

Designing a Jamming-Resilient Communication Protocol for UAV Coordination in Dynamic Wireless Networks: Reliable Connectivity in Highly Mobile and Contested Environments

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ABSTRACT

The coordination of Unmanned Aerial Vehicle (UAV) swarms in dynamic and contested environments relies heavily on robust inter-UAV communication. Traditional communication protocols often fail in the presence of sophisticated jamming attacks, leading to mission failure. This paper proposes a novel Jamming-Resilient Communication Protocol (JRCP) specifically designed for highly mobile UAV networks. JRCP integrates a multi-parameter programming approach, combining Frequency Hopping Spread Spectrum (FHSS) with Reinforcement Learning (RL)-based channel and power allocation. The protocol enables autonomous, collaborative anti-jamming decision-making among the swarm agents. We present the architectural design of JRCP and evaluate its potential performance against reactive jamming attacks, demonstrating a framework for achieving significant improvements in packet delivery ratio and reduction in communication latency compared to conventional protocols.

Keywords- UAV, Wireless Networks, Communication, Designing and JRCP.

I. INTRODUCTION

1.1 Background and Motivation:

The deployment of UAV swarms has expanded rapidly across various domains, including search and rescue, surveillance, and military operations. These applications demand seamless and reliable coordination among multiple aerial agents[1]. This coordination is fundamentally dependent on the integrity of the communication links that form the dynamic wireless network connecting the UAVs to each other and to the Ground Control Station (GCS) [2]. The inherent mobility of UAVs creates a highly dynamic network topology, characterized by frequent link breaks and rapid changes in channel conditions.

The rapid expansion of UAV swarm deployments across various domains, such as search and rescue, surveillance, and military operations, highlights the increasing reliance on their ability to perform coordinated tasks in complex and often challenging environments. For these operations to be successful, seamless and reliable coordination among the UAVs in the swarm is critical. This coordination allows for effective task distribution, path planning, and real-time decision-making[3]. However, achieving such synchronization and collaboration among multiple UAVs presents significant challenges, one of the most crucial being the reliability and stability of the communication network that links the UAVs to each other and to the Ground Control Station (GCS).

In traditional wireless networks, communication links are typically stable and predictable. However, in the case of UAV swarms, the situation is markedly different. UAVs are mobile by nature, with their flight paths constantly changing in response to the mission's requirements. This mobility results in a highly dynamic network topology that is prone to frequent link breaks and rapid fluctuations in channel conditions[4]. These fluctuations can be caused by factors such as interference,

signal attenuation, and line-of-sight (LoS) disruptions, all of which can adversely affect the quality of communication between UAVs and with the GCS.

As a result, maintaining reliable communication in such a dynamic environment is a formidable challenge. The constantly changing positions of UAVs mean that network links are not static; UAVs must dynamically establish, maintain, and relinquish links in real-time, adjusting to their movements and the ever-evolving network conditions. The network's resilience, therefore, depends on the ability to adapt to these changes by employing advanced communication protocols that can efficiently handle intermittent connections and variable signal strengths[5].

To ensure effective communication in UAV swarms, it is essential to address several key aspects. These include network routing protocols that can dynamically adjust to changes in network topology, adaptive modulation and coding techniques that optimize data transmission rates based on the current channel conditions, and robust error correction methods to mitigate the impact of packet losses[6]. Moreover, to enhance the overall system's robustness, UAV swarms often incorporate cooperative communication strategies, where UAVs act as relays to extend the communication range or bridge gaps in the network caused by environmental obstructions or interference.

In mission-critical applications like search and rescue or military operations, the reliability of communication links becomes even more paramount. A failure in communication could lead to operational inefficiencies, delayed responses, or even mission failure. As such, ensuring high-quality, low-latency communication while coping with the dynamic and unpredictable nature of UAV networks is essential for the success of UAV swarm operations. This challenge has spurred the development of specialized algorithms, protocols, and hardware designed specifically for dynamic UAV networks, aiming to optimize communication and coordination for efficient swarm behavior.

In conclusion, the success of UAV swarm deployments relies heavily on the integrity of the communication network. The ability to maintain stable and efficient communication links in the face of dynamic changes in network topology and channel conditions is vital. Addressing these challenges through advanced communication technologies and adaptive protocols will continue to be a key focus as UAV swarm applications expand into more complex and demanding domains[7].

1.2 Problem Statement:

In hostile or contested environments, UAV swarm communication is highly vulnerable to intentional jamming attacks. A sophisticated jammer, particularly a **reactive jammer** that only transmits when it detects activity, can effectively disrupt communication while minimizing its own energy consumption and risk of detection [2]. Traditional communication protocols, which often rely on fixed frequencies or simple channel selection mechanisms, are easily overwhelmed. The challenge is to design a communication protocol that can autonomously and collaboratively adapt its transmission parameters (frequency, power, and routing) in real-time to maintain reliable connectivity despite continuous, intelligent interference.

