International Journal of Engineering Research and Reviews ISSN 2348-697X (Online)
Vol. 12, Issue 3, pp: (90-115), Month: July - September 2024, Available at: www.researchpublish.com

A Review Paper on Hybrid RF/FSO System for Communication

Rugved Bopardikar [1], Chinchu Joseph[2], A.A Bazil Raj[2]

[1] Electronics and Telecommunication Department, Pune Vidyarthi Griha's College of Engineering and Technology and G.K. Patel (Wani) Institute of Management, Vidyanagari, Parvati, Pune, Maharashtra, India, 411009

[2] RF Photonics Laboratory, Defence Institute of Advanced Technology, Girinagar, Pune, Maharashtra, India, 411025

DOI: https://doi.org/10.5281/zenodo.13848040

Published Date: 27-September-2024

Abstract: **In our fast-evolving world, effective communication systems are crucial for seamless connectivity. This review paper delves into the details of Hybrid RF/FSO systems, which seamlessly blend Radio Frequency (RF) and Free Space Optical (FSO) communication technologies. The combination of these two innovative approaches offers an impressive solution to common communication challenges, such as achieving high data rates and ensuring robust security. RF communication is praised for its reliability in varied weather conditions, like storms and heavy fog. On the other hand, FSO technology stands out for its ultra-fast data transmission and enhanced security, making it tough to intercept by unauthorized persons. The Hybrid RF/FSO system capitalizes on the strengths of both, presenting a versatile and efficient communication model. By strategically toggling between RF and FSO channels, this hybrid system promises a resilient network that remains stable and swift, even under adverse conditions like foggy or rainy weather. As technology continues to shape our future, this review highlights how Hybrid RF/FSO systems are set to become a cornerstone of fast and reliable communication, bridging the gap between speed and security with finesse.**

Keywords: **Radio Frequency (RF), Free Space Optics (FSO), Hybrid, Data Rates, Atmospheric Disturbances.**

I. INTRODUCTION

Hybrid RF/FSO communication systems are examples of revolution and advancements in the field of wireless communication. By combining both of these technologies we can achieve results which cannot be achieved by a standalone system. These hybrid systems offer a promising solution to the requirements as we go towards emerging advanced technologies, various applications like VR, real time gaming, accurate weather prediction,etc., 5G and beyond [1-2]. The main advantage of a FSO communication system is the offering of high data rates. The LASER beam transmission technique in FSO communication requires clear Line of Sight(LoS) which is hard to intercept [3]. This makes the FSO system more secure. However FSO links are very sensitive to atmospheric conditions, hence can be easily disturbed by heavy rain, fog, etc. degrading the signal quality and decreasing the overall reliability of the system.

On the other hand the traditional RF communication system is not affected by the weather conditions and can travel through various obstacles without requiring clear line of sight making it a robust communication technique [4]. But RF technology can only offer limited bandwidth hence giving low data rates. RF waves can be easily intercepted, raising security concerns. Conventional Radio Frequency(RF) method of communication is not sufficient to fulfil these requirements [1]. A standalone FSO system also cannot give a reliable communication system .Hence Hybrid Radio Frequency/Free Space Optical(FSO) Communication was introduced as an alternative for this. This system was combined with the advantages of both RF and FSO communication techniques [4]. Making the communication system more strong, reliable and fast.

FSO communication is developing in various fields such as deep space communication, Internet of Things(IoT), 5G communication. Development in FSO communication techniques such as Wavelength Division Multiplexing(WDM), sub-carrier multiplexing(SCM0, Worldwide interoperability for Microwave access, Visible Light Communication(VLC) are done over the decades[5]. FSO communication is done with the help of a laser beam and this laser beam is prone to atmospheric turbulence which causes the fluctuation of the laser beam [6-7]. The motion of the beam is one of the main causes for power loss. Beam wandering is also the main cause of major power loss in FSO communication systems [8-10]. Hence a stabilization system is required with beam wandering mitigation. To resolve this issue a neuro controller can be designed in the Field Programmable Gate Array(FPGA) which can stabilize the receiver beam [11-12].Similar to atmospheric turbulence there are frequent sandstorms in the desert. These sandstorms are a combination of dust and sand particles which can absorb and scatter most of the optical signal and weaken it [13]. Focal spot wandering is another cause for power loss in FSO communication systems [14]. Hence mitigation of the focal spot is the most important requirement to improve the performance. To avoid these effects, a convergent triple-hop reconfigurable intelligent surface(RIS) RF-FSO system can be used for communication [15]. This system is generally used in underwater wireless optical communication(UWOC). A controller which can control the beam motion and increase the stability of the beam is also important at certain points [16-18]. FSO is also very sensitive to atmospheric turbulence as adverse weather conditions can degrade the signal quality. To identify the strength of the turbulence a model is required which will work on meteorological parameters [19-21]. In FSO communication beam position is a very important aspect as wrong beam position can degrade the quality of the signal. To avoid this a fast steering mirror is used to control the beam with the help of fuzzy logic controllers and PID [22].

Factors such as atmospheric attenuation, strength of the turbulence are considered and a model can be made with the help of FPGA. Optical amplifiers play a vital role to expand the coverage area for a network with the help of amplify-forward and amplify-received configurations. Laser steering system is used to increase the efficiency of coupling which in turn makes the performance of the system better [23-25].. An accurate model design can predict the exact optical attenuation with the help of data from meteorological departments in different seasons to permit the data transmission. Mono pulse beam tracking mechanism is used to concentrate the beam at the center of the detector plane under adverse atmospheric conditions [26-27]. The biggest concern in communication is security. While transmitting the data an eavesdropper can retrieve the transmitted information. To avoid this Quantum Key Distribution(QKD) is used [28-30].Adaptive optics (AO) is a technology used to improve the performance of optical systems by compensating for distortions and aberrations. These distortions can be caused by various factors, such as atmospheric turbulence, which affects the quality of images captured by telescopes, or imperfections in optical components used in other systems [31]. Raman Amplifiers(RA) can be used to extend the length of optical propagation path under harsh atmospheric turbulence in FSO communication systems. It improves SNR, average BER and link distance significantly [32].

Airspace targets have micro-Doppler(mD) signatures and can be differentiated one from another. The development in the field of C-band continuous wave RF photonic sensors is capable of detecting this signature and identifying different targets such as drones, warheads, bionic birds,etc [33]. The use of photonic based radar is opening new doors of opportunity as it is more effective as compared to the conventional radar system. Photonic radars have advantages such as broader bandwidth, faster signal processing and high resolution [34-35].

The hybrid RF/FSO communication technology is used in vehicular communication and hoc networks where each device(node) communicates directly with the other device within its range[36]. The laser transmissions used in FSO have various errors such as beam misalignment, atmospheric fading. These errors can be removed by the use of multiple hopping and relay based systems. This method is used in space communication where transmission distance is very large [37-39]. The weather sensitivity of the FSO link is the major problem for the loss of the signal. Due to this outage probability of FSO link increases and strength of the signal reduces in turn. The strong turbulence, dense fog can wither the FSO link [40-43]. Some systems have multiple components which act together as a single receiver or transmitter. These systems follow one single component known as leader and other components act as followers. When the FSO is incompatible to transmit the signal it borrows some part of RF for transmission, the stackelberg game analogy is given to this [44]. The power factor is important in every communication system and for RF and FSO power is different. This power factor is used to switch between RF and FSO communication links. This switching is used in defense and 5G backhaul connection applications [45-46]. The outage performance is based on multi use mixed underlayRF/multi destinations FSO links. Interface cancellation scheme and optimal power allocation are the key factors that enhance the performance of the system [47]. The use of orthogonal space-time block coding and transmission antenna selection have benefits such as less outage probability. This method is effective as compared to conventional Single Input Single Output(SISO) systems [48-49]. RF and FSO link parameters have great influence on the performance of the system and can affect outage probability, diversity order and coding gain [50]. A relay based hybrid RF/FSO system is beneficial for adverse weather environments. In this system a relay acts as a node which performs functions such as amplify and forward or decode and forward. This method makes the communication system more efficient and reliable [51-53].

Pointing error occurs due to the misalignment of the laser beam and can be encountered with the help of different modulation schemes such as Phase Shift Keying(BPSK,MPSK). To avoid further errors coded modulation is used where error correcting codes are combined with modulation schemes [54-56]. To model a RF channel various fading techniques are used such as Rayleigh fading or Nakagami fading. These fading channels ensure the reliability and robustness of the link. Even with the help of multi hopping the strength of the signal can be increased and every hop maintains the integrity of the signal. With hopping generally a relay is used to further simplify the process and increase the reliability of the system [57-61]. The switching between RF and FSO can be done with the help of soft switching where a software program does the switching, in this program bit rate control can be used to reduce the errors, this makes the system highly efficient [62-64]. Hybrid RF-FSO communication systems can be used to establish ground to air connection links. These links are useful in the fields such as deep space communication, satellite communication,etc. For this a relay based multi-hop system can be used. A partial relay based system where relay is operated by hardware impairments. Due to this the system is less affected by weather conditions such as atmospheric turbulence, rain, fog, etc [65-68]. In all the hybrid systems power loss is the major factor for system's inefficiency. Hence, dynamic power allocation technique is important which allocates the power wisely and reduces excess power losses while switching. In some systems hoppers and relays are used which can demand excess power, in that case power optimization is important which can be achieved with the help of software programs (coding techniques). These systems can be implemented in rural areas for last mile connectivity[69-71].

The paper is further classified into different sections.

Section I explains the frequency spectrum, section II goes deeper into the concept of radio frequencies, section III offers explanation on Free Space Optics communication, section IV delves into the details of hybrid RF/FSO communication system and the last section is conclusion.

II. FREQUENCY SPECTRUM

A. Detailed Discussion on Electromagnetic Spectrum

Hybrid RF/FSO systems are examples of revolution and advancements in the field of wireless communication. Combining both of them we can achieve results which cannot be achieved by a standalone system. These hybrid systems offer a promising solution to the requirements as we go towards emerging advanced technologies, various applications like VR, real time gaming, accurate weather prediction,etc., 5G and beyond [1-2].

The main advantage of a FSO system is the offering of high data rates. The LASER beam transmission technique in FSO requires clear Line of Sight(LoS) which is hard to intercept [3]. This makes the FSO system more secure. However FSO links are very sensitive to atmospheric conditions, hence can be easily disturbed by heavy rain, fog, etc. degrading the signal quality and decreasing the overall reliability of the system.

On the other hand the traditional RF communication system is not affected by the weather conditions and can travel through various obstacles without requiring clear line of sight making it a robust communication technique [72]. But RF technology can only offer limited bandwidth hence giving low data rates. RF waves can be easily intercepted, raising security concerns.

Conventional Radio Frequency(RF) method of communication is not sufficient to fulfil these requirements [1]. A standalone FSO system also cannot give a reliable communication system .Hence Hybrid Radio Frequency/Free Space Optical(FSO) Communication was introduced as an alternative for this. This system was combined with the advantages of both RF and FSO communication techniques [2]. Making the communication system more strong, reliable and fast.

Table 1. Frequency Spectrum

Frequency Band	Range
VLF(Very Low Frequency)	3 Hz to 30 KHz
LF(Low Frequency)	30 KHz to 300 KHz
MF(Medium Frequency)	300 KHz to 3000 KHz
HF(High Frequency)	3 MHz to 30 MHz
VHF(Very High Frequency)	30 MHz to 300 MHz
UHF(Ultra High Frequency)	300 MHz to 3 GHz

SHF(Super High Frequency)	3 GHz to 30 GHz
EHF(Extremely High Frequency)	30 GHz to 300 GHz
Infrared	300 GHz to 400 THz
Visible	400 THz to 800 THz
Ultra-Violet	800 THz to 30 PHz
X-Ray	30 PHz to 30 EHz
Gamma Rays	Above 30 EHz
Cosmic Rays	10^{23} Hz approx.

B. Information and Applications of frequencies in the Electromagnetic Spectrum

The frequency spectrum is also known as electromagnetic spectrum, it consists of all the frequencies ranging from very low frequency to cosmic rays. This spectrum is generally divided into various parts. Each of these parts has their own unique properties and application and can be used for different purposes.

