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Overcoming Maritime Connectivity Challenges with Hybrid RF/FSO Links

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***Abstract*—Various applications in maritime scenarios, including offshore operation, navigation, and search and rescue, require reliable high-speed communication. However, wireless maritime communication remains challenging due to limited available radio frequency (RF) bandwidth. Additional challenges are imposed by ducting and water surface reflections that lead to high packet loss rates. This work aims to provide a free-space optical (FSO) communication-based solution to address the limited bandwidth issues. An unlicensed 6 GHz RF link is used as a backup for the FSO link during outage events. The hybrid link deployment was conducted on an island located 19 km offshore at the Red Sea shore. The location was chosen based on the need for construction operations led by Red Sea Global (RSG). In addition, the deployment area is considered a challenging environment for FSO due to its high temperatures, humidity, wind speed, and sand/dust storm events. Our findings indicate that the FSO solution successfully achieves a 20 Gbps full duplex with an availability of 98.71%. The overall connectivity remained at 99.999% with the RF as a backup mode. These results highlight the potential of using FSO for high-speed maritime communication and thus connecting remote and unconnected areas.**

***Index Terms*—Free space optics, hybrid RF/FSO, digital divide, maritime communication, atmospheric turbulence**

I. Introduction

PROVIDING reliable maritime communication is essential for various applications, including offshore operations, search and rescue, and Internet of things (IoT) maritime networks [1]. The increase in technological advances and maritime activities has led to a high demand for reliable and high-speed communication [2]. Installing subsea optical fibers can be a solution to provide the needed throughput. However, the installation cost of new fibers may reach up to $200 per meter depending on the terrain [3]. New fiber installation costs can lead to extremely expensive deployments, especially for islands and remote areas, requiring tens and hundreds of kilometers. Existing maritime communication technologies such as satellites and radio frequency (RF) in low frequencies do not meet the bandwidth requirements of modern maritime applications [4]. Satellites, for example, can cover larger areas, but the latency and data rates are limited, which makes satellite network-based solutions suitable only for applications without strict quality of service requirements, such as those not requiring ultra-low latency. RF links are susceptible to various weather factors in maritime conditions that can impact communication stability and achievable capacity [5]. Seawater surface water reflections and atmospheric ducting can also cause self-interference, affecting RF maritime performance ([2], and references therein).

To address these challenges, we propose a quickly deployable solution using FSO links for high data rates. 6 GHz microwave links are used as a backup during FSO outages. The FSO terminals operating at a 1550 nm wavelength are used to carry data from one point to another with a 20 Gbps speed transmission in a full-duplex configuration.

Connecting the island was part of a collaboration between KAUST University and the Red Sea Global (RSG) company to bridge the connectivity gap to Shebara island, located 19 km offshore, as illustrated in Fig. 1. One of the RSG's goals is to use green energy to maintain zero carbon emission in their resorts and hotels, which led to utilizing solar power for our proposed connectivity solution. The location is considered a harsh environment due to the ongoing construction activities and the high temperatures. To address this, we designed an enclosure to house both the network devices and the batteries. Two existing 35-meter towers were facilitated by RSG for our use, as these have a clear line of sight (LoS) to each other. This experimental work aims to address the limitations of maritime communication, provide a detailed analysis on the challenges faced during deployment, and present the results of our study. The study shows the effectiveness of deploying FSO terminals to overcome the limitations of RF-based maritime communication solutions. The structure of this paper is as follows: Section II provides background information and discusses related work. Section III presents the methodology employed in the hybrid link deployment. Section IV details the experimental results across various scenarios, followed by a discussion in Section V. Finally, Section VI concludes the paper and outlines future work.