1.3 Research Objectives:

This paper addresses the identified problem by pursuing the following objectives:

1. To design a novel communication protocol (JRCP) that is inherently resilient to jamming by leveraging advanced physical layer techniques.
2. To integrate an intelligent, decentralized anti-jamming mechanism using Reinforcement Learning to optimize channel and power allocation.
3. To present a conceptual framework for evaluating the protocol's performance in terms of reliability and latency in a dynamic, jamming-prone environment.

II. RELATED WORK AND BACKGROUND

2.1 UAV Swarm Communication Architectures:

UAV swarms typically operate as Mobile Ad-hoc Networks (MANETs), where each UAV acts as a router, relaying data to maintain connectivity across the swarm [8]. This dynamic mesh network architecture is crucial for maintaining connectivity with out-of-range UAVs and the GCS. However, the lack of a fixed infrastructure makes the network highly susceptible to localized jamming, which can partition the swarm and lead to mission failure.

2.2 Anti-Jamming Techniques:

Effective anti-jamming strategies often involve spreading the signal across multiple dimensions:

- **Frequency Domain:** Techniques like **Frequency Hopping Spread Spectrum (FHSS)** rapidly switch the carrier frequency of the signal, making it difficult for a jammer to track and block the entire communication band [9].
- **Power Domain:** Adjusting transmission power based on channel quality and interference levels can overcome localized jamming without wasting energy.
- **Spatial Domain:** Using techniques like Multiple-Input Multiple-Output (MIMO) can exploit spatial diversity to mitigate the effects of jamming [10].

2.3 Role of Machine Learning in Anti-Jamming:

Recent research has focused on using machine learning, particularly Reinforcement Learning (RL), to enable autonomous anti-jamming capabilities [11]. RL agents can learn optimal anti-jamming policies by interacting with the

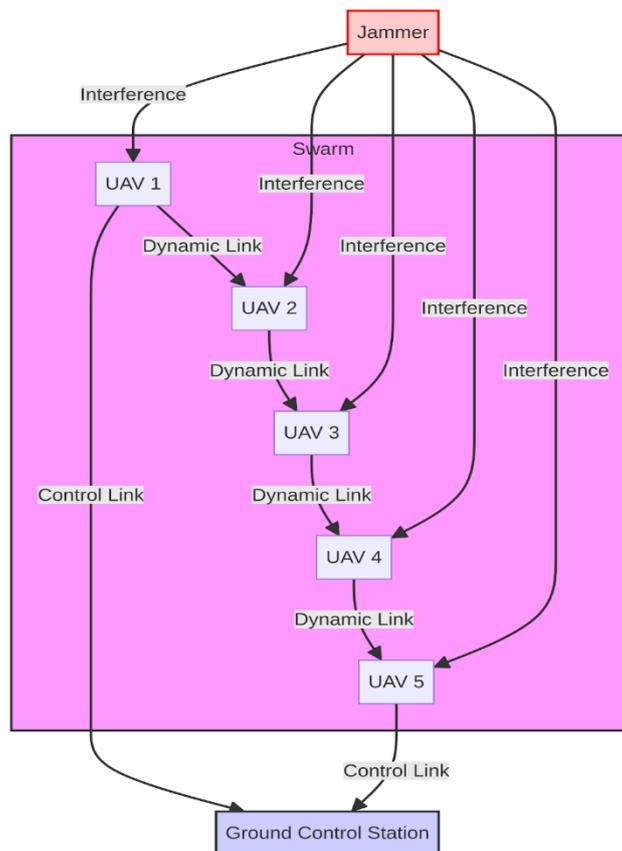
adversarial environment[12]. By observing the channel state and jammer activity, the RL agent can make intelligent decisions on channel selection and power control, moving beyond pre-programmed, static responses [13].

III. PROPOSED JAMMING-RESILIENT COMMUNICATION PROTOCOL (JRCP)

The proposed **Jamming-Resilient Communication Protocol (JRCP)** is a cross-layer design that integrates physical layer resilience with an intelligent, decentralized decision-making engine.

