MQLINK: A Scalable and Robust Communication Network for Autonomous Drone Swarms

Wen-Chun Huang
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
g110064030@smail.nchu.edu.tw

Chun-Liang Lin*
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
chunlin@dragon.nchu.edu.tw

Yang-Yi Chen
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
kd04957@email.nchu.edu.tw

Chia-Hsuan Lai
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
nchuxuan@smail.nchu.edu.tw

Chian-Yu Lu
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
sixthousand916@gmail.com

Syu-You Ciou
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan
g111064045@mail.nchu.edu.tw

2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE) | 979-8-3503-9971-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/ISIE51358.2023.10228080

***Abstract*—This paper presents a novel drone network architecture, MQLINK, for autonomous drone swarms, addressing communication, coordination, and scalability problems. The proposed system utilizes a lightweight, efficient MQTT protocol and incorporates a self-developed UAVLINK module to ensure robust communication in various scenarios, including emergencies and infrastructure failures. The effectiveness of MQLINK in leader-follower formation and proximity detection is demonstrated through real-world experiments on the prototypes. This work advances drone swarm technology, offering a practical solution for enhancing mission efficiency, completion rate, group complementarity, and system flexibility in various applications such as performance, surveying, logistics, inspection, and disaster relief.**

Keywords—UAV swarm, ad-hoc network, Robot sensing systems, Distributed control, Edge AI, communication

I. Introduction

Autonomous drones are increasingly used in various fields, such as performance, surveying, logistics, inspection, and disaster relief [1,2]. The focus is shifting towards autonomous drone swarms, which offer improved mission efficiency, completion rate, group complementarity, and system flexibility. However, those vehicles require extensive information exchange for stable formation and flight. Although building reliable and scalable drone networks has been historically challenging, the emergence of 5G provides highly scalable, reliable, and secure connectivity for mobile networks, facilitating rapid deployment of new drone services. While 5G networks provide scalable and reliable connectivity, it is crucial to have point-to-point communication for emergencies.

As UAV autonomy advances rapidly, research on formation control and networks has increasingly grown. Yanpeng Cui et al. [5], propose an adaptive topology-aware flexible routing strategy using Q-learning for decentralized and autonomous routing decisions, aiming to enhance the flexibility and throughput of networks supporting heterogeneous 5G drone swarms. Gary B. Lamont et al. [6], developed a technique to control drone formations by defining ten basic behavioral rules and assigning appropriate weights to each task according to the situation. Many studies have been conducted in simulated environments.

A. Current swarm drone network

Infrastructure-based, Flying Ad-Hoc Networks (FANETs), and Cellular Networks architectures are three common approaches to drone swarm communication [7]. UAV performances typically utilize infrastructure-based architectures to manage data transmission and communication. FANETs enable drones to form temporary, decentralized networks, enhancing autonomy and robustness. However, small drones may face limitations with dynamic routing and data exchange. Due to the advent of 5G networks, cellular networks can offer high data rates and better coverage, facilitating the communication of UAVs, streaming videos in real-time, and sending LiDAR point clouds.

B. MQ Telemetry Transport

MQTT is a lightweight binary protocol that outperforms HTTP because of its minimal packet overhead. MQTT is widely used and popular worldwide to connect constrained devices of all deployment sizes, such as V2X, manufacturing systems, and logistics. MQTT is superior to the proprietary TCP protocol in car networking scenarios, especially, as the number of vehicles on the platform increases. This makes many car manufacturers such as BMW and Audi to adopt MQTT for communication. Jafet Morales et al. [4] found that MQTT outperformed PUBNUB in a 4G environment. Furthermore, the ROS (Robot Operating System) was selected as the main framework for UAV development due to its modular design, scalability, and ease of maintenance. Lennart Reiher et al [8] developed a ROS-MQTT interface for edge cloud lidar object detection. The cluster of brokers enhances the overall reliability and availability of the messaging system by allowing service continuity in case of a broker failure.

To tackle the challenging issues still remained, we focus on the following solutions.

