CLAN: A Robust Control Link for Aerial Mesh Networks in Contested Environments

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Abstract. Huge increase in the availability of commercial off-the-shelf unmanned aerial vehicles drastically shifts the way these devices operate and interact, enabling easy and affordable deployment of multiple drones to form a mesh network to perform aerial multi-robot missions such as 3D mapping, surveillance. This trend led to the development of unique applications and services relying on aerial mesh networks in contested environment, but also enables adversaries to improve their ability to counteract using simple techniques such as jamming. In this paper, we propose a robust Control Link for Aerial mesh Networks, namely CLAN, jointly disseminating mesh and UAV control traffic, to ensure reliable control communication for aerial mesh networks, via multi-path, multi-hop control links in contested environment. CLAN forms a dynamic tree topology, where control traffic is forwarded through multiple hops and utilizes multiple access technologies enabling multi-path end-to-end links in order to mitigate the effects of decreased signal power in longer ranges and the possibility of jamming attacks. Computer simulations of the contested environment show that the proposed CLAN algorithm that uses modified B.A.T.M.A.N. algorithm to selectively rebroadcast traffic control messages in order to significantly reduce the traffic control message number by 90% while improving the connectivity of the nodes compared to single hop MAVLink communication up to 72% in simulation results.

Keywords: Wireless mesh networks · B.A.T.M.A.N. · Proactive routing · Traffic control messages · Connectivity · Dynamic tree topology · Jamming · MAVLink

1 Introduction

Unmanned Air Vehicles (UAVs) are getting more affordable, smaller and more capable everyday, extending their domain from military to public and civil use with various new applications such as crowd monitoring, surveillance, traffic

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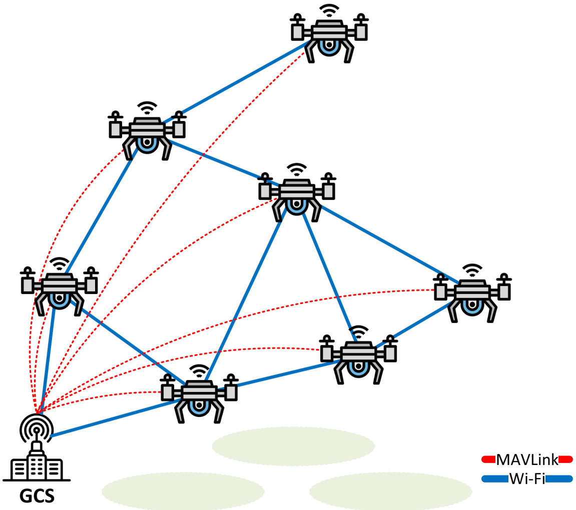

Fig. 1. Both MAVLink and UAV-to-UAV mesh links are up

control, cellular data offloading and logistics [1–4]. This trend also enables having multiple UAVs cooperating in order to perform shared tasks such as reconnaissance or monitoring hostile environments [5,6]. In most of these applications, UAVs require an active direct one-hop link with a Ground Control Station (GCS) for downstreaming sensor data to GCS and getting command and control parameters from GCS. Due to the nature of electromagnetic waves, the received power is inversely proportional to the square of the distance between the source and the destination, thus limiting the operation range of a UAV. This communication channel becomes susceptible for a jamming attack since the received power weakens as the UAV travels farther from the GCS. With above challenges in mind, we propose to use ad-hoc links between UAVs that are used to forward UAV-to-UAV messages in order to create and maintain logical e2e connections for the control messages between the GCS to UAV. However, any proactive mesh network protocol relies on its own control traffic to be generated and forwarded periodically in order to maintain an up-to-date topology. Considering this mesh control traffic is flooded through network, this traffic alone poses a risk to saturate ad-hoc links in larger networks. This, additional control traffic of UAVs burden de-facto protocol (shown in Sect. 3 and Sect. 4). Therefore, we develop a robust Control Link for Aerial mesh Networks, abbreviated as CLAN, that forms employing selective rebroadcast mechanisms in order to reduce the amount of traffic control messages. As our target scenario, we assume that the leaves in the formed tree structure are *mission nodes* that perform the main task of the multi-UAV system and the rest of the nodes, called *network nodes* act as a backbone to relay these messages to the GCS.

