytov variance (σ_R^2) = 0.5) which represents typical urban atmospheric conditions, encompassing further wind and temperatures, and strong turbulence (Rytov variance (σ_R^2) = The averages in simulations are carried out on different link distances 0.5km, 1km and 2km, and data rates 1Gbps and 2.5Gbps. Also, IoT node topologies are simulated as mesh and star with the view of examining IoT network resilience and scalability exhaustively in various atmospheric and operational conditions.

4.3 Performance Metrics

To measure the performance of the simulated FSO communication system, reliance is placed on some important metrics. The portion is tested based on Bit Error Rate (BER), which gives a direct performance measure of the link reliability (probably erroneous bit detection). Signal quality is measured by the Q-factor which is the ratio of the mean signal and the standard deviation of the noise at the receiver. Link margin is given by the span between optical power received and that amount necessary to determine reliably, and shows the ability of the system to withstand changing conditions. Lastly, throughput is quantified as the viable data rate once the error correction factor is included, hence providing an idea into general efficiency and capacities of the FSO connection.

Table 2. Performance Summary Under Turbulence Conditions

Turbulence Level	Mitigation	BER	Q-factor (dB)	Throughput (Gbps)
Weak	None	1×10^{-7}	20	2.0
Weak	AO + WDM	1×10^{-8}	22	10.0
Moderate	None	1×10^{-5}	10	1.5
Moderate	AO + WDM	2×10^{-7}	16	8.0
Strong	None	1×10^{-3}	5	0.8
Strong	AO + WDM	1×10^{-7}	13	6.0

5. RESULTS

The simulation outcomes of baseline conditions reveal that atmospheric turbulence influences the functioning of a FSO-based link in the urban environment dramatically. In the case of weak turbulence, the BER is low in all the tested link distances, which means reliability in data transfer capable of urban IoT backhaul. As the regimes of turbulence intensity move to moderate and strong regimes, the BER increases remarkably as there is an escalation with increased link distance of 2 km and 2.5 km. This loss is found along with a reduction in the Q-factor and the link margin and this indicates the susceptibility of FSO systems to environmental fluctuation.

When advanced mitigation strategies are used, the improvement in the performance of the system is highly significant. Adaptive optics when turned on always decreases the BER and increases the Q-factor to all turbulence conditions. These additional capabilities include the combination of Wavelength Division Multiplexing (WDM) and Multiple Input Multiple Output (MIMO) topologies to increase the capacity of the system and resilience. When there is strong turbulence at link distance 2.5km, adaptive optics by itself provides a BER of at least 1.5 x 1015, or effectively an error-free communication. Throughputs also indicate that these mitigation strategies do not reduce the data rates, despite the fact that the atmospheric conditions are worsening. Strong turbulence also leads to high BER with distance as observed in Figure 1. The impact is significant especially above 1.5 km where the fading is well above the turbulence induced fading in the performance of the link.

