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Comparative Analysis of Communication Network Technologies in Terms of Bandwidth, Latency, Security, And Cost-Effectiveness Using the ARAS Method

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Abstract: *Five communication network technologies, namely free space optical, radio frequency, visible light communication, low Earth orbit satellite networks and power line communication, are evaluated and compared using a sophisticated multi-criteria integration rate evaluation technique. Four important criteria were selected for the evaluation, which are bandwidth, latency, security and cost-effectiveness. The utility score of each network technology is calculated based on the results obtained from normalization and matrix calculation. From the results, radio frequency communication ranks highest, and its Ki value is 0.811573, which shows that it performed well in all the criteria. Visible light communication ranks second, and it performs exceptionally well in security. Free space optical communication ranks third. Satellite communication networks and power line communication rank fourth and fifth, respectively. It is clear from the results that each technology considered had its own strengths and weaknesses, highlighting the need for a context-specific approach to selecting technologies. The ARAS framework was found to be a viable and transparent means for the comparative evaluation of technologies for communication networks.*

Keywords: *Optical Communication Networks, Radio Frequency Communication, Free-Space Optical, Visible Light Communication, Low Earth Orbit Satellite Networks, Power Line Communication, Additive Ratio Assessment, Multi-Criteria Decision Making, Wavelength Division Multiplexing, Network Performance Evaluation.*

1. INTRODUCTION

Optical communication networks are the backbone of the current telecommunications industry, as they are capable of transmitting large amounts of data at high speeds around the world. The essence of these optical communication networks lies in the use of light, often in the form of laser pulses, to transfer data through optical fibers, which are strands of glass or plastic about the diameter of a human hair [1]. This ability to transmit information over vast distances at the speed of light, without significant signal degradation, has made optical networks an essential tool in today's digitally connected world. The basic idea behind the operation of an optical communication system is quite simple: a light source is modulated to encode the information to be transmitted, reflected back through an optical fiber using the phenomenon of total internal reflection, and then decoded using a photo detector[2] .This phenomenon, called total internal reflection, allows light to pass through the dense core of the fiber, strike the boundary between the core and the outer cladding at a shallow angle, bounce back and forth through the fiber, and travel hundreds of kilometers without getting lost. This allows signals to travel hundreds of kilometers with very little attenuation [3]. Typically, the light sources used are semiconductor laser diodes or LEDs in the near-infrared band of the spectrum, i.e., 850 nm, 1310 nm, or 1550 nm. The 1550 nm band is often used for long-haul networks because optical fibers have very little attenuation at this wavelength, allowing signals to be transmitted over long distances before being amplified [4]. Several key components work together in an optical communication network. The transmitter converts electrical signals into optical signals. Optical fibers serve as the medium for transmission. Optical amplifiers, such as the erbium-doped fiber amplifier, increase the strength of the signal along the path without converting it back into an electrical signal, which is a great advantage for performance [5]. Receivers are used to convert these optical signals back into electrical form. In addition to these, modern networks also use optical switches, multiplexers, and demultiplexers to efficiently manage data traffic [6]. Among these, one of the most important technologies that can change the face of this field is wavelength division multiplexing and its more powerful cousin, dense WDM [7]. By sending multiple data streams simultaneously over a single fiber, but with different wavelengths of light, DWDM has the potential to increase the capacity of a single fiber to hundreds of terabits per second. As discussed in [8], optical networks have a hierarchical structure. At the highest level, long-haul networks, also known as backbone networks, span continents and ocean basins, providing connectivity between cities and countries via submarine cables. Next, metro networks handle data distribution within cities and regions [9]. At the edge, there are access networks that provide connectivity to the end user - fiber to the home and increasingly fiber to the premises [10]. In North America, the synchronous optical network and its equivalent synchronous digital hierarchy are popular data communication architectures. This standard outlines the formatting and transmission of data to provide interoperability between different equipment manufacturers [11]. Recently, a new standard in the form of optical transport networks has been proposed as the future of networking, which provides better management, error correction, and multi-protocol support [12]. Optical networks have several advantages over traditional electrical networks based on copper wires. First, the bandwidth capacity of optical networks is huge compared to electrical networks. This is important due to the exponential growth in global data traffic [13]. Optical fibers are resistant to electromagnetic interference, making them ideal for use in industrial and urban settings. They are light, thin, and can be transmitted over long distances without repeaters, reducing infrastructure costs. Optical signals also have very low latency, which is important for applications that require real-time processing, such as financial trading, telemedicine, and interactive media [14]. The security of fiber – since it is physically impossible to tap an optical fiber without disrupting the signal – has also made it an attractive option for secure communications. As the world's demand for data transmission increases, the evolution of optical communication networks is accelerating. New technologies such as space segment multiplexing, photonic integrated circuits and software-defined networking for optical networking are on the horizon. Quantum communication through optical fibers is another exciting area of promising research to achieve quantum encrypted communication. In short, optical communication networks are the backbone of the Internet. They are quiet, fast, and incredibly efficient. The continued advancement of optical communication networks will be crucial to meeting the communication challenges of the 21st century. [15].

