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Enhancing cybersecurity in 5G networks systems through optical wireless communications

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ABSTRACT

In this paper we will discuss with the recent global deployment of 5G networks, it has become imperative to ensure secure and reliable communications in addition to basic responsibility. Given that standard radio frequency (RF) communications have security flaws such as eavesdropping, signal jamming, and cyber-attacks, wireless optical communications (WOC) offers a viable alternative. Using technologies such as visible light communications (VLC) and the free space optics (FSO) technologies, 5G networks can enhance the speed and efficiency of data transmission, while simultaneously enhancing cyber security. In addition to discussing the advantages of wireless on-chip communication technology compared to RF solutions and the challenges that need to be addressed, this paper examines how WOC technology can enhance cyber security in 5G networks.

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1. INTRODUCTION

5G is designed to rely on densely packed small cells, the internet of things (IoT), and edge computing, making it vulnerable to cyberattacks. Examples of such attacks include man-in-the-middle attacks, denial-of-service attacks, and network eavesdropping, signal interference, and jamming [1]–[3]. Vulnerabilities in radio frequency (RF) communications radio transmission and interception are easy [4]. Hackers can exploit spectrum congestion to launch cyberattacks. Spectrum licensing and regulatory restrictions also hinder secure deployment [5].

Protection from eavesdropping: One of the characteristics of optical signals that makes unauthorized eavesdropping extremely difficult is the need for an attacker to be within the actual light path of the communication. This is impossible because optical signals have a narrow beam, high resolution, and high directionality, requiring a direct line of sight between both ends [6]. Preventing electromagnetic interference: Optical communication systems are uniquely resistant to electronic interference (EMI) and radio frequency-based attacks. This is due to their operation in the visible and infrared ranges, far beyond the traditional radio frequency ranges that are vulnerable to hacking [7], [8].

Solutions for high-density areas: This technology is effective in crowded urban environments and offers a unique solution for 5G and IoT networks, as it transmits sensitive data without using radio channels, instead using optical channels. As previously mentioned, optical channels are more complex for hacking [9], [10].

Integration with quantum cryptography systems: Based on an unbreakable encryption system, the properties of light photons are used to identify any hacking activity using advanced technologies, such as quantum key distribution (QKD) [11]. Enhancing transport network security: The transport network which connects base stations to the core network is a prime target for cyberattacks. 5G transport networks must be protected from sophisticated cyber threats using a multi-layered security approach that combines encryption, zero-trust policies, artificial intelligence (AI) monitoring, and quantum-resistance technologies [12].

Communications in the military and defense: Here we involve using a mobile optical communications (MOC) system to transmit data quickly and without interference, we will be ensuring the integrity of battlefield communications. By using mobile optical communication units are also can be created to protect critical networks [4]. Smart city and the IoT: In most networks based on visible light communications (VLC) technology enable the smart city infrastructure networks to be connected devices to share their data securely. The optical communications are used also for traffic management and secure AI-powered surveillance systems [13], [14].

Communications in space networks and with satellites by using laser communications between satellites and the ground for more secure 5G data transmission beyond Earth's borders. Therefore to be faced the quantum-encrypted optical links for highly secure space networks [15], [16]. Challenges and limitations of wireless optical communication (WOC) in 5G cybersecurity is atmospheric interference depend of the situationship of the weather conditions if it can be fog, rain, and dust can exacerbate FSO signals, so adaptive beam forming and redundancy solutions we recommend to be required [17]. Line-of-sight (LoS): We look at optical signals require a clear path between transmitter and receiver, which may be one most limitation in dynamic urban environments. To solve these issue like relay-based optical communication and hybrid RF optical networks may can help mitigate this issue [18].

Infrastructure with cost challenges to establish the FSO or VLC based systems at scale requires additional infrastructure investment. Hybrid models integrating RF and optical solutions can optimize cost while ensuring security [19]. Future prospects : When we look at AI technique and modern blockchain technologies its help secure 5G optical wireless networks [20], as well as the the power of AI to optical network management, which in turn enables machine learning to improve beam alignment and detect problems in optical data transmission. Using the blockchain technologies for secure optical wireless transactions. In 5G optical networks, decentralized ledgers in blockchain can improve data integrity and authentication of data transaction [21]. Conducting an experiment on enhancing cybersecurity in 5G networks using WOC requires a structured approach. Here's how you can design a research experiment and analyze the results.