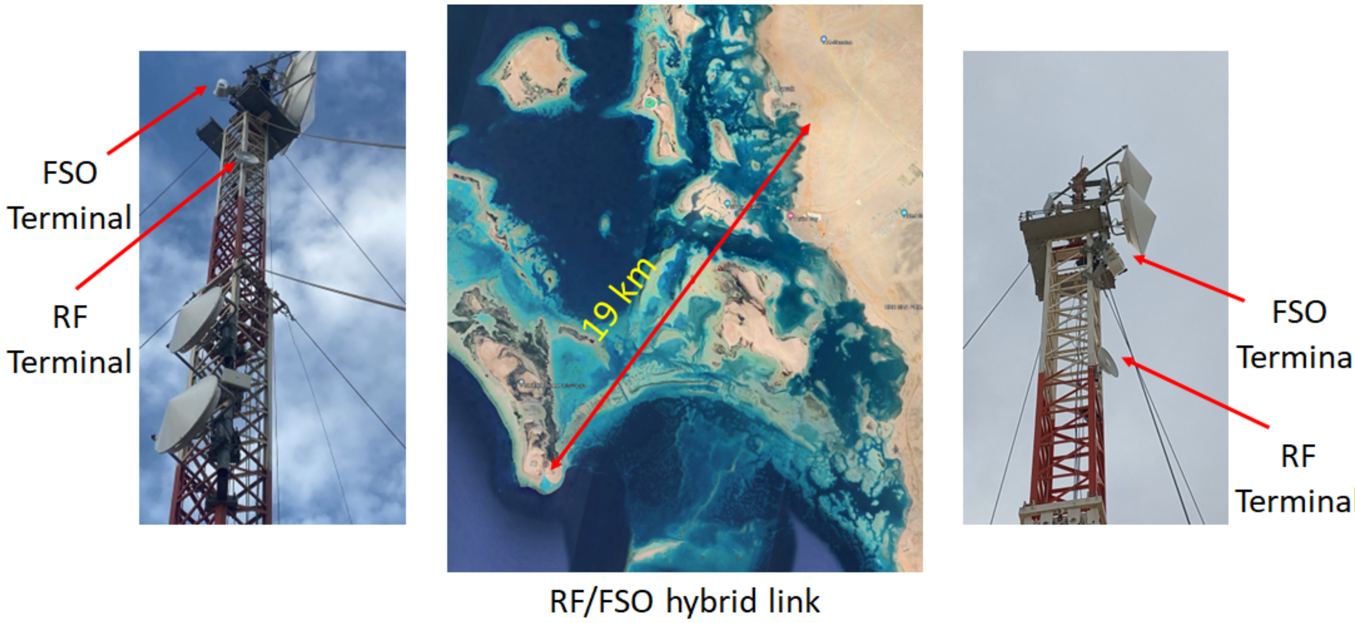

Fig. 1: Deployment images and map of the 19 km offshore links connecting Shabara island, and showing the towers and mounted FSO and RF terminals.

II. Background and Related Work

Several applications benefit from advancements in maritime communication, including navigation, security, offshore oil exploration, and island operational processes. Additionally, there is a growing demand for higher data rates to support real-time monitoring, such as using mesh networks to track ships or monitor habitats [6]. However, maintaining reliable communication services in maritime environments remains challenging mainly due to the limited capacity for long-range applications and the high costs of deploying new submarine fiber cables. For example, a 20 km offshore island may cost around \$20M for submarine fiber cable deployment. In our case in the RSG project, the estimated cost for the submarine fiber cable is more than \$19M, and the deployment would require more than one year. Therefore, alternative solutions were required to provide traffic at rates comparable to those offered by optical fibers.

FSO has attracted considerable attention and has been successfully used in multiple use cases and applications [7]. Although FSO can provide a fiber-like speed, the technology is sensitive to low-visibility situations like fog, dust/sand storms, and heavy rain. These situations led to signal attenuation and alignment issues. An experimental study by Esmail et al. assessed the performance of FSO in dusty conditions, which can potentially affect FSO performance in the Middle Eastern region [8]. This study showed that FSO links could operate for long distances under weak and moderate dust storms, while short distances ($<$ 200m) are possible under severe dust storms. Another demonstration highlights the importance of using RF as a backup during heavy fog situations to ensure the stability of the overall communication [9].

Utilizing RF links for maritime communication offers robust services for long distances in severe weather situations. The most used RF spectrum is at the very high-frequency (VHF) bands and in the satellite links. These links provide a wide range of coverage and can travel long distances; however, they suffer from limited bandwidth, low data rates, and high latency. Thus, applications that require high capacity and low latency will need another approach. As the FSO may be exposed to weather conditions, RF with lower capacity can maintain connectivity during the FSO outages. FSO outages can originate from different types of scattering related to weather conditions such as fog and dust and high turbulence regimes that affect the propagation of laser beams through the atmosphere [10], [11].

Hybrid FSO/RF has been explored in several studies and found to provide a balance between achieving high data rates and maintaining continuous reliability [12], [13]. A demonstration of hybrid FSO/RF during adverse weather conditions showed the practical feasibility of this approach, which ensures connectivity for a longer time [14].