Starting from low frequencies, spectrum has radio waves. Range of radio waves is from 3 Hz to 300 GHz [2]. We use radio waves in our daily life. For example AM, FM radio uses radio waves, even television signals and mobile networks use radio waves. As they fall on the lower side of the frequency spectrum they have large wavelengths which makes them able to travel long distances and penetrate through obstacles such as mountains and buildings.

As we go further in the spectrum, next comes microwaves. They are popularly also known as mmWaves, since they have millimetre wavelengths. Their frequency range is from 300 MHz to 300 GHz. Microwaves have a wide variety of applications ranging from home appliances to advanced satellites. Microwaves are used in a microwave oven, in Bluetooth® technology and in satellite communication. They have short wavelengths as compared to radio waves hence have high frequencies.

Next region is the Infrared Region(IR) in the frequency spectrum. Infrared waves range from 300 GHz to 400 THz. Generally hot bodies emit infrared waves such as human bodies or a cup of hot tea or coffee. Due to this, the applications of infrared waves are night vision equipment, remote sensors or thermal imaging cameras [1][73]. Another most common application is that they are used in optic fibre communication, which can transmit the data to long distance with minimum loss.

Our naked eyes cannot see every wave in the frequency spectrum but can see waves of wavelengths ranging from 380 to 700 nanometers. They have a frequency of 400 THz to 800 THz. This region consists of all colours of the rainbow from red to violet. Visible light is used in optical communication, photography,etc [74].

After the visible light region comes the Ultraviolet(UV) radiation region. UV light has a frequency range from 800 THz to 30 PHz [75]. UV light has more energy than visible light hence can go through soft tissues of skin. Hence, they have great medical use but excessive exposure to UV radiation can have harmful effects on human skin and can also cause skin cancer.

Going towards the end we have X-Rays and Gamma rays, very powerful rays with very high energy. X rays have a range of 30 PHz to 30 EHz. Their ability to penetrate human skin is used to do scans of internal human organs [76]. Gamma rays have a frequency above 30 EHz. They are the rays with the most energy and are mostly emitted by supernova explosion or by a neutron star. They are used in treatment of cancer as they have the ability to kill the cancer cells. At last, we have cosmic rays. The rays which are made by stars like the sun or explosion of stars and even black holes [77]. They have great speed almost equal to that of light, but are blocked by the atmosphere of the earth which makes them harmless.

Out of this the RF and Optical Spectrum are mostly used for communication purposes. Hence we have 2 types of communication namely RF communication and Free Space Optical(FSO) communication. The different types of waves and their frequency range are given in table 1.

III. RADIO FREQUENCY

A. Radio Frequency Communication

Radio Frequency uses electromagnetic waves ranging from 3 KHz to 300 KHz [1][78]. RF waves have great capabilities of travelling through various mediums such as air, vacuum or any other materials. Reflection, diffraction and absorption are some important properties of RF waves.

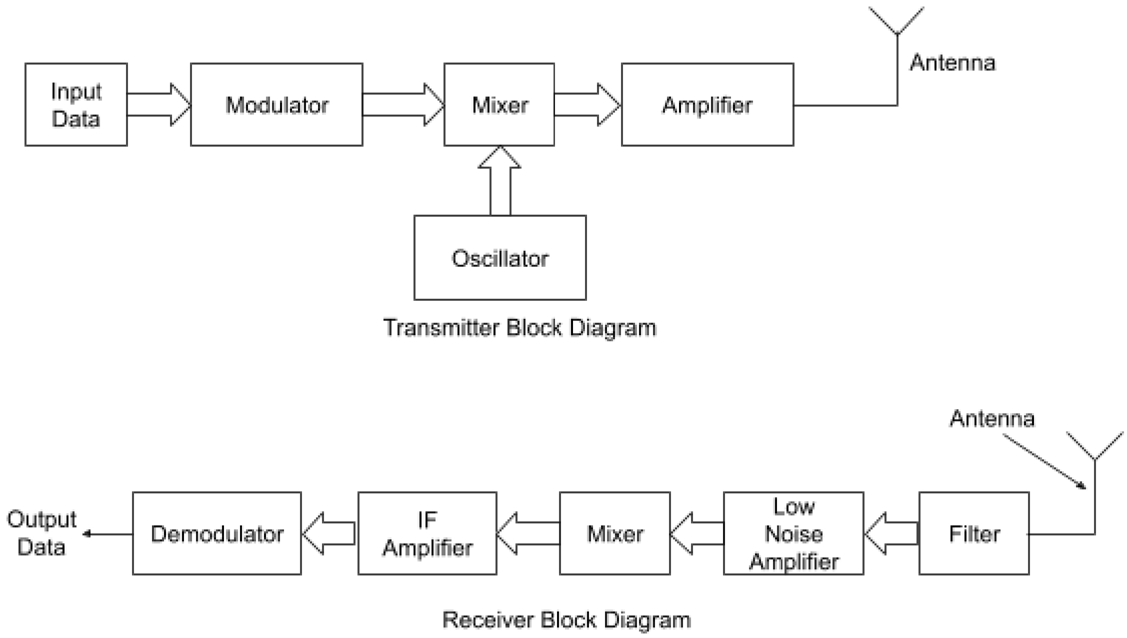

Fig.1 Basic Radio Frequency Communication Diagram

In the block diagram of the transmitter shown in fig 1, input data represents the data for transmission which can be digital, audio or video signal. The modulator superimposes the original signal on the carrier wave. For this superimposing various modulation techniques such as AM(Amplitude Modulation), FM(Frequency Modulation), PM(Phase Modulation). Modulation makes sure that the wave travels to the destination over a long distance. After this the modulated wave is combined with a signal from the oscillator in the mixer [79]. This process is known as heterodyning which shifts the frequency of signal to higher frequency bands. The height of the antenna is inversely proportional to the frequency of the signal. Hence larger frequency allows use of smaller antennas and also reduces interference. LC oscillator is used commonly in these systems due to their easy implementation and good phase noise characteristics.While travelling through the atmosphere major attenuation of wave can occur which distorts the original signal. To avoid this the power of the wave must be increased to a certain level, this is done by the amplifier. After completing this process the signal is transmitted with the help of an antenna.

The receiver block diagram given in fig 1 shows various blocks such as filter, amplifier, mixer,etc. The antenna captures the transmitted electromagnetic waves and converts them back into electrical signals.The received signal is typically very weak, so it is first amplified by a low noise amplifier(LNA). The LNA boosts the signal strength while adding minimal noise, making it easier to process. The filter removes unwanted frequencies and noise from the received signal, allowing only the desired frequency range to pass through. This filtering improves the signal-to-noise ratio. The filtered signal is mixed with a signal from a local oscillator to shift its frequency down to an intermediate frequency (IF). This process, known as downconversion, simplifies the signal processing.The intermediate frequency signal is further amplified to make it strong enough for demodulation. The demodulator extracts the original data from the modulated signal. This process is the reverse of modulation and can be performed using various techniques depending on the modulation scheme used in the transmitter. The final stage where the original transmitted data is retrieved and ready for use. This could be in the form of audio, video, or digital data [80].

B. Radio Frequencies and their applications

Table 2. Radar IEEE Microwave Frequency Bands

Name	Range	Frequency
L - Band	1 - 2	GHz
S - Band	2 - 4	GHz
C - Band	4 - 8	GHz
X - Band	8 - 12	GHz

K_u - Band	12 - 18	GHz
K - Band	18 - 27	GHz
K_a - Band	27 - 40	GHz
Millimetre Wave Band	40 - 300	GHz

IEEE has given Radar bands, which are used in various applications such as satellite communication, microwave technologies. Table 2 shows the classification of all the bands.

Most common applications of RF waves are Cell Phone communication, AM and FM radios, 2G,3G technologies.

- AM and FM Radios: Following are the ranges of AM and FM radios:

  AM Radio - 535 KHz to 1705 KHz

  FM Radio - 88 MHz to 108 MHz [81]

  In India there are different radio channels which operate on different radio frequencies between these ranges. For Example:

  93.5 MHz - Radio FM

  91.1 MHz - Radio City

- Bluetooth® Technology: The Bluetooth® technology which is a short range technology we use in our phone also works on RF waves with frequency ranging from 2400 MHz to 2483.5 MHz [1][82]. Due to this technology, sharing of different files such as images, music, contacts, etc. became very convenient and easy.

- RFID Tag: Radio Frequency Identification(RFID) is the near field communication technology [1][2]. RFID has mainly two components: reader and a tag. Tag is a passive component which detects signal energy from objects, whenever the object having the same energy signal (in this case reader) comes in contact with the tag the identification is done wirelessly. Since the reader emits radio waves which are matching with that of a tag, it can be identified by a tag [1][83].

- Microwave Oven: In our daily life, the microwave oven plays an important role by heating the food in a very short period of time. This device emits microwaves, which are absorbed by the particles in the food. As a result these particles start to vibrate and this vibration generates heat [84].

- WiFi: WiFi is Wireless fidelity technology. This technology makes use of RF spectrum. Generally we have WiFi communication with the frequency of 2.4 GHz or 5 GHz [85]. This technology allows devices to communicate within the short range. For example there is WiFi in education institutes, corporate offices or at home. WiFi acts as a bridge between wired internet connection and wireless devices. It provides high data rates and can handle multiple devices at the same time. WiFi uses WPA(WiFi Protected Access) for encryption of the data. Latest security technology is WPA 3, this keeps your WiFi network private.

- Internet of Things(IoT): Today almost all devices are SMART devices which can be connected to a single WiFi network present at home [86]. This WiFi network controls the working of these devices with the help of RF communication. You can make an ecosystem of electronic devices within the home with the help of IoT. IoT technology allows you to control these devices smartly with the help of your phone or laptop. For example SMART AC, SMART TV, SMART Washing Machine these are the devices that can be connected to a single network and can be controlled from there.

- Television Broadcasting: RF communication is used by the broadcasters to provide channel services on the TV. Due to this we can watch live matches, news, etc. from all over the world at home. RF communication can efficiently transmit audio and video signals over a long distance [87].

- Remote Controls: Remote control devices use RF technology to operate. For example car alarms or car doors, garage doors and home automation systems [88].

- Satellite Communication: RF communication is used to communicate between ground stations based on the Earth and satellites in space. Due to this we can use various applications such as GPS, weather forecasting [89].

IV. FREE SPACE OPTICS COMMUNICATION

A. FSO Communication

Radio Frequency uses spectrum to assign a unique frequency to each user. As the number of users are increasing day by day there is a need for a reliable solution [90]. FSO(Free Space Optical) communication can meet modern day requirements such as network traffic management, high data rates and security [1][82][88].Aside from this, the FSO system is easy to maintain and initial cost is low for its setup. Compared to optical fibre technology, FSO is more effective and fast, providing data rates up to certain Tbps.

As the name suggests FSO is Free Space communication, the main need here is empty space that is a clear Line of Sight(LoS). Without a clear LoS FSO system lacks in performance [91]. But this is also profitable while doing satellite communication, since in space there are no major obstacles and a satellite can communicate with great speed to ground stations based on earth [90-91]. Nowadays scientists and researchers are looking at FSO as a potential alternative to the traditional communication technique due to its properties and benefits.