- A novel drone network, MQLINK, is developed, offering high scalability and robustness.
- Developing a UAVLINK module, which is independent of infrastructure.

The results presented in this paper demonstrate the outcomes of real-world experiments on the prototypes..

II. Methodology

Current drone swarm communication architectures, such as infrastructure-based systems, flying ad-hoc networks (FANETs), and cellular networks, face limitations like scalability, infrastructure dependence, limited range, interference susceptibility, and network latency. The MQLINK framework addresses these challenges by providing robust, flexible, and reliable communication.

Figure 1 shows the proposed network architecture. The blue line signifies the drone's use of MQTT to transmit information such as flight position, attitude, and power levels via the Internet. Simultaneously, the ground station sends commands to the drone and tracks its status through the network. The red line represents the UAVLINK broadcast packet, which facilitates the transmission of information required for coordinating tasks between drones. UAVLINK uses the radar symbol table to scan nearby drones. If drones are detected within a specified range, a packet is sent to notify them, helping to prevent potential collisions.

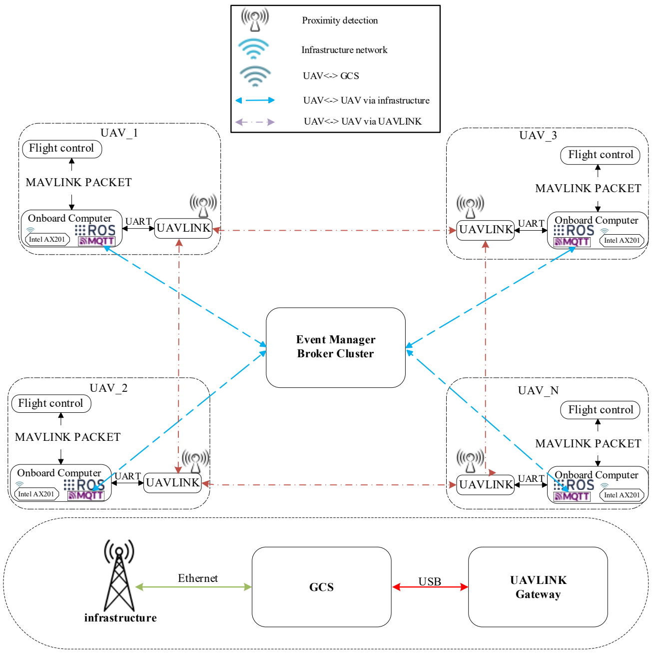


Fig. 1. Swarm coordination communication framework

A. MQTT

1) Optimizing Swarm comm. With Pub/Sub pattern

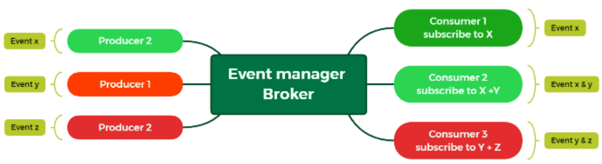


Fig. 2. Decoupled event-driven architecture

Published/subscribed pattern show in Fig. 2, utilizing an event-driven approach, offers an efficient and effective solution for communication and selective information sharing, particularly in the context of a growing number of drones. The systems prevent overload by enabling drones to subscribe only to the relevant topics or data streams related to their specific roles and missions only when needed. The event-driven nature minimizes communication overhead ensuring drones receive real-time updates on essential information and allowing them to react quickly to environmental changes or evolving mission objectives. This approach improves the overall system responsiveness and agility while conserving communication resources. Moreover, the unmanned aerial systems can avoid chain reactions by utilizing the published/subscribed model, which decouples publishers from subscribers. The separation ensures that changes or expansions in one part of the system do not directly affect others, allowing the entire communication network to grow and adapt to accommodate new drones without experiencing performance degradation or bottlenecks.

