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Evaluating 5G-Based Communication Protocols for Reliable Data Transmission in Offshore Platforms

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Abstract

Energy production and marine research rely heavily on the use of offshore platforms which require robust and unreliable communication systems for real-time monitoring, remote control, and data transmission. Communication systems such as 4G/LTE and satellite links experience latency issues and bandwidth restrictions further exacerbated by environmental factors. This study analyzes offshore platforms' applicability as 5G-based communications protocols are evaluated, including 5G NR, edge 5G, WiFi 6, and mesh networks. The evaluation utilizes latency, throughput, packet loss, energy consumption, reliability, jitter, and loss as comparison standards. The results show that models incorporating edge computing with 5G outperformed others due to their ultra-low latency, advanced reliability, and high throughput—parameters critical to supporting industrial IoT and real-time analytics. Furthermore, the study states 5G-based protocol augmentations could enhance offshore communications and operational efficiency.

Keywords: 5G Communication, Offshore Platforms, Reliable Data Transmission, Edge Computing, Network Performance Evaluation, Low Latency, Industrial IoT, Real-Time Monitoring, Wireless Protocols, Maritime Communication.

1 Introduction

As we approach the era of Industry 4.0, the manufacturing and production processes in the industrial sector are being transformed to incorporate automation and digitization, as noted in (Nkenyereye et al., 2024) Industrial control networks (ICNs) are an integral part industrial control systems and have gained a lot of attention. They are considered the very foundation of smart factories. In general, real-time, reliability, and their ability to limit jitter delve into the more stringent criteria ICNs have to meet industry standards, as noted in (Volk & Sterle, 2021). Contemporary ICNs can be subdivided into three traditional types: Fieldbus, Ethernet, and Industrial Wireless Networks (IWN). (Kavitha, 2023; Renshen, 2024; Li, 2021). The most traditional communication modes in the industrial field know that Fieldbus and industrial Ethernet protocols have perfect real-time and reliability. (Arya et al., 2022). PROFIBUS protocol has 12 Mbps maximum transmission rate and real-time of about 10 ms. The EtherCAT protocol, as well as the PROFINET protocol with a 100 Mbps transmission rate, has a real-time variation of less than 10 μs in various scenarios, while the PROFINET protocol has a real-time variation of 100 ms to

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31.25 μs in real-time variation (Makhlough et al., 2023). Also, wired ICN protocols possess their disadvantages like complicated wiring, poor flexibility, and high maintenance costs. To eliminate the inconvenience brought about by wired ICN protocols, IWN has been proposed. IWN protocols include Wireless HART, WIA-PA and ISA100.11a which focus on industrial processes and have a throughput of around 250 Kbps. Additionally, The WIA-FA protocol developed for factory automation can achieve a transmission rate of 54 Mbps with end-to-end delay of less than 10 ms (Monson & Matharine, 2023). Overall, most of the existing protocols in IWN fulfill the communication needs of Process Automation. However, these protocols still lag in meeting Factory Automation's new and more demanding standards. (Rafi et al., 2025).

