Signal Jamming Resilience Study

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Abstract

Reliable wireless communication is an important element of many robotic systems today, especially when robots work together or operate autonomously. Unfortunately, robots using wireless communication can be disrupted by both unintentional and intentional forms of physical interference (e.g., electromagnetic noise, traffic congestion on a communication network, or even a malicious attacker intentionally jamming signals). This paper will describe and analyze how disruption of robot-to-robot communication by signal jamming affects key performance parameters (packet loss, latency, and reliability) of the communication process in the presence of controlled amounts of interference. In addition to understanding the impact of interference to robot communication, this research also explores possible ways to increase the resilience of the communication process through adaptive hardware and software-based "digital shield" technologies (including frequency hopping, dynamically changing communication channels, and correcting errors that occur during transmission).

I. Introduction

Wireless communication is very important when it comes to how a robot functions, works, and performs tasks. These connections should be precise and stable for robots to operate accurately. However, these connections can sometimes be affected or disrupted by other signals interfering with them. In modern robotics, it is essential to maintain a strong and stable connection for accuracy and reliability, because unstable signals can cause robots to perform poorly or respond incorrectly to commands. There are different ways to reduce these problems, such as limiting unnecessary wireless signals in the surrounding environment or reducing interference from nearby devices. Understanding how interference affects robotic communication is important to improve system reliability and ensure that robots can continue to function correctly even in environments with many wireless signals.

II. State of the Art

A. Advanced Antenna and Reflecting Surface Technologies

Recent literature has heavily emphasized the use of environmental modifications to enhance wireless channel reliability. For instance, multi-reconfigurable intelligent surfaces (RIS) have been proposed to proactively augment propagation environments and establish multi-reflection line-of-sight links [4]. Similarly, the use of multi-active multi-passive intelligent reflecting surfaces allows for opportunistic signal amplification, effectively compensating for severe product-distance path-loss in complex settings [5]. Furthermore, rotatable antennas offer significant potential to enhance communication and sensing performance by flexibly adjusting the boresight of directional antennas to mitigate interference [6]. While these technologies present robust strengths in dynamically shaping the signal path, their primary weakness lies in the requirement for extensive external infrastructure and complex scheduling algorithms. In contrast to these environment-centric approaches, our work focuses on localized, onboard protection mechanisms that the robot can utilize independently of external infrastructure.

B. Channel Modeling and Error Probability

A second major category of research revolves around mathematically modeling fading channels and calculating theoretical error bounds. Comprehensive studies have introduced unified expressions for analyzing the capacity and bit error probability of wireless communication systems across generalized fading channels [2]. Additionally, investigations into medium band wireless communications have characterized the specific impacts of delay spread and multipath phenomena on received signals [1]. A distinct advantage of these models is their mathematical rigor and ability to optimize bandwidth and power allocations to approach infinite capacity limits under specific parameters [7]. However, a notable weakness is that these theoretical constructs often assume idealized hardware responses and do not account for the mechanical inertia and kinematic lag of robotic systems when packets are dropped. Our proposed methodology translates these theoretical communication failures into observable mechanical deficits, explicitly connecting bit error rates to missed physical displacement.

C. Security and Alternative Communication Modalities

To circumvent traditional radio frequency vulnerabilities, researchers have explored both enhanced physical-layer security and entirely alternative communication modalities. Studies on semantic security for indoor terahertz wireless communication have demonstrated that weakly directed transmitter antennas result in large insecure regions, highlighting the need for physical-layer security models utilizing additive white Gaussian noise frameworks [3]. Other novel approaches include optical wireless communication utilizing mixed orthogonal frequency division multiplexing waveforms to guarantee non-negative signals [8], as well as biologically inspired diffusion-based molecular communication using bacteria for highly specialized environments [9]. The strength of these alternative modalities is their inherent immunity to standard electromagnetic jamming. However, they suffer from practical weaknesses such as strict line-of-sight requirements for optical systems or extremely low data rates for molecular systems. Therefore, our research remains focused on standard radio frequency systems, seeking to secure them through practical hardware shielding and software filtering rather than abandoning the RF spectrum entirely.