III. Methodology

This section describes the hybrid RF/FSO link deployment, including the system installation, infrastructure, sensors, and data collection methods used.

A. Hybrid Link Design

The FSO systems are commercially available Taara transceivers from Google X. Each transceiver is equipped with a 1550 nm laser with a maximum transmit power of 30 dBm, a photodetector, and an automatic search and acquisition system. Each terminal also has a gyro sensor that monitors link vibrations. The automatic search and acquisition system can track vibrations up to 3 degrees to maintain the link's stability. Each transceiver consumes 60 W of power. An unlicensed Mimosa C5x, operating in the 6 GHz band, is also deployed. The RF link features a dish antenna with a 25 dBi gain, a maximum radio output power of 27 dBm, and a maximum power consumption of 12.9 W. The primary link is the FSO, while the RF link remains idle without traffic unless needed. The decision to use this RF band was made based on the RSG team recommendations, which reported that higher-frequency microwave links lacked stability based on their previous experiences. Consequently, the unlicensed band between 4.8 GHz and 6 GHz was proposed for this deployment.

The FSO and RF terminals are mounted on two 35-meter-long towers with clear LoS, where the main point of presence (PoP) is at the mainland, delivering several services like internet and GSM to the 19 km island called Shebara, see map in Fig. 1. Cisco switches were used to route traffic from the FSO to the RF link in the event of an FSO outage. These switches also have the capability to monitor the FSO traffic and automatically return the traffic to the primary FSO path once normal conditions are restored. Switching between the FSO and the RF happens at the networking level. Both links are connected to a Cisco switch configured to run with Rapid Spanning Tree Protocol (RSTP) based on IEEE 802.1w [15]. The primary link was set to be the FSO link, while the RF link acted as a secondary link. By default, each port on the switch transmits Bridge Protocol Data Units (BPDUs) "hello" messages every two seconds as a keep-alive mechanism between bridges. If hellos are not received three consecutive times on a given port, the bridge is considered to have lost connectivity, hence forwarding the traffic to the secondary link. The traffic will continue traversing through the secondary RF link until the primary FSO link returns to normal operation.

B. Infrastructure

This case study was conducted in a maritime environment subject to high humidity and elevated temperatures, requiring an IP67 enclosure with an AC unit to keep the network equipment cool in a confined space, as no dedicated telecom rooms were available. The solar cabinet shown in Fig. 2 includes 10 kW batteries used as backup power, which harvest energy from solar panels with a capacity of 1100 W. The cabinet also contains AC/DC converters, PoE injectors for the RF and FSO terminals, network components such as switches and WiFi routers, and sensor kits for visibility and weather data.

Two Ambient Weather WS-2000 stations were installed on the island and mainland to collect weather data, including temperature, wind speed, rainfall, humidity, and pressure.

Visibility sensors were installed on both sides to capture fog or haze throughout the study. The recorded data is visibility in km, and the sensors are connected to a data logger and then to a WiFi port in order to send the data to the cloud using a message queuing telemetry transport (MQTT) protocol.

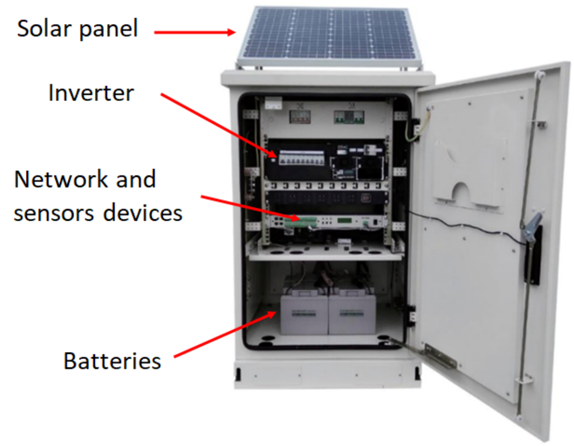

Fig. 2: A photograph of the solar cabinet used to host the infrastructure devices powering the equipment and storing measurement data.