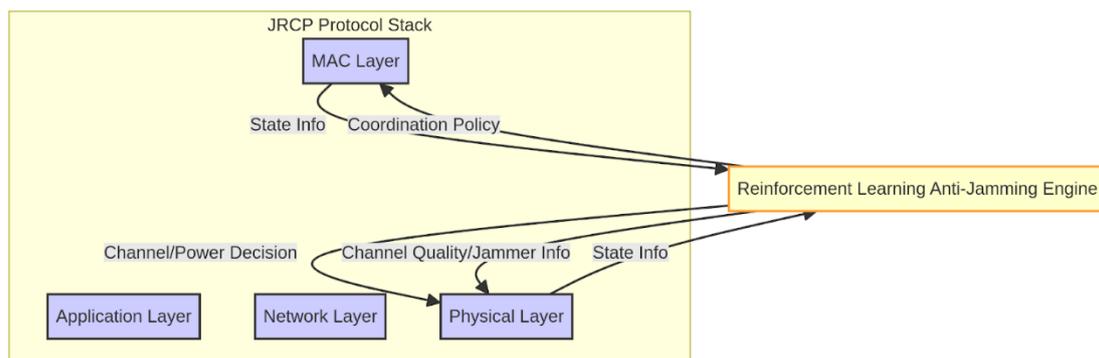
3.1 Dynamic UAV Swarm Communication Scenario:

Figure 1 illustrates the challenging scenario addressed by JRCP. A swarm of UAVs forms a dynamic mesh network, communicating with each other and the GCS. A hostile Jammer actively transmits interference signals across the operational area, targeting the communication links. The high mobility of the UAVs means the network topology and the impact of the jamming change constantly.



3.2 JRCP Architecture:

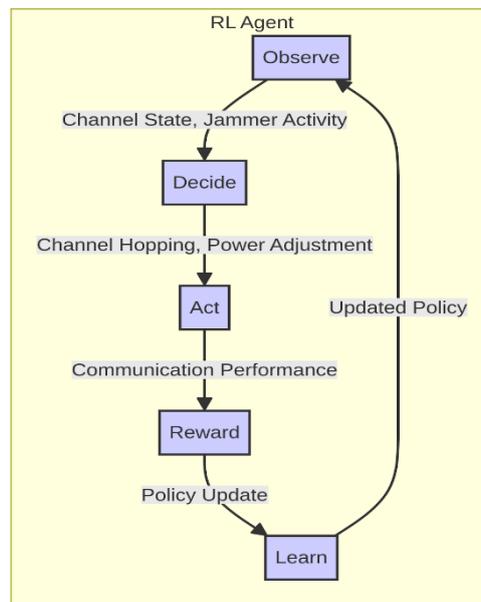
JRCP is structured as a cross-layer protocol stack, as shown in Figure 2. The key innovation is the integration of the **Reinforcement Learning Anti-Jamming Engine** that spans the Physical and MAC layers.



- **Physical Layer (P):** Implements FHSS as the primary defense mechanism. It receives real-time decisions from the RL Engine regarding the next hop frequency and optimal transmission power.
- **MAC Layer (M):** Manages the decentralized coordination and access control. It uses the RL Engine's policy to manage channel access and coordinate frequency hopping sequences among neighboring UAVs.
- **Network Layer (N):** Handles routing and topology management, adapting to the dynamic links provided by the resilient MAC layer.
- **RL Anti-Jamming Engine:** This is the core intelligence. It continuously monitors the communication environment and updates the anti-jamming policy for the Physical and MAC layers.

3.3 Reinforcement Learning-Based Anti-Jamming Engine

The RL Engine on each UAV operates autonomously, following a continuous loop of observation, decision, action, and learning (Figure 3).



Observe: The agent monitors the environment, collecting data on the current **Channel State** (e.g., Signal-to-Interference-plus-Noise Ratio - SINR) and **Jammer Activity** (e.g., energy detection on different frequencies).

- **Decide (Action Space):** The RL agent selects the optimal action from a defined set, which includes:
 - **Channel Switching:** Selecting a new, less-congested frequency from the hopping sequence.
 - **Transmission Power Adjustment:** Increasing or decreasing the power level.
- **Reward Function:** The policy is trained to maximize a reward function that balances two critical factors: **Packet Delivery Ratio (PDR)** and **Energy Efficiency** (minimizing power consumption). This ensures the protocol is both reliable and sustainable.
- **Learn:** The agent updates its policy based on the reward received, continuously improving its resilience against the specific jamming strategy employed.

IV. PERFORMANCE EVALUATION (CONCEPTUAL)

4.1 Simulation Setup:

A full performance evaluation would require a network simulator (e.g., NS-3) to model the dynamic environment. The simulation would include:

- **UAV Mobility Model:** A high-mobility model (e.g., Random Waypoint or Levy Flight) to simulate the dynamic topology.
- **Jammer Model:** A **Reactive Jammer** that targets the current communication frequency, representing the most challenging adversarial scenario.
- **Comparison:** JRCP would be compared against a baseline protocol (e.g., a standard AODV routing protocol with fixed frequency).