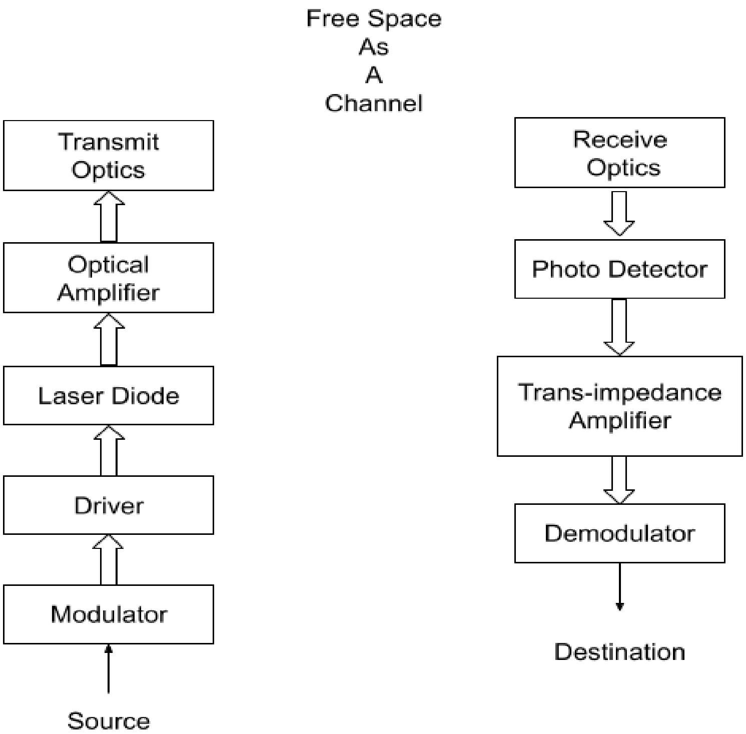

Fig 2. Implementation of FSO Communication

FSO communication as the name indicates uses free space for communication. FSO links generally work with wavelengths of 850nm to 1550nm. When converted into frequency, it goes high up to certain terahertz.As shown in the fig.2, the source contains information that needs to be transmitted and it is modulated by the modulator. In the modulator block encoding of data on the optical carrier wave is done. Driver controls the laser diode with the help of electrical signals making sure that operation of the laser is correct. The laser diode acts as a coherent light source, a coherent light source emits light at the same frequency, wavelength and same phase or constant phase difference. This light beam carries the signal through the atmosphere. The laser beam is modulated with different techniques such as Differential Pulse Position Modulation(DPPM), Differential Phase Shift Keying(DPSK), Subcarrier Intensity Modulation(SIM), etc. Transmit Optics makes sure that the laser beam is focused and directed towards the receiver. Due to the use of a laser beam, normal antennas become inefficient in the case of FSO communication. Hence FSO communication uses beam steering antennas, adaptive optics antennas, lens antennas etc. For this a laser beam is used to transmit the data [92].

Receiver antenna contains components which can collect maximum light from the atmosphere. Receive opticsare used to direct and focus the collected light on the photo detector. Photo detector converts this light into an electrical signal again. This process is done with the help of photodiodes or avalanche photodiodes. The amplifier block makes the signal strong enough for further processing. The demodulation process is the opposite process as that of modulation. The original signal is extracted from the wave in this block. Due to the use of light as a transmission medium, FSO communication can achieve high data rates as compared to other conventional communication techniques such as RF communication. The main challenge faced by the FSO system is atmospheric turbulence but scientists are researching to eliminate this issue [93]. Solar scintillation is a natural phenomena which occurs due to the solar wind plasma, which changes the refractive index of the atmosphere frequently. This phenomena can disturb the FSO communication link [94].

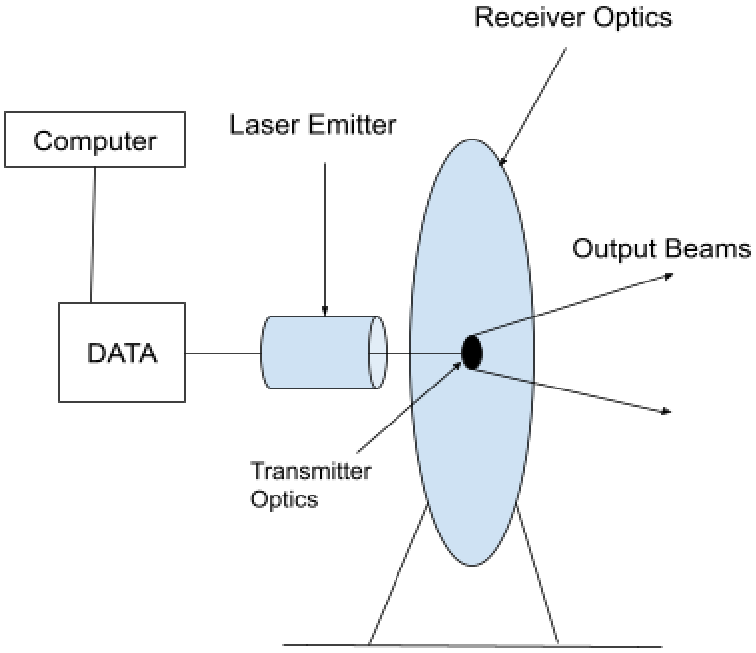

Fig 3. Laser Beam Transmission in FSO

B. Advantages and Application of FSO

FSO communication has advantages which helps in building a reliable and high speed communication system. Some of them are listed below

- High Bandwidth - High bandwidth gives higher data rates making it suitable for various applications such as fast WiFi or 5G and beyond cellular network [95].
- Cost effective - Unlike Fibre Optics, FSO doesn't need any cable for transmission. This eliminates the cost of expensive cables and hardware setup. Due to this the initial setup cost is also decreased to a certain extent.
- Security - FSO has one of the best security due to the use of LASER beam. Laser beams are hard to intercept without proper detection. This ensures the security of the original signal. Quantum Key Distribution is one of the most effective methods to secure the FSO communication link [96].
- Flexibility - The simple setup makes it easy to deploy the FSO system quickly and wherever required. It can also be reconfigured as there is need. With the help of simple phase modulation the two way communication is possible [97].
- Low Latency - Latency is a time taken by a data packet to travel from its source to destination. Latency depends on factors such as network congestion, processing time, distance between source and destination. In FSO communication, light source is the medium of transmission hence travelling speed of data is very high, resulting in low latency.

These advantages make FSO more efficient, fast, and reliable than conventional RF communication systems. The high data rate is the most important aspect of a FSO system. This is used in services such as IoT, 5G, VR, real time gaming, etc.

Following are some of the most important applications of FSO5G and Beyond(6G)

We are moving towards a futuristic world where AI, Robots and IoT will take over. For all these applications, reliable and fast internet connection is a primary requirement. Hence 5G and upcoming generations such as 6G are going to use FSO most commonly [98]. As FSO can achieve goals like high data rates, security and reliability, it is the first option for every communication system in future.

VR and Real Time Gaming

Virtual reality is the next biggest attraction, since it gives you an immersive experience of almost any scenario or situation, where you can feel the objects in your surroundings [99]. With this evolution of technology, eSports is the next big thing. Gamers all over the world are playing with each other in real time. To give the users best and lag free experience, servers need to have reliable and fast internet for data transmission ,without any packet loss. These requirements can be met by use of FSO [93]. AR and VR are going to shape the future of human beings.

Satellite Communication

Almost every country is doing space research, discovering secrets of different celestial objects and interesting facts about our vast universe. For this, research satellites are used which make use of FSO technology[1]. The connection between ground stations based on the Earth and satellites in space must be strong and reliable [1][47]. This distance is very large and high speed is required for transmission of data [90]. This data can be anything like images or videos of celestial objects. Inter satellite connection is also done with FSO [1][100].

Campus Network

FSO is a technology which can be deployed without any need of extra cables and wiring. It also gives high data rates which are similar to optic fibres. This is useful when connecting the buildings on a large campus such as universities or corporate offices. FSO system is also cost effective and less time consuming system for setting up, hence it can reduce tedious tasks of digging the holes, trenches for connecting the wires [101]. Due to the high bandwidth and low latency of FSO online learning, video conferencing and large file transfer can be done within the campus. Additionally, FSO does not require any special measurements for integrating with the existing network. Due to this overall network performance is enhanced.

MAN(Metropolitan Area Networks)

MAN is the large network connection within the city. It uses FSO technology to create a high speed network in the different parts of the city. This is particularly useful for connecting facilities such as hospitals, police stations, fire departments, etc [102]. With the help of FSO it is possible to set up an emergency or a temporary network on the occasion of various events or exhibitions. FSO systems cannot be easily affected by the electromagnetic spectrum making them suitable to set up in the area where there is high noise. As FSO does not require spectrum licensing it reduces operational cost and simplifies rules and regulations.

C. Difference between FSO and RF

Table 2. Difference between FSO and RF communication technique

Point of Difference	FSO	RF
Frequency Spectrum	Optical Spectrum	Radio Spectrum
Frequency	in TeraHertz	in GigaHertz
Wavelength	Nanometers	mm wavelength
Size of Antenna	Small	Large
Spreading of Beam	Narrow	Large
Data Rates	in Gbps	in Mbps
Sensitivity to Atmospheric Conditions	Very Sensitive to atmospheric conditions	Can work in adverse atmosphericconditions
Applications	5G and beyond cellular network	AM, FM Radio

V. HYBRID RF/FSO

A. Introduction to Hybrid RF/FSO Communication

Till now we have seen how RF and FSO systems work. RF and FSO communication systems both have their own advantages and disadvantages. Traditional RF system is a robust system which can work in adverse environment conditions such as fog, rain, etc [91]. But cannot give benefits such as high data rates and security. FSO system gives high data rates up to certain Gbps, security, low initial cost but FSO requires clear Line of Sight(LoS) for proper connection, hence rain, fog disturbs the communication link. Due to these issues, scientists and researchers came up with a solution which is a 'Hybrid RF/FSO Communication' [103]. This smart link analyses weather conditions and establishes connection accordingly.

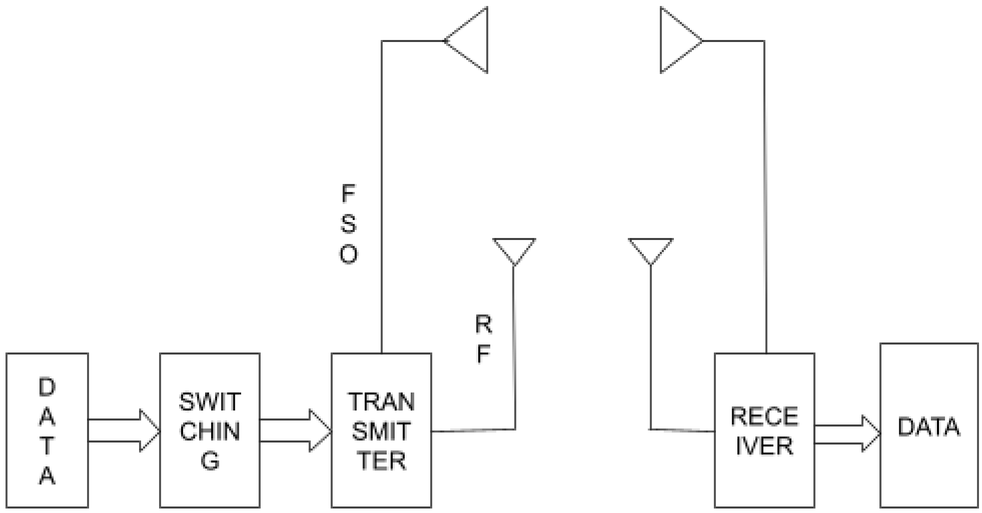

Fig 4. Basic RF/FSO Hybrid Switching Diagram

As shown in fig 4, smart switching occurs between RF and FSO links with respect to atmospheric conditions [104]. Here FSO is a primary communication link, which in case of clear weather transmits the data. But there are some scenarios where atmospheric turbulence occurs due to which the FSO link becomes ineffective hence the system changes to RF link [48][49]. The scintillation effect can also cause disturbance in the FSO link [98][105]. Scintillation is a phenomenon where a light from another star passes through the atmosphere of the Earth [98][106]. This can be seen as twinkling with our naked eyes. Scintillation affects the FSO link disturbing it and it causes disruption of data [107-109]. In these situations RF link is used as an alternative communication link.

According to [104], the novel hard switching technique between RF and FSO communication link is given in case of atmospheric turbulence and pointing error. The author mentions the incapability of the FSO system to work under harsh weather conditions such as rain, dense fog, atmospheric turbulence as it degrades the quality of signal. To avoid this problem, a novel RF-FSO system is proposed in the paper with the help of hard switching between RF and FSO communication links.

B. Different Methodologies for the Hybrid System

In [110], the author proposes a switching based transmission scheme between RF and FSO communication links. FSO links are known for their high data rates but are vulnerable to harsh atmospheric conditions like fog, while RF systems can withstand the weather but in return provides limited bandwidth [111]. The proposed system works on a mechanism where only one communication system that is either FSO or RF is active at a time. The switching is based on channel conditions, enhancing the reliability of the system and provides high data rates. This paper is highly relevant in the case of modern wireless communication networks particularly in the case of highly populated areas or urban areas. The author proposes a hybrid, simple and low complexity hard switching mechanism where only one link is used at a time. Here the FSO link is prioritized as a primary communication link for use since it provides high data rates. This hard switching helps to decrease power consumption and simplifies the system design. In this paper, dual threshold SNR technique is used to prevent frequent switching between RF and FSO links. Expressions are derived for various performance metrics such as outage probability, average Bit Error Rate(BER) and ergodic capacity. These metrics are evaluated for both single and dual threshold schemes, providing robust comparison of performance of the system under various conditions.