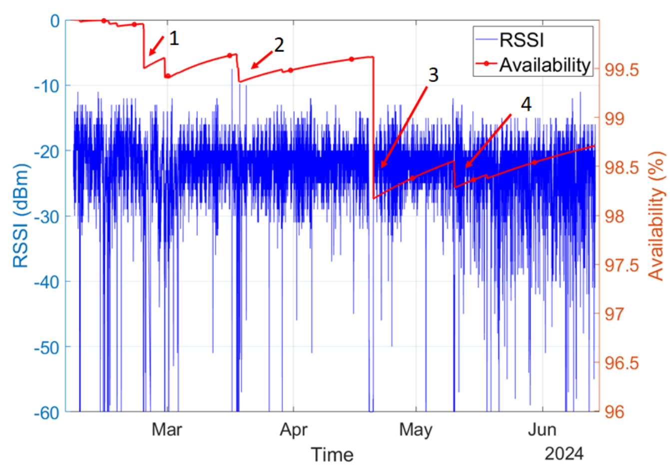

Fig. 3: RSSI over time with availability in percentage measures with four marked outage events.

C. Data Collection Methods

Both FSO and RF performance data are recorded in the network management system (NMS). The NMS has the received signal strength indicator (RSSI) for both FSO terminals as well as traffic measures, including latency, packet loss rate (PLR), and throughput. The RF performance data is limited to accessibility measures as On and OFF as it is not our main focus in this study. However, maintaining the overall connectivity is a key to using the RF link.

We also used a commercially available weather station to record weather information in 5-minute intervals. Weather data is useful for capturing the potential causes of FSO link outages.

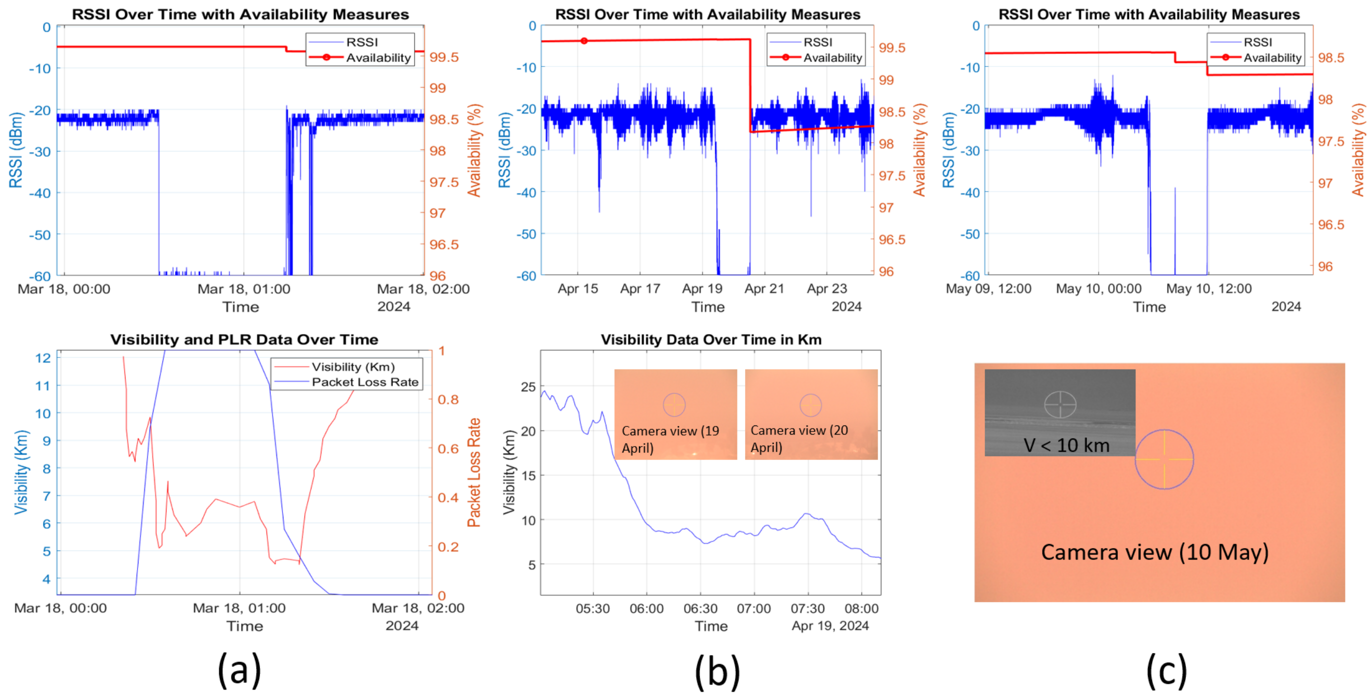

Fig. 4: Three NMS recorded outages: RSSI as a function of time, outage reasons, and visibility data. (a) Outage event 2 (Mar 18, 00:22 - 01:30), (b) Outage event 3 (Apr 19, 05:00-08:00), and (c) Outage event 4 (May 10, 00:00-12:00).