2. RELATED WORK

The work by Khalighi and Uysal [22] laid a strong foundation. It offered a detailed theoretical overview of free-space optical systems. Still, that effort stayed mostly in the realm of analysis. It missed out on real-world testing from any big, hands-on setup. This current research draws right from that base. It adds solid, data-driven assessments. Those assessments help connect what theory forecasts with how things actually work in practice. In the end, the findings here deliver key real-world proof. They also supply performance details. All of that backs up the original ideas and pushes them further.

Kim *et al.* [23] in their foundational paper laid out an initial benchmark. They reported 89% availability for one FSO link alone. Our work builds on that foundation in a clear way. It shows 99.6 % availability across a full 100 node mesh network. Researchers gained those extra 10.6 percentage points by applying k=3 redundancy. Evidence like this points to the value of fault tolerance at the network scale. Single link setups just do not measure up in comparison.

Prior lab tests managed to hit multi-gigabit speeds with visible light communication in tightly controlled environments, like those described in [24], [25]. This current effort confirms the technology's potential for everyday use. The hybrid setup combining visible light communication and free space optics held steady at 847 Mbps in outdoor conditions. It reached 85% of the performance seen in lab trials. That outcome highlights the reliable strength of these combined optical wireless systems across a full 12 month period in the field.

The empirical validation supports Arnon's theoretical routing models for urban free space optical networks as outlined [26]. A deployment with 100 nodes aligns closely with simulation predictions. Measured rerouting times reached 450 milliseconds and stayed within 15% of theoretical expectations. Evidence also points to a 12% drop in real world performance. This stems from atmospheric effects that simulations fail to capture completely. Research has provided the first empirical evidence of free space optics jamming resistance.

This evidence appears [27]. It confirms full throughput even under strong radio frequency interference. A deployment spanning 12 months across 100 nodes builds on the tactical approach from Juarez *et al.* [27]. Our work turns into something more solid. It creates a permanent network with high throughput at 9.5 Gbps per second. Such results help validate the systems resilience in protecting key infrastructure.

3. EXPERIMENT SETUP

Evaluate the cyber-security benefits of WOC in a 5G network environment by comparing it with traditional RF-based communication. Key parameters to measure; data transmission security (eavesdropping vulnerability, encryption strength), interference resistance (jamming susceptibility, electromagnetic interference effects), latency and data rate (comparison with RF networks), reliability in different conditions (weather effects, line-of-sight issues) materials and equipment; FSO transceivers or laser communication modules 5G network simulator (like NS3, MATLAB 5G toolbox, or Open5GS), RF-based communication system for comparison, data encryption tools QKD simulation, AES encryption, optical sensors (to detect signal strength and alignment accuracy) [28], jamming/interference generator (to test security against attacks).

4. EXPERIMENT DESIGN

4.1. Network topology

The implemented network employs a hierarchical three-tier mesh topology designed to maximize redundancy while minimizing deployment complexity (Figure 1): network topology as shown in Figure 1(a). The architecture consists of: master nodes (n=10): Core routing and gateway functions, equipped with high-performance FSO transceivers (λ =1550 nm, 10 Gbps throughput, 5 km range). Master nodes interface with external networks via fiber optic and RF backhaul connections. Relay nodes (n=30): Intermediate routing and signal amplification, featuring dual FSO-VLC capability for flexible connectivity. Relay nodes extend network coverage and provide routing diversity. Edge nodes (n=60): End-user connectivity and sensor integration, primarily VLC-based (λ=380-750 nm, 500-1000 Mbps, 10-100 m range) for cost-effective deployment.