2. MATERIALS AND METHODS

Free Space Optical Communication: Free space optical communication technology allows for high-speed data transmission through invisible laser beams or infrared light, which propagate through space without any physical connection, thus allowing fiber-optic bandwidth over distance.

Radio Frequency Communication: Radio frequency communication uses electromagnetic signals over specific frequency bands for wireless connectivity, including cellular networks, satellite communications, radar, and long-range microwave backhaul networks.

Technology / Visible Light Communication / LiFi: Visible light communication technology uses wireless high-speed data transmission by modulating LED light signals that are invisible to the naked eye, thus providing an interference-free connection as an alternative to Wi-Fi networks.

Satellite communication networks: Low Earth orbits use a constellation of small satellites at altitudes of 200-2000 km to provide global broadband internet connectivity with reduced latency, making them ideal for remote, maritime, aviation, and rural areas worldwide.

Power line communication: Power line communication is the transmission of digital data signals through existing power line infrastructure, enabling the provision of broadband internet connectivity, smart grid management, and home networking without the need for separate communication cables.

Bandwidth: Bandwidth refers to the maximum data transfer capacity of a communications network, expressed in terms of bits per second or Tbps, and it defines the amount of information that can be transmitted simultaneously over a communications channel in a given period of time.

Latency: A measure of the time it takes between data transmission and data reception on a communications network, measured in milliseconds and affecting real-time applications such as video conferencing, online gaming, and automated control systems.

Security: Security of communication networks is defined as protection from unauthorized interception, eavesdropping, physical eavesdropping, and cyber-attacks, and is measured by assessing encryption strength, reliability uptime percentage, fault tolerance, mean time between failures, etc.

Cost efficiency: The total economic value of using a communications network, measured in terms of capital cost, operating costs, infrastructure reuse, energy consumption, and return on investment per kilometer.