The CLAN framework that we propose uses the information from received traffic control (TC) packets at each drone and therefore operate using local information of that drone. Since the network is highly dynamic that has three degrees of freedom of movement, we think that the topology would change before having every information of the current state. Furthermore, CLAN framework designed to work in contested environments where jammers exist against drone surveillance missions. We propose a heuristic approach to move the network nodes in order to maintain connectivity of the mission nodes to the GCS while being able to sense and escape from jammers in such contested areas. The network nodes move autonomously with respect to the changing position of the other nodes or sensing a high received signal power that is interpreted as jamming attack with respect to proposed movement algorithms in order to increase connectivity and to form possible multiple paths from a node to the GCS to provide more resiliency.

We list the main contributions of the paper as follows:

- We conduct set of preliminary experiments, showcasing how existing mesh protocols suffers in maintaining e2e connection due to the large overhead of traffic control messages saturating the network containing multi-hop links and how long range links are vulnerable to jamming attacks.
- We design and implement CLAN framework, jointly optimizing the dissemination of both mesh and UAV control traffic, where MAVLink and B.A.T.M.A.N. protocols are used together as the baseline approach.
- We evaluate the performance of CLAN through extensive simulations, showing CLAN allows UAVs to operate in longer range, provide resilience against jammer attacks and improve connectivity.

The rest of the paper is structured as follows. Section 2 layouts the related works. The system overview and the details of CLAN are explained in Sect. 3. The evaluation results are presented in Sect. 4 and we conclude the paper with Sect. 5.

2 Related Work

In [7–9] researchers propose using the cellular network for both UAV-to-UAV (U2U) and UAV-to-GCS (U2G) communication for better performance. [10,11] study the network structure when there is no need for communicating with a central infrastructure node. Multicast trees in AODV [12] introduce packet delay, OLSR [17] makes the nodes learn the complete view of network and computationally more complex and active tree route finding mechanism in IEEE 802.11s [13] required three messages back and forth to complete tree finding. Instead of these protocols, we have changed the structure of OGM messages in B.A.T.M.A.N. and rebroadcasting of TC messages to form a node tree with low computational complexity.

In [14], OLSR (proactive) and DSR (reactive) protocols are compared in MANET with nodes having low mobility and it is shown that OLSR has outperformed DSR in terms of packet delays. The drawback of reactive protocols

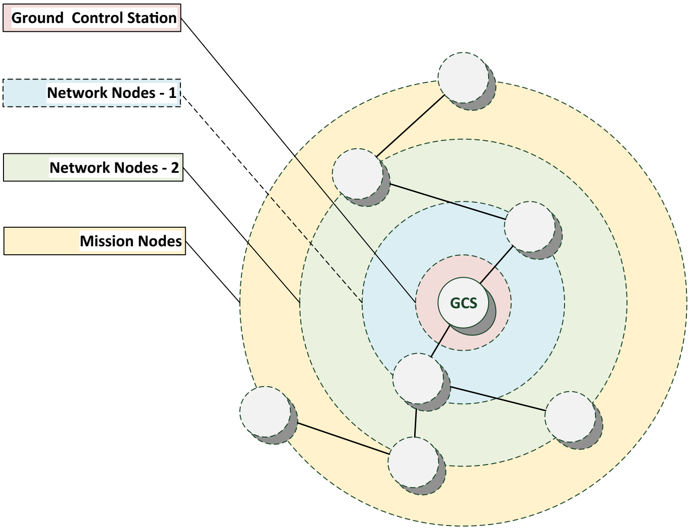

Fig. 2. Tree structure of nodes

is that there is a route finding delay before being able to send packets to their destination[14]. We have opted to use a proactive routing protocol because a) it ensures fresh and ready route tables and b) there is no route finding delay. However, the TC messages and the data traffic in the network can cause packet losses due to interference. In addition to this, Flying Ad-Hoc Networks (FANETs) have different challenges than MANETs and VANETs in terms of mobility and three degrees of freedom in the movement. To tackle with this situation [15,16] have proposed using directional antennas.

In [17] a wireless mesh network based on B.A.T.M.A.N. protocol with multiple ground potential receivers has been used to improve resiliency at the cost of compromising network throughput. These approaches are not suited for small rotary wing UAVs in a hostile environment. In this study, we propose a method to maintain UAV-GCS communication using the available wireless mesh network where the C2 Link fails. We achieve this by creating a tree structure of nodes with minimal Traffic Control messages by modifying the B.A.T.M.A.N. protocol [17] (Fig. 3).