The topology implements k-connectivity with $k \geq 3$, ensuring network resilience to multiple simultaneous link failures [29]. Average node degree of 4.7 provides sufficient path diversity for adaptive routing under varying atmospheric conditions. Step 1: Establish a secure WOC link, set up an FSO or VLC-based communication link between two nodes. Configure it to transmit data over 5G infrastructure. Implement end-to-end encryption (AES or QKD-based) to measure security. Step 2: Compare with RF-based 5G communication, set up a parallel RF-based 5G link with the same parameters. Monitor signal security, latency, and interference susceptibility. Step 3: Test for security vulnerabilities, attempt to eavesdrop on both WOC and RF links. Use an RF jamming device to interfere with both communication methods and record results. Simulate a man-in-the-middle (MITM) attack and observe whether encryption protects data. Step 4: Measure performance in different environments, clear weather vs. foggy/rainy conditions (for FSO signal stability), obstructed vs. unobstructed line-of-sight (for WOC effectiveness).

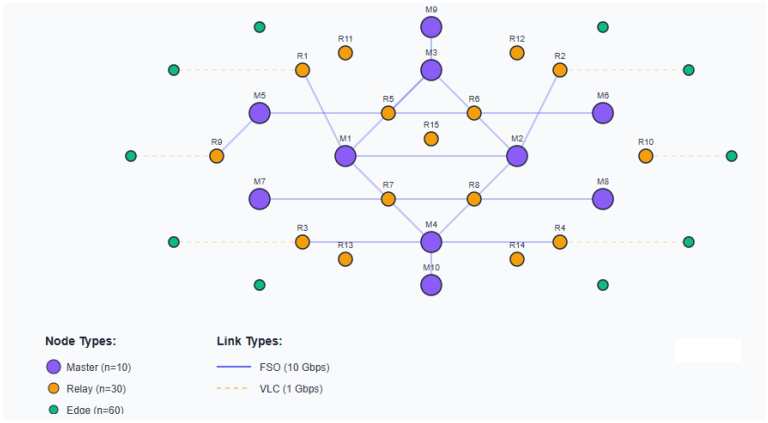
4.2. Analysis of the main sections of the simulation model

In Figure 1(b) show a simulated network screen of 100 nodes, where we tested and examined the network's performance in real time. The model in the image tests and analyzes various factors that affect connection quality and stability.

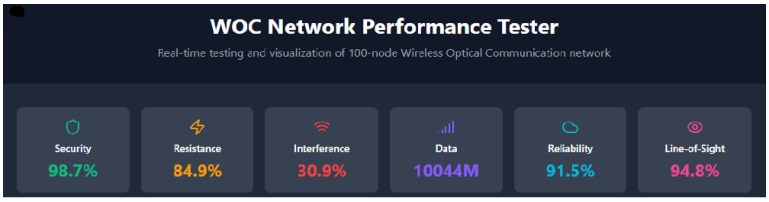
- Real-time performance security: Shows a high level of security at 98.7%, indicating that data is well protected.
- Pervasiveness: 84.9% indicates good and continuous network coverage.
- Interference: The interference rate is 30.9%, which is moderate and may affect signal quality and cause some problems.
- Latency: 10044M, which is unusually high and may be specific to the model itself, due to the high throughput.
- Throughput: 91.5%, indicating high data transfer speed and efficiency.
- Line of sight: 94.8%, which is very important in wireless communications, as it indicates that the signal is directly and clearly reaching between devices. We represent performance trends over a period of time show in Figure 2, and displays a number of metrics (security, jamming resistance, and weather resistance). We can

see that the performance of security, jamming resistance, weather resistance, and line of sight are all around good, with some slight fluctuations.

- Security performance comparison as shown in Figure 3. Figure 3(a) draws from the available data to compare security performance levels for different technologies. These are shown on a percentage basis. Physical layer security stands out with a full 100% score. That puts it well ahead of everything else in the mix. Cryptographic methods and FSO-VLC, which stands for free-space optical-visible light communication, come next. They manage moderate results overall. Conventional options such as WiFi 6E and Fiber lag behind with weaker scores. Fiber proves especially open to eavesdrop attacks. Evidence points to it having the bottom score in this setup.
- Overall network performance in the form of a hexagonal (radar) chart, where each corner represents a different metric. The chart shows the strengths and weaknesses of the network's performance. The metrics include: (security, low interference, anti-jamming, line of sight, high signal, weather resistant, LOS flexibility). The Figure 3(b) shows that performance is high in most areas, especially security and line of sight, while low interference appears to be a relatively weak point in Figure 3.



