Leveraging LTE links for Multi-UAV Collaboration & Communication in Mesh Ad-hoc Network Utilizing BATMAN-adv Routing

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Abstract

Outdoor implementation for multi-UAV collaboration heavily depends on the reliability of communication links between multiple UAVs in a dynamic environment. Furthermore, network infrastructures are not always available or limited and routing needs to be optimal to provide an efficient communication and data transmission among the UAVs. This paper presents a system architecture for collaborative multi-UAV search and rescue operations in outdoor environments. By leveraging Wireless Mesh Ad-hoc Networks (WMANs) with LTE links and modified BATMAN-adv routing protocol, the architecture enables decentralized control, allowing UAVs within a swarm to perform tasks autonomously while facilitating effective collaboration. WMANs offer flexibility in network mobility and reconfiguration without introducing a single point of failure (SPoF), making them suitable for dynamic environments. BATMAN-adv ensures continuous connectivity with proactive routing, load balancing, and low overhead. Integration of LTE technology provides broader coverage and high throughput, with modifications to BATMAN-adv enabling the use of LTE link quality metrics. UAVs can act as internet gateways, extending LTE coverage to areas with limited cellular coverage. This system architecture enhances search and rescue mission effectiveness by providing reliable communication, efficient routing, and seamless collaboration among UAVs.

Ⅰ. Introduction

Unmanned Aerial Vehicles (UAVs) have emerged as a versatile technology with applications which includes surveillance and reconnaissance, disaster response and communication relay, and even in logistics industry. In scenarios where traditional infrastructure is lacking or compromised, UAVs can establish ad-hoc networks to enable communication and collaboration, cooperation, or coordination among themselves. Flying Ad-hoc Network (FANET) [1], Mobile Ad-hoc Network (MANET) [2], and Wireless Mesh Ad-hoc Network (WMAN) [3] are some of the existing ad-hoc network technologies used for multi-UAV applications. However, establishing and maintaining reliable communication links between multiple UAVs in dynamic environments poses significant challenges.

Wireless mesh network is a decentralized network system that uses an ad-hoc communication mode based on the available wireless technology, e.g., 802.11 standards. [3] WMAN have been a solution to enable a flexible communication between UAVs in a swarm without relying on fixed infrastructure. WMAN has a self-organizing manner where it allows drones to autonomously form and reconfigure network connections based on proximity and signal strength. By dynamically forming and reforming connections between nodes, WMANs can adapt to changes in topology and environmental conditions, making them suitable for dynamic scenarios such as disaster response and search and rescue operations. Several communication protocols aside from Wi-Fi are utilized in mesh network implementation such as Zigbee, Bluetooth, and LoRaWAN. Although, it is ideal for cellular or next-generation communication due its flexibility and extensive coverage, there is a lack of research and study for integration of this technology.

Nowadays, cellular networks have taken a big part in the industry for machine-to-machine communication and Internet-of-Things. LTE technology offers several advantages over traditional wireless communication technologies such as Wi-Fi, Zigbee, and LoRaWAN [4]. First, LTE provides higher data rates, lower latency, and better reliability, making it suitable for high-bandwidth applications and real-time communication requirements. Second, LTE offers wider coverage, enabling communication over longer distances and in areas where other technologies may struggle to maintain connectivity. Additionally, LTE networks are typically more robust and secure, providing encryption and authentication mechanisms that ensure the confidentiality and integrity of transmitted data.

Comparing LTE to other technologies, Wi-Fi suffers from limited coverage and is susceptible to interference in crowded environments. Zigbee, while suitable for low-power and low-data-rate applications, lacks the bandwidth required for high-throughput communication. LoRaWAN, although offering long-range communication, suffers from low data rates and high latency, making it less suitable for real-time applications.

In this paper, LTE technology will serve as the primary communication medium for the WMAN, providing high-speed links between UAVs and ground stations. By leveraging LTE, we can enable direct communication paths between sender and receiver, bypassing intermediate nodes and reducing latency in the network. This direct communication capability is facilitated by the BATMAN-adv (Better Approach to Mobile Ad-hoc Networking) [5] routing protocol, which dynamically selects the most efficient paths for data transmission based on link quality and network conditions. Furthermore, even in areas without cellular coverage, our proposed strategy utilizes UAVs as internet gateways to extend LTE coverage from the nearest cell tower to the mission area. This enables seamless communication between client node UAVs in the mesh network and effectively extending the coverage almost globally.

Ⅱ. Methodology

The proposed system architecture is primarily created for collaborative multi-UAV [6] search and rescue operations in an outdoor environment. The system utilizes WMAN with LTE links as the communication medium and BATMAN-adv as the routing protocol. The architecture is designed to facilitate a decentralized control, where UAVs within a swarm perform their tasks autonomously, such as mapping and surveying the target area. Additionally, each UAV has the ability to analyze and recognize situations, determining the need for collaboration with other UAVs within the swarm.

The WMAN is structured in a decentralized manner, allowing each node (UAV) to communicate directly with neighboring nodes. This flexibility enables network mobility and reconfiguration, allowing drones to join or leave the network dynamically without disrupting communication. The network is self-organizing, enabling drones to autonomously form and reconfigure network connections based on proximity and signal strength. Notably, WMANs have no single point of failure (SPoF) and possess less overhead compared to other aerial network structures like Flying Ad-hoc Networks (FANETs) or Mobile Ad-hoc Networks (MANETs). FANETs, while suitable for certain applications, are more prone to single points of failure due to centralized control. Additionally, they suffer from increased overhead and complexity in managing node mobility. MANETs, on the other hand, require more manual configuration and lack the self-organizing capabilities of WMANs. MANETs are also less suited for dynamic environments where node mobility is high.