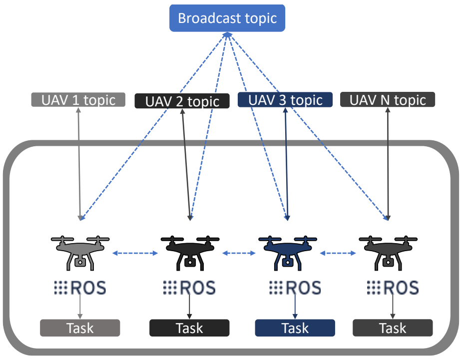


Fig. 3. Swarm drone MQTT

In the drone swarm system shown in Fig. 3, we implement dynamic subscription management to optimize communication resource usage and minimize overhead. Before takeoff, all drones subscribe to GPS messages from their peers as part of the leader selection process. Once a leader is chosen, each drone unsubscribes from other drones' GPS messages, maintaining its subscription solely to the leader's GPS updates until an alternative leader is required. This adaptive approach streamlines communication and enhances the system operating efficiency.

2) Handling Unexpected Disconnections

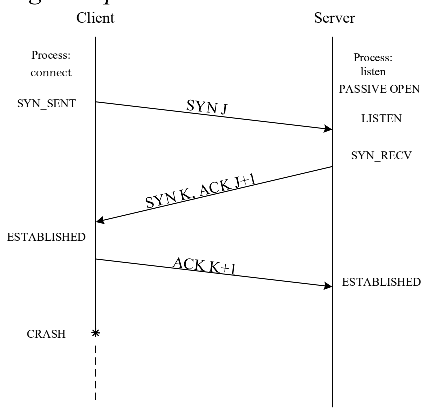


Fig. 4. TCP half-open

An indicator such as the remaining power and motor status can be used to evaluate health of a drone during flight. However, it is crucial to consider unexpected situations that may cause the drone to fail. In theory, in the event of an onboard computer failure, TCP/IP should be notified when the socket is disconnected. However, in practice, especially with mobile and satellite links, TCP may "black hole" the session. This situation creates the appearance of an open connection, in general, the data is discarded.

TCP half-open connections can be fatal to drone swarms, as a single point of failure may trigger a chain reaction. Mavlink's heartbeat mechanism exhibits some shortcomings in drone swarm systems, partly due to its original design needing to be tailored for such applications. The most notable limitations involve the potential overhead and absence of automatic notifications. Even amidst stable connections, continuously transmitting heartbeats at 1Hz generates excessive communication overhead. In addition, the drone must actively monitor the heartbeat information of other drones in the swarm, which will further introduce additional overhead.

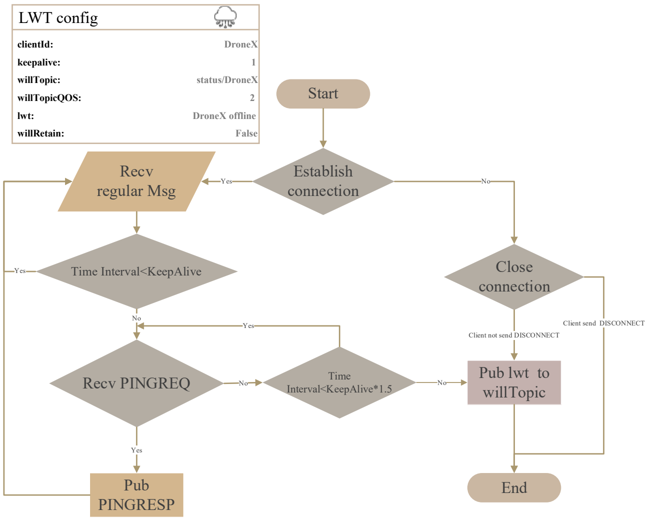


Fig. 5. Heartbeat mechanism flow chart

As shown in Figure 5, this study employs MQTT's Keep Alive and LWT(Last Will and Testament) functionalities to address the challenges above to implement a heartbeat mechanism. The Keep-Alive mechanism ensures that the broker and client communication link remains open and acknowledged. Messages are exchanged regularly, and the Keep-Alive interval is not bypassed; no supplementary messages are required to verify the connection state. The LWT feature empowers the broker to broadcast a message on a predetermined topic in case of an unexpected client disconnection, effectively notifying other drones within the cluster of the unexpected disconnection.