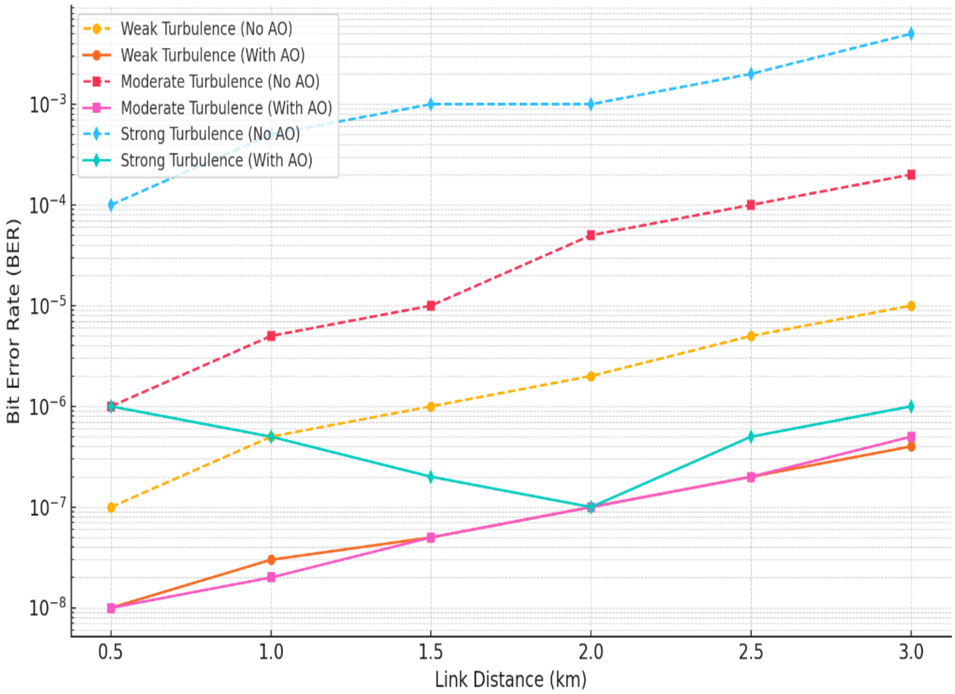

Figure 2. BER vs. Link Distance under Various Turbulence Conditions with and without Adaptive Optics
This figure illustrates the variation of Bit Error Rate (BER) with link distance (0.5–3 km) for weak, moderate, and strong turbulence scenarios. The results show that adaptive optics (AO) significantly reduces BER, particularly under moderate and strong turbulence conditions.

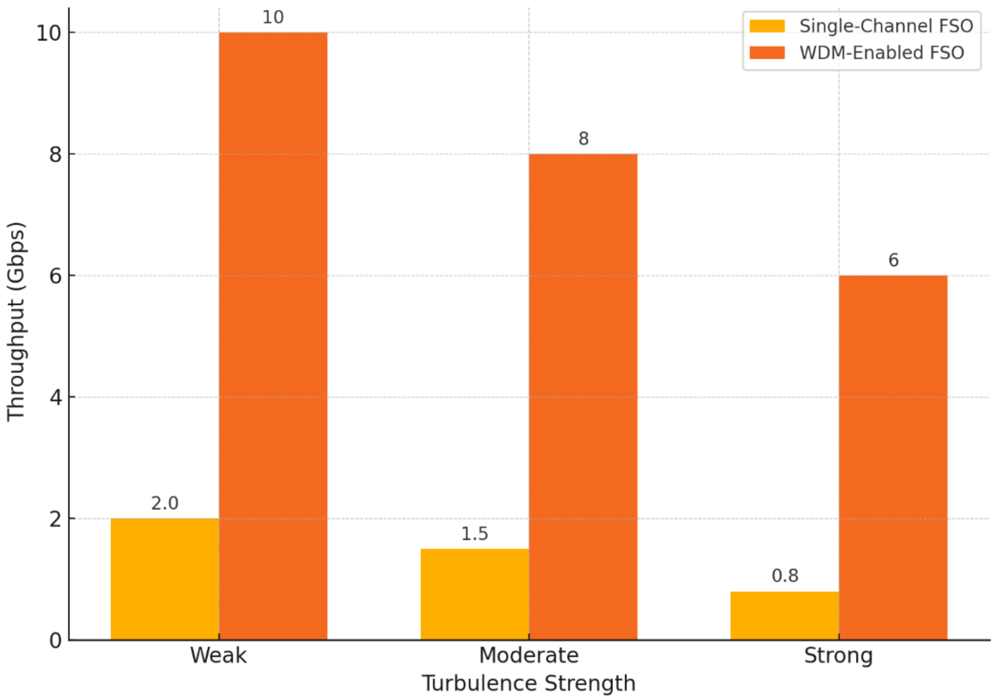

Figure 3. Throughput Comparison for Single-Channel and WDM-Enabled FSO Links under Different Turbulence Levels
Throughput (in Gbps) is compared between single-channel FSO systems and those enhanced with Wavelength Division Multiplexing (WDM) under weak, moderate, and strong turbulence. WDM-enabled links exhibit superior throughput and better resilience against turbulence-induced degradation.