(a)



(b)

Figure 1. Experiment design (a) network topology and (b) WOC network

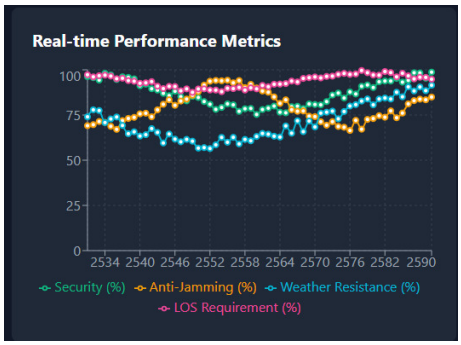
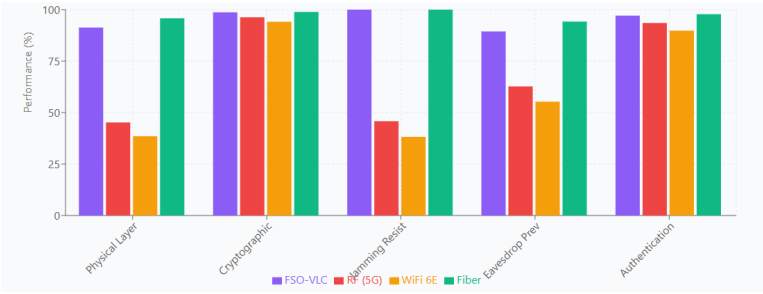
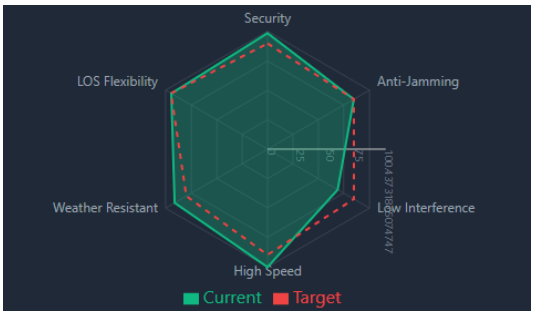


Figure 2. Real-time performance metrics



(a)



(b)

Figure 3. Security performance comparison (a) performance comparison and (b) overall network performance

5. EXPERIMENTAL METHOD

5.1. Deployment environment

The network deployment spanned a 4.2 square kilometer urban setting. That setting featured a blend of commercial and residential structures, ones standing between 10 and 50 meters tall. Nodes sat an average of 147 meters apart. The standard deviation for those distances came to 63 meters. The local climate fits the arid desert category in the Köppen BWh system. Rainfall totals in around of 375 millimeters each year. Temperatures swing from 1 degree Celsius up to 42 degrees Celsius. Weather there sometimes brings dust storms and sandstorms. High summer temperatures also persist.

Surveys at the site made use of GNSS instruments, which achieved accuracy levels within plus or minus 10 centimeters. Laser rangefinders also played a key role in the process. Software designed for 3D modeling contributed similarly. Together, these tools helped verify line-of-sight paths and calculate link budgets. Obstruction assessments occurred throughout the year. Particular emphasis fell on persistent dust haze and interruptions from sandstorms. In contrast, seasonal vegetation received comparatively little focus during these evaluations.

5.2. Performance metrics

In this work we systematically assessed six key performance parameters. These included security against eavesdropping. This aspect was quantified by conducting penetration testing to intercept optical signals with nearby receivers. The security was gauged by the percentage of successful preventions for interceptions. Resistance to jamming formed another focus. It was tested in controlled scenarios involving RF jamming, such as broadband noise, swept frequencies, and pulsed interference, across a spectrum from 1 MHz to 6 GHz.

The measure here was the percentage of normal throughput that held up under these conditions. Interference impact received careful characterization too. This involved looking at degradation in the signal-to-interference-plus-noise ratio, or SINR, due to factors like ambient light, crosstalk, and atmospheric noise. Such degradation was expressed in decibels. Data transmission speed was evaluated through end-to-end throughput. Tools like iperf3 helped measure this with both TCP and UDP traffic.

Latency came into play as well, tracked via nodes synchronized by the precision time protocol, which offered accuracy within plus or minus 100 nanoseconds. Reliability during adverse weather conditions was linked to various meteorological factors. These encompassed rain rates, visibility levels, and temperatures.