The FSO system is modeled with the help of a log-normal fading model. For the sake of simplicity the system assumes zero pointing error. The model captures fading effects induced due to atmospheric turbulence. RF link is modeled using the Nakagami-m fading model. This model is suitable for urban environments. The switching between links happens on the basis of SNR thresholds. In a single threshold case system uses FSO initially, if SNR goes below the threshold level it switches to RF communication link. Due to the use of dual threshold SNR technique performance degradation and more energy consumption occurs. According to the expressions derived by the author the system experiences link failures under different conditions. The BER expression is derived with the help of M-PSK modulation for both links. Expressions provided in the paper for ergodic capacity help to measure average achievable data rate over different channel conditions. The simulation result shows that the hybrid system outperforms the standalone FSO system. The dual threshold technique reduces outage probability at high SNR levels. Compared to only FSO system, the hybrid system shows improvement in BER. The results stated that the hybrid system achieved better capacity compared to the standalone FSO system.

In [104], double threshold SNR technique is used to make the lifetime of the main paths longer. In double threshold two threshold SNRs are set, a primary threshold SNR for strong signals and secondary threshold SNR for weak signals. Heterodyne technique or Intensity Modulation with Direct Detection (IM/DD) technique can be used for detection of the signal.[112]. For modeling of FSO links, the Gamma-Gamma distribution is used to represent atmospheric turbulence . Similarly, Rayleigh fading is used for modeling the RF communication link.Analysis of outage probability is done with the help of mathematical expressions, considering the atmospheric turbulence and pointing errors [113]. Outage probability is a metric used in wireless or fading channels to evaluate the robustness and reliability of a communication system.

Monte Carlo simulation is used to prove the derived analytical expressions. Monte Carlo simulation is the tool used to model the probability of a process with different outcomes which involves random variables. Monte Carlo simulations show that the proposed scheme overpowers the conventional method of single SNR threshold value for the signal, increasing the lifetime of the FSO link. This result shows that even in high turbulence and pointing error, this system can work better than traditional design giving satisfying outage performance. The use of heterodyne detection offers significant improvements in performance but the design becomes more complex.

The hybrid RF-FSO system in case of solar scintillation is proposed in [114]. The solar scintillation is mainly caused by irregular solar wind plasma[115]. This phenomena occurs in deep space communication when the Sun comes between the ground station based on Earth and deep space probe [116]. The paper proposes a dual-hop relay based systemconsisting of both RF and FSO communication models. The RF link is used to communicate between ground based station and satellite while the FSO link communicates between satellite and deep space probe. The uniqueness of this system lies in the use of hybrid L Pulse Position Modulation(L-PPM), Binary Phase Shift Keying(BPSK), Subcarrier Intensity Modulation(SIM) scheme to make a better design in the presence of solar scintillation.

Similar to [104], the Rayleigh fading for RF link and Gamma-Gamma Distribution is used for modelling the FSO communication link in [114]. The effect of pointing error is also considered during analysis. The combined use of L-PPM, BPSK and SIM is a novel approach. The provision of spectral efficiency by L-PPM and improved resilience against the noise due to the use of BPSK makes the system efficient. This hybrid modulation reduces bit error rate(BER) significantly in theory calculations. The paper analyses performance metrics such as outage probability, average channel capacity and average BER with the help of closed-form expressions. Assessment of deep space communication systems is by these metrics and the reliability and efficiency of the system is determined. The produced results showed that the hybrid system performed better than the standalone FSO system in solar scintillation. While using a larger pointing error instrument, the dual-hop decreases the outage probability. In case of weak solar scintillation a hybrid system achieved BER which was 10-30 times improved from the single FSO communication link. At higher Signal to Noise(SNR) ratios the hybrid system outperformed conventional BPSK and L-PPM systems when thoroughly analyzed. Due to the scintillation effect the channel capacity decreases. Excessive pointing errors also leads to reduced channel capacity, hence increasing robustness of the system can benefit deep space communication. The improvement in BER is seen while using shorter wavelengths, these wavelengths are less affected by coronal making them preferable for deep space optical communication.

In [98], the author points to the most important challenge in modern communication systems, which is reliability of data transmission in varying weather conditions, specifically for the Unmanned Aerial Vehicle(UAV) assisted hybrid RF-FSO communication system. The common problem for FSO communication links is the effect of atmosphere. Conditions like fog, rain, turbulence can easily distort the signal, while RF systems are more robust and can work well in these conditions. But the downside of RF links is the lower bandwidth, which cannot give high data rates. The combination of RF and FSO communication in a UAV assisted hybrid system aims to escalate the performance of the system by merging strengths of these communications. This paper mentions the context of 6G technology where speed, accuracy and reliability are main constraints. According to the author of [98], a multi-hop UAV assisted relay system can provide improved communication reliability and long range coverage [117]. The closed-form expressions for average Bit Error Rate(BER) and atmospheric turbulence are derived in the same way as [114]. The analysis of system performance is done under conditions like unstable weather conditions, receiver aperture size and modulation techniques. RF channel fading is modeled by Nakagami-m fading model and atmospheric turbulence is modeled by Exponentiated Weibull distribution [118]. The influence of these RF channel fading and atmospheric turbulence are evaluated in this paper.

The FSO link is modeled by Exponentiated Weibull distribution which is considered for atmospheric attenuation and turbulence. UAVs work in air and are unstable, hence misalignment caused by movements of UAVs can create pointing errors in FSO links. Coherent Binary Phase Shift Keying(CBPSK), Differential Binary Phase Shift Keying(DBPSK), Coherent Binary Frequency Shift Keying(CBFSK), Non-Coherent Binary Frequency Shift Keying(NBFSK) form a hybrid modulation scheme which are considered in the paper. Average BER and outage probability are used as performance metrics. Simulation results stated that the UAV assisted system improves BER due to its relay capability. Results also indicated that fog and haze affects the communication link and light rain affects both RF and FSO communication. But, due to the use of UAV this impact is weakened by providing different communication paths. The modulation scheme tested, gave the result as CBPSK providing great BER performance under all conditions. While NBFSK showed the worst performance in high-power transmission scenes. The multi-hop and relay selection gives enhanced reliability, this is particularly effective in adverse weather conditions. This majorly reduces outage probability Higher Nakagami-m fading parameters and larger receiver aperture improves performance of the system. Pointing errors are causing degradation in the performance of FSO links, this scenario is occurring mainly in high-power transmission.

According to [119], the crucial challenge in next generation wireless communication is cost effective small-cell base stations (SCBSs). Traditional backhaul methods such as optic fibre(OF) are expensive to deploy and hard to maintain. RF cannot give higher data rates and is susceptible to latency. The paper proposes a hybrid system where RF and FSO links are used to reduce overall cost and make the performance of the system better. This solution is profitable for future 5G and beyond networks. The problem of minimizing the cost of hybrid backhaul deployment is framed as a weighted Steiner tree problem, which is complex for calculations. The paper introduces a graph-theoretic heuristic that approximates the solution by considering multiple link-disjoint paths between base stations, ensuring resilience against link failures while minimizing costs.The algorithm focuses on reducing costs by intelligently selecting between OF and hybrid RF/FSO links, taking into account factors like distance, weather conditions, and target data rates.

The cost of the system was reduced significantly as compared to the Optic Fibre system due to the use of both RF and FSO communication. This was particularly applicable in the case of a large number of SCBSs. The hybrid approach was able to save almost 37% in some configurations. The increasing number of small cells improved the cost effectiveness of the hybrid RF/FSO system. The break even point reached around 1000 SCBSs. The reliability factor was improved due to the use of hybrid RF/FSO systems. The switching from FSO to RF link was happening successfully as the FSO system was performing poorly under adverse weather conditions.

C. Strengths of Hybrid RF-FSO Systems

In [110], the hard switching mechanism used is easy to implement and it reduces the complexity of the design as well as power consumption of the system. Due to the use of dual threshold SNR the unnecessary switching is reduced which in turn reduces the energy consumption. This is beneficial for extending the lifetime of the FSO link. The author provides closed-form analytical expressions for various performance metrics such as average BER, ergodic capacity and outage probability. This offers a rigorous mathematical foundation to measure the performance of the hybrid RF/FSO system.

The author of [104] proposes an innovative method of double threshold SNR technique, this ensures the adaptive and balanced switching between RF and FSO communication link according to conditions. This method makes higher utilization of FSO links and enhances the reliability of the system in adverse weather conditions. The detection techniques, outage probability, channel model are analyzed in great detail and are supported with complex and thorough mathematical equations. This makes sure that the proposed system is valid and can work in real life. This hybrid method is suitable for last mile connectivity and backhaul links in 5G cellular networks, where harsh weather conditions are responsible for the degradation of optical communication links.

In [114], a novel dual-hop RF-FSO hybrid system is introduced. This hybrid system is useful specifically for deep space communication under the effect of solar scintillation. This scenario is vital for future space missions. The expressions for outage probability, channel capacity and BER are calculated with detailed analysis. These expressions are supported with the help of validated simulations, which make all the outcomes reliable. The system integrates realistic effects in deep space communication such as pointing errors, solar scintillation and use of modern and advanced modulation techniques.

According to [98], a detailed analysis of performance of the UAV assisted system is done under different weather conditions and system configurations. Multiple factors are included in the paper such as pointing error, modulation schemes, weather which further increases the depth of the study. The validity of the system is enhanced by the use of realistic channel models such as Nakagami-m model for RF link and Exponentiated Weibull distribution for FSO links. The use of multiple relays for multiple hops with the help of UAVs offers a promising communication system, which can be used in future communication generations(6G). The improved BER and outage probability makes this system reliable even in adverse weather conditions.

The author of [119], proves that the hybrid RF/FSO system is able to provide cost-efficient and scalable solutions for future wireless networks. The author points to the limitations and advantages of standalone RF and FSO technologies and offers a balanced system which can combine strengths of both these technologies. This includes achieving high data rates at a reduced cost. The use of graph theory by the author to optimize backhaul planning under multiple constraints is novel and provides guidelines for practical implementation of the design. The heuristic algorithm which is used in the paper effectively approximates the optimal solution with low computational complexity. The paper considers real life scenarios such as urban areas with dense SCBS deployments. The adaption of the hybrid RF/FSO system to varying weather conditions enhances its applicability.

D. Limitations of Hybrid RF-FSO Systems

In [110], the FSO link model does not account for pointing errors, which can significantly impact performance in real-world systems. Future work could incorporate more realistic FSO channel models, including pointing errors and stronger turbulence effects.While the paper focuses on reducing power consumption by switching between RF and FSO, it does not provide a detailed analysis of energy efficiency. Given the importance of power management in wireless systems, a deeper exploration of energy consumption would strengthen the practical applicability of the proposed solution.The paper assumes fixed backhaul links between the RF and FSO systems. Future research could explore how the hybrid system performs in mobile environments or with larger, more complex network topologies involving multiple hops or UAV-assisted relays.

In [104], the results show the heterodyne technique providing better performance as compared to others. But it also introduces additional complexities in the design and increases cost of the overall system while implementing practically. The deeper discussion on the trade-offs between IM/DD technique and heterodyne technique can further enhance the relevance of paper. The paper is more reliant on link reliability and outage probability without addressing the energy consumption cost linked with frequent switching between RF and FSO links. This cost is high particularly in large scale networks. The proposed system is not discussed in the context of scalability. In future work, the author can explore the possibilities of implementing this hybrid RF-FSO system in densely populated areas with numerous links.

According to [114], the use of hybrid modulation schemes with L-PPM, SIM, BPSK outperforms the conventional BPSK and L-PPM schemes. But this hybrid scheme introduces complexity to the system. More in depth research on balance between performance gains and implementation complexity will make the paper more resourceful. This paper mainly focuses on factors like BER and outage probability but energy efficiency is not addressed properly. The power consumption is very important in case of deep space communication and could beaddressed in future work. This system is typically designed for deep space communication in case of solar scintillation, but scalability of this system in other scenarios such as interplanetary communication is not discussed properly.

