Reliable and Robust Monitoring System for Space Habitats

Saurabh Band[1], Florian Stechmann[2], Malavika Unnikrishnan[1], Shadi Attarha[1], Christiane Heinicke[2], and Anna Förster[1]

[1]dept. Sustainable Communication Networks (ComNets), University of Bremen, Germany
[2]dept. Center of Applied Space Technology and Microgravity (ZARM), University of Bremen, Germany
Email: {*sband, stechflo, mal_unn,sattarha, anna.foerster*}*@uni-bremen.de, christiane.heinicke@zarm.uni-bremen.de*

***Abstract*—In recent years, much research has been done to settle a civilization on Mars. Among the various required resources for this civilization, a habitat to survive and conduct experiments during exploration is one of the most crucial requirements. Currently, multiple institutes are trying to design and build a space habitat for this purpose. These space habitats are designed to provide a safe place to live during the initial missions and are equipped with monitoring and life support systems to ensure the astronauts' safety. In this work, we propose a robust monitoring system for space habitats. Similar to a typical monitoring system, the key components are sensor nodes (sensor boards), a sink node (server), and a wireless communication link (LoRa) to connect the two. However, the novelty of our system is its robustness to sensor-node failure. In case of a sensor node failure, the system will continue to function with the help of redundant nodes. We also introduce a custom medium access control (MAC) algorithm called Slotted-ALOHA with Random Backoff (SARB) in combination with a message queue to make the LoRa communication more reliable. Here we propose an architecture of the monitoring system for different IoT applications in extreme environments. Using the hardware prototype of the system, we demonstrate the redundancy concept and how it avoids data loss in case of sensor node failures which is crucial in life-critical missions. The results also show the improvement of the packet delivery ratio (PDR) by 34% with the proposed MAC algorithm.**

***Index Terms*—Monitoring System, Space habitat, Life Support System, LoRa, Wireless Communication, Smart Home Automation**

I. Introduction

The main focus of current monitoring systems is in predictive maintenance, where a monitoring system is deployed to predict failure in the system being monitored. However, the monitoring system can also fail. The failure of monitoring systems in space habitats can lead to catastrophic events. Such occurrences are rare and can be resolved if it occurs in the system on Earth. However, the space habitats are not accessible physically, and the communication delay makes things more complex. In the case of Mars, the round-trip communication delay to Earth can be around 20 minutes. Due to this delay, it becomes essential to have a system that is very robust to failures and a self-diagnostic system that can detect faults without human interference.

Forming a colony on Mars is close to the future, as private companies have joined this race. The recent works [1], [2] show us clearly that research is being done in all directions to have a sustainable life on martian land. One of the critical resources for sustainable energy is a habitat for the crew to survive, known as Space Habitat. Various institutes [3]–[6] have already designed and built prototypes of a space habitat. One such space habitat [6], called 'Moon and Mars Base Analog' (MaMBA), is developed at the Center of Applied Space Technology and Microgravity (ZARM), University of Bremen. MaMBA is built to test various human-centric technologies like the Life Support System, the power system and the monitoring system for the habitat. This monitoring system needs to be robust to all forms of failure due to its remote nature and difficulty in communication. Thus to make the system robust, we propose an architecture to tackle the problem of sensor node failure. The robustness to node failure is achieved by implementing redundancy in the system. The redundancy is added in the form of redundant sensor nodes that will ensure that no packets are lost in case of failure of any sensor node.

We use LoRa PHY for wireless communication. As LoRa PHY provides the radio interface without a MAC layer, the packets from multiple boards can collide at the gateway receiver. In [7], [8], authors propose MAC algorithms with sensing capability like lightweight carrier sense (LCS) and CSMA/CA for LoRa. However, these methods include additional hardware and modified libraries to perform sensing. Even with the built-in sensing mechanism on the LoRa chips, Channel Activity Detection (CAD), it is not possible to access it via standard drivers for transmission. Thus we propose MAC implementation for LoRa without channel sensing called Slotted ALOHA with Random Backoff (SARB). In addition, we also implement a message queue to re-transmit the lost packets, thus making the communication reliable.