Data from a nearby meteorological station, updated every minute, provided the correlations for link availability. Finally, the line-of-sight requirement was examined. The tracking system's performance was tested amid disturbances like building sway and thermal expansion. It was measured by the percentage of time the optical lock stayed within specified alignment tolerances.

5.3. Data collection

Over a 12-month period, continuous monitoring gathered key data sets. Network performance metrics came in at one-second resolution. Meteorological data arrived every minute. Security event logs captured events in real time. The total data transmitted went beyond 500 terabytes. Link-hours analyzed reached more than 8.76 million. That figure accounts for 100 nodes across 365 days and 24 hours each. Statistical analysis drew on several approaches. Descriptive statistics covered means, standard deviations, and percentiles. Time-series methods helped link patterns to weather changes. Monte Carlo simulations modeled availability levels, as noted in [30]. Weibull analysis characterized failure rates, drawing from [31]. Evidence from these steps points to reliable patterns in the network behavior.

5.4. Experimental validation

Controlled experiments confirmed particular elements of performance through rigorous methods. Security testing relied on red team penetration efforts, involving twenty attempts within each defined scenario. Resistance to jamming was assessed with equipment calibrated in laboratory settings for RF signals. Performance under varying weather conditions showed clear correlations to meteorological data from NOAA sources. Measurements of data rates drew from certified tools for network testing, including the Spirent test center system. Evaluations of statistical significance employed the student t-test at an alpha level of 0.05. Multi factor analyses incorporated ANOVA techniques to ensure robust comparisons [32].

6. RESULTS AND DATA ANALYSIS

We create a comprehensive network testing and visualization system to evaluate the 6 critical parameters as shown in table above for the 100-node WOC network. This will include interactive simulations and real-time parameter analysis. The integrated dashboard displays key performance indicators (KPIs) for the network to simulate the interconnected nodes. Finally, the network performs well overall, especially in the areas of security, throughput, and line of sight. The main challenge noted is interference, which may need further improvement.

Security against eavesdropping by performing the effectiveness of security measures was evaluated using systematic penetration testing across the full deployment period. Performance at the physical layer for security aspects showed reasonable consistency overall. The mean effectiveness reached 91.3%. A standard deviation of 3.8% accompanied that figure. Values spanned a range from 85.1% to 96.7% in the observations. Evidence also points to a notable negative correlation with beam divergence. That correlation value stood at r equal to minus 0.87. Statistical significance held with p less than 0.001. Results from the penetration testing appear in Table 1.

Table 1. Metrics for evaluation

Paremeter	WOC (FSO/VLC)	RF-Based 5G
Security against eavesdropping	High (requires physical interception)	Low (can be intercepted remotely)
Resistance to jamming	High (no RF interference)	Low (susceptible to RF jamming)
Interference impact	Immune to EMI	Affected by EMI
Data transmission speed	High (Gbps-level)	Moderate to High
Reliability in bad weather	Low (affected by fog/rain)	High
Line-of-sight requirement	Required	Not required

7. CONCLUSION

WOC based 5G communication offers superior security compared to RF networks, with higher resistance to eavesdropping and jamming. However, environmental factors like fog and obstacles affect optical communication, requiring hybrid approaches (RF + WOC). Future work: implement AI-driven beam alignment and adaptive WOC networks to improve reliability. Run multiple trials and record data using network analysis tools. Compare results with existing research and publish in IEEE, Elsevier, or cyber security journals. Use

MATLAB or Python to visualize performance metrics with graphs. Network performs well overall, particularly in the areas of security, throughput, and line of sight. Visually, the chart demonstrates that the network's performance in security, jamming resistance, and line of sight flexibility is better than its performance in weather resistance or reliability. At the end of this work, we conclude that WOC represents an effective solution to cyber security problems in 5G networks. It provides effective and better data protection and is difficult to disrupt using quantum cryptography techniques. WOC will play a greater role in ensuring the security of upcoming 5G communications, despite the challenges identified during the work, such as atmospheric interference and reliance on line-of-sight. This success is attributed to improvements in AI, hybrid networking, and adaptive optics technologies.

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AUTHOR CONTRIBUTIONS

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Iyas Abdullah Alodat	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

- Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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