3 System Model

In this paper, we approach the problem of UAV-GCS communication using wireless mesh network , where there are multiple drones in the system. We are mainly motivated by B.A.T.M.A.N. protocol [18] used for routing in multi-hop Mobile Ad-Hoc Networks (mhMANET). We modify this existing protocol to suit our needs. The system model that we study here is as follows: The drone network that performs the mission is initialized with at least one drone in each branch. The

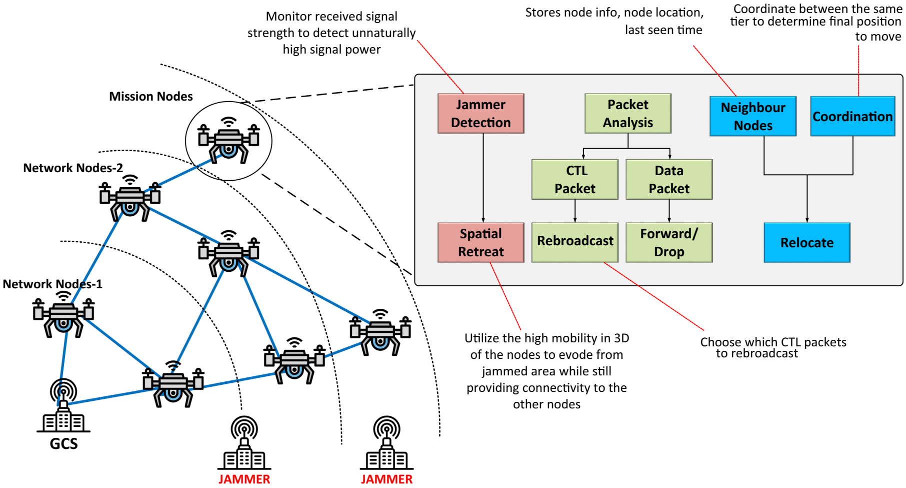

Fig. 3. CLAN concept

network drones are prohibited from their initial mission in order to ensure that there are drones closer to the Ground Control Station to relay the messages from further nodes. In the next section we will compare the original B.A.T.M.A.N. with our modified approach. The system model in normal situation is shown in Fig. 1. In the scenario of hardware fail on the GCS or an intentional disruption on the MAVLink is present, the communication can only be achieved by using the present wireless mesh network.

As mentioned above, in order to decrease the number of the traffic control messages and the data messages we form a tree of nodes. The OGMs, also called originator messages, in B.A.T.M.A.N. is only rebroadcasted if the received OGM has come from a node in the lower branches. Therefore, the source of this originator node designates the node in the upper branches as the best next hope. In the Fig. 2 the tree formed in the example scenario is shown.

This selective rebroadcast of messages decrease the number of TC packets in the network. Downstream messages from the UAVs to the GCS is aggregated along the tree. This way, total number of data packets are reduced. Similarly, upstream messages from the GCS to the UAVs are sent as a one big packet and disaggregated along the way, also helping reducing the number of packets in the network. Since we decrease both the TC messages and command-and-control messages we decrease the packet loss rate.

Jammer Detection: Jammer detection block analyses the received signal levels and checks if a packet is received successfully. If the received signal power is high and the UAV doesn't receive a packet, it triggers spatial retreat.

Spatial Retreat: Randomly move to another position within the signal range of nodes in lower branch in order to evade the jammed area while maintaining connectivity of the nodes.

Packet Analysis: The packet analysis module checks if the received packet is a traffic control (TC) packet or a data packet. If the received packet is a TC packet, the packet is sent to the Selective Rebroadcast block as an input. If the received packet is a data packet, the packet is sent to the upper layers in the network.

Selective Rebroadcast: The block parses the received TC packet. If the received TC packet is sent from a node in higher branch, immediately drops the packet. If the packet is received from the same branch or from lower branches, check the "Original Sender" field and "Sequence Number" field in the TC message header to determine if the node has rebroadcasted this message recently by checking the circular buffer allocated for recently sent messages. If the buffer doesn't contain this message, i.e., the received message is fresh, then the node rebroadcasts this TC message to its neighbours. The selective rebroadcast algorithm is described in Algorithm 1.

Neighbour Nodes Table: Stores and updates the list of neighbour node information from the received TC packets. The information contains the location of the node, last time a message is received from the node and the branch of the node. If a connection is lost to a previously connected node, the information about the lost neighbour node is sent to the coordination block.

