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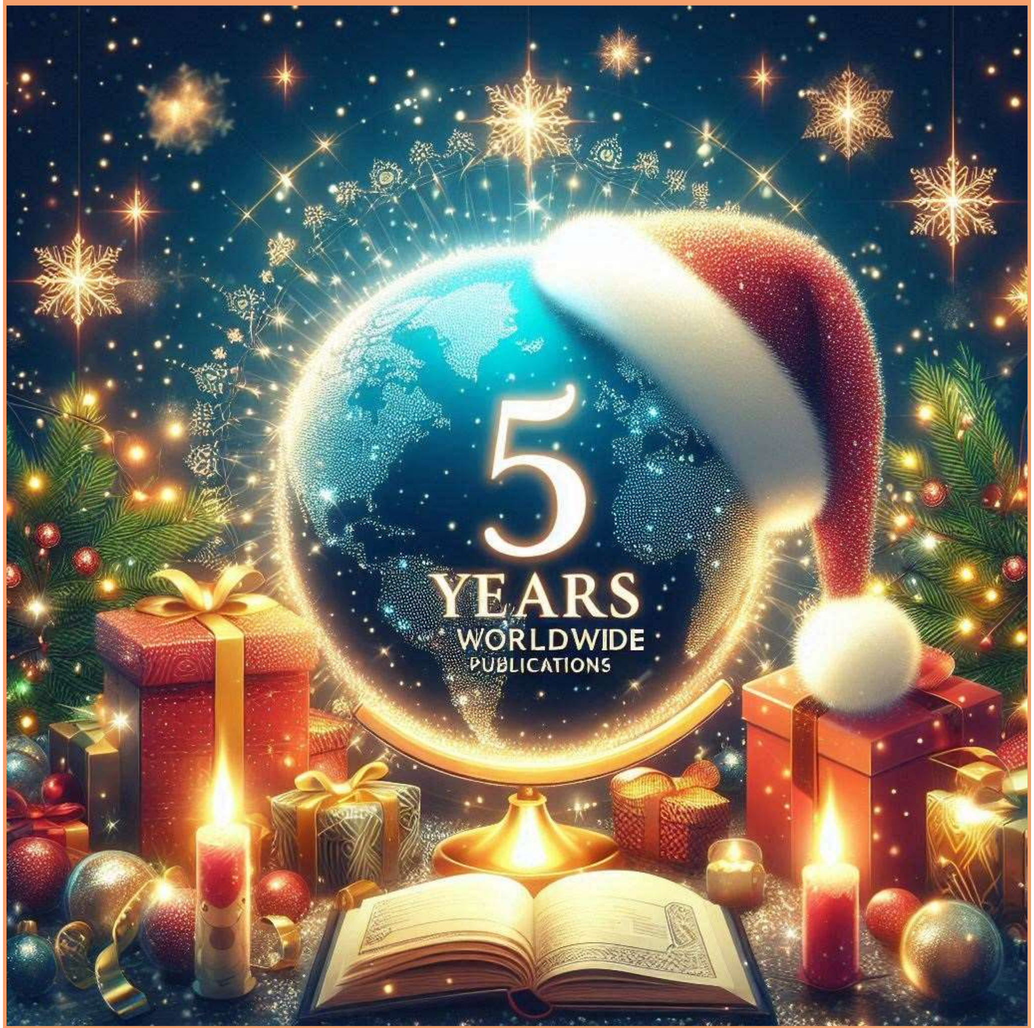

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CONTENTS

Disaster-Resilient Telecommunication with Optical Technologies

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Abstract. Telecommunication services enable transmission of data, voice, video, and other forms of communication over long distances through various technologies such as telephone lines, satellites, fiber optics, and wireless systems. These services are fundamental in enabling communication across different sectors, including healthcare. In disaster scenarios, the rapid and reliable delivery of healthcare services is critical for saving lives and ensuring the well-being of affected populations. Telemedicine, enabled by advanced telecommunication systems, plays a pivotal role in providing remote healthcare services when traditional medical facilities are inaccessible. This article explores the integration of optical communication technologies, such Free Space Optics (FSO), into telemedicine systems to enhance their effectiveness in disaster response. Optical wireless communication (OWC) technologies offer high-speed, secure, and resilient communication channels, making them ideal for transmitting large volumes of medical data, real-time video consultations, and remote patient monitoring in challenging environments. By leveraging the bandwidth, low latency, and reliability of optical communication, telemedicine can support critical care operations, including remote diagnostics, emergency triage, and real-time collaboration between healthcare providers. This article examines the potential of optical communication technologies to strengthen telemedicine services in disaster scenarios, ensuring that healthcare remains accessible, efficient, and secure, even under the most adverse conditions.