3. ARAS METHOD

A - Let's assume that the modern world runs on data. Every video call, cloud upload, financial transaction, and social media interaction depends on a network infrastructure that can transmit massive amounts of information instantly and reliably [16]. Given the current state of technology, the basic assumption of research on optical communication networks is that light is the best medium for transmitting digital information. We assume that conventional copper-based networks do not improve beyond a certain point. [17]. Bandwidth limitations, thermal dissipation, and signal degradation over distance make copper wire unsuitable for 21st century needs. Optical fibers, which are glass strands much thinner than a human hair, are capable of transmitting data encoded as pulses of light over vast distances with little signal degradation [18]. Another assumption is that the growth of international data traffic will continue to rise exponentially. The expansion of 5G networks, artificial intelligence, cloud computing, smart cities and streaming services will continue to drive the growth of international data traffic, which is doubling every two years. This growth will be fueled not only by faster but also more powerful network infrastructure. This is what optical networks provide. Research on the history of optical communications shows a technology that has been steadily evolving since its practical beginnings in the 1970s, when Corning Incorporated developed low-loss silica glass fibers for light transmission over long distances [19]. This revolution paved the way for the rapid innovation that characterizes the field today. At its core, an optical communication system consists of three main components: a transmitter that converts electrical signals into light using a laser diode, a fiber optic used to transmit the light signal through total internal reflection, and a receiver that converts the light signal back into electrical signals [20]. It operates within certain wavelength windows, such as 1310 nm and 1550 nm, in which the attenuation of the signal is reduced. An important milestone was the invention of the erbium-doped fiber amplifier, which was introduced commercially in the early 1990s. The EDFA amplifies the optical signal within the fiber without the need to convert the signal to an electrical form, thus allowing the signal to be transmitted over distances of thousands of kilometers [21]. With this single discovery, transcontinental and underwater optical networks became economically feasible. Research also gave us wavelength division multiplexing, which allows multiple independent data streams to be transmitted simultaneously over a single fiber optic cable using different wavelengths. Advanced WDM, known as dense WDM, can carry more than 80 channels per fiber optic strand in 100 slots per second or more, each at a rate of one terabit per second [22]. Modern research has also advanced the concept of coherent optical transmission, where the amplitude and phase of light are used to convey additional information. This, combined with the power of sophisticated digital signal processing, has enabled current long-haul networks to achieve significant capacity and distance. A - Analysis of the research results reveals the significant strengths and challenges of optical communication networks. [23]. Modern research has also advanced the concept of coherent optical transmission, where the amplitude and phase of light are used to convey additional information. This, combined with the power of sophisticated digital signal processing, has enabled current long-haul networks to achieve significant capacity and distance. A - Analysis of the research results reveals the significant strengths and challenges of optical communication networksb [24]. This is because optical signals are resistant to electromagnetic interference. This makes optical signals more reliable in complex environments. In addition, optical signals have low latency. This is important in real-time applications in finance, medicine, and defense. However, there are significant challenges associated with optical communication. First, chromatic dispersion occurs when different wavelengths propagate at different rates in the same optical fiber. This means that the integrity of optical signals gradually deteriorates as they are transmitted over long distances [25]. Nonlinear effects such as four-wave mixing and cross-phase modulation also affect signal quality when multiple high-power channels are multiplexed on a single fiber. Network complexity has increased manifold compared to the early days of DWDM. Managing hundreds of wavelengths in a multi-vendor, multi-domain network requires highly sophisticated software tools. The high cost of installing fibers, especially in rural and remote areas, is a major barrier to universal access - based on research findings and analysis; several solutions have been proposed to overcome the challenges by leveraging the strengths of optical networks [26]. To address the problem of chromatic dispersion and linearity, coherent reception and advanced DSP allow receivers to compensate for physical imperfections, allowing the signal to be recovered without any distortion even after traveling thousands of kilometers. This has replaced traditional dispersion correction tools with elegant software-based correction. Beyond DWDM, the next major step in capability is space division multiplexing. [27]. By utilizing the various spatial paths possible through multi-core fibers with multiple individual cores or single-mode fibers with multiple light transmission modes, the capacity of the fibers is multiplied without the need for additional wavelengths. Software-defined networking simplifies the management of the network by using a control layer independent of the physical hardware [28]. These networks are supplemented by artificial intelligence and machine learning technologies, enabling networks to predict failures before they occur and heal themselves with minimal human intervention. The last mile problem is solved by passive optical networks, including recent versions such as XGS-PON and NG-PON2, which provide high-speed fiber connections to end users in a cost-effective manner by passively sharing fiber infrastructure among multiple users [29]. These systems eliminate expensive active electronic components from the distribution network, significantly reducing deployment and maintenance costs. In conclusion, optical communication networks have become a very powerful tool for moving information around the world. Based on assumptions, research and honest analysis, the ARAS architecture demonstrates that technology is not only sufficient for current needs, but is also evolving to power the connected world of the future. [30].