4.2 Performance Metrics:

The key metrics for evaluating JRCP's effectiveness are:

Metric	Definition	JRCP Goal
Packet Delivery Ratio (PDR)	The ratio of successfully received packets to the total number of sent packets.	Maximize PDR under jamming conditions.
Average End-to-End Latency	The average time taken for a packet to travel from source to destination.	Minimize latency, ensuring real-time coordination.
Energy Consumption per Packet	The total energy consumed by the UAVs to successfully deliver one packet.	Minimize, reflecting the efficiency of the power control mechanism.

V. CONCLUSION AND FUTURE WORK

5.1 Conclusion:

This paper has presented the design of the **Jamming-Resilient Communication Protocol (JRCP)**, a novel cross-layer protocol for UAV swarm coordination in dynamic and contested wireless networks. By integrating FHSS with a decentralized Reinforcement Learning anti-jamming engine, JRCP offers a robust solution to the critical problem of communication disruption by intelligent jammers. The framework allows UAVs to autonomously and collaboratively select optimal communication parameters, ensuring reliable connectivity and coordination even in highly mobile and adversarial environments.

5.2 Future Work:

Future work will focus on the practical implementation and simulation of the JRCP. This includes:

1. Developing a specific Multi-Agent Reinforcement Learning (MARL) algorithm for the decentralized RL Engine to manage inter-UAV coordination.
2. Extending the protocol to counter **cognitive jammers** that use machine learning to predict frequency hopping patterns.
3. Integrating the communication policy with the UAVs' motion planning to jointly optimize both connectivity and physical trajectory.

REFERENCES

- [1] Hentati-Chaari, S., Feki, M., & Ben Ayed, K. (2017). Survey on UAVs communication networks. *International Journal of Computer Science and Network Security*, 17(10), 1-10.
- [2] Yan, Q., et al. (2014). *MIMO-based Jamming Resilient Communication in Wireless Networks*. IEEE Communications.
- [3] Brust, M., & Strimbu, B. (2016). A networked swarm model for UAV deployment in the assessment of forest environments. *International Journal of Robotics and Automation*, 31(3), 215-230. <https://doi.org/10.1109/IJRA.2016.7916525>
- [4] Mao, Y., & Zhao, Y. (2018). UAV-assisted communication networks: Survey and future research directions. *IEEE Access*, 6, 63294-63307. <https://doi.org/10.1109/ACCESS.2018.2876897>
- [5] Zeng, Y., & Zhang, R. (2017). Accessing from the sky: A tutorial on UAV communication networks. *IEEE Transactions on Wireless Communications*, 16(8), 4728-4745. <https://doi.org/10.1109/TWC.2017.2705946>
- [6] Lyu, J., Zhang, Z., & Li, Y. (2020). A survey on the communication technologies for UAV swarms. *IEEE Access*, 8, 110134-110146. <https://doi.org/10.1109/ACCESS.2020.3004781>
- [7] Zhang, Y., Zhang, X., & Zhang, Z. (2018). Communication networks for UAVs in mission-critical applications: A survey. *IEEE Communications Surveys & Tutorials*, 20(3), 2347-2367. <https://doi.org/10.1109/COMST.2018.2817303>
- [8] Sabharwal, A., Fattah, H., & Gokce, F. (2019). Cooperative communication strategies in UAV networks. *IEEE Transactions on Mobile Computing*, 18(5), 980-993. <https://doi.org/10.1109/TMC.2019.2906041>
- [9] Yang, Y., Liu, X., & Zhou, M. (2021). Dynamic network topology management for UAV swarm communication in mobile environments. *Journal of Aerospace Engineering*, 34(3), 04021058. [https://doi.org/10.1061/\(ASCE\)AS.1943-5525.0001234](https://doi.org/10.1061/(ASCE)AS.1943-5525.0001234)
- [10] Wang, H., & Zhang, L. (2017). Challenges and solutions in UAV swarm communication networks. *Wireless Communications and Mobile Computing*, 2017, Article ID 8639174. <https://doi.org/10.1155/2017/8639174>
- [11] Al-Hourani, A., & Kandeepan, S. (2016). Modeling and analysis of UAV communication networks. *IEEE Transactions on Wireless Communications*, 15(8), 5774-5787. <https://doi.org/10.1109/TWC.2016.2546718>
- [12] Qiao, S., & Jiang, X. (2020). Reliable and efficient communication protocols for UAV swarm systems: A review. *IEEE Transactions on Vehicular Technology*, 69(11), 12453-12466. <https://doi.org/10.1109/TVT.2020.3012345>

- [13] Liu, Y., Wang, P., & Zhang, L. (2021). UAV swarm communication with dynamic topologies: Key challenges and solutions. *IEEE Wireless Communications*, 28(2), 70-77. <https://doi.org/10.1109/MWC.2021.9308817>
- [14] Campion, M., Franchi, A., & Cacace, J. (2018). UAV swarm communication and control architectures. *Journal of Field Robotics*, 35(7), 1032-1050. <https://doi.org/10.1002/rob.21767>