The theoretical discussion of implementation of hybrid RF-FSO systems with the help of UAV is excellent in [98] but it lacks the practical implementation scenarios of the system. UAVs are costly and use of multiple UAVs for the system can increase the cost of the system significantly. The factors such as power consumption and UAV mobility are also not discussed in the paper. UVAs have limited power capacity, hence the power consumption is an important factor and energy utilization should be discussed in the future work. The paper does not discuss the system requirements for large area networks with dense population and high network traffic. These topics can be included in the future work.

While [119] focuses on cost reduction and performance, it lacks a detailed analysis of the energy consumption of the hybrid system. Since energy efficiency is a critical factor in modern network deployments, future work could explore how the hybrid RF/FSO system can be optimized for power consumption.The hybrid system introduces additional complexity in terms of switching between RF and FSO, particularly in environments with rapidly changing weather conditions. A discussion on the practical challenges of implementing such dynamic switching would strengthen the paper.The paper focuses on fixed backhaul scenarios, but future networks will likely include mobile small cells (e.g., mounted on UAVs). The performance of hybrid RF/FSO backhaul in scenarios involving mobility and dynamic topology changes should be explored.

E. Bit Error Rate

As discussed in the above cases one of the most important parameters as a performance metric is BER. The improvement in BER increases the efficiency of the system significantly. It measures the number of bit errors compared to total bits sent. BER is used to identify how reliable and efficient a system is [120]. BER also helps in error correction techniques used in digital communication. Achieving lower BER needs sophisticated equipments, which increases the stress on the budget. Hence engineers need to balance the BER with the given budget. BER is calculated with respect to the modulation scheme used in that system. Below is an example of BER calculation with the help of MATLAB.

Let's assume that the system is working on On-Off Keying(OOK) and on the Additive White Gaussian Noise(AWGN) channel. Here is the skeleton of code for the BER:

Code:

```
% Parameters
numBits = 1e6; % Number of bits to be transmitted
EbNo_dB = 0:2:20; % Eb/No range in dB
M = 2; % OOK modulation

% Generation of random bits
data = randi([0 1], numBits,
1);

% OOK
Modulation
txSignal = data;

% Pre-allocation of BER array
BER = zeros(length(EbNo_dB),
1);

for i = 1:length(EbNo_dB)
   % Calculating noise
   variance EbNo =
   10^(EbNo_dB(i)/10);
   noiseVar = 1/(2*EbNo);

   % Generation AWGN noise
   noise = sqrt(noiseVar) * randn(numBits, 1);

   % Received signal
   rxSignal = txSignal + noise;

   % OOK
   Demodulation
   rxData = rxSignal >
   0.5;

   % Calculation of BER
   [numErrors, BER(i)] = biterr(data,
rxData);end

% Plotting of BER vs
Eb/Nofigure;
semilogy(EbNo_dB, BER, 'b-
```

```
o');xlabel('Eb/No (dB)');
ylabel('Bit Error Rate (BER)');
title('BER vs Eb/No for FSO System with OOK Modulation');
grid on;
```

Above code gives the graph of BER vs Eb/No.

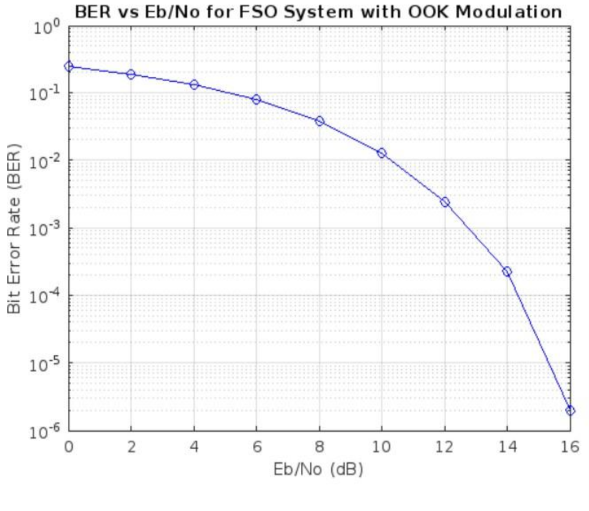

Fig 5. Graph of BER vs SNR per bit

Explanation:

The MATLAB code is used for simulation of performance of FSO communication system using On-Off keying modulation scheme. It calculates and plots the BER for different values of Eb/No(Energy per bit to Noise Power Spectral Density ratio). In the beginning the number of bits to be transferred, modulation scheme, the range of Eb/No values in dB are defined. The code generates a random sequence of bits and modulation of these bits is done with the help of OOK. Here the transmitted signal is a simple data bit. For each Eb/No value, the code calculates the noise variance and generates Additive White Gaussian Noise (AWGN) to simulate the channel noise. By adding noise and transmitted signal received signal can be obtained. The code then demodulates the received signal by comparing it to a threshold of 0.5 and calculates the BER by comparing the demodulated bits with the original data. After this, the plot of BER against Eb/No is plotted on the semi-logarithmic scale which provides the visual representation of the system's performance under various noise conditions.

F. Code for switching between RF and FSO communication link

To switch between RF and FSO link coding is required. Following is the skeleton of a C++ code to switch between RF and FSO links.

Code:

```
#include
<iostream>
#include
<string>

// Function to collect the current weather data
std::string getWeatherCondition() {
   // Placeholder for actual weather data retrieval
   // In practical, a proper weather API will be called here
   return "clear"; // Possible values: "clear", "foggy", "rainy", etc.
}

// Switching to FSO link function
void switchToFSO() {
```

```
    std::cout << "Switching to FSO link." << std::endl;
    // Code required for activating FSO link
}

// Switching to RF link
functionvoid switchToRF() {
    std::cout << "Switching to RF link." << std::endl;
    // Code required for activating RF link
}

int main() {
    std::string weatherCondition = getWeatherCondition();

    if (weatherCondition ==
        "clear") {switchToFSO();
    } else {
        switchToRF();
    }

    return 0;
}
```

Explanation:

In the above code, the first condition is to call a weather API. A weather API contains data of the atmospheric conditions of a particular region. These files can be accessed from a government website. In code, the **getWeatherCondition()** function is used to retrieve the current weather condition, which returns ‘clear’ as placeholder. After getting the result of weather conditions the main code decides which link to use. If the output is clear it calls the **switchToFSO()** activating the FSO link for communication. If weather conditions are not clear, **switchToRF()** function is called, which activates the RF link for communication. After that hardware interfacing is required, as different hardwares can be used to transmit the data, each will have its different ports and protocols which will need to be followed. Hence choosing hardware accordingly is also important as it can make the whole system a lot more complex. FSO and RF devices will be different hence we will need to write 2 codes, first for activating the primary FSO link, second to activate the secondary RF link. As the above code is only a sample code, the original code will have hardware components specification to activate the respective links.

G. Advantages of Hybrid RF/FSO communication

- Quality of Service(QoS) - QoS contains several things such as controlling network traffic, making sure the performance of a system does not drop and limited resources are used by the system [1][78]. By using Hybrid RF/FSO communication link, the overall QoS of a system increases [1][121].

- Throughput - Throughput is the measurement used in communication to determine how much data is received against how much data was transferred. The loss of data decreases the throughput of the system [1][122]. Use of Hybrid systems increases throughput by switching between FSO and RF. Due to this enhanced throughput the data rate increases and allows fast transmission of the data.

- Reliability - FSO link is the primary link in the system but due to factors such as rain, haze, fog this linkgets disturbed. Hence data transmission stops decreasing the reliability of the system. While using a Hybrid system the link is switched to RF link immediately if weather conditions are not suitable [1][123]. Due to this the system becomes reliable.

- Energy efficiency - For transmission of data energy is required. In traditionala systems the energy requirements is very high as it uses only single type of communication [1][124]. In Hybrid systems effective utilisation of energy is done by optimising the system. This is done by switching between RF and FSO communication. This technique is used in modern communication methods such as 5G [1][125]. This energy efficiency is also required by the IoT devices as it needs fast and reliable internet connection [1][126].

- Extended Coverage - As mentioned above FSO link is mainly dependent on the atmospheric conditions, due to this limitations arises for long distance communication [1][127]. The RF system is a robust system and can be used to transmit the data to far away places irrespective of atmospheric conditions [1][128]. Due to this switching, a large area can be covered by a Hybrid system.
- Security - Every messenger service has one motto that is end to end to encryption of all the messages. This means the service provider tries to give maximum security and privacy to the user [1][128]. But due to the usage of single communication the message can be intercepted by a third person. To avoid this, the capabilities of both FSO and RF can be combined together. FSO signal is difficult to intercept and hence cannot be accessed by a third party [129]. RF signals are harder to jam due to their robustness. In a Hybrid system the combined security of both these communications is achieved [130].
- Cost-Effectiveness - The Hybrid RF/FSO system is more cost efficient than, only RF or only FSO system. This system is more cost saving for long distance communication. The advantages of both RF and FSO will save expenditure on special equipment for transmitter and receiver [109][119].
- Adaptive Communication - Adaptive communication means switching dynamically between FSO and RF communication link [114][131]. This smart switching makes sure to give optimal performance and best QoS[1][132].

H. Disadvantages of Hybrid RF/FSO Communication

- Complexity and Cost: Implementing a hybrid RF-FSO system requires integrating two different technologies, which increases the complexity of the system design and operation. This integration often leads to higher costs for both installation and maintenance[133].
- Synchronization Issues: Ensuring seamless switching between RF and FSO links can be challenging. Synchronization between the two systems is crucial to maintain continuous communication, and any delay or mismatch can degrade performance [134].
- Environmental Sensitivity: While hybrid systems aim to mitigate the weaknesses of each technology, they are still susceptible to environmental factors. FSO links are highly sensitive to atmospheric conditions like fog, rain, and dust, while RF links can be affected by electromagnetic interference and physical obstructions [135].
- Power Consumption: Operating both RF and FSO systems simultaneously or switching between them can lead to higher power consumption [136]. This is particularly problematic for battery-powered or energy-constrained applications.
- Security Concerns: FSO links, due to their narrow beam and line-of-sight requirement, are generally more secure than RF links. However, the hybrid nature of the system can introduce vulnerabilities, especially if the RF link is intercepted or jammed [137].

I. Applications of Hybrid RF/FSO communication

Due to the advantages of the hybrid RF/FSO communication systems, they can be implemented in many places and are effective for most of the modern world applications such as 5G communication, IoT, satellite communication,etc. Following are some of the applications of Hybrid RF/FSO System:

- Backhaul Connection for Mobile/Cellular Network - Backhaul or also known as exchange backhaul are the links that connect the core data centre to local exchange[1][138]. These local exchanges then provide service to our home router or to our cell phone. 5G services uses backhaul connection as a backup if primary links fail to communicate, providing excellent customer service[106][139].
- Disaster recovery and emergency situation communication - During emergencies or natural disasters the communication link gets disturbed [140]. In this situation a hybrid system can establish a temporary connection to that particular region helping local people and military to do the needful[140]. This helps in saving and aiding the people suffering from the wrath of natural calamities.
- Remote Sensing and Monitoring - Hybrid systems can be used to transmit data from various devices such as cameras, sensors or monitoring devices to any computer or mobile phone. Various devices to analyse ECG or EEG data of patients are available in the market today and they use this hybrid technology[1][141]. Multiple Biomarkers can be

observed and the data can be transferred to mobile phones for remote access[142].

- Earth to Satellite Link - When doing deep space communication a strong and reliable connection is required. The telescope captures many photographs, videos of planets, comets, asteroids, etc. in space[1][143]. These all need to be transmitted to the ground station based on the Earth. During Solar scintillation establishment of communication links using FSO becomes difficult. To avoid this, use of hybrid RF/FSO systems can help, as RF has that robustness and efficiency to communicate[144].
- Vehicular Communication - Vehicle to vehicle communication can be done to avoid traffic congestion or to help people who were in a road accident[1][145]. Hybrid systems are also used in vehicles such as submarines for underwater communication[146]. The development in the field of Unmanned Aerial Vehicles(UAVs) is truly fascinating and this technology is changing the world. These UAVs use hybrid RF/FSO communication for communicating with centres on the ground and they have a range of up to few kilometres[147]. In some cases a whole RF/FSO communication system can be implemented on a UAV[12][148].
- Military Communication - The security provided by the hybrid RF/FSO communication is of great advantage for military application due to the sensitive data transmission[149]. The robustness of hybrid systems and their ability to work in various operational areas is profitable for military communication. These revolutionary applications are discovering new possibilities in various fields such as defence,

healthcare, space research, etc. The combined advantages of RF/FSO communication systems are making them more robust, more reliable and systems with higher data rates. UAV, satellites are helping to make progress in fields such as education. Due to high speed internet real time gaming is possible, which is expanding the global eSports market. Streaming of videos with more than one person at the same time is possible because of these systems[150].