Several options exist when considering the choice of routing protocols for WMANs in multi-UAV scenarios. In this paper, BATMAN-adv was selected which would best fit the use-case scenario and proposed system architecture. BATMAN-adv is a proactive routing protocol that ensures continuous connectivity even in dynamic environments, making it well-suited for multi-UAV collaboration scenario. BATMAN-adv was designed to replace Optimized Link State Routing (OLSR) that is based on link-state information. BATMAN-adv enables multi-hop communication, which facilitates data relay through intermediate UAVs, extending effective communication range and increasing network resilience. BATMAN-adv calculates the best route to destination based on metrics like throughput and packet loss. Hence, providing load balancing across the network, ensuring that no single node becomes overwhelmed by traffic and maintain optimal network performance. BATMAN-adv also has low overhead against other routing protocols. This is achieved by broadcasting routing information periodically rather than by flooding the network with routing updates which are beneficial in a multi-UAV application. Its dynamic configuration, encryption and authentication mechanisms, and high scalability, capable of supporting large number of nodes in the network makes it suitable for our use-case.

BATMAN-adv also runs at the kernel level in Linux operating systems which are commonly used in robotics. A protocol running in the kernel level in an operating system reduces the amount of processing time and produces minimal latency. Therefore, comparing with protocols that do not run in the kernel makes it more suitable for multi-UAV applications. Each node in BATMAN regularly broadcasts Originator's Message (OGM) packet. The OGM packet contains the Source Address, Transmitter's Address, Time to Live (TTL), Hop Count (HC), Transmission Quality (TQ), and Sequence number. TQ represents the quality of a link between two nodes in the mesh network in terms of throughput, packet loss, and other factors affecting data transmission. The Higher TQ values indicate better link quality, suggesting higher throughput and lower packet loss. TTL represents the maximum number of hops that a packet can traverse before being discarded. TTL prevents packets from circulating indefinitely in the mesh network, ensuring packets are eventually dropped if it cannot reach the destination. Hence, preventing routing loops and ensures efficient packet delivery. HC represents the number of hops between a source node and the destination node in the mesh network. BATMAN-adv uses HC to assess the proximity of neighboring nodes and to determine the shortest or most optimal paths for routing packets. These are the information used to determine the best possible route in reaching the destination. There are two types of nodes within the mesh network—the gateway and client. Gateway nodes serve as entry and exit points for the mesh network, connecting it to external networks, such as the internet. They typically have stable connections to the wider network and are responsible for relaying traffic between the mesh network and external networks. Client nodes are regular nodes within the mesh network that communicates with each other and a gateway node to relay data within the mesh network.

Wi-Fi is the standard or commonly used communication protocol in a wireless mesh network. In this paper, LTE technology is leveraged due to its nature. The utilization of LTE technology to the WMAN enhances the system's capabilities by providing global or broader coverage, high throughput for faster data transmission, and the ability for some communication paths to become direct, bypassing intermediate nodes in multi-hop communication and establishing direct links between sender and receiver. Due to the different nature of LTE technology compared to Wi-Fi, Zigbee, Bluetooth, and other several wireless communication protocols, the BATMAN-adv routing is modified to use LTE link quality metrics. LTE link quality metrics such as Reference Signal Received Power (RSRP), Signal-to-Interference Noise Ratio (SINR), and Reference Signal Received Quality (RSRQ) are added and these metrics will be used to determine the quality of LTE links and optimize routing decisions. Additionally, parameters such as OGM interval, link quality thresholds, and enabling gateway mode are also modified considering our proposed system. By enabling gateway mode, the system will be able to utilize UAVs as internet gateways which extends LTE to the target area in cases where LTE coverage is non-existent or limited. This enables seamless communication between client node UAVs in the mesh network and effectively extending the coverage almost globally.

Ⅲ. Conclusion

The proposed system architecture has been developed to support collaborative multi-UAV search and rescue operations in outdoor environments. By leveraging Wireless Mesh Ad-hoc Networks (WMANs) with LTE links as the communication medium and modifying BATMAN-adv to accommodate LTE link quality parameters as the routing protocol, the proposed architecture aims to provide decentralized control, enabling UAVs within a swarm to perform tasks autonomously while facilitating effective collaboration.

The decentralized structure of the WMAN allows each UAV to communicate directly with neighboring nodes, ensuring flexibility in network mobility and reconfiguration. This self-organizing capability enables drones to form and reconfigure network connections autonomously based on proximity and signal strength, without introducing a single point of failure (SPoF). Among the various routing protocols available, BATMAN-adv was selected for its proactive nature and suitability for our multi-UAV collaboration scenario. The integration of LTE technology into the WMAN enhances system capabilities by providing broader coverage, high throughput, and possible direct communication paths between sender and receiver. Modifications to the BATMAN-adv routing protocol accommodates the use of LTE link quality metrics such as RSRP, SINR, and RSRQ to optimize routing decisions accordingly. By enabling gateway mode, UAVs can act as internet gateways, extending LTE coverage to areas with limited or no cellular coverage, effectively extending communication coverage globally.

In conclusion, the proposed system architecture, utilizing WMAN with LTE links and modified BATMAN-adv routing protocol, offers a robust and scalable solution for collaborative multi-UAV operations in search and rescue scenarios. The integration of advanced technologies ensures reliable communication, efficient routing, and seamless collaboration among UAVs, ultimately enhancing the effectiveness and safety of search and rescue missions in outdoor environments.

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