B. *UAVLINK modules*

In most instances, MQTT over TCP/IP effectively caters to the communication requirements of the swarm. Nonetheless, communication disruptions may arise during exceptional situations or within isolated locations. To counteract these issues, we have devised a tailor-made UAVLINK module. Moreover, we aim to employ UAVLINK as a radar warning system to circumvent potential collisions among drones, enhancing overall safety and efficiency.

1) *Design of the UAVLINK Module*

TABLE I. UAVLINK MODULES SPEC

UAVLINK modules			
			
AL702T		SN720M	
SPEC	Typical	Unit	Condition
VDD Power	3.3	V	VDD
Baud rate	250000	bps	8, N, 1
Operating	2482	MHz	RF

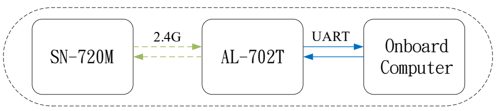


Fig. 6. UAVLINK block diagram

The UAVLINK system is a custom communication module designed for drone swarm applications, consisting of an AL702T core and an SN720M chip. The block diagram for UAVLINK can be found in Figure 4. The AL702T is the core component responsible for communication with the onboard computer. The SN720M is equipped with the integrated 900 MHz and 2.4GHz chips, which serve point-to-point communication and radar scanning, respectively.

2) *Data Size Compression Using Protobuf*

UAVLINK's communication module has a long transmission distance, but its speed is limited. Protobuf will be used for packet size compression to increase transfer speed. Smaller packets result in faster transmission, as demonstrated by the Shannon-Hartley theorem. The formula for channel capacity (C) in bits per second involves bandwidth (B) in Hertz and signal-to-noise ratio (SNR). Channel capacity is directly proportional to bandwidth and logarithmically proportional to SNR, so reducing packet size enhances channel capacity and speeds up a transmission.

$$C = B\log(1 + SNR) \qquad (1)$$

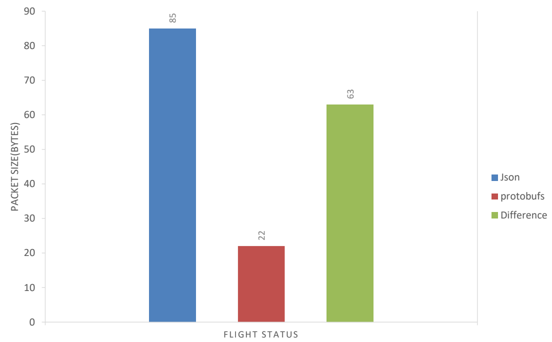


Fig. 7. Comparison of data size for Protobufs and JSON

As shown in Fig. 2, using protobuf for flight status (shown in TABLE III) data reduces the data size by 63 bytes compared with JSON. Reducing data size can improve transfer speeds and the efficiency of drone communications.

3) *Network Packet Design*

TABLE II. PACKET DESIGN ARCHITECTURE

Header (1byte)	MODE_ID (1byte)	MSG_ID (1byte)	PAYLOAD (22bytes)	SYS_ID (2bytes)	RSSI (1byte)	CHECKSUM (2bytes)

UAVLINK network packets contain several fields to ensure efficient communication and data integrity during transmission. The custom package design structure is illustrated in the accompanying figure. These fields ensure efficient communication and data integrity during transmission. The Header verifies if a message belongs to a new packet, while Mode_ID differentiates between communication modes. MSG_ID contains unique identifiers for different information types, while the payload carries information content based on MSG_ID. SYS_ID identifies the sender's number, and RSSI indicates the receiver's signal strength. Checksum is used for error-checking calculations and verification.