VI. CONCLUSION

The hybrid RF/FSO (Radio Frequency/Free Space Optical) communication system represents a significant advancement in the field of wireless communications, combining the strengths of both RF and FSO technologies to enhance overall system performance and reliability. This integration addresses the limitations inherent in each individual technology, such as the susceptibility of FSO to atmospheric conditions and the limited bandwidth of RF systems.

The primary advantage of hybrid RF/FSO systems lies in their ability to maintain robust communication links under varying environmental conditions. FSO links, which offer high data rates and large bandwidth, are highly effective in clear weather but suffer from performance degradation in adverse conditions like fog, rain, and dust. Conversely, RF links, while offering lower data rates, are less affected by such environmental factors. By dynamically switching between RF and FSO links based on real-time environmental assessments, hybrid systems ensure continuous and reliable communication. Moreover, hybrid RF/FSO systems enhance the overall capacity and flexibility of communication networks. They can be particularly beneficial in scenarios requiring high data throughput and low latency, such as in urban environments with high user density or in backhaul networks where maintaining high-speed data links is critical. The use of advanced modulation and coding schemes further optimizes the performance of these hybrid systems, ensuring efficient utilization of available spectrum and minimizing error rates.

However, the implementation of hybrid RF/FSO systems is not without challenges. The increased complexity and cost associated with integrating two distinct communication technologies can be significant. Additionally, ensuring seamless switching and synchronization between RF and FSO links requires sophisticated control algorithms and real-time monitoring systems. Despite these challenges, the potential benefits of hybrid RF/FSO systems in enhancing communication reliability, capacity, and flexibility make them a promising solution for future wireless communication networks. In conclusion, hybrid RF/FSO systems offer a compelling approach to overcoming the limitations of traditional communication technologies, providing a robust and adaptable solution for modern communication needs.

REFERENCES

[1] Mohsan Syed Agha Hassnain, and Hussain Amjad. "A comprehensive survey on hybrid wireless networks: practical considerations, challenges, applications and research directions." Optical and Quantum Electronics 53.9 (2021): 523.

[2] Shafi, M., et al.: 5G: a tutorial overview of standards, trials, challenges, deployment, and practice. IEEE J. Sel. Areas Commun.35(6), 1201–1221 (2017)

[3] Al-Gazzi, Esraa K., Ekbal H. Ali, and Assel J. Mohammed. "Development And Execution Of An FSO Communication System To Track The Scattered Laser Beam During Atmospheric Turbulence." Journal of Optics (2024): 1-8.

[4] Chaduc, Jean-Marc, and Gerard Pogorel. The radio spectrum. John Wiley & Sons, 2008.

[5] Raj Arockia Bazil, and Arun K. Majumder. "Historical perspective of free space optical communications: from the early dates totoday's developments." Iet Communications 13.16 (2019): 2405-2419.

[6] Arockia Bazil Raj, A., et al. "Mitigation of beam fluctuation due to atmospheric turbulence and prediction of control quality usingintelligent decision-making tools." Applied optics 53.17 (2014): 3796-3806.

[7] Arockia Bazil Raj, A., and S. Padmavathi. "Statistical analysis of accurate prediction of local atmospheric optical attenuation with a new model according to weather together with beam wandering compensation system: a seasonwise experimental investigation." Journal of Modern Optics 63.13(2016): 1286-1296.

[8] Bazil Raj, Arockia A., et al. "Intensity feedback-based beam wandering mitigation in free-space optical communication using neural control technique." EURASIP Journal on Wireless Communications and Networking 2014 (2014): 1-18.

[9] Raj Anthonisamy, Arockia Bazil, Padmavathi Durairaj, and Lancelot James Paul. "Performance analysis of free space optical communication in open-atmospheric turbulence conditions with beam wandering compensation control." IET Communications 10.9(2016): 1096-1103.

[10] Arockia Bazil Raj, A., et al. "A direct and neural controller performance study with beam wandering mitigation control in freespace optical link." Optical Memory and Neural Networks 23 (2014): 111-129.

[11] A Arockia Bazil Raj “Low power and compact RSM and neuralcontroller design for beam wandering mitigation with a horizontal-path propagating Gaussian-beam wave: focused beam case” Free Space Optical Communication.De Gruyter Oldenbourg.-2015/12/18

[12] Arockia Bazil Raj, A., J. Arputha Vijaya Selvi, D. Kumar, and N. Sivakumaran. "Mitigation of beam fluctuation due to atmospheric turbulence and prediction of control quality using intelligent decision-making tools." Applied optics 53, no. 17 (2014):3796-3806.

[13] De, Sampurna, and AA Bazil Raj. "Experimental study of sand-storm effect on digital fso communication link." 2020 International Conference on Recent Trends on Electronics, Information, Communication & Technology (RTEICT) . IEEE, 2020.

[14] Kumar, L. Bhargava, Ramavath Prasad Naik, Prabu Krishnan, A. Arockia Bazil Raj, Arun K. Majumdar, and Wan-Young Chung."RIS assisted triple-hop RF-FSO convergent with UWOC system." IEEE Access 10 (2022): 66564-66575.

[15] Lahari, Sreerama Amrutha, ArockiaBazil Raj, and S. Soumya. "Control of fast steering mirror for accurate beam positioning in FSO communication system." 2021 International Conference on System, Computation, Automation and Networking (ICSCAN) . IEEE,2021.

[16] Eguri, Samson Vineeth Kumar, Arockia Bazil Raj A, and Nishant Sharma. "Survey on acquisition, tracking and pointing (ATP) systems and beam profile correction techniques in FSO communication systems." Journal of Optical Communications 0 (2022).

[17] Siby, Ashly, Arockia Bazil Raj, and S. Soumya. "Controller design for optical wave-front stabilization in FSO communication system." 2021 international conference on system, computation, automation and networking (ICSCAN) . IEEE, 2021.

[18] Raj A. Arockia Bazil, et al. "Design of cognitive decision making controller for autonomous online adaptive beam steering in freespace optical communication system." Wireless Personal Communications 84 (2015): 765-799.

[19] Arockia Bazil Raj A., J. Arputha Vijaya Selvi, and S. Durairaj. "Comparison of different models for ground-level atmospheric turbulence strength (Cn 2) prediction with a new model according to local weather data for FSO applications." Applied optics 54.4(2015): 802-815.

[20] Raj A. Arockia Bazil. Free space optical communication: system design, modeling, characterization and dealing

with turbulence.Walter de Gruyter GmbH & Co KG, 2015.

[21] ArockiaBazilRaj A., and Ucuk Darusalam. "Performance improvement of terrestrial free-space optical communications bymitigating the focal-spot wandering." Journal of Modern optics 63.21 (2016): 2339-2347.

[22] Kumar L. Bhargava, Ramavath Prasad Naik, Prabu Krishnan, A. Arockia Bazil Raj, Arun K. Majumdar, and Wan-Young Chung."RIS assisted triple-hop RF-FSO convergent with UWOC system." IEEE Access 10 (2022): 66564-66575.

[23] Darusalam U., Raj, A.B., Zulkifli, F.Y., Priambodo, P.S. and Rahardjo, E.T., 2020. Performance of free-space optical communication systems using optical amplifiers under amplify-forward and amplify-received configurations. Makara Journal ofTechnology, 24(3), p.4.

[24] Raj A.A.B., Selvi J.A.V., Sathiya, R., Shanthi, A., Sharmila, M. and Soumya, L.K., 2012, March. Low cost beam steering system for FSOC to SMF coupling. In IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM-2012) (pp. 49-54). IEEE.

[25] Anthonisamy Arockia Bazil Raj, and Arputha Vijaya Selvi James. "Formulation of atmospheric optical attenuation model in termsof weather data." Journal of Optics 45 (2016): 120-135.

[26] Majumdar, Arun K., Zabih Ghassemlooy, and A. Arockia Bazil Raj. Principles and applications of free space opticalcommunications. No. 78. The Institution of Engineering and Technology, 2019.

[27] Raj, A. Arockia Bazil. "Mono-pulse tracking system for active free space optical communication." Optik 127.19 (2016):7752-7761.

[28] Raj, Arockia Bazil, Vishal Sharma, and Subhashish Banerjee. "Quantum-based satellite free space optical communication and microwave photonics." Principles and applications of free space optical communications, IET Telecommunications Series 78 (2019).

[29] Ghassemlooy, Zabih, Arun Majumdar, and Arockia Bazil Raj. "Introduction to free space optical (FSO) communications." (2019):1-26.

[30] Patle Nidhi, Raj Arockia Bazil, Joseph Chinchu and Sharma Nishant. "Review of fibreless optical communication technology: history, evolution, and emerging trends" Journal of Optical Communications, vol. 45, no. 3, 2024, pp. 679-702. https://doi.org/10.1515/joc-2021-0190

[31] A. A. B. Raj and J. A. V. Selvi, "Lower-order adaptive beam steering system in terrestrial free space point-to-point laser communication using fine tracking sensor," 2011 International Conference on Signal Processing, Communication, Computing and Networking Technologies, Thuckalay, India, 2011, pp. 699-704, doi: 10.1109/ICSC CN.2011.6024641.

[32] Darusalam Ucuk; Raj Arockia Bazil; Zulkifli Fitri Yuli; Priambodo, Purnomo Sidi; and Rahardjo, Eko Tjipto (2023) "The Relaying Network in Free-Space Optical Communications using Optical Amplifiers in Cascaded Configuration," Makara Journal ofTechnology: Vol. 27: Iss. 2, Article 3.DOI: 10.7454/mst.v27i2.1583

[33] Akhter, Nargis, Harish C. Kumawat, and A. Arockia Bazil Raj. "Development of RF-photonic system for automatic targets' nonlinear rotational/flapping/gliding signatures imaging applications." Journal of Circuits, Systems and Computers 32.08 (2023):2350131.

[34] Raj, AA Bazil. "Tunable Dual-Band RF Exciter-Receiver Design For Realizing Photonics Radar." 2021 International Conferenceon System, Computation, Automation and Networking (ICSCAN) . IEEE, 2021.

[35] Kopeika, Natan, and A. Arockia Bazil Raj. "Special Issue on “Optical and RF Atmospheric Propagation”." Sensors 23.7 (2023):3644.