Coordination: When a previously existing connection fails between the neighbouring nodes, this block uses the information in the Neighbour Nodes Table block to determine a new position a node should be placed in order to restore the broken connection. The output of this block is the new position of the node in order to try to restore the recently broken connection.

Relocate: Gets the input from Neighbour Nodes and Coordination blocks to decide to stay or compute the next position to move.

Algorithm 1 Selective Rebroadcast Algorithm

```
$m_j \leftarrow received\ traffic\ control\ message\ from\ node_j$
if $m$ is not in the messages set then
    $orgSender \leftarrow Originator\ Address\ field\ in\ the\ packet\ header$
    $seqNo \leftarrow Sequence\ Number\ field\ in\ the\ packet\ header$
    if $nodeTier_j > nodeTier_i$ or $TTL == 0$ then
        drop $m$
    else if didn't receive $m$ before then
        decrease TTL by one
        Rebroadcast $m$
        add (orgSender, seqNo) pair to sent messages set
    else
        drop $m$
    end if
end if
```

The selective rebroadcast algorithm significantly reduces the number of TC messages in the network especially where the operation area is smaller and the number of nodes is higher.

Algorithm 2 Movement Algorithm of the Network Nodes in CLAN

```
for time = 1 to SimulationTime do
  for each node i do
    if ($senseJammer(i)$) then
      Move(i)
    end if
    if ($nodetier_i$ < MAX_TIER_NUMBER) then
      for each node j != i do
        if ($receive\ packet\ from\ node_j$) then
          $Add\ node_i\ to\ recentlyCommunicatedList\ of\ node_j$
          lostTimer[i, j] = 0
        else
          increment lostTimer[i, j] by 1
        end if
        if ($lostTimer[i, j] == TIMEOUT\_THRESHOLD$ and $j\ is\ in\ list\ recentlyCommunicatedList\ of\ node_i$) then
          Move(i, j)
          giveUpCounter(j)++
          if ($giveUpCounter(j) == TIMEOUT\_THRESHOLD$) then
            $Remove\ node_j\ from\ recentlyCommunicatedList\ of\ node_i$
          end if
        end if
      end for
    end if
    if ($recentlyCommunicatedList\ of\ node_i\ is\ empty$) then
      MoveRandomlyInsideOperatingArea()
    end if
  end for
end for
```

4 Performance Evaluation

In this section, we compare the experimental results with the current approach in order to demonstrate the performance improvements. Mainly, CLAN provides two major improvements to the overall performance of UAV-GCS communication. The first improvement is the reduced number of the traffic control messages in the network using a proactive routing protocol. We validate this by comparing the number of the traffic control messages between the original B.A.T.M.A.N. algorithm and our proposed selective rebroadcast method. We generate the nodes randomly while guaranteeing that there is at least one node in each branch. Then, we record the initial position of the nodes in order to simulate the both B.A.T.M.A.N. and CLAN algorithm using the same initial parameters. The simulations are run with varying maximum area and the number of nodes. Each simulation is run for 100 seconds and the simulations are run 1000 times and the average number of generated traffic control messages are shown in Fig. 4.

We observe that as the area gets smaller and the number of nodes gets larger, the selective rebroadcast algorithm significantly reduces the number of