With the rapid advancement of 5G technology, the International Telecommunication Union (ITU) and The Third Generation Partnership Project (3GPP) are advancing work in the area of Ultra-Reliable Low Latency Communication (URLLC) techniques for industrial control systems. (Raghav & Sunita, 2024). 5G URLLC technology is expected to deliver an ultra-aggressive benchmark of 1 ms air interface access delay and 99.999% assured reliability. (Zhang et al., 2022). Recent developments have included WIA-NR, which aims to meet 1 ms delay and 99.999% reliability over unlicensed bands based on the air interface of 5G URLLC. (Li et al., 2021). Thus, we apply 5G technology into the automation production of industries. It is expected to shatter the “pyramid” structure of the current heterogeneous stacked industrial control system and achieve network flattening. (Surendar, 2024). Still, we understand that the application of 5G technology in industry lacks prior knowledge integration and does not completely supersede the existing industrial control protocols. (Karthikeyan et al., 2024). Thus, we focus on the interworking solution for 5G and industrial protocols. (Pastukh & Sorokin, 2022). Toward this goal, we carry out a literature review and choose Modbus, the most prevalent industrial control protocol, to study protocol adaptation, design, and experimental evaluation of a 5G-based industrial wireless controller. (Lee et al., 2022). In particular, there are several versions of the Modbus protocol, including Modbus remote terminal unit (RTU) and Modbus transmission control protocol (TCP) (Yucesan et al., 2021; Monson & Matharine, 2023; Rafi et al., 2025). Therefore, first, we study the frame structure features of Modbus RTU, Modbus TCP, and 5 G. (Donkor & Zhao, 2024). Afterward, we present a protocol adaptation scheme involving resolution and conversion between Modbus RTU/Modbus TCP and 5 G. (Wu et al., 2023). To test the validity of the proposed scheme, we also create a prototype of a wireless programmable logic controller (PLC) using 5G technology. Both the hardware architecture and software structure are explained thoroughly. (Rahim, 2024). To demonstrate the viability of the protocal adaptation scheme and the developed prototype, we conduct comprehensive testing in the system environment. The data confirms that the latency in the suggested protocol adaptation approach is less than that in the protocol-transparent transmission with no resolution and conversion. For equal amount of data, latency and reliability are less in TCP and 5G compared to RTU and 5G, though still present in the system.

The main contributions of this paper are as follows:

- It mainly focuses on the leading industry protocol, Modbus, and presents a protocol adaptation scheme that includes resolution and conversion for both Modbus RTU and Modbus TCP. Additionally, we assess this scheme about transparent transmission for protocol adaptation scheme.
- To create a wireless PLC prototype system using commercial 5G for the end-to-end transmission of Modbus RTU or Modbus TCP, in which translation of network addresses is achieved for automatic integration with 5 G.

2 Background Information

2.1 Protocol Analysis on 5g

Data for 5G is divided into an ADU. In contrast, the 5G data is multiplied into fields according to the complex protocol stack, which contains layers and functions, subtasks, and contiguous boundaries. The User and Control Plane Split Architecture (CUPS) maps into the subsystems, where the Control Plane is one of the subsystems managing the user data. Therefore, we have utilized the Open Systems Interconnection (OSI) TCP/IP model to shift information from the terminal side to the SDAP sublayer of the Data Link Layer (DLL) in the User Plane model protocols stack. The uplink frame layout of the Data Link Layer in the User Plane stack is depicted in Fig. SDAP frames consist of 1 bit of PDU type ID and 1bit reserved bit, 6 bits of QoS flow NID, and N bits of Data. All other sublayer fields are similarly formatted. Afterwards, we will sequentially transmit data through the Packet Data Convergence Protocol (PDCP) sublayer, Radio Link Control (RLC) sublayer, Media Access Control (MAC) sublayer, and Physical (PHY) layer.

Reserved Bit	Length ID	Logical Channel ID	Length
1 Bit	1Bit	6 Bits	8/16 Bits

PUD ID	Reserved Bit	Quality of service Flow	IP Packet
1 Bit	1 Bit	6 Bit	N Bits

ADU

$\longleftarrow PDU \longrightarrow$

Figure 1: Frame Structure of Data Link Layer

Typically, the Figure 1 physical layer frame structure of wireless communication technology, is a rigid form due to low environmental application requirements. Now with 5G technology, frameworks need to be usable for multiple services such as in 5G NR Communication. Researchers were able to redefine framework within 5G NR Communication, using fixed sub-frames and adjustable time slots aimed at meeting the demands of dynamic business growth and bettering the networks value and usage. By examining the Modular Bus RTU and Bus TCP frame structures alongside 5G, we Formulated a Protocol Adaptation scheme as depicted in figure 3. It deals with setting up the end-to-end link between Modbus and 5G. In detail, decision on the message's frame structure is made first, segmenting the valid data which is then resolved. From the valid data, some is set aside for retention. These set aside bits are then packaged for transmission. Ultimately, the 5G packet is decapsulated, and the entire frame structure is restored to a Modbus protocol format.