This paper proposes a framework for enabling a self-diagnostic process to guarantee system robustness. The system described in this paper is adapted for MaMBA; however, it can be implemented for any other space habitat with minimal changes. The rest of the paper is organized as follows. Related works are discussed in Section II. A brief overview of MaMBA is given in Section III. The system architecture of a proposed method is explained in Section IV. Implementation details and system validation are presented in Section V and VI respectively, followed by the conclusion in Section VIII.

II. Related Works

Monitoring systems using a Wireless Sensor Network (WSN) is widely used for applications like environment surveillance [9] and smart homes [10]. A WSN is an excellent option for monitoring systems due to its low power consumption and low-cost [11]. In addition, they come with some added benefits, the duplication of the nodes to ensure large-scale coverage, flexibility to incorporate new sensor nodes, and the relatively small size of the node [12].

Many studies focus on WSN monitoring systems with embedded machine learning strategies for improving the system performance [13], [14]. The study [15] proposes a ”low-power failure detector” to detect the failure of a node due to insufficient power. [12] examines the performance of the WSN without the implementation of any acknowledgements or message re-transmissions to conclude that, given the lower congestion in the network, the rate of successful delivery of messages is satisfactory.

Furthermore, the study [16] reviews various methods for fault tolerance in WSN to address failures in sensing and routing. The first method aims to develop a fault-tolerant system, which handles the breakdown of one or more components and does not imply an overall system failure. As described in [16], a common way of implementing a fault-tolerant WSN system is by replicating system logic and system functions using physical redundancy, leaving out the faulty node from the whole system. Re-transmission is the second technique for reliable communication and routing failure. After sending data, the sender node waits for an acknowledgement from the receiver node. Upon failure of the acknowledgement, the sender node assumes a packet loss and re-transmits the message [17]. In some studies, [18], [19], a negative acknowledgement from the receiver conveys the message of missing packets to the sender.

Meanwhile, redundancy also brings specific issues like the increased data processing cost, higher delay and bottleneck in the overall network and significant energy depletion as discussed in [20]. The paper discusses the spatial redundancy reduction approach to account for some of these problems, with no compromise to the system's reliability.

III. Moon and Mars Base Analog Overview

Moon and Mars Base Analog (MaMBA) consists of six upright cylindrical vessels designed to withstand high pressure. Out of the six modules, we focus on the mock-up of the laboratory module. For simplicity, we refer to it as 'the module' from here on. Figure 1 shows the module's exterior and its miniature version. The module is a 2-storied structure where the lower part would be used for working and the upper part for leisure. The inner diameter of the module is around 4.40 meters, and the internal walls are divided into eighteen segments. These segments are modular to accommodate required equipment in the future. This module is planned to be equipped with *Life Support System (LSS)* that can generate oxygen for the crew, *Power System* to power up the module, and *Communication System* to deliver the sensor data from all the modules to the central processing server of the habitat [6], [21].

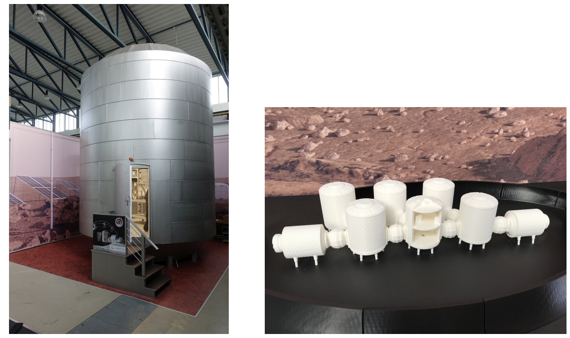


Fig. 1: Structure of Moon and Mars Base Analog. (a) The external structure of the MaMBA habitat mock-up module [6], (b) The miniature model of Habitat