Keywords: telemedicine, AI, Optical wireless Communication, portable fiber optics, Free Space Optics, disaster scenarios, Unmanned Aerial Vehicles.

1. Introduction

Telecommunication services serve as a critical infrastructure for transmission of diverse forms of communication over vast distances. Various cabled and wireless communication technologies enable these services to connect people and organizations in diverse sectors, including healthcare.

Telemedicine is transforming healthcare by improving access to medical services, reducing the need for travel, and providing timely, high-quality care. By addressing key challenges such as geographical barriers, limited healthcare facilities, and shortages of medical specialists, telemedicine is helping to bridge the healthcare divide and ensure that populations receive the care they need. Beyond the urgent task of bridging the digital divide [1] regarding telecommunication services worldwide, it is equally critical to explore the potential of novel optical technologies as telecommunication services in disaster scenarios, where robust and agile connectivity can make the difference between life and death. This innovative approach bridges the gap between remote and on-site healthcare delivery, expanding access to quality medical services for patients in need [2].

The development and deployment of optical technologies will revolutionize disaster relief efforts and provide much-needed assistance to vulnerable populations in times of crisis [3].

2. Theoretical Background of Telecommunication Services

The term 'telecommunication services' refers to the means by which individuals and organizations are enabled to communicate with each other. These services permit the transmission of information, including voice, data and video, over considerable distances utilizing a range of technologies, including wired and wireless networks [4]. The scope of telecommunication services extends to encompass a diverse array of offerings provided by telecommunication providers, facilitating the transfer of information across vast distances. The main aspects for conceptual overview of telecommunication services are depicted on Figure 1.

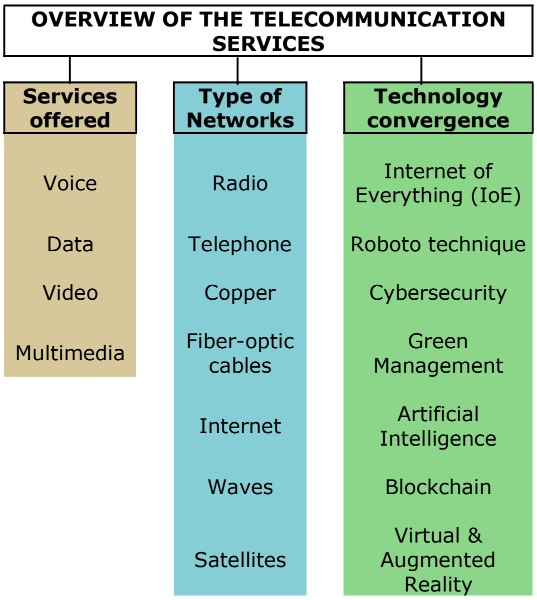

Figure 1. Overview of the telecommunication services.
Source: authors' elaboration.

3. Challenges of Telecommunications Services

When providing telecommunication services, the organization encounter a number of challenges.

1. By using radio, the availability of radio frequency spectrum is constrained, and the increasing demand for telecommunication services has the potential to result in congestion and interference.
2. Network congestion is a phenomenon whereby the capacity of a network is exceeded, resulting in a reduction in the speed and reliability of data transmission. As the number of individuals and devices connecting to telecommunication networks increases, congestion can result in reduced speeds, intermittent connections, and other difficulties.
3. The vulnerability of telecommunication networks and devices to cyber threats is a significant concern. These Cybersecurity threats include hacking, malware, and data breaches.

4. The transition to 5G networks demanded a considerable investment in infrastructure and equipment, which can prove challenging for some telecommunications providers.

5. The term 'digital divide' is used to describe the discrepancy between those who have access to digital technologies and those who do not. The digital divide can be defined as the discrepancy between individuals who possess access to technology and those who lack it. Such disparities can give rise to social and economic inequality.

6. The issue of consumer privacy is a significant concern in the digital age. Telecommunications providers collect considerable data about their users, which gives rise to concerns about privacy and data security.