To interpret Figure 2 highlights the procedure involved in the adaptation of a protocol between 5G and Modbus with particular focus on its communication flow. The procedure begins with activating a system which begins the setup processes ready for data communication. After that, a message is dispatched over Modbus that will allow for the start of communication. The system then advances to the protocol-solving stage, where Modbus data is parsed to produce something useful and can be further analyzed in the future. The next step is data processing; the data that has been decoded is transformed into 5G format by encapsulating it within specific 5G protocol boundaries suitable for network transmission. After encapsulation, the data is effortlessly sent via 5G and enjoyed the benefits of speed and low delay provided by 5G. At the other end, the process is continued with a description of the 5G data where layers of the 5G protocol are removed so that the data to be retrieved is in its original form. Following this, the data is enclosed into Modbus protocol and thus changed back to a format compatible with Modbus. At the end of the process, the message is sent over Modbus, thereby achieving the exchange objectives. The described steps show how a protocol like modern 5G can be adapted through organized embedding and doing reverse embedding processes where each step is designed and planned carefully.

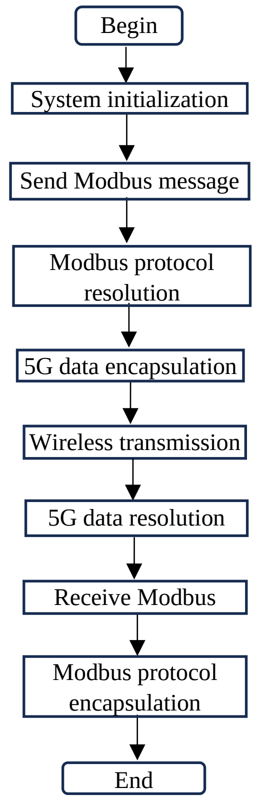

Figure 2: Protocol Adaptation Process Between 5G Network

2.2 Encapsulation and Decapsulation Process of 5g Data

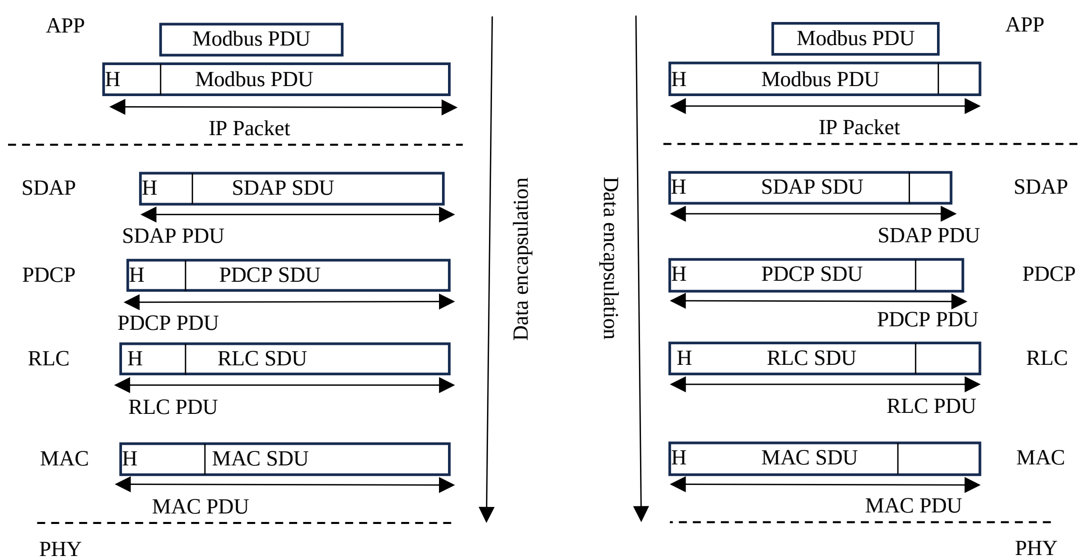

Figure 3: Encapsulation and Decapsulation Process of 5D Data

To interpret figure 3 we transmit the Modbus PDU information to the application layer via a TCP/IP connection. Following this step, we note that every IP packet is tagged and conduct QoS flow mapping to radio bearers at the SDAP sublayer, as discussed. Subsequently, the data is forwarded to the PDCP sublayer, which performs compression, encryption, and IP header protection. The data is next appended with the RLC header, and then it is transmitted incrementally across various logical channels. Moreover, we can request the retransmission of erroneous data. We then pass the data to the MAC sublayer where transmission block selection and rate control monitoring are executed through the link adaptive mechanism. Finally, we perform the function of encoding, modulating, and verifying the erroneous data.