4. ANALYSIS AND DISCUSSION

From Table 5, it is clear that radio frequency had the highest Ki value of 0.811573, which ranked first, while power line communication had the lowest value of 0.519612, which ranked last. This shows that radio frequency had the optimal balance.

TABLE 1. Optical communication network

	Bandwidth	Latency	Security	Cost Efficiency
Free-Space Optical	68	98	46	56
Radio Frequency	66	56	68	68
Visible Light Communication	69	89	98	85
Satellite Communication Networks LEO	58	82	58	82
Power Line Communication	98	49	69	98

This table compares five optical communication networks based on bandwidth, latency, security, and cost-effectiveness criteria. Power line communication has the best bandwidth and cost-effectiveness, while visible light has the best security.

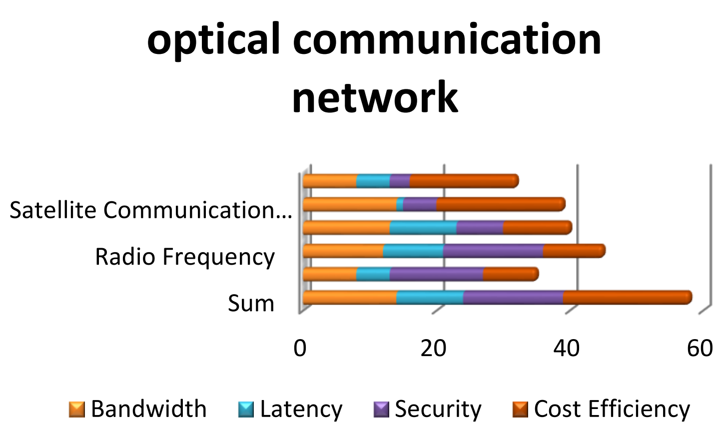

FIGURE 1. optical communication network

Figure 1 shows a comparison of optical communication networks, including metrics for bandwidth, latency, security, and cost efficiency. In this figure, it is clear that power line communication has better bandwidth and cost efficiency than other optical communication networks, while visible light communication has better security than other optical communication networks.

TABLE 2. Calculation of maximum value

	Bandwidth	Latency	Security	Cost Efficiency
Sum	14	10	15	19
Free-Space Optical	8	5	14	8
Radio Frequency	12	9	15	9
Visible Light Communication	13	10	7	10
Satellite Communication Networks LEO	14	1	5	19
Power Line Communication	8	5	3	16

Table 2 shows the maximum values for each optical communication network in terms of bandwidth, latency, security, and cost efficiency. The sum of the values emphasizes the performance of each network, where satellite communication networks have higher performance for LEO cost efficiency and bandwidth.

TABLE 3. Normalized matrix

Normalized Matrix				
	Bandwidth	Latency	Security	Cost Efficiency
	0.2028986	0.25	0.2542373	0.2345679
Free-Space Optical	0.115942	0.125	0.2372881	0.0987654
Radio Frequency	0.173913	0.225	0.2542373	0.1111111
Visible Light Communication	0.1884058	0.25	0.1186441	0.1234568
Satellite Communication Networks LEO	0.2028986	0.025	0.0847458	0.2345679
Power Line Communication	0.115942	0.125	0.0508475	0.1975309

Table 3 shows a normalized matrix comparing the performance of each optical communication network in terms of bandwidth, latency, security, and cost efficiency. For example, visible light communication has higher bandwidth and latency, and satellite has higher cost efficiency.