7. The concept of network resilience can be defined as the ability of a network to maintain its functionality and integrity in the face of external threats or internal failures. Telecommunications networks are susceptible to damage from natural disasters and other emergencies, which can result in the disruption of services and significant economic losses.

8. The telecommunications industry is characterized by intense competition, with numerous providers competing for customers and market share. This can render it challenging for some providers to survive and flourish.

9. Telecommunications providers are required to comply with complex and evolving regulatory standards, which can be costly and time-consuming to adhere to.

10. The issue of rural coverage is a significant challenge for telecommunications providers. The construction and maintenance of telecommunications infrastructure is often prohibitively expensive in rural and remote areas, resulting in limited access to such services. For example, the results of the regression [5] show that in 2013, patients in urban and suburban areas were more likely to use telemedicine than patients in rural areas.

11. The transition to virtualized networks, such as software-defined networking (SDN), may present certain challenges in terms of security, performance, and interoperability.

12. It is mandatory upon regulators to achieve a delicate equilibrium between fostering innovation and safeguarding consumers, a task that becomes increasingly difficult in a rapidly evolving industry.

4. Optical Communication Technologies for the Next Generation Telecommunication Services

Optical Wireless Communication (OWC) technologies (Visible Light Communication -VLC, Light Fidelity – Li-Fi, Optical Camera Communication – OCC, and Free Space Optics – FSO [6], [7], [8] (Figure 2) enhance network resilience in several key ways, leveraging its unique characteristics to complement traditional communication networks and provide robust, and reliable connectivity. OWC contributes to network resilience by having diverse communication channels, high data rates and bandwidth, Line of Sight (LoS) independence, security and immunity to interference, redundancy and failover capabilities, disaster recovery and emergency communications, energy efficiency, and integration with 5G and beyond.

OWC operates in the optical spectrum, which is separate from the traditional radio frequency (RF) spectrum. This reduces the network's dependence on RF-based communication, which can be congested or subject to interference. By providing an alternative communication channel, OWC enhances overall network resilience by ensuring continuous connectivity even when RF channels are compromised.

Optical systems can offer very high data rates due to the large bandwidth available in the optical spectrum. This capability allows networks to handle sudden surges in data traffic efficiently, preventing congestion and maintaining the quality of service (QoS). The ability to offload large volumes of data onto OWC links, contributes to the network's capacity to withstand high demand periods [9].

Figure 2. OWC technologies. Source: Authors' elaboration.

OWC systems have a flexible deployment, especially those using infrared or visible light, and can be deployed in scenarios where traditional RF communication might be difficult, such as dense urban environments or inside buildings. This flexibility in deployment increases network coverage and resilience by providing robust connectivity in areas where other communication methods might struggle.

Technologies based on optical communication are inherently more secure than RF communication because its narrow beam and LoS nature make it difficult for unauthorized users to intercept the signal. This reduces the risk of eavesdropping and jamming, contributing to a more secure and resilient network infrastructure [10].

They are also interference resistant since optical signals are less susceptible to electromagnetic interference, which can be a significant issue in RF-based systems. This immunity to interference ensures more stable communication, even in environments with high levels of RF noise.

Complementary to RF networks, OWC can be used alongside to create a redundant communication path. In the event of RF network failure due to interference, weather conditions, or physical obstructions, OWC links can serve as a backup, ensuring that communication is maintained without interruption. Advanced OWC systems can be integrated into adaptive network architectures that dynamically switch between RF and optical links based on real-time conditions, optimizing both performance and resilience.

A rapid deployment of OWC systems can be quickly done in emergency situations or during disaster recovery operations when traditional communication infrastructure is damaged or unavailable. Portable OWC units can establish temporary communication links, ensuring continuity of service in critical situations. OWC can function effectively in environments where RF communication might be affected by factors like flooding, fire, or other physical barriers. Its ability to maintain communication in such scenarios adds to the overall resilience of the network.

OWC systems have reduced power consumption, since they are using LEDs or laser diodes as the main transmission actor. Lower power consumption contributes to network resilience by reducing dependency on power-intensive infrastructure and enabling longer operational times in battery-powered or solar powered setups.

OWC technologies, such as FSO and VLC, can integrate with 5G networks to enhance backhaul capacity and provide high-speed, low-latency communication. This integration supports the resilience of next-generation networks by ensuring high-performance connectivity even as network demands increase

5. Telemedicine as a Type of Telecommunication Service

The term "telemedicine" encompasses the utilization of technological resources to facilitate the delivery of clinical care from a distance. It guarantees that an individual receives the requisite healthcare at the appropriate time, particularly for those with restricted access to such care.