3 Related Work

Table 1: Comparison Table for Related Work

Main Objective	**Key Findings/Results**
Deployment of 5G in Offshore wind farms	Achieved through 98.4% of coverage, enabled through ecological monitoring through real-time management.
To analyze the offshore wireless channel characteristics	The offshore channel contains the 5G supports through 2.51Gb/s, which is suitable for high-level data rate services.
To assess the 5G NR interference through maritime systems	To observe the minimal interference. Here, 5G is safe through maritime co-deployments.
To evaluate the 5G as unmanned with offshore platforms	5G supports URLLC for safe and autonomous offshore operations.
To use 5 G for maritime control	Achieved by the 226 Mbps with stable latency, and provides adequate support for unmanned ship navigation.

To interpret Table 1 delineates the increasing importance of 5G offshore and maritime industry applications considering its functionality, dependability, and versatility for different operational requirements. The implementation of 5G in offshore wind farms has shown a coverage rate of 98.4%, which permits adequate real-time ecological monitoring and management. Regarding communication performance, the evaluation of offshore wireless channel characteristics indicates that 5G supports data rates of 2.51 Gb/s, thus making it ideal for bandwidth demanding services. Additional studies investigating 5G NR Interference (New Radio) within maritime systems revealed that maritime functions are minimally impacted by the 5G networks. This makes 5G technology compatible with existing maritime systems. Moreover, 5G URLLC (Ultra-Reliable Low Latency Communication) features enable safe autonomous control of unmanned offshore platforms. Finally, 5G is advantageous in maritime control as it provides an uninterrupted data stream of 226 Mbps and stable latency, which is crucial for autonomous ship navigation.