[36] Zhou, K., Gong, C., Wu, N., Xu, Z.: Distributed channel allocation and rate control for hybrid FSO/RF vehicular ad hoc networks.IEEE/OSA J. Opt. Commun. Netw. 9(8), 669–681 (2017)

[37] Vats, A., Aggarwal, M., Ahuja, S.: Outage and error analysis of three hop hybrid VLC/FSO/VLC–based relayed optical wirelesscommunication system. Trans. Emerg. Telecommun. Technol. 30(5), e3544(2019)

[38] Touati, A., Abdaoui, A., Touati, F., Uysal, M., Bouallegue, A.: On the effects of combined atmospheric fading and

misalignmenton the hybrid FSO/RF transmission. J. Opt. Commun. Netw. 8(10), 715–725 (2016)

[39] Rödiger, B., Ginthör, D., Labrador, J.P., Ramirez, J., Schmidt, C., Fuchs, C.: Demonstration of an FSO/RF hybrid-communicationsystem on aeronautical and space applications. In: Laser Communication and Propagation through the Atmosphere and Oceans IX, 11506, 1150603 (2020)

[40] Rakia, T., Gebali, F., Yang, H.-C., Alouini, M.-S.: Cross layer analysis of P2MP hybrid FSO/RF network. J. Opt. Commun. Netw.9(3), 234–243 (2017)

[41] Rakia, T., Yang, H.-C., Alouini, M.-S., Gebali, F.: Outage analysis of practical FSO/RF hybrid system with adaptive combining.IEEE Commun. Lett. 19(8), 1366–1369 (2015)

[42] Nadeem, F., Kvicera, V., Awan, M.S., Leitgeb, E., Muhammad, S.S., Kandus, G.: Weather effects on hybrid FSO/RFcommunication link. IEEE J. Sel. Areas Commun. 27(9), 1687–1697 (2009)

[43] Khan, M.N., Kashif, H., Rafay, A.: Performance and optimization of hybrid FSO/RF communication system in varying weather.Photonic Netw. Commun. 41(1), 47–56 (2021)

[44] Huang, S., Safari, M.: Spectrum trading in hybrid RF/FSO communications: a stackelberg game approach. IEEE Wirel. Commun.Netw. Conf. (WCNC) 2020, 1–6 (2020)

[45] Haluška, R., Šuľaj, P., Ovseník, Ľ, Marchevský, S., Papaj, J., Doboš, Ľ: Prediction of received optical power for switching hybridFSO/RF system. Electronics 9(8), 1261 (2020)

[46] Graceffo, G.M., Talamonti, J., Campbell, L., Ashrafi, S., Kowalevicz, A.M.: Hybrid RF & FSO for defense and 5G backhaul.IEEE Globecom Workshops (GC Wkshps) 2019, 1–6 (2019)

[47] F. S. Al-Qahtani, A. H. A. El-Malek, I. S. Ansari, R. M. Radaydeh, and S. A. Zummo, “Outage analysis of mixed underlaycognitive RF MIMO and FSO relaying with interference reduction,” IEEE Photonics Journal, vol. 9, no. 2, pp. 1–22, 2017.

[48] N. Varshney and A. K. Jagannatham, “Cognitive decode-and-forward MIMO-RF/FSO cooperative relay networks,” IEEECommunications Letters, vol. 21, no. 4, pp. 893–896, 2017.

[49] N. Varshney, A. K. Jagannatham, and P. K. Varshney, “Cognitive MIMO-RF/FSO cooperative relay communication with mobile nodes and imperfect channel state information,” arXiv preprint arXiv:1805.05381, 2018.

[50] H. Arezumand, H. Zamiri-Jafarian, and E. Soleimani-Nasab, “Outage and diversity analysis of underlay cognitive mixed RF-FSOcooperative systems,” Journal of Optical Communications and Networking, vol. 9, no. 10, pp. 909–920, 2017.

[51] A. Tahami, A. Dargahi, K. Abedi, A. Chaman-Motlagh, A new relay based architecture in hybrid RF/FSO system, Phys. Commun.36 (2019), https://doi.org/10.1016/j.phycom.2019.100818.

[52] M.A. Amirabadi, V. Tabataba Vakili, Performance of a relay-assisted hybrid FSO/RF communication system, Phys. Commun. 35(2019), 100729, https://doi.org/10.1016/j.phycom.2019.100729.

[53] B.B. Yousif, E.E. Elsayed, M.M. Alzalabani, Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system, Opt Commun. 436 (2019) 197–208, https://doi.org/10.1016/j.optcom.2018.12.034.

[54] P.V. Trinh, T. Cong Thang, A.T. Pham, Mixed mmWave RF/FSO relaying systems over generalized fading channels with pointingerrors, IEEE Photonics J 9 (1) (2017), https://doi.org/10.1109/JPHOT.2016.2644964.

[55] Chatzidiamantis, N.D.; Karagiannidis, G.K.; Kriezis, E.E.; Matthaiou, M. Diversity combining in hybrid RF/FSO systems with PSK modulation. In Proceedings of the 2011 IEEE International Conference on Communications (ICC), Kyoto, Japan, 5–9 June 2011;pp. 1–6.

[56] He, B.; Schober, R. Bit-interleaved coded modulation for hybrid RF/FSO systems. IEEE Trans. Commun. 2009, 57, 3753–3763.

[57] Kazemi, H.; Uysal, M.; Touati, F.; Haas, H. Outage performance of multi-hop hybrid FSO/RF communication

systems. In Proceedings of the 2015 4th International Workshop on Optical Wireless Communications (IWOW), Istanbul, Turkey, 7–8 September2015; pp. 83–87.

[58] Shakir, W.M. Performance analysis of the hybrid MMW RF/FSO transmission system. Wirel. Pers. Commun. 2019, 109,2199–2211.

[59] Odeyemi, K.O.; Owolawi, P.A. Selection combining hybrid FSO/RF systems over generalized induced-fading channels. Opt.Commun. 2019, 433, 159–167.

[60] Miridakis, N.; Matthaiou, M.; Karagiannidis, G. Multiuser relaying over mixed RF/FSO links. IEEE Trans. Wirel. Commun. 2014,62, 1634–1645.

[61] Bhatnagar, S.A.; Bhatnagar, M.R. Performance of an Amplify-and-Forward Dual-Hop Asymmetric RF-FSO CommunicationSystem. J. Opt. Commun. Netw. 2015, 7, 124–135. [CrossRef]

[62] Zhang, W. and Hranilovic, S. and Shi, C., "Soft-switching hybrid FSO/RF links using short-length Raptor codes: Design andimplementation," IEEE J. Sel. Areas Commun., vol. 27, no. 9, pp. 1698–1708, Dec. 2009.

[63] H. Moradi, M. Falahpour, H. H. Refai, P. G. LoPresti, and M. Atiquzzaman, "Toward an optimal combined FSO/RF system via anadaptive bit rate control," in Proc. SPIE Photonics West, 2010, vol. 7587, pp. 75870X-1–75870X-10.

[64] S. Vangala and H. Pishro-Nik, "A highly reliable FSO/RF communication system using efficient codes," in Proc. IEEEGLOBECOM, Nov. 2007, pp. 2232–2236.

[65] H. Wu and M. Kavehrad, "Availability evaluation of ground-to-air hybrid FSO/RF links," Int. J. Wireless Inf. Netw., vol. 14, no. 1,pp. 33–45, Mar. 2007.

[66] Balti, E., Guizani, M., Hamdaoui, B., &Maalej, Y. (2019, December). Partial relay selection for hybrid RF/FSO systems withhardware impairments. In 2016 IEEE Global Communications Conference (GLOBECOM) (pp. 1-6). IEEE.

[67] Esmail, M. A., Ragheb, A. M., Fathallah, H. A., Altamimi, M., &Alshebeili, S. A. (2019). 5G-28 GHz Signal Transmission overHybrid All-Optical FSO/RF Link in Dusty Weather Conditions. IEEE Access, 7, 24404-24410.

[68] Korai, U. A., Luini, L., Nebuloni, R., &Glesk, I. (2017, March). Statistics of attenuation due to rain affecting hybrid FSO/RF link:application for 5G networks. In 2017 11th European Conference on Antennas and Propagation (EUCAP) (pp. 1789-1792). IEEE.

[69] Wu, Y., Yang, Q., Park, D., &Kwak, K. S. (2017). Dynamic Link Selection and Power Allocation With Reliability Guaranteesfor Hybrid FSO/RF Systems. IEEE Access, 5, 13654-13664.

[70] Enayati, S., &Saeedi, H. (2016). Deployment of hybrid FSO/RF links in backhaul of relay-based rural area cellular networks:Advantages and performance analysis. IEEE Communications Letters, 20(9), 1824-1827.

[71] Mai, V. V., & Pham, A. T. (2015). Adaptive multi-rate designs and analysis for hybrid fso/rf systems over fading channels. IEICE Transactions on Communications, 98(8), 1660-1671.

[72] Seybold, John S. Introduction to RF propagation. John wiley & sons, 2005.

[73] You, X., Chen, J., Yu, C.: Efficient indoor data transmission with full dimming control in hybrid visible light/infraredcommunication systems. IEEE Access 6, 77675–77684 (2018)

[74] Zhang, Y., Wang, L., Wang, K., Wong, K.S., Wu, K.: Recent advances in the hardware of visible light communication. IEEEAccess 7, 91093–91104 (2019)

[75] Arya, S., Chung, Y.H.: Novel indoor ultraviolet wireless communication: design implementation, channel modeling, andchallenges. IEEE Syst. J. 15(2), 2349–2360 (2020)

[76] Suckewer, S., and C. H. Skinner. "Soft X-ray lasers and their applications." Science 247.4950 (1990): 1553-1557.

[77] Anchordoqui, Luis A. "Ultra-high-energy cosmic rays." Physics Reports 801 (2019): 1-93.

[78] Chowdhury, M.Z., Hossan, M.T., Islam, A., Jang, Y.M.: A comparative survey of optical wireless technologies: Architectures andapplications. IEEE Access 6, 9819–9840 (2018)

[79] Paul, Bryan, Alex R. Chiriyath, and Daniel W. Bliss. "Survey of RF communications and sensing convergence research." IEEEAccess 5 (2016): 252-270.

[80] Du, Ke-Lin, and Madisetti NS Swamy. Wireless communication systems: from RF subsystems to 4G enabling technologies.Cambridge University Press, 2010.

[81] Fedunkiw, Marianne. Inventing the Radio. Crabtree Publishing Company, 2007.

[82] Collotta, M., Pau, G., Talty, T., Tonguz, O.K.: Bluetooth 5: a concrete step forward toward the IoT. IEEE Commun. Mag. 56(7),125–131 (2018)

[83] Juels, A.: RFID security and privacy: a research survey. IEEE J. Sel. Areas Commun. 24(2), 381–394 (2006)

[84] Mello, Paola A., Juliano S. Barin, and Ricardo A. Guarnieri. "Microwave heating." Microwave-assisted sample preparation fortrace element analysis. Elsevier, 2014. 59-75.

[85] Rincon, Fabian, Yasuyuki Tanaka, and Thomas Watteyne. "On the impact of wifi on 2.4 GHz industrial IoT networks." 2018 IEEEInternational Conference on Industrial Internet (ICII). IEEE, 2018.

[86] Gokhale Pradyumna, Omkar Bhat, and Sagar Bhat. "Introduction to IOT." International Advanced Research Journal in Science,Engineering and Technology 5.1 (2018): 41-44.

[87] El-Hajjar Mohammed, and Lajos Hanzo. "A survey of digital television broadcast transmission techniques." IEEE Communications surveys & tutorials 15.4 (2013): 1924-1949.

[88] Kaphungkui, N. K. "Rf based remote control for home electrical appliances." International Journal of Innovative Research inElectrical, Electronics, Instrumentation and Control Engineering 3.7 (2015): 42-44.

[89] Shi, Yingli, et al. "Flexible radio-frequency micro electro-mechanical switch towards the applications of satellite communications." npj Flexible Electronics 6.1 (2022): 80.

[90] Malik, A., & Singh, P. (2015). Free space optics: current applications and future challenges. International Journal of Optics, 2015

[91] Kaur Navdeep, and Harmeet Singh. "A survey on recent work in hybrid FSO/RF communication link." Int. J. Electron. Commun.Instrum. Eng. Res. Develop. 9.1 (2019): 25-32.

[92] A. Akbulut, H. G. Ilk and F. Ari, "Design, availability and reliability analysis on an experimental outdoor FSO/RF communication system," Proceedings of 2005 7th International Conference Transparent Optical Networks, 2005., Barcelona, Spain, 2005, pp. 403-406Vol. 1, doi: 10.1109/ICTON.2005.1505831

[93] Yahia, Olfa Ben, et al. "A weather-dependent hybrid RF/FSO satellite communication for improved power efficiency." IEEEWireless Communications Letters 11.3 (2021): 573-577.

[94] Jin, Meng, et al. "Hybrid dual-hop RF/FSO terrestrial-deep space communication system under solar scintillation during superiorsolar conjunction." Applied Sciences 12.2 (2022): 619.

[95] Al-Gailani, Samir Ahmed, et al. "A survey of free space optics (FSO) communication systems, links, and networks." IEEE Access9 (2020): 7353-7373.

[96] Alshaer, Nancy, Ahmed Moawad, and Tawfik Ismail. "Reliability and security analysis of an entanglement-based QKD protocol in a dynamic ground-to-UAV FSO communications system." IEEE Access 9 (2021): 168052-168067.

[97] Li, Chung-Yi, et al. "A flexible two-way PM-based fiber-FSO convergence system." IEEE Photonics Journal 10.2 (2018): 1-9.