Though the modules are interconnected, they are still independent. Each module would be equipped with suitable instruments to serve a distinct purpose. As each module is independent, monitoring every module in the MaMBA is crucial for the crew's safety and the habitat's smooth functioning. A typical monitoring system consists of sensor nodes to collect data and a backend server to analyze the data. In further sections, we propose the architecture of the monitoring system that can be used to monitor living habitats. The safe running of all systems in a single module is ensured by monitoring various parameters. These parameters include temperature, humidity, air pressure, carbon dioxide, carbon monoxide, and oxygen. Additionally, various parameters must be monitored for LSS. As the LSS consists of elements in the liquid and gaseous phases, parameters are measured for both phases. Dissolved oxygen, pH, temperature, and optical density are monitored for the liquid phase. Oxygen, carbon dioxide, temperature, relative humidity, and pressure are monitored for the gaseous phase. All the parameters need to be updated at least every *40 seconds*; this interval is called **Maximum Monitoring Delay** (maximum time between two readings to ensure smooth and safe operation).

IV. System Architecture

This section describes the architecture of the proposed monitoring system, which consists of three main components, namely: *sensor nodes*, *server (backend)* and *communication link between the sensor nodes and the server*.

The placement of sensor nodes must be determined very carefully. If a sensor node fails, its respective area will not be monitored and will fail to detect catastrophic events. To overcome this problem, we suggest having redundancy in the sensor node. The sensor node comprises two identical sensing boards, each capable of sensing and transmitting the sensor data. One board acts as the main sensing device, also called the primary board, while the other acts as a redundant backup. The two boards are denoted in Figure 2 with blue and red colours. In the rest of the paper, we will refer to the primary and redundant board pair as **sensor node**.

- **Primary board:** The main board of the sensor node that will collect and send the data.
- **Redundant board:** Replica of the primary board that has identical monitoring scope and collects the same data. It is the backup to the primary board.

The redundant board will only send the data if the primary board fails to do so. The detailed working of the redundant board is explained in Section V-A2. The sensor node communicates with the server with converge-cast single-hop routing. A group of sensor nodes will send the data to a common gateway, which sends the data to the server via Ethernet. The implementation of the MAC algorithm, Slotted ALOHA with Random Backoff and message queue with re-transmission, is discussed in Section V-B.

Figure 2 shows a general architecture of the proposed monitoring system. The system can be adapted for any space habitat by choosing a concrete technology for each component. In this work, we have adapted this system for the MaMBA space habitat, and we will discuss the implementation details in the upcoming sections.

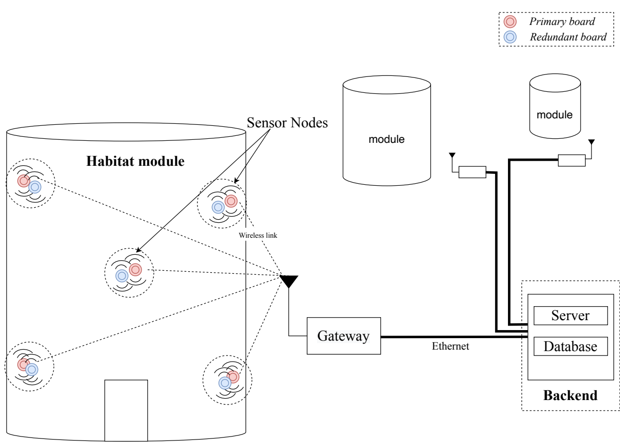


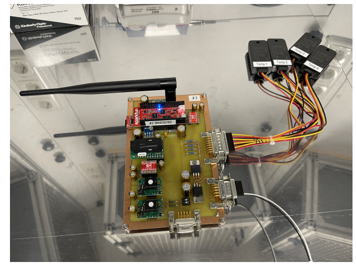
Fig. 2: Generalized System Architecture of the monitoring system for extraterrestrial living habitats.