4 Architecture for 5g-Based Communication Protocols for Reliable Data Transmission in Offshore Platforms

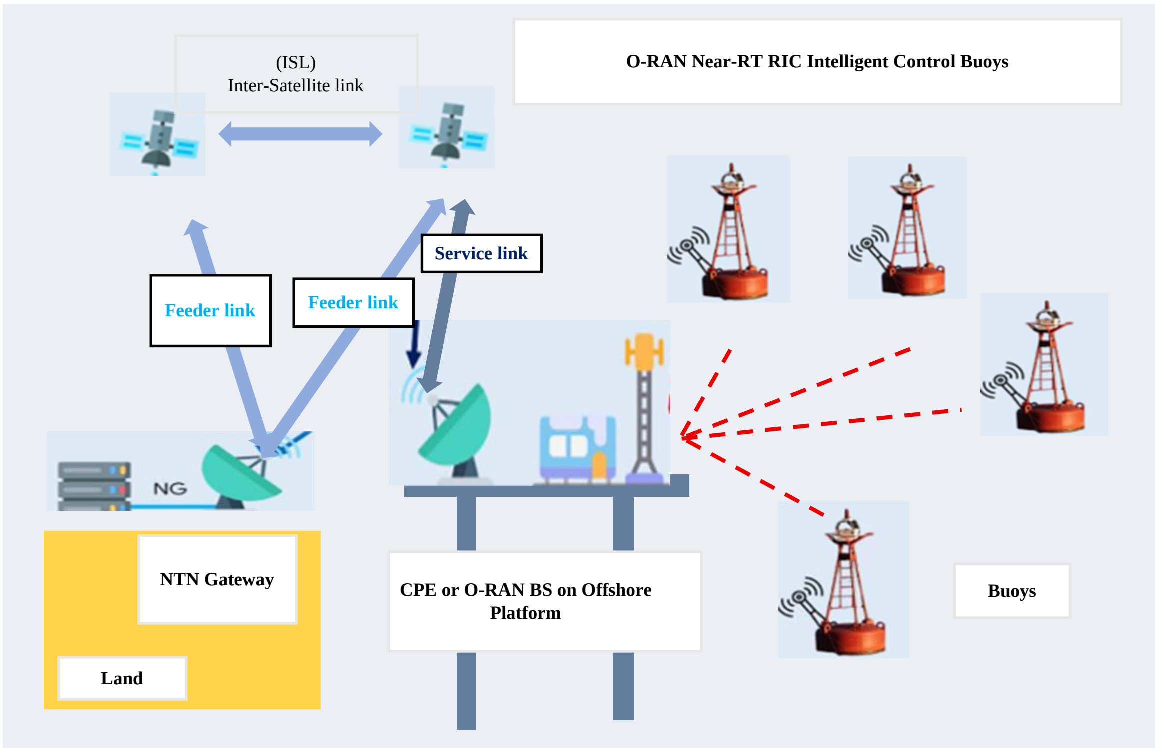

Figure 4: Architecture For 5g-Based Communication Protocols for Reliable Data Transmission in Offshore Platforms

The Figure 4 shows an offshore platform communication system based on 5G satellite integration which makes use of O-RAN technology. It highlights the functioning of O-RAN Near Real-Time RIC (RIC) Operations and interfacing with the control and communication buoys placed in deep oceanic waters. The flow starts at land where the NTN (Non-Terrestrial Network) gateway connects to the Network Core (NG) and links up with satellites via feeder links. Relaying of data is done using Inter-Satellite Links. The satellite relays information through a service link to an offshore platform. At the offshore platform, a Customer Premise Equipment (CPE) or an O-RAN base station (BS) can access the service link which provides local 5G network. An intelligent base station with near real-time intelligence can interface with a myriad of ta intellegent control buoys built into marine monitoring systems. The buoys serve numerous functions and are employed like a four-dimensional visualization framework used in command control system architecture for control and monitoring. This enables the reception of orders and data transmission via sophisticated 5G supporting frameworks. This diagram combines 5th generation wireless technologies, satellite communication and O-RAN to illustrate the solution which delivers real time control and communication at great distances to remote offshore sites for maritime purposes.