D. Data analysis methods

A homemade Matlab software was used to perform statistical analysis, including the RSSI of the FSO terminals, the status of the RF (ON/OFF), visibility data, and all-weather data recorded during the period of the study. We also process wind speed data and compare it with the visibility to assess the impact of sandstorms.
In the analysis of the hybrid link availability, we cover a period of 4.2 months from the 7th of February to the 13th of June 2024. The key parameter is the RSSI of the FSO link. Once an outage in the FSO link is recorded, we analyze the recorded data from the weather and visibility sensors to determine the causes.

IV. Experimental Results

The total recorded RSSI data from the FSO link, along with the availability measurements, are shown in Fig. 3 covering the period between the 7th of February 2024 and the 13th of June 2024. The mean RSSI was -22.57 dBm, and the total FSO availability was 98.71%. Recalling that the FSO sensitivity is -40 dBm and seen in Fig. 3, several instances of RSSI dropped below the sensitivity level, leading to outages where traffic was rerouted to the RF link. However, there are four prolonged outages that will be the main focus of our detailed analysis.

- **Outage Event 1:** On the 24th of February, the link experienced a power outage, and there was no significant weather effect during this event.
- **Outage Event 2:** On the 18th of March, from 00:22:00 to 01:30:00 as shown in Fig 4(a), the visibility dropped to between 4.5 and 6 km. This reduction in visibility increased RSSI losses and led to a long outage.
- **Outage Event 3:** The outage that occurred between the 19th and mid-day of the 20th of April, as shown in Fig. 4(b), was caused by a dust/sand storm. Visibility measurements and images taken during this period showed that visibility dropped from below 10 km to nearly 5 km.
- **Outage Event 4:** Similar to the conditions during outage event 3, on the 10th of May, as shown in Fig. 4(c), dusty weather led to reduced visibility below 10 km, resulting in an FSO outage.

Fig. 5 shows three main causes for either outage or high PLR. The first situation occurred when the wind speed was high; in this case, one can see the wind speed and correlate that with the gyro data and the RSSI. During high wind speed events, the RSSI tends to fluctuate more due to misalignment, as the tracking system may struggle to track the movement of the laser beam. The second observation is that the temperature level between the 25th and 31st of March (highlighted in red square) is higher than the period between the 8th to the 15th of April (highlighted in blue square) at 90°F. Periods with high temperatures have a higher PLR, mainly due to the accompanying high humidity in the deployment region (as similarly observed in [16]. The third observation is that during the outage event on the 29th of March,