D. Connection to This Study

While these studies explore advanced communication technologies, theoretical channel models, and alternative transmission methods, they mainly focus on improving signal reliability at the network or infrastructure level. On the other hand, this research investigates how wireless interference affects the physical performance of a robotic system during operation. Specifically, the robot is programmed to move forward for 10 seconds, and the distance travelled is measured under different interference conditions. By connecting communication disruptions such as packet loss or signal instability to measurable mechanical outcomes like reduced displacement, this study provides a practical evaluation of how communication reliability directly impacts robotic behavior. While these studies explore advanced communication technologies, theoretical channel models, and alternative transmission methods, they mainly focus on improving signal reliability at the network or infrastructure level. On the other hand, this research investigates how wireless interference affects the physical performance of a robotic system during operation. Specifically, the robot is programmed to move forward for 10 seconds, and the distance travelled is measured under different interference conditions. By connecting communication disruptions such as packet loss or signal instability to measurable mechanical outcomes like reduced displacement, this study provides a practical evaluation of how communication reliability directly impacts robotic behavior.

III. Concept

The concept of this study is to experimentally evaluate how communication disruption influences the operational behavior of a robotic system. Instead of focusing only on theoretical communication metrics, the design of this experiment connects communication reliability to the robot's observable physical performance during motion.

The experiment uses a Thymio II robot programmed with a predefined movement routine. The control code is uploaded to the robot before the experiment begins, allowing the robot to execute the programmed instructions autonomously. This approach ensures that the robot performs the same task consistently during each trial, enabling reliable comparison between different experimental conditions.

The experiment is based on a simple and controlled motion task. After the program starts, the robot moves forward continuously for 10 seconds, and the distance travelled during this time interval is measured and recorded. This motion serves as a measurable indicator of the robot's performance.

To examine the potential influence of communication disruption and interference, the experiment is conducted under different wireless signal environments. By comparing the measured distances across these conditions, it becomes possible to determine whether signal interference has any observable impact on the robot's movement.

The experimental design includes the following main components:

- Autonomous Execution: the robot runs a pre-uploaded program without manual control during the experiment.

- Controlled Motion Task: the robot moves forward for a fixed duration of 10 seconds.

- Performance Measurement: the total distance travelled is measured after each trial.

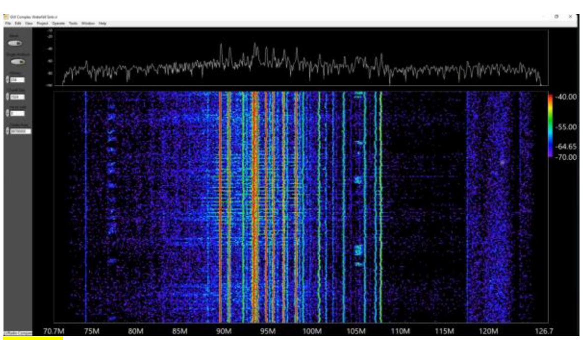
- Variable Signal Environment: tests are performed under normal wireless conditions and in environments with increased surrounding signals.

Through this design, the study provides a practical method for linking communication disturbances to measurable robotic performance outcomes.

IV. Implementation

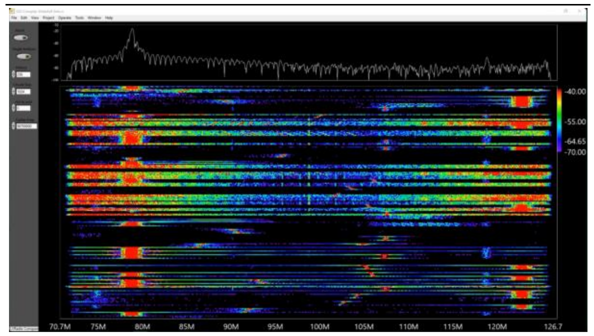
The experimental setup was implemented using the Thymio II robot in order to evaluate how wireless signal interference and noise can affect the communication environment surrounding robotic systems. The experiment focused on observing the wireless spectrum conditions and applying both hardware and software adjustments to reduce interference before performing the robotic movement test.

The first step of the implementation involved analyzing the normal wireless signal environment in the 2.4 GHz frequency band. A signal monitoring tool was used to observe the baseline spectrum activity in the testing area in order to determine the amount of wireless traffic and channel usage under normal conditions. This baseline measurement provided a reference for comparison with later interference scenarios (Fig. 1).