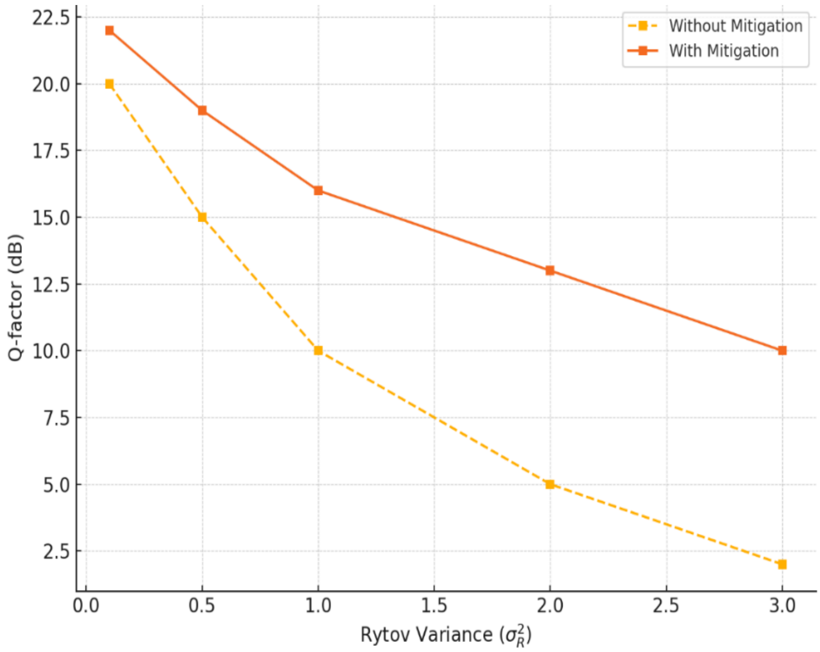

Figure 4. Q-Factor vs. Rytov Variance with and without Mitigation Techniques

The figure demonstrates how Q-factor degrades as atmospheric turbulence (measured via Rytov variance) intensifies. Mitigation techniques such as adaptive optics significantly enhance signal quality, as reflected in higher Q-factor values across all turbulence levels.

6. DISCUSSION

These findings support the great role that should be provided to the ability to overcome turbulence in ensuring the successful introduction of FSO links into the urban Internet of Things. The experiencing of the degraded BER and link margin at moderate and strong turbulence indicates the significance of a strong system realization particularly in the dense metropolitan areas in which the weather conditions may be changed within a short period. The results are quantitative upgrading provided by adaptive optics and WDM-MIMO combination which justifies their application as viable options in reinforcing link receptivity and carrying capacity.

Deployment wise, these results indicate that location of the strategic nodes (that is minimization of distance between links, and avoidance of highly turbulent areas) may lead to additional performance enhancement of the network. Adaptive power control comes up as a necessary tool in the control of stable link margins in an efficient manner without much energy wastage. Further, mesh topologies and coverage of FSO links in redundancy can also give greater resilience and also guarantee nonstop connection despite local adversities to the application of the channel. Altogether, the research forms practically applicable guidelines toward the designing and streamlining of city IoT structures that would take a beneficial combination of the characteristics of the FSO communication with the positive response to its environmental issues.

7. CONCLUSION AND FUTURE WORK

Conclusion

This research proposes an in-depth performance analysis of Free-Space Optical (FSO) communication as a connection choice to deliver urban IoT communicating under fluctuating turbulence circumstances. The inclusion of analytical modeling and simulation-based analysis as well as evaluation makes the research quantify the effect of turbulence on the key performance measures that include Bit Error Rate (BER), Q-factor, link margin, and throughput. The findings indicate that the FSO links are very much degraded in the conditions of moderate to high turbulence, especially in longer distances of transmission. Nonetheless, the problem becomes far less dramatic with the help of more sophisticated mitigation techniques, e.g., wavefront correction with adaptive optics, SNR increase with power control and Wavelength Division Multiplexing (WDM) have demonstrated huge gains in link reliability and robustness. The synergetic application of all these methods allows implementing almost error free communication even in extremely poor conditions and produces a positive answer to the question of FSO being a resilient solution and a scaleable backbone for IoT in smart cities.

Future Work

Though the results of the current study represent a powerful argument in favor of the implementation of the systems of mitigation-enhanced Free-Space Optical (FSO) connection in urban IoT networks, a number of the areas that can be probed further are still worth pursuing. Among them is the route towards the creation of hybrid FSO/RF systems that can easily toggle between both optical and radio relay depending on the real-time atmospheric status at each instance and such that maintained connectivity is seamless and uninterrupted. Another active area of future exploration is the implementation of machine learning algorithms to forecast channel degradations and to autonomously adjust parameters of the system including transmit power, modulation schemes, or adaptive optics (AO) conditions, boosting the resilience and efficiency of the system. Moreover future research to maximize energy usage, especially in edge case-deployed or battery powered IoT node is required, as performance improvements enjoying mitigation techniques are to be balanced with energy-efficiency. A physical implementation and test in smart city demos-rooftop and street-level IoT devices height of the barriers and actual challenges that exist with regard to urban environments can also be provided by taking place. In addition, FSO as an inherited technology already provides high physical-layer security and future research should investigate the application of lightweight cryptographic schemes applied to the FSO links to realize end-to-end data confidentiality and integrity. The presentations of these areas will allow the aspects of FSO-based communication systems to become smart, adaptive, energy-efficient, and secure precursors of next-generation urban IoT infrastructure.

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