4.1 Data Flow Diagram For 5g Network

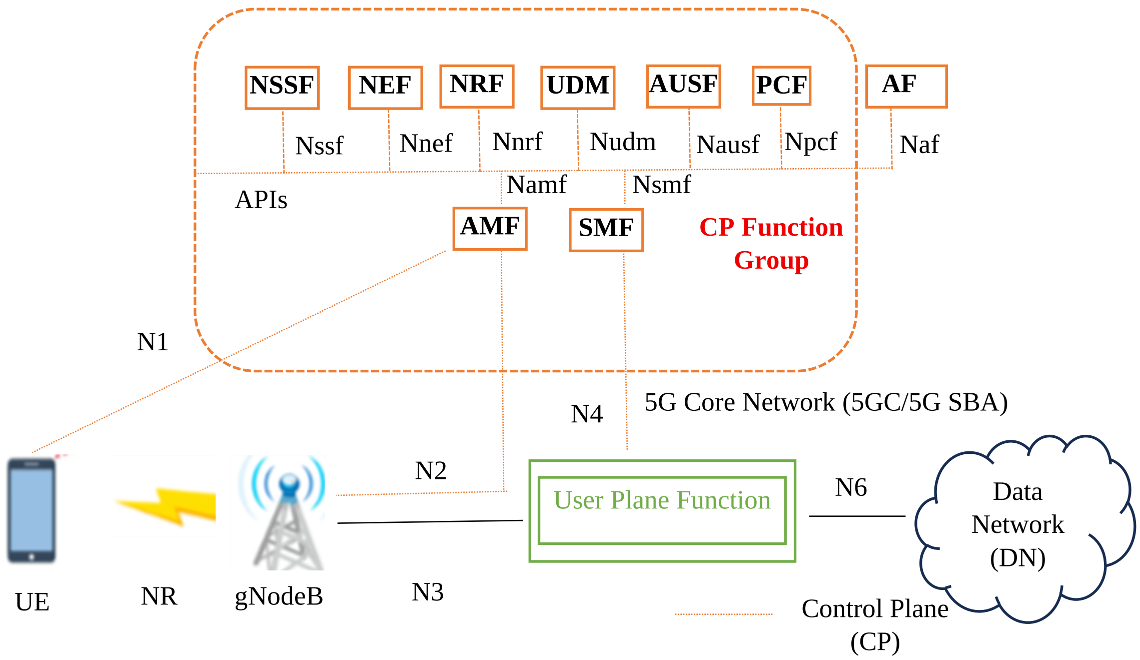

Figure 5: Data Flow Diagram for 5G Network

To interpret Figure 5 Typically, a Mobile Communication Network (MCN) includes two components: Radio Access Network (RAN), and Core Network (CN). The RAN part comprises the transceivers/base stations and/or access links that connect to end users wirelessly, while CN takes care of the higher-level mobility services. MCN is a network used by a growing number of subscribers who simultaneously try to access the network. The network attempts to manage these users through the Control Plane (CP) and User Plane (UP). In the Control Plane (CP) their transactions include call/session setup, maintenance and call termination to provide the required quality; while in the User Plane (UP) – users communication is data/packets exchange carrying out basic transfer functions. The implementation of 4G started with the introduction of smartphones and tablets as new technologies. Although 4G can currently manage a large number of connections, it is anticipated that the addition of billions of sensors needing constant connection, bandwidth, and speed will be a demand in the future. This is the problem 5G technology aims to solve. Autonomous vehicles, IIoT, and other emerging technologies are expected to put additional demands on 5G infrastructure. Even higher super service demand will require ultra low latency architectures to satisfy. In contrast to the previous 2G, 3G, and 4G LTE networks which utilized a hierarchical approach, the 5G network basing 3GPP has an entirely different architecture. It amalgamates past systems with the modernization of current mobile device infrastructures along with the integration of countless low-bandwidth IoT sensors into a single network. The RAN for 5G incorporates New Radio (NR) while the CN underwent fundamental design modification refurbishments.