(Fig.1) Baseline wireless spectrum in the 2.4 GHz band showing normal signal activity before interference is introduced.

To simulate a noisy communication environment, additional wireless traffic was intentionally introduced near the experiment area. Multiple nearby devices such as smartphones and laptops were used to stream content and generate continuous network activity, increasing congestion within the 2.4 GHz band. This process created overlapping signals and higher channel utilization, which represents the type of interference commonly encountered in environments with many active wireless devices (Fig. 2). The physical setup of the devices used to generate this traffic is shown in (Fig. 3).

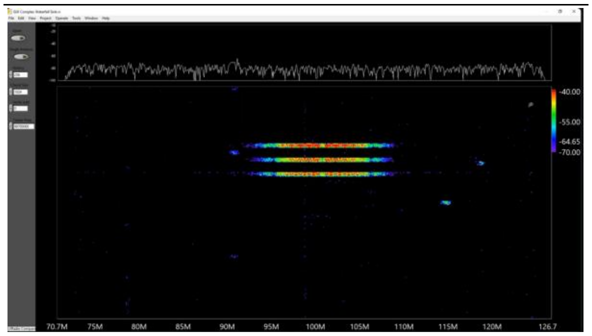


(Fig.2) Wireless spectrum under high interference conditions caused by increased nearby network traffic.

(Fig.3(*It is **AI Generated** to illustrate the idea*)) Devices used to generate additional wireless traffic near the experiment area.

After introducing interference, several hardware-based adjustments were applied to reduce the effect of external noise. These adjustments included adding metal foil around the robot and reducing unnecessary wireless devices operating near the experiment area. By controlling the surrounding environment, the level of electromagnetic interference affecting the communication system could be partially minimized.

In addition to hardware adjustments, software-based mitigation techniques were considered in order to improve communication reliability. One of the primary strategies involved selecting a less congested wireless channel within the spectrum. By shifting communication to a channel with lower signal activity, it becomes possible to reduce packet collisions and signal overlap. The difference between the congested channel and the quieter channel can be observed in the spectrum analysis results (Fig. 4).



(Fig.4) Spectrum analysis after switching to a less congested wireless channel.

After these adjustments were implemented, the robot was used to perform the motion experiment. The Thymio II robot was programmed with a predefined routine in which it moves forward continuously for 10 seconds. The program was uploaded to the robot prior to the experiment, allowing it to execute the movement autonomously once it started. The robot was placed at a fixed starting position in the testing area before initiating the test run.

At the end of the 10-second interval, the robot automatically stopped, and the distance travelled from the starting point to the final position was measured. This distance measurement served as the primary performance indicator for evaluating whether interference conditions could potentially influence the robot's movement performance.

Through this implementation, the experiment was able to observe the wireless communication environment, introduce controlled interference, apply mitigation strategies, and measure the resulting robotic performance.

V. Results

The results of the experiment were obtained by measuring the distance traveled by the robot during the 10-second forward movement test under different wireless signal conditions. Each test scenario was performed after observing the surrounding wireless spectrum and applying the corresponding interference or mitigation condition.

Before presenting the experimental measurements, a theoretical displacement was estimated based on the expected constant speed of the robot operating under ideal conditions, assuming no wireless interference or communication instability. This value serves as a reference for comparing the experimental results obtained under real-world conditions.

Table 1 – Robot displacement under different signal conditions

Test Condition	**Distance Travelled (cm)**
Theoretical distance (ideal condition)	170
Normal signal environment	165
High interference environment	158
After hardware shielding	162
After software channel adjustment	166
Hardware and software mitigation combined	168

The experiment showed that the robot travelled a slightly shorter distance when the wireless environment had more interference. In situations where many signals were present, the displacement was lower than it was during normal operation. This suggests that unstable communication conditions can affect how the robot performs.

When interference-reduction methods were introduced, the measured displacement increased. Adding hardware shielding helped block part of the external electromagnetic noise, and switching to a less crowded wireless channel also improved performance. When both methods were applied together, the robot achieved its highest displacement and came close to the theoretical value expected under ideal conditions.

Although the differences between the measurements were not very large, the results still indicate that wireless interference can influence the robot's movement. They also show that combining different mitigation techniques can improve communication stability and help the system operate more reliably.

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