[98] Wu, Y.; Kong, D.; Wang, Q.;Li, G. Performance Analysis of UAV-Assisted Hybrid FSO/RFCommunication Systems underVariousWeather Conditions. Sensors 2023, 23, 7638.

[99] Gupta, Himanshu, et al. "Cyclops: An fso-based wireless link for vr headsets." Proceedings of the ACM SIGCOMM 2022Conference. 2022.

[100] Khalid, H., Muhammad, S.S., Nistazakis, H.E., Tombras, G.S.: Performance analysis of hard-switching based hybrid FSO/RFsystem over turbulence channels. Computation 7(2), 28 (2019)

[101] Corral, Fabián Vinicio, Christian Cuenca, and Ismael Soto. "Design of an optical wireless network using free space optics technology (FSO), in 5G/6G networks environment." 2021 IEEE International Conference on Automation/XXIV Congress of theChilean Association of Automatic Control (ICA-ACCA). IEEE, 2021.

[102] Majumdar, Arun K. "Fundamentals of free-space optical (FSO) communication system." Advanced free space optics (FSO) asystems approach. New York, NY: Springer New York, 2014. 1-20.

[103] Ansari, I. S., Alouini, M. S., & Yilmaz, F. (2013, April). On the performance of hybrid RF and RF/FSO fixed gain dual-hop transmission systems. In 2013 Saudi International Electronics, Communications and Photonics Conference (pp. 1-6). IEEE.

[104] Nikbakht-Sardari, Negin, et al. "Novel adaptive hard-switching based hybrid RF-FSO system architecture using two threshold values in the presence of atmospheric turbulence and pointing error." Results in engineering 17 (2023): 100813.

[105] A.A. Farid, S. Hranilovic, Outage capacity optimization for free-space optical links with pointing errors, J. Lightwave Technol.25 (7) (2007) 1702–1710

[106] Jurado-Navas, A.; Garrido-Balsells, J.M.; Paris, J.F.; Puerta-Notario, A.; Awrejcewicz, J. A unifying statistical model foratmospheric optical scintillation. Numer. Simul. Phys. Eng. Process. 2011, 181, 181–205.

[107] Andrews, L.C.; Phillips, R.L.; Hopen, C.Y.; Al-Habash, M. Theory of optical scintillation. J. Opt. Soc. Am. A—Opt. Image Sci.Vis.1999, 16, 1417–1429.

[108] A. K. Majumdar, "Free-space laser communication performance in the atmospheric channel," in Free-Space Laser Communications: Principles and Advances, ser. Optical and fiber communications reports, A. K. Majumdar and J. C.Ricklin,Eds.NewYork,USA:Springer, 2008, vol. 2, pp. 57–108.

[109] Bag, Banibrata, et al. "Performance analysis of hybrid FSO systems using FSO/RF-FSO link adaptation." IEEE Photonics Journal10.3 (2018): 1-17.

[110] Usman Muneer, Hong-Chuan Yang, and Mohamed-Slim Alouini. "Practical switching-based hybrid FSO/RF transmission and itsperformance analysis." IEEE Photonics journal 6.5 (2014): 1-13.

[111] F. Nadeem et al., "Weather effects on hybrid FSO/RF communication link," IEEE J. Sel. Areas Commun., vol. 27, no. 9, pp.1687–1697, Dec. 2009.

[112] A. Tahami, A. Dargahi, K. Abedi, A. Chaman-Motlagh, Two novel hybrid architectures for improving the system performance inlong length FSO links, Opt Commun. 451 (2019)

[113] Mosavi, N.; Sequeira, H.B.; Copeland, D.J.; Menyuk, C.R. Solar scintillation study during planetary conjunction. In Proceedingsof the 2016 IEEE Aerospace Conference, Big Sky, MT, USA, 5–12 March 2016; pp. 1–7.

[114] Jin, M.; Liu, W.; Hao, Y.; Wu,R.; Wei, Z.; Deng, D.; Liu, H. Hybrid Dual-Hop RF/FSO Terrestrial-Deep Space CommunicationSystem under Solar Scintillation during Superior Solar Conjunction. Appl. Sci. 2022, 12,619.

[115] Mosavi, N.; Sequeira, H.B.; Copeland, D.J.; Menyuk, C.R. Solar scintillation study during planetary conjunction. In Proceedingsof the 2016 IEEE Aerospace Conference, Big Sky, MT, USA, 5–12 March 2016; pp. 1–7.

[116] Xu, G.; Song, Z. Effects of Solar Scintillation on Deep Space Communications: Challenges and Prediction Techniques. IEEEWirel. Commun. 2019, 26, 10–16.

[117] Alathwary, W.A.; Altubaishi, E.S. On the performance analysis of decode-and-forward multi-hop hybrid FSO/RF systems withhard-switching configuration. IEEE Photonics J. 2019, 11, 1–12.

[118] F. Nadeem et al., "Weather effects on hybrid FSO/RF communication link," IEEE J. Sel. Areas Commun., vol. 27, no. 9, pp.1687–1697, Dec. 2009.

[119] H. Dahrouj, A. Douik, F. Rayal, T. Y. Al-Naffouri, and M. S. Alouini, "Cost-effective hybrid RF/FSO backhaul solution for nextgeneration wireless systems," IEEE Wireless Commun., vol. 22, no. 5, pp. 98–104, Oct. 2015.

[120] Ali, Irfan. "Bit-error-rate (BER) simulation using MATLAB." International Journal of Engineering Research and Applications 3.1(2013): 706-711.

[121] Wu, Z.-Y., Ismail, M., Serpedin, E., Wang, J.: Data-driven link assignment with QoS guarantee in mobile RF-

Optical HetNet ofthings. IEEE Internet Things J. 7(6), 5088–5102 (2020a)

[122] Yang, H., Marzetta, T.L.: A macro cellular wireless network with uniformly high user throughputs. In: 2014 IEEE 80th VehicularTechnology Conference (VTC2014-Fall), pp. 1–5 (2014)

[123] Wu, X., Soltani, M.D., Zhou, L., Safari, M., Haas, H.: Hybrid LiFi and WiFi networks: a survey. IEEE Commun. Surv. Tutor.23(2), 1398–1420 (2021a)

[124] Al Hammadi, A., Muhaidat, S., Sofotasios, P.C., Al Qutayri, M.: A robust and energy efficient NOMA-enabled hybrid VLC/RFwireless network. In: 2019 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6 (2019)

[125] Lu, H., Proietti, R., Liu, G., Chen, X., Ben Yoo, S.J.: ERON: an energy-efficient and elastic RF-optical architecture for mmWave5G radio access networks. J. Opt. Commun. Netw. 12(7), 200–216 (2020)

[126] Zhang, D., Zhou, Z., Mumtaz, S., Rodriguez, J., Sato, T.: One integrated energy efficiency proposal for 5G IoT communications.IEEE Internet Things J. 3(6), 1346–1354 (2016)

[127] Pesek, P., Zvánovec, S., Chvojka, P., Ghassemlooy, Z., Haigh, P.A.: Demonstration of a hybrid FSO/VLC link for the last mileand last meter networks. IEEE Photonics J. 11(1), 1–7 (2018)

[128] Huang, Z., et al.: Hybrid optical wireless network for future SAGO-integrated communication based on FSO/VLC heterogeneousinterconnection. IEEE Photonics J. 9(2), 1–10 (2017)

[129] Arfaoui, M.A., et al.: Physical layer security for visible light communication systems: a survey. IEEE Commun. Surv. Tutor.22(3), 1887–1908 (2020)

[130] Blinowski, G.: Security of visible light communication systems—a survey. Phys. Commun. 34, 246–260(2019)

[131] Wang, Y.; Xu, H.; Li, D.; Wang, R.; Jin, C.; Yin, X.; Gao, S.; Mu, Q.; Xuan, L.; Cao, Z. Performance analysis of an adaptive optics system for free-space optics communication through atmospheric turbulence. Sci. Rep. 2018, 8, 1124. [CrossRef]

[132] Osman, R.A., Peng, X.-H., Omar, M.A.: Adaptive cooperative communications for enhancing QoS in vehicular networks. Phys.Commun. 34, 285–294 (2019)

[133] Han, Boyu. "A comprehensive review of performance analysis of RF-FSO hybrid communication systems." Journal of Physics:Conference Series. Vol. 2649. No. 1. IOP Publishing, 2023.

[134] Soleimani-Nasab Ehsan, and Murat Uysal. "Generalized performance analysis of mixed RF/FSO cooperative systems." IEEETransactions on Wireless Communications 15.1 (2015): 714-727.

[135] Khan, Muhammad Nasir, Hasnain Kashif, and Abdul Rafay. "Performance and optimization of hybrid FSO/RF communicationsystem in varying weather." Photonic Network Communications 41 (2021): 47-56.

[136] Ali Amirabadi, Mohammad, and Vahid Tabataba Vakili. "Performance analysis of a novel hybrid FSO/RF communicationsystem." IET Optoelectronics 14.2 (2020): 66-74.

[137] Pattanayak, Dipti R., Vivek K. Dwivedi, and Vikram Karwal. "On the physical layer security of hybrid RF-FSO system inpresence of multiple eavesdroppers and receiver diversity." Optics Communications 477 (2020): 126334.

[138] Graceffo, G.M., Talamonti, J., Campbell, L., Ashrafi, S., Kowalevicz, A.M.: Hybrid RF & FSO for defense and 5G backhaul.IEEE Globecom Workshops (GC Wkshps) 2019, 1–6 (2019)

[139] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M. S. Alouini, “FSO-based vertical backhaul/fronthaul framework for 5G+wireless networks,” IEEE Commun. Mag., vol. 56, no. 1, pp. 218–224, Jan. 2018.

[140] Ghoname, Sherif, Heba A. Fayed, Ahmed Abd El Aziz, and Moustafa H. Aly. "Performance evaluation of an adaptive hybrid FSO/RF communication system: impact of weather attenuation." Iranian Journal of Science and Technology, Transactions of ElectricalEngineering 44 (2020): 119-128.

[141] Saleem, Muhammad, et al. "Intelligent FSO link for communication in natural disasters empowered with fuzzy inference system." 2019 International Conference on Electrical, Communication, and Computer Engineering

(ICECCE). IEEE, 2019.

[142] Hasan, M.K., Shahjalal, M., Chowdhury, M.Z., Jang, Y.M.: Access point selection in hybrid OCC/RF Ehealth architecture for real-time remote patient monitoring. Int. Conf. Inf. Commun. Technol.Converg. (ICTC) 2018, 716–719 (2018b)

[143] An, J., Pham, N.Q., Chung, W.-Y.: Multiple bio-monitoring system using visible light for electromagnetic-wave free indoorhealthcare. Opt. Commun. 405, 107–113 (2017)

[144] Raible, D.E., et al.: On the physical realizability of hybrid RF and optical communications platforms for deep space applications.In: 32nd AIAA International Communications Satellite Systems Conference, p. 4482 (2014)

[145] Xu, Guanjun, and Qinyu Zhang. "Mixed RF/FSO deep space communication system under solar scintillation effect." IEEETransactions on Aerospace and Electronic Systems 57.5 (2021): 3237-3251.

[146] Takai, I., Harada, T., Andoh, M., Yasutomi, K., Kagawa, K., Kawahito, S.: Optical vehicle-to-vehicle communication systemusing LED transmitter and camera receiver. IEEE Photonics J. 6(5), 1–14(2014)

[147] Zhang, D., N'Doye, I., Ballal, T., Al-Naffouri, T.Y., Alouini, M.-S., Laleg-Kirati, T.-M.: Localization and tracking control using hybrid acoustic-optical communication for autonomous underwater vehicles.IEEE Internet Things J. 7(10), 10048–10060 (2020b)

[148] Xu, G.; Song, Z. Performance analysis of a UAV-assisted RF/FSO relaying systems for internet of vehicles. IEEE Internet ThingsJ. 2021, 9, 5730–5741.

[149] Wang, J.Y.; Ma, Y.; Lu, R.R.; Wang, J.B.; Lin, M.; Cheng, J. Hovering UAV-based FSO communications: Channel modelling,performance analysis, and parameter optimization. IEEE J. Sel. Areas Commun. 2021, 39,2946–2959.

[150] Pal, Bishnu P., ed. Fundamentals of fibre optics in telecommunication and sensor systems. Bohem press, 1992.