V. Implementation

This section presents the implementation details of the proposed framework. The following subsections discuss the *sensor nodes* and *communication setup*. In the scope of this paper, the server only receives and acknowledges the packets and thus is not discussed.

A. Sensor Boards

The individual sensor boards are equipped with eight sensors in the current prototype. As shown in Table I, temperature and humidity sensors have four instances, while all the other sensors have a single instance. The functioning of the board is handled by ESP32 microcontroller. This microcontroller is booted with Micropython firmware. The prototype of the sensor board is illustrated in Figure 3



(a)

Fig. 3: Prototype of the sensor board

The schematic diagram of the sensor board can be found on the GitHub repository[1]. SPI and I2C protocols are used for onboard communication. Since the working voltage for ESP32 ranges between 2.2V to 3.6V, there is a voltage level converter on board to interface the sensors that work with voltages different than that of the controller. Based on the functionality, the boards are categorized as *primary board* and *redundant board*.

1) Primary Board: Out of the two boards in the sensor node, the primary board is responsible for sensing. The board senses the data from all the sensors continuously. It allows the system to detect any changes in the environment quickly. However, the data is transmitted at a lower rate than sensing in the form of packets. The transmission of the packets is handled by the MAC layer, which is discussed in Section V-B. For each sensor, pre-defined upper and lower thresholds define the normal values. If the detected values cross any threshold, it indicates an emergency and the packets are transmitted without delay. However, in a regular scenario, the packets are transmitted according to transmission interval. The rate at which packets are transmitted is called **transmission interval**.

2) Redundant Board: The redundant board is a backup for the primary board. The function of a redundant board is to send the sensor data packets if the primary board fails to do so; otherwise, while it is idle, it sends a smaller packet to indicate it is alive, known as *heartbeat signal*. This function is explained in Figure 4 with a timing diagram. The diagram contains three plots: $a)$, $b)$, and $c)$, which show packet transmission of the primary board, redundant board and sensor node (primary + redundant), respectively. For better understanding, the transmission interval of the primary board in plot a) is assumed to be constant at 30 $seconds$. The redundant board waits for 5 $seconds$ more than the maximum transmission interval, i.e. 35 $seconds$ in this scenario, to check if the primary board is working; this interval is called **sensing interval**.

Plot 4.c) shows the resultant packets received from the sensor node and the maximum allowed delay for each packet (red dotted line). Plot 4.a) shows the packets received from the primary board with the transmission interval of 30 $seconds$. As the primary board transmits the first three packets before

[1] https://github.com/saurabh-2905/sensorboard-mamba

TABLE I: List of Sensors.

Parameter	Component name	Unit	Measurement range	Interface	Quantity
CO_2	SCD30	ppm	400 - 10000 ppm	I^2C	1
Ambient Pressure	BMP180	hPa	300 - 1100 hPa	I^2C	1
O_2	O2 SS Micro	percent	0 - 25 %	I^2C	1
CO	CO SS Micro	ppm	0 - 1000 ppm	I^2C	1
Temperature and Humidity	AM2301	°C, %	0 - 80 °C, 0 - 100 %	one-wire protocol	4

the *sensing interval*, the redundant board will not send the packet. However, it will send the heartbeat signal (yellow bar) every 60 $seconds$. After the third packet, as the redundant board does not sense any packet from the primary board till completion of *sensing interval*, it will send a packet immediately. The difference between the completion of the sensing interval and packet transmission denotes the time required to read the sensor data. Even after the failure of the primary board, the packet from the redundant board reaches the server within the *maximum monitoring delay*. The same phenomenon is seen for the next packet as well. As soon as the primary board is online, the redundant board stops transmitting packets and returns to transmitting $heartbeat\ signal$.