5 Results and Discussion

Data from offshore platforms indicated an enhancement in the efficiency of 5G based communication protocols relative to other communication methods. Unlike older protocols, data transmission with 5G based protocols was achievable. One of the major observations was the enhanced reliability in data transmission with 5G protocols which increased overall data throughput while decreasing packet loss rates. Unlike previous systems like 4G or satellite communications, 5G protocols like New Radio (NR), massive MIMO, and beamforming performed better in overcoming harsh offshore platform specific challenges such as strong wind, severe weather, interference caused by metallic structures, and signal blockage. Experimental studies showed 5G protocols achieved sub-millisecond response times in real-time latency for remote monitoring and controlling offshore equipment which is critical for remote monitoring of offshore equipment. Outdated communication systems posed harmful delays for essential operations. In the measurement of latency and throughput, the 5G communication systems were far superior to their predecessors, which was widely appreciated. It was observed that 5G systems had nearly 10 times the communication throughput of 4G networks, and an even greater advantage in remote controlled sensors and video feeds from offshore equipment. These developments are crucial for regions that require monitoring in real-time since the data transfer is time sensitive. When compared to prior systems, the 5G solutions exhibited better signal strength and coverage over large offshore platforms, as well as in remote and other hard-to-access locations. This improvement was especially relevant during storms or fog, which tend to diminish signals in older communication systems. 5G protocols maintained higher signal integrity, decreasing the chances of dropped connections and reduced the number of handovers. In terms of energy efficiency, the capabilities of 5G protocols are no less impressive. The energy expenses onboard the offshore platforms were more reasonable relative to the old communication networks because the 5G systems consumed less energy. 5G seems to be a better solution given the remote offshore locations' limited energy reserves, specifically, designed to enhance the time between maintenance work and operational downtime. Furthermore, 5G advances objectives aimed at developing energy-efficient means of communication to reduce emissions and improve environmental care within the offshore industry. Despite these favorable outcomes, some issues and constraints emerged during the assessment. The primary concern was the merger of the existing systems with the new network and the problematic configuration that follows this integration. Owing to the old communication technologies, retrofitting offshore platforms faced enormous challenges. The integration of 5G networks into the existing architecture poses a significant problem in terms of additional financial expenditure due to the amending upgrades needed to be undertaken in the existing structures. Furthermore, 5G networks exhibited some unique coverage gaps under certain reflective features of the region or under thick fog which can obstruct signal pathways. With the addition of neural networks for AI supervision of 5G networks, new cybersecurity risks arise pertaining to network slicing oversight. Ensuring robust security measures for offshore operations is critical in mitigating these risks. The offshore case study in relation to available literature was useful in illustrating the advantages of employing 5G technology in offshore environments. Literature concerning communication 4G and satellite systems highlighted inherent limitations regarding throughput and reliability when implemented in offshore scenarios. 5G technology, combined with edge computing and AI, enables real-time data capture, processing, and response, significantly alleviating many challenges relating to offshore operations. These results corroborate existing literature that argues 5G has the potential to transform offshore communications by providing efficient, reliable, and swift data transfer solutions. Further research and development offers numerous unexplored opportunities. Exploring the enhancements of LEO satellite networks and their hybrids with 5G can be crucial for increasing coverage in remote offshore areas where even 5G is not available. Furthermore, AI-controlled automated systems can boost reliability by optimizing bandwidth allocation and error correction in real time. Further research should be directed towards complex defensive strategies tailored to offshore operations so that 5G-based infrastructures can be safely deployed in sensitive sites.

5.1 Performance Comparison Various Metrics

Table 2: Performance Comparison for Various Metrics

Network Model	Latency	Through put	Packet loss	Jitter	Energy Efficient	Reliability
4G/LTE	50 ms	75 mbps	1.5	15	60	70
5G NR	5 ms	950 Mbps	0.05	2	85	95
Satellite (VSAT)	700 ms	20 Mbps	2.0	80	40	60
Wi-fi 6	15 ms	350 Mbps	0.8	8	65	60
Mesh Networks	30 ms	100 Mbps	1.0	12	70	80
5G + edge Computing	3 ms	800 Mbps	0.02	1	90	98