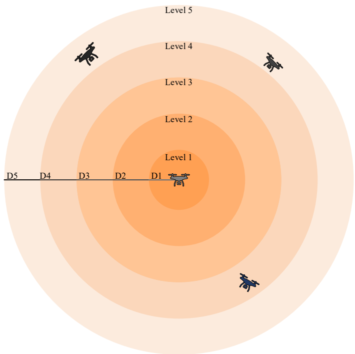
TABLE III. PACKET STRUCTURE AND PAYLOAD INFORMATION

MSG ID/Name	**PAYLOAD**			
120/Fly_status	Lat	Lng	Alt	Heading
121/heartbeat	Mode	RTK_Status	SYS_Time	
122/ACK	Command_Number	Result	SYS_Time	

This study designed three network packets for UAVLINK to facilitate efficient communication and information sharing within a drone swarm. MSG120 provides essential data for group formation, including latitude, longitude, altitude, and heading. MSG121 is a heartbeat message sharing each drone's health status, mode, RTK status, and system time. MSG122 is a confirmation packet after receiving instructions containing the command number, result, and system time.

4) Proximity detection

UAVLINK utilizes the received signal strength indication (RSSI) and time difference to detect nearby drones within the swarm, providing proximity detection that is particularly beneficial when GPS signals are unreliable or unavailable. This feature allows drones to take appropriate action to avoid collisions and maintain a safe distance from other drones in the group. Moreover, proximity sensing reduces the need for active GPS monitoring of all drones. It enables passive monitoring of drone swarms by detecting nearby drones and issuing warnings, which reduces network throughput and minimizes the risk of information overload.



Alter level	Distance	Interval
L1(D1)	1.5M-3.5M	0s
L2(D2)	3.5M-5.5M	2s
L3(D3)	5.5M-7M	5s
L4(D4)	7M-8.5M	8s
L5(D5)	8.5M-10M	10s

Fig. 8. UAVLINK proximity detection of alert levels and intervals

III. REAL-WORD EXPERIMENTS

To prove the effectiveness of the method used in this study, we provide three video clips with their URLs given as follows

- https://www.youtube.com/playlist?list=PLnv7vfbbhQ1Rwd_YZh6D4xMo5KcKD9K4w

The first video clip demonstrates three UAVs flying in a group using the MQLINK communication protobuf with a TCP/IP network without the UAVLINK communication module. The formation change is completed, and the experiment achieves the goal as scheduled. The second video clip aims to prove effectiveness of the UAVLINK. In the first half of the video clip, the UAVLINK module is tested to measure the relative distance between two drones. The results show that when drones are close to each other, the warning is indeed adequate. The second half of the video clip demonstrates another drone transmitting its coordinates to the tested drone, with the latitude and longitude on the video constantly updating. As a result, UAVLINK is capable of transmitting simple messages. The third video clip shows a comprehensive test using the communication structure of MQLINK with the UAVLINK module while turning off the TCP/IP network function. Six drones were used in this test. The results show that the drones can accept commands and take off simultaneously, but the UAVLINK still requires adjustments as the group flight remains unstable. This shortcoming will be addressed in our future work.

IV. CONCLUSIONS AND FUTURE WORKS

This study presents MQLINK, a novel drone network architecture, to address communication and coordination challenges in autonomous drone swarms. MQLINK leverages MQTT for its lightweight and efficient communication capabilities and incorporates a self-developed UAVLINK module to ensure robust communication even in emergencies or infrastructure failures. Real-world experiments on the prototypes have demonstrated the effectiveness of the proposed system in various scenarios, including leader-follower formation and proximity detection.

Our future works will concentrate on enhancing and expanding MQLINK's capabilities. Crucial areas of investigation involve measuring the impact of round-trip latency on system performance, particularly about using protobuf for packet compression to boost communication efficiency and assessing the effect of serialization/deserialization on latency. Additionally, exploring the integration of proximity detection with MQTT for dynamic subscription management will enable the system to adapt to real-time changes in swarm configurations. Further refinements to the UAVLINK module are anticipated to augment efficiency and dependability. This continued research will advance MQLINK and its applications in autonomous drone swarm technology and the reliability of the network.

ACKNOWLEDGMENT

THIS PROJECT IS SUPPORTED BY THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL OF TAIWAN UNDER GRAND NO. MOST 110-2811-E-005 -508 -MY2 AND NSTC 111-2634-F-005-001 - PROJECT SMART SUSTAINABLE NEW AGRICULTURE RESEARCH CENTER (SMARTER).

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