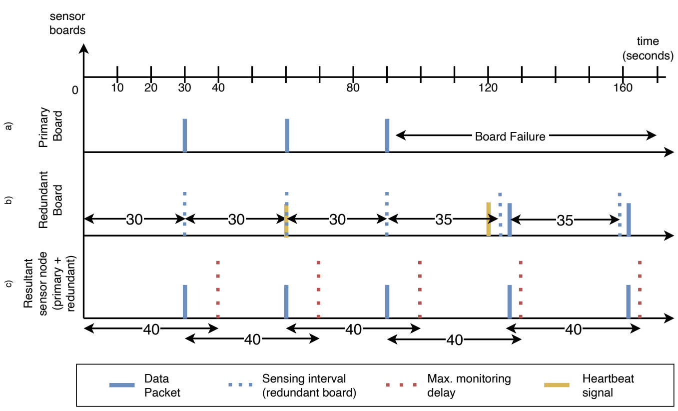


Fig. 4: Packet reception at the server to demonstrate the redundancy concept. a) shows the packet transmission of the primary board. For simplicity, the transmission is considered constant at 30 seconds (max. transmission interval). b) shows the working of the redundant board. c) packet reception at the server from the sensor node.

B. Communication

Several other wireless technologies were compared for communication, as shown in Table III. Other popular technologies like Bluetooth, WiFi and Zigbee operate in the most crowded frequency band (2.4 GHz) and thus are more susceptible to interference. While other technologies like Zigbee, Z-wave and EnOcean work at lower frequency bands, the range is short compared to LoRa. Moreover, the compatibility of LoRa wireless technology in outer space is established in several other studies [22]. The configuration parameters of the LoRa node can be modified to obtain optimized reliability as discussed in studies [23], [24]. Table II shows the selected values for respective LoRa parameters based on literature [25].

TABLE II: LoRa parameters used

Parameter	Selected value
Frequency	868 MHz
Bandwidth	125 kHz
SF	7
CR	4/5

For SARB, similar to slotted ALOHA, the packets are sent at specific time slots. Here, the slots are defined as the transmission interval duration. However, we introduce a random back-off mechanism to make these time slots variable. As we want each packet to be delivered at the server within 40 seconds from the previous packet *(max. monitoring delay)*, we define the range for transmission interval as $20 - 30\ seconds$. The transmission interval can vary with a step size of $500ms$. This interval varies randomly for each sensor node.

There is also a message queue on board which enables the re-transmitting of lost packets. The packets are added to this queue during transmission and removed from the queue if acknowledgement is received. If the acknowledgement is not received, it indicates the packet is lost and remains in the queue to be re-transmitted. Figure 5 shows the transmission mechanism. There are two re-transmission slots between two consecutive transmission slots. We define the re-transmission interval as 6 $seconds$ and can be varied based on the requirement. This queue can store up to 10 packets. The packets in the queue are accessed according to Last-In-First-Out (LIFO) rule. If the queue is full, the oldest packet is deleted to accommodate the new packet. All the intervals in the system can be defined by the developer based on the system requirements.

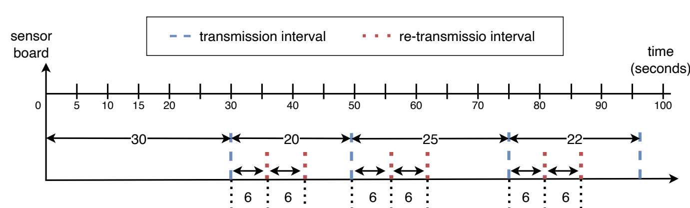


Fig. 5: Visualization of variable transmission interval and re-transmission slots.

VI. Performance Analysis

In this section, we validate our proposed methods that make the system robust to sensor node failure and packet loss. To verify this, we perform two sets of experiments. First, to check the redundancy feature in case of sensor node failure

TABLE III: Comparison of different existing wireless technologies.