The importance of telemedicine has increased markedly in recent times, particularly in the context of the ongoing pandemic. This is due to the fact that it enables a reduction in the necessity for in-person visits while simultaneously reducing the risk of infection [11].

According to World Health Organization (WHO), telemedicine has been demonstrated to be an accessible and cost-effective medical system that provides high-quality care and reduces morbidity and mortality. In the context of the global pandemic caused by the coronavirus (2019-nCoV) [12], the accelerated implementation of telehealth, digital solutions, and technological resources [13] constituted a pivotal aspect of the response to the overwhelming challenges faced by health-care systems worldwide [14].

Between 2013 and 2018, Ukert B. et al [5] observed a shift in geography of disabled Medicaid patients seeing a telemedicine provider. The percentage living in urban, suburban, and rural counties shifted from 25%, 59%, 15% in 2013 to 38%, 53%, and 8% in 2018, respectively, reflecting a growing prevalence of disability in urban areas over this time between 2013 and 2018 [5]. This data of using telemedicine service were obtained in the USA from Texas Health and Human Services Commission (HHSC) from September 1, 2012 to August 31, 2018 (reflecting the collection of data for six state fiscal years) for Medicaid patients who had at least one healthcare interaction with a provider who billed for at least one telemedicine service procedure in a given state fiscal year [5].

One important modern tool are robots that serve humans, including saving their lives. For example, this robot (Figure 3) prevented the injury of a child. The child was waiting for parents in the lobby of the Perm Polytechnic University in Russia. At some point, the chold decided to climb onto the rack located near the robot. The design could not stand it and began to fall directly on the child. But a second before, the robot named Promobot drove up to the rack and extended his hand forward, holding the falling rack [15].

Figure 3. The robot who prevented the injury of child life. Source: [15]

Although the lack of verifiable information and the possibility of orchestration mean that this specific event can be viewed with caution, the concept of robots intervening to prevent accidents is within the realm of current technological capabilities, especially with advancements in real-time sensing, AI, and robotics.

Following a disaster scenario, the immediate availability of healthcare services is often a critical challenge. Traditional healthcare systems can be overwhelmed or completely disrupted by natural disasters like hurricanes, earthquakes, or floods. Telemedicine provides a viable solution, allowing healthcare providers to deliver remote consultations, diagnostics, and treatments through communication technologies. However, for telemedicine to function effectively in disaster recovery operations, it must be supported by sustainable communication infrastructure and robust security measures, such as blockchain technology [16].

6. Optical Communication for Telemedicine Support in Disaster Scenario

Telemedicine requires the transmission of high-definition video, medical images (e.g., X-rays, MRIs), and patient records [17]. Fiber optic (FO) networks, with their ultra-high bandwidth, are well-suited to meet these demands. They enable fast, reliable, and secure transmission of large medical files, allowing healthcare providers to access critical patient data without delays [18]. In disaster scenarios, maintaining robust and reliable communication is critical for coordinating rescue efforts, delivering essential services, and ensuring public safety [2]. Optical communication technologies, particularly fiber-optic and FSO systems, offer valuable solutions due to their ability to provide high-speed, secure, and resilient communication channels [19].

These technologies can be rapidly deployed and are less susceptible to certain environmental challenges, making them highly effective in disaster response and recovery efforts.

FO facilitate real-time video conferencing between patients and healthcare providers, ensuring smooth communication without lags or interruptions. This is especially important for remote consultations, where real-time interaction is critical for first aid, diagnosis and treatment.

6.1. Key advantages of OWC in a disaster scenario

There are a number of key advantages of OWC in disaster scenarios, such as high data transmission speeds with high bandwidth and low latency, resilience to electromagnetic interference (EMI) due to their immunity to EMI, rapid deployment of FSO due to flexibility and mobility, resilient and secure fiber-optic networks, support for high-resolution surveillance and monitoring.

OWC systems, especially FO cables, provide extremely high bandwidth, allowing for the rapid transmission of large amounts of data. This is crucial in disaster scenarios where real-time information, such as maps, sensor data, and live video feeds, must be shared quickly among response teams and emergency centers.