TABLE 4. Weighted normalized matrix

	Weighted Normalized Matrix			
	Bandwidth	Latency	Security	Cost Efficiency
	0.050725	0.0625	0.063559	0.058642
Free-Space Optical	0.028986	0.03125	0.059322	0.024691
Radio Frequency	0.043478	0.05625	0.063559	0.027778
Visible Light Communication	0.047101	0.0625	0.029661	0.030864
Satellite Communication Networks LEO	0.050725	0.00625	0.021186	0.058642
Power Line Communication	0.028986	0.03125	0.012712	0.049383

Table 4 below is a weighted normalized matrix comparing different communication technologies based on four criteria: bandwidth, latency, security, and cost-effectiveness. From the above table, it is clear that satellite networks have relatively high values compared to other communication technologies, especially in terms of bandwidth. On the other hand, power line and free-space optical networks have moderate performance based on the other evaluated criteria.

TABLE 5. Final Result

	Si	Ki	Rank
	0.235426	1	
Free-Space Optical	0.144249	0.612715	3
Radio Frequency	0.191065	0.811573	1
Visible Light Communication	0.170127	0.722633	2
Satellite Communication Networks LEO	0.136803	0.581087	4
Power Line Communication	0.12233	0.519612	5

Table 5 presents the final evaluation results using Si and Ki values to rank communication technologies. The results show that radio frequency is the best communication technology, followed by visible light communication, and power line communication is given the lowest ranking.

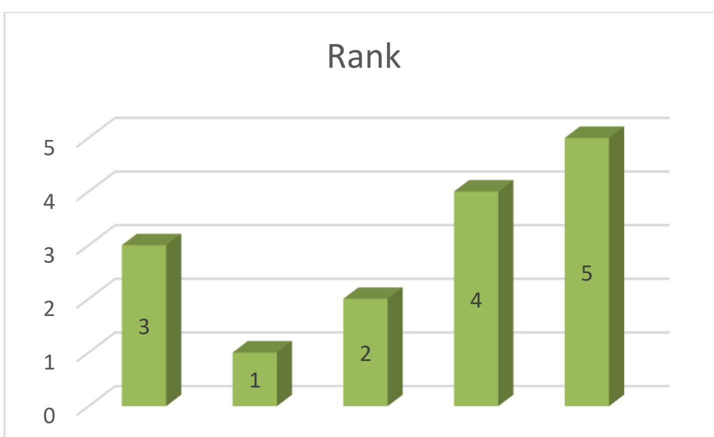

FIGURE 2. Rank value

Figure 2 illustrates the ranking values of the evaluated communication technologies. The results revealed that the best performance was achieved by Rank 1, followed by Rank 2 and Rank 3, while Rank 4 and Rank 5 represented the lowest performance levels.

5. CONCLUSION

Optical communication networks have firmly secured their place as the fundamental infrastructure of the contemporary digital world, enabling the seamless transmission of massive amounts of data over vast distances in a remarkably fast, efficient, and reliable manner. This study, using a structured approach to multi-criteria decision-making through the ARAS method, examined and compared various communication network technologies, such as free-space optics, radio frequency, visible light communication, low-Earth orbit satellite networks, and power line communication, based on four important criteria: bandwidth, latency, security, and cost-effectiveness. The analysis results depicted in the final ranking table indicate that the best performance, with a Ki value of 0.811573, was achieved by the radio frequency communication technique, which received the first rank based on its consistent performance across all criteria. Visible light communication came in second place, showing impressive security properties, followed by free space optical communication. Satellite communication networks and power line communication, while performing exceptionally well in some criteria such as bandwidth and cost efficiency, ranked lower, considering the performance criteria where they did not perform well. These results reinforce that no medium is universally better than another, but that the best medium depends on the specific operational situation, deployment scenario, and performance criteria of interest. The ARAS framework was successful in providing a useful method for measuring these trade-offs so that decision makers can make informed decisions. In the future, further advances in optical and wireless communication systems are expected to be achieved through innovations in synchronous transmission, space division multiplexing, photonic integration, and artificial intelligence-based management systems. As global data needs grow rapidly, a hybrid approach that leverages the strengths of various communication technologies will be essential in building a robust and future-proof network infrastructure.

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