	Bluetooth	Zigbee	Z-wave	ENOCEAN	LoRa	Wi-Fi
ISM Frequency bands	2.4GHz	2.4 GHz, 915 GHz, 868 MHz	2.4 GHz, 908.4 MHz, 868.4 MHz	315 MHz, 868 MHz, 902.87 MHz	433 MHz (Asia), 868 MHz (Europe), 915 MHz (North America)	2.4 GHz, 5 GHz
Range	1 - 10 meters	1 - 100 meters	30 meters	30 meters	10 Km	1 -100 meters
Data rate	1 Mbps (v1.2) 3 Mbps (v2.0) 24Mbps (v3.0)	250 kbps, 40 kbps, 20 kbps	120 kbps (868.3 Hz)	120 kbps (868.3 Hz)	250 - 5470 bps (depends on SF)	11 - 65 - 450 Mbps (IEEE 802.11n)
Nodes per cluster	8	255	255	255	1000	32
Bandwidth per channel	1 MHz	2 MHz	100 KHz	280 KHz	125 KHz	22 MHz
Transmit power	4 dBm	0 dBm	3 dBm	6 dBm	13 dBm	20 dBm
Network Topology	Star, Peer-to-Peer	Star, Peer-to-Peer, Mesh	Mesh	Star, Peer-to-Peer, Mesh	Star	Star, Peer-to-Peer

and second, to check the proposed MAC algorithm (SARB) performance to reduce packet loss in LoRa communication.

For redundancy, we run two sensor nodes in parallel for 50 minutes. One sensor node is without redundancy (only primary board), while the other node is with redundancy (primary + redundant). The two nodes emulate the failure during the experiment. The failure is imitated by switching off the primary boards in each node. Since the node without redundancy has only a primary board, no packets are delivered during this duration. In contrast, the node with redundancy can send the packets with the redundant board.

As seen in Figure 6, the number of packets delivered by the node without the redundant board is significantly lower compared to another node. Without the redundant board, more than 50% of the packets are lost. Figure 7 demonstrates how the redundant board acts as a backup when the primary board fails. As the primary board fails around 600 $seconds$, it is immediately detected by the redundant board and acts as a substitute for the time the primary board is not working. As soon as the primary board is back online, the redundant board detects it and stops transmitting data. Between 2500 to 3000 $seconds$, even when the primary board is working, two packets are lost, which is also substituted by the redundant board. Even though these lost packets would be re-transmitted by the primary board, they would still miss the monitoring limit of 40 $seconds$. These results show that the redundancy feature makes the system robust to sensor node failure and packet losses with high responsiveness.

Further, to validate the proposed MAC algorithm, we need a baseline performance to compare. The baseline setup consists of 3 sensor nodes without redundancy (only primary boards). Each node transmits packets at the fixed transmission interval without the MAC algorithm. The noise signal is transmitted using an additional transmitter every 0.5 $seconds$ to emulate the interference. The baseline performance is obtained for three transmission intervals, i.e. $5, 15$ and 30 $seconds$. Once the baseline was obtained, these experiments were repeated for the same setup but with the MAC algorithm (SARB). These results will be referred to as 'MAC performance'. Thus, we

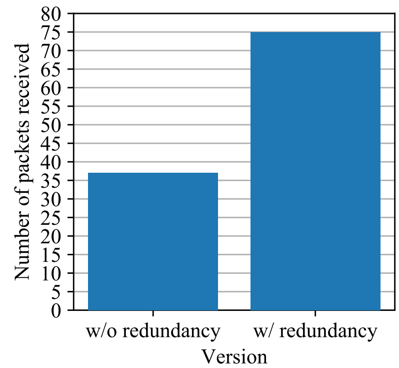


Fig. 6: The number of packets delivered by sensor nodes during the failure. The diagram contains nodes without redundancy and node with redundancy for comparison.

have baseline performance and MAC performance for each board. The results shown for all experiments are the average of 3 iterations. The performance of the boards is evaluated using the Packet Delivery Ratio (PDR).