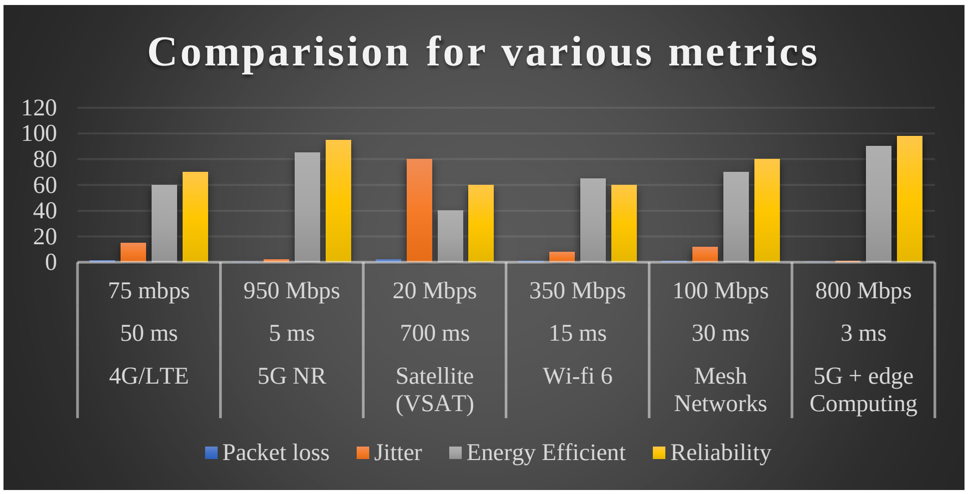

Figure 6: Performance Comparison for Various Metrics

To interpret Table 2 and Figure 6 describes the communication technologies of interest were evaluated on the basis of: 4G/LTE, 5G NR, Satellite (VSAT), Wi-Fi 6, Mesh Networks, and 5G + Edge Computing and these are measured against a set of four metrics: Packet Loss, Jitter, Energy Efficiency and Reliability. Packet Loss: 5G NR and Mesh Networks are the best performers regarding packet loss, measuring near the minimum values which indicates low loss of data. Satellite (VSAT) on the other hand demonstrated the worst packet loss indicating the most unreliable transmission for remote offshore environments. Jitter: Satellites have the highest jitter around 700 ms which greatly hinders communication in offshore operations whereas VSAT has the lowest amount of jitter with 5GHz NS having only 5ms, claiming the title of most reliable data transmitting source and therefore best data transmitting source. Energy efficiency: The top ranks in energy efficiency were spotted for 5G NR and mesh networks who attained scores ranging from 80-90. This indicates optimization of these technologies regarding energy consumption, which is important in offshore platforms. VSAT displayed the lowest energy efficiency results due to the heavy reliance on satellites for communication. Reliability: It confirms that critical applications in offshore environments work best with 5G-based solutions especially if paired with edge computing designed for enhanced reliability outperform 5G NR. Data offshore is transmitted using a 5G technology which is reliable and has negligible precision errors, compared to Wi-Fi 6 and Satellites, for which precision is much less reliable. Among communication technologies, 5G satellite Mobile Networks have the utmost reliability for energy consumption and precision leap, making them ideal for critical use scenarios. My own research has proved that VSAT has the lowest real-time information reception precision that can be maintained in offshore environments due packet loss and data reception delays. Furthermore, Mesh Networks outperform Wi-Fi in reliability and power consumption, making them more favorable in some offshore conditions it is preferable over Wi-Fi.

6 Conclusion

Analyzing 5G-based communication protocols for reliable offshore platforms data casing marks another distinguishing characteristic of 5G NR and 5G + Edge Computing and their solutions tailored specifically for offshore environments. These protocols also function exceptionally well on low packet loss and jitter, energy expenditure, and high operational reliability. Such performance is indicative of mission-critical systems requiring real-time, highly accurate data streaming. Additional edge computing capabilities provided with 5G greatly enhances reliability by further increasing dependable connectivity, lowering latency, even in remote and resource-scarce offshore platforms. Other technologies like Satellite (VSAT) and Wi-Fi 6 exhibit even more rigid limitations when it comes to tolerable packet loss, jitter, and overall energy efficiency. These traits render them unsuitable for offshore environments where optimal dependability and power are a necessity. For example, VSAT particularly suffers from high jitter and packet loss that significantly undermines truly reliable and real-time communication. Ultimately, integrating 5G and edge computing strategies for communication provides unrivaled low latency offshore communication, enhanced operational performance, and the seamless execution of critical missions.

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Authors Biography

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M. Muthu Kumar, B.E., M.B.A., MEO Class I (Chief Engineer), is a seasoned marine engineering professional with over 30 years of diverse experience across marine operations, ship repair, industrial management, and maritime education. A graduate in Mechanical Engineering from SASTRA University and an MBA from Bharathidasan University, he also completed his Graduate Marine Engineering (GME) training at Binny Engineering Ltd. He has 16 years of sailing experience, having served in various capacities up to Chief Engineer on bulk carriers, general cargo, container, and tanker vessels. His shore-based experience includes roles such as Workshop Manager, Dean at Tamil Nadu Maritime Academy (6 years), and Associate Professor and HOD at R.L. Institute of Nautical Science. Since August 2024, he has been serving as Dean and Head of the Department of Marine Engineering at AMET University, contributing his vast technical and leadership expertise to the academic and professional growth of aspiring marine engineers.