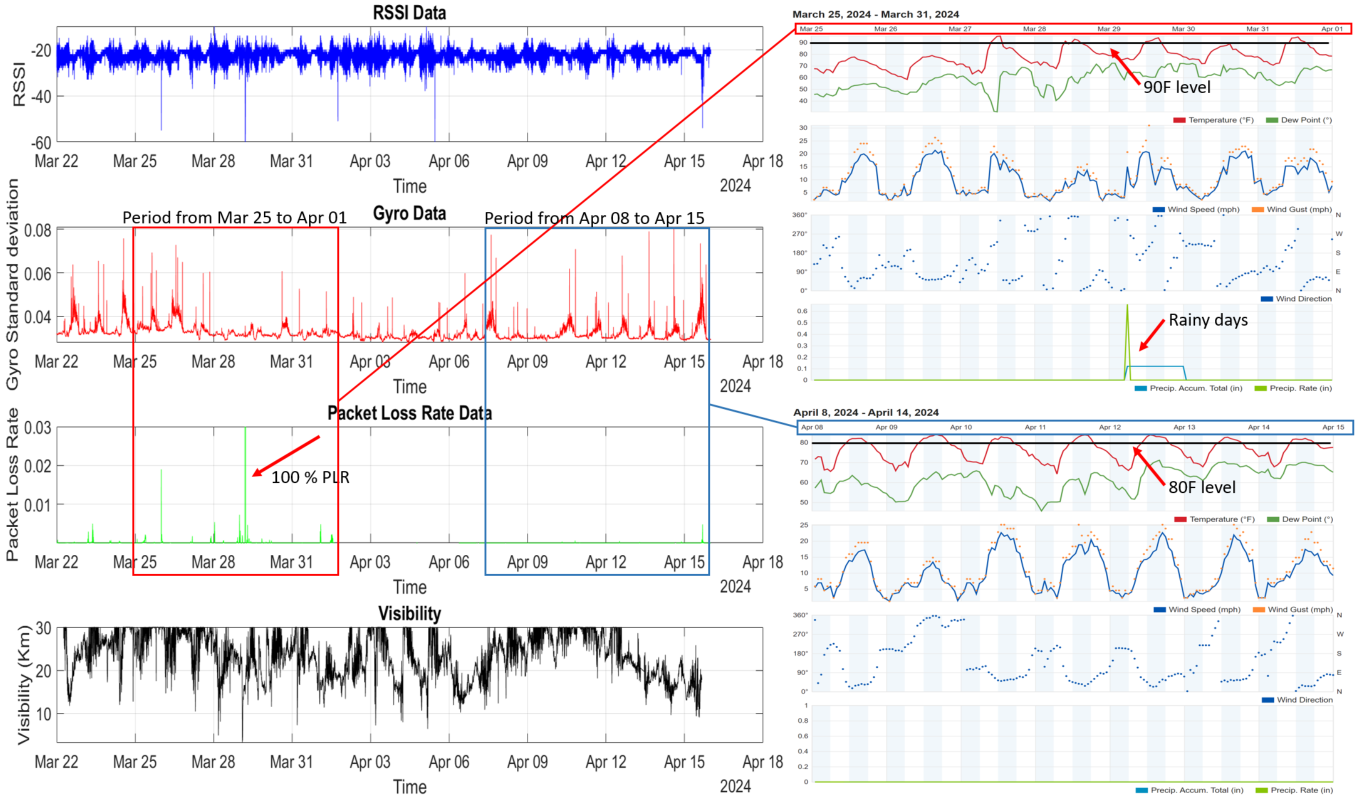

Fig. 5: Data visualization of the RSSI, Gyro sensor, and PLR from the FSO terminal in addition to the visibility data from the visibility sensor and the weather data recorded from the weather station.

the PLR reached 100%, primarily due to rain at a rate of approximately 0.66 in/hr, which reduced visibility to nearly 4.9 km.

TABLE I: RSSI Analysis Results

Metric	Value
Total observation time in months	4.20 months (127.96 days)
Total time with average RSSI under -40 dBm	39:33:10 (hh:mm:ss)
Availability	98.71%
Level crossing rate (LCR) downward for threshold -40 dBm	0.000294 crossings per second
Average fade duration (AFD) for threshold -40 dBm	00:00:4.81 (hh:mm:ss)
Mean RSSI	-22.57 dBm
RSSI standard deviation	4.79 dB
Mean Time To Repair (MTTR)	48.11 seconds
Total hybrid link availability	99.999 %

V. Discussion

Conducting experiments beyond laboratory test benches comes with several challenges. While software like Google Earth can be used to roughly plan the deployment location and the LoS configuration between the FSO and microwave links, it is crucial to physically test the LoS configuration, especially in areas still under construction. An example of an initially chosen deployment location blocked by a crane used at the construction site is shown in Fig. 6.

The second challenging scenario we faced during the deployment was the instability of the RF link with high bandwidth. Fig. 7 shows a fluctuation of the data rates. To solve this issue, we reduced the RF link bandwidth from 80 to 20 MHz. Increasing the RF link throughput in case of FSO primary link outages may potentially require using parallel channels.

Fig. 6: The LoS link was blocked by a crane for the first chosen location in RSG.

Fig. 7: Bandwidth test for the RF link with 80 MHz.

VI. Conclusion and Future Work

This study highlights the potential of using FSO for maritime communication, where RF has a limited capacity for the same scenario. FSO provided a 20 Gbps full duplex for a 19 km offshore island with an availability of 98.71%, reducing the cost of laying a submarine fiber cable. An availability of 99.999% is possible with backup RF links at lower capacity over 1.29% of the operation time in our case. A LoS configuration is mandatory for this technology, and ridged towers are crucial for stability. The 6 GHz band is the best match with FSO in maritime communication, and it can operate in events that cause outages for FSO, like fog and dust/sand storms. In future work, we will explore using multiple relays to extend communication to islands over 20 km from the shore. Even for a 20 km long link, splitting the path into two hops can help reduce the effects of weather and turbulence.

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