As seen in Figure 8, the MAC performance is always better than the baseline for all three boards. For 30 seconds interval, the average PDR improves 34% with MAC implementation compared to baseline. Even for other intervals, the performance with MAC is better. The PDR values of all the boards are more consistent with the MAC implementation than the baseline. For 5 seconds interval, the transmission slots are minimal due to the $500ms$ step size for transmission interval. Thus the PDR ratios drop might be due to congestion in the channel. Even in this scenario, the performance is marginally better with MAC implementation.

VII. Applications and Future Scope

The proposed solution can be applied in different IoT applications where WiFi or cellular communication is not possible or affordable. For example, in smart farming, space habitats or smart buildings. Our proposed solution can be leveraged to increase system robustness and reliability. This system can

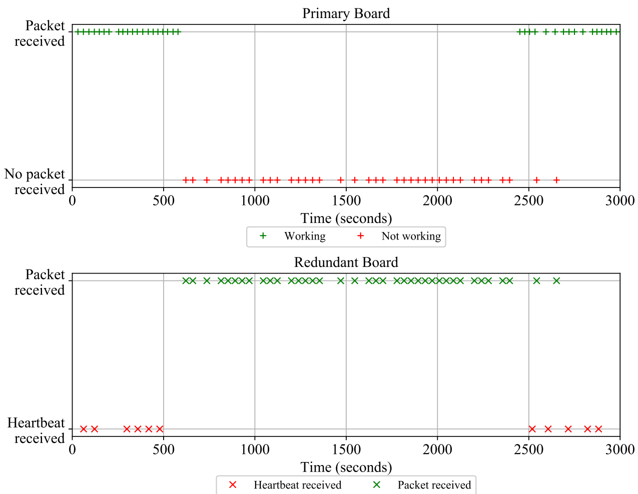


Fig. 7: Packet reception at the server from respective boards during failure. The first plot represents the packet received from the primary board. The upper line marks the received packets while the lower line marks the not received packet (Failure). The second plot shows the working of the corresponding redundant board.

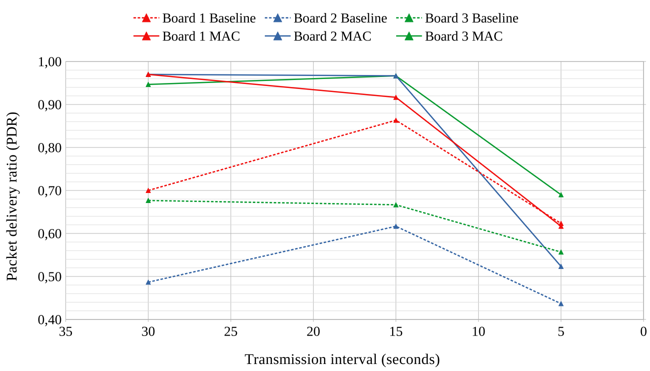


Fig. 8: comparison of baseline and our MAC implementation. Each experiment was performed with three sensor nodes. The dashed line represents curves for the baseline, and the solid line represents curves for our implementation (MAC).

also be used for critical applications where reliability is of utmost priority.

One of the drawbacks of the system is that it can only handle the failure of the boards by deploying a substitute and not by identifying the actual fault. Many resources would be wasted if each primary board had its respective redundant board. This makes a difference when the system needs to be deployed for space applications where resources are limited. Thus, optimizing the redundant network is essential.

VIII. Conclusion

In this work, we demonstrated the concept of redundancy which is very responsive and ensures that packets reach the destination within the defined monitoring delay in case of node failure. The redundant board not only acts as a backup for node failure but also helps to meet the monitoring requirement in case of packet loss or corruption. The proposed MAC algorithm, SARB, shows an improvement of 34% in packet delivery for 30 seconds intervals compared to raw LoRa implementation (LoRa PHY). Based on these results, the monitoring system is robust to sensor node failure, which is crucial in life-critical applications. Also, the proposed MAC algorithm, Slotted-ALOHA with Random Backoff (SARB) for LoRa PHY, combined with the message- queue based re-transmission, makes wireless communication more reliable in the environment with high noise and channel interference.

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