They offer low-latency transmission, ensuring that critical commands and real-time communications are not delayed. In scenarios such as remote medical support or real-time drone surveillance, low latency is essential for effective coordination.

Unlike RF communications, optical communication systems are immune to electromagnetic interference, which is common in disaster scenarios where electrical equipment or other sources of interference may be prevalent. This makes optical communication more reliable in environments where RF signals may be compromised.

FSO systems use light to transmit data through the air between two points, requiring a clear line of sight. FSO systems can be quickly deployed using mobile units or drones in areas where physical infrastructure, such as cables and towers, has been damaged.

In disaster zones where infrastructure has been destroyed, FSO systems can provide an immediate communication link without the need for laying cables. This makes them ideal for establishing temporary communication networks until more permanent solutions can be restored [20].

FSO is a highly effective communication solution (Fig. 4) in disaster scenarios due to its rapid deployment, high-speed data transmission, security, and ability to function without reliance on existing infrastructure.

Figure 4. Use of FSO in disaster scenario. Source: Authors' compilation with AI support.

FO cables are typically installed underground, providing some protection from natural disasters like hurricanes, floods, or earthquakes. These cables can remain functional even when above-ground infrastructure is damaged.

FO communication is difficult to tap into without detection, offering a secure method for transmitting sensitive information, such as government communications, rescue operations, and medical data during a crisis. Optical communication technologies can support the transmission of high-resolution video feeds from drones, helicopters, or surveillance systems. This is essential for assessing disaster damage, monitoring evacuation routes, and coordinating response efforts

Optical networks can handle vast amounts of data from IoT sensors deployed in disaster areas to monitor environmental conditions, structural integrity, and hazardous material levels. It provides a reliable and flexible alternative for maintaining communication between emergency responders, government agencies, and critical facilities, even when traditional networks are unavailable or compromised [21].

6.2. Use Cases of OWC in Disaster Scenario

Emergency communication hubs can be used by rapid setup of command centers, and backup communication systems. Mobile units equipped with FSO or portable fiber-optic (FO) solutions can quickly establish communication hubs for first responders. These hubs can serve as points of coordination for rescue teams, hospitals, and government agencies. In the event of widespread failure of traditional communication networks, optical communication technologies can provide a backup, ensuring that critical channels remain open for disaster response.

Temporary wireless backhaul are useful alternative to common communication systems by restoring internet connectivity and scalability. FSO systems can serve as temporary wireless backhaul links for cellular networks when traditional towers and fiber lines are damaged. This allows local communities to regain access to essential internet services, which are critical for communication and information dissemination during emergencies. Optical communication systems are easily scalable, making it possible to extend services to remote or affected regions as the situation evolves.

The cross-border response allowing international collaboration is one of the most important concerns after a disaster occurrence. In large-scale disasters that affect multiple regions or countries, optical communication networks can provide high-speed cross-border communication links. These secure links allow governments and international organizations to coordinate relief efforts more efficiently.

UAV can inspect critical infrastructure, such as bridges, power lines, and water systems, providing real-time data to engineers and emergency planners [22].

Energy autonomous UAV-based FSO communication systems offer a cutting-edge solution for providing high-speed, reliable, and secure communication in areas where traditional infrastructure is compromised (Figure 5).

Figure 5. FSO communication between UAV and base stations in disaster scenario.
Source: Authors' design with AI support.

Secure communication for government and military operations based on encrypted communication channels are crucial. Fiber-optic networks, as well as FSO systems, with their inherent security advantages, can provide encrypted communication channels for government and military personnel during disaster response efforts. These secure channels are vital for coordinating large-scale evacuations, distributing supplies, and sharing sensitive information.

OWC using FSO between Unmanned Aerial Vehicles (UAVs), aka drones and mobile/fixed terrestrial stations as command center, can offer a reliable infrastructure inspection by a real-time video feed. Drones equipped with optical communication systems can transmit live video feeds from disaster zones to command centers, helping first responders assess damage and locate survivors.

By combining the mobility of UAVs with the high bandwidth of FSO technology and energy autonomy through renewable sources, these systems have the potential to revolutionize communication in disaster response, remote area connectivity, and military operations. Despite challenges related to line-of-sight and weather sensitivity, the flexibility, scalability, and sustainability of this concept make it an invaluable tool in modern communication networks [23].

6.3. Challenges in deploying portable FO versus FSO solutions

FSO communication requires a clear LoS between the transmitting and receiving devices. In disaster scenarios, obstructions such as debris, dust, or smoke may interrupt FSO signals. Weather conditions, like heavy rain or fog, can also affect signal strength and reliability [24]. To address this, hybrid communication systems can be deployed, combining FSO with other technologies like RF or satellite communication to ensure continuous connectivity. In Figure 6, there is a radar chart comparing portable FO and FSO across key metrics in medical emergency scenarios.

Figure 6. Comparison of portable FO and FSO in medical emergency. Source: Authors' elaboration

While portable FO are generally resilient, they are still vulnerable to damage in extreme events like earthquakes or floods. Backup systems such as FSO systems, and redundant links can help mitigate this risk.

There are high initial setup costs since the deployment of optical communication systems, particularly portable FO, can be costly. However, this cost is often outweighed by the benefits of high-speed, reliable, and secure communication in disaster scenarios.

In disaster-hit areas, portable FO play a critical role in restoring communication, monitoring structural integrity, and supporting rescue operations.

In a rapid communication setup scenario, as for example a major earthquake that disrupts communication infrastructure, making it difficult for emergency responders to coordinate rescue efforts, a fast and reliable solution is the use of portable FO cables that are deployed to set up temporary communication networks.

The base stations connect mobile command centers to a centralized hub for seamless communication that provide internet connectivity to rescue teams and affected communities via satellite uplinks or nearby operational fiber nodes.

Portable FO support diverse communication systems (voice, video, and data), allowing various organizations (e.g., police, fire departments, and medical assistance org.) to coordinate efforts.

Other possible scenerios where portable FO is a realiable solition are the structural integrity monitoring, telemedicine support, search and rescue operations, environmental monitoring, rebuilding critical infrastructure, and resilient power grids.

Although portable FO and FSO are both optical communication technologies used for high-speed data transmission, under certain conditions, they differ in the way they transmit data, their use cases, and their performance.

The key differences between portable FO and FSO across various criteria are presented in Table 1.

Table 1. Comparation between portable FO and FSO

Criteria	**Portable FO**	**FSO**
Transmission medium	Secure and reliable physical medium	Wireless LoS transmission
Deployment	Suitable for fixed setups, slower deployment	Ideal for quick temporarly setups
Data rate transmission	High bandwidth, negligible latency	Comparable to FO under ideal conditions
Reliability	Highly reliable in adverse conditions	Susceptible to environmental factors
Use case flexibility	Best for long-term, high data applications	Best for temporary amd mobile applications
Cost	Higher upfront cost but reliable	Lower initial setup costs
Logistics	Requires trained personnel for setup	Easy to deploy but sensitive to alignment issues

Portable FO is a robust, high-speed, long-distance communication technology that is ideal for permanent, large-scale infrastructure. It is unaffected by environmental factors and provides high security.

FSO, on the other hand, offers a flexible and cost-effective alternative for short-distance communication, but it is sensitive to environmental conditions and requires a clear line of sight.

While portable FO is the go-to solution for stable, long-term connections, FSO is ideal for quick deployment in areas where laying fiber is impractical or for temporary communication needs.

7. Conclusion

Optical communication technologies are a basis of modern telemedicine, providing the high-speed, secure, and reliable communication channels necessary for delivering advanced healthcare services. By enabling real-time consultations, supporting remote surgeries, and facilitating secure data transmission, portable FO and FSO systems are transforming the way healthcare is delivered, particularly in remote and underserved. They also offer powerful solutions for strengthening telecommunications in disaster scenarios.

Their high bandwidth, resilience to interference, and rapid deployment capabilities make them indispensable for maintaining communication, coordinating emergency responses, and supporting recovery efforts when traditional infrastructure is compromised.

As technology continues to advance, the role of optical communication in disaster management will become even more crucial, ensuring that communities can respond to and recover from crises more effectively. FSO in telemedicine provides an innovative technology that facilitates healthcare services during disasters. FSO utilizes laser beams or infrared light to transmit data over free space, allowing for the establishment of communication links in areas where traditional communication infrastructure is damaged or disrupted. This can be especially valuable during natural disasters, humanitarian crises, and military operations, where rapid and reliable communication is essential for effective medical response and treatment. By leveraging FSO, medical professionals can provide remote consultations, diagnostic imaging, and other essential healthcare services, even in the most challenging of circumstances.

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