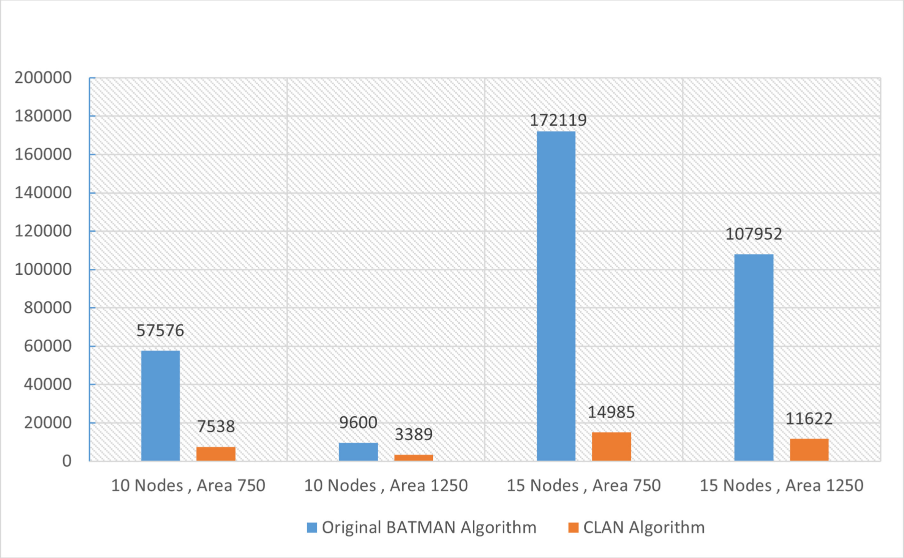

Fig. 4. Number of traffic control messages in proactive routing

traffic control messages. In larger areas with lower number of nodes, the nodes are sparse and there are less loops between the nodes, so the number of traffic control messages in B.A.T.M.A.N. is fewer.

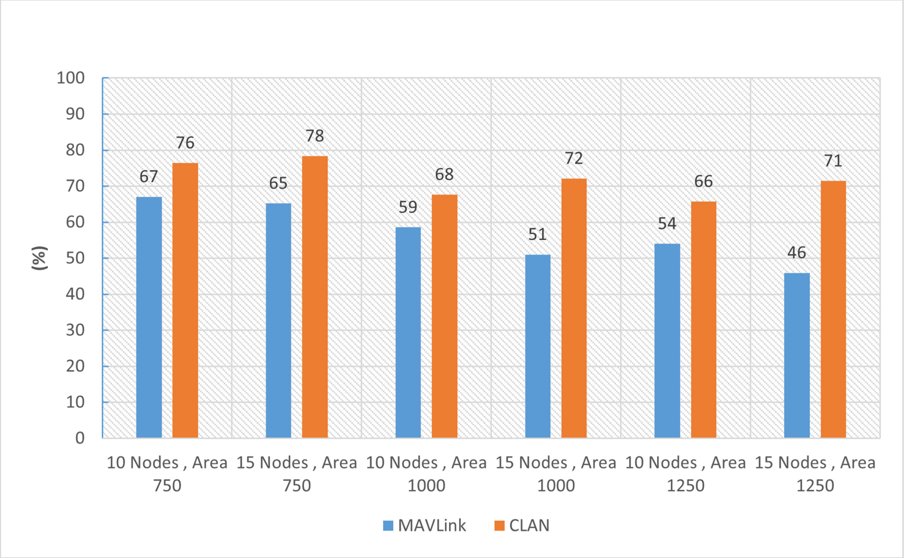

Fig. 5. Average connectivity

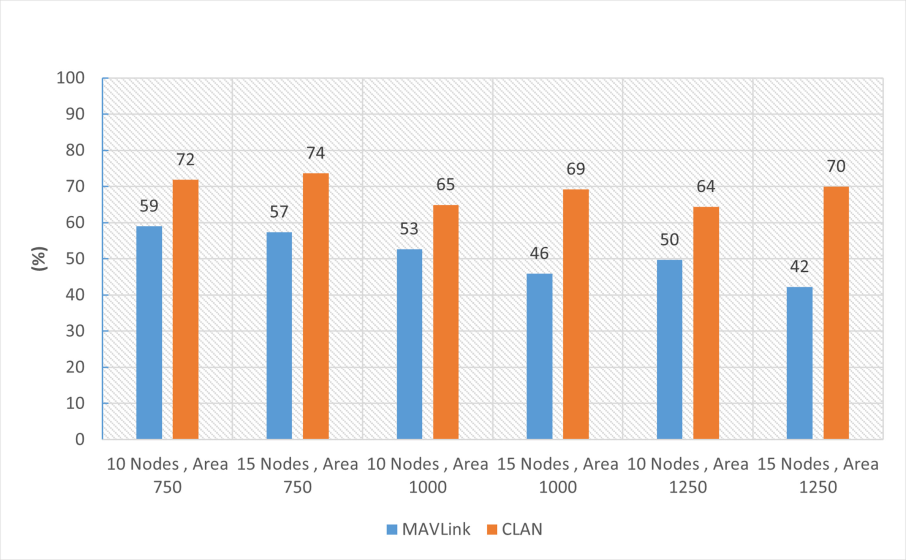

Fig. 6. Average connectivity (1 Jammer)

However, even in this situation CLAN algorithm reduced the number of the traffic control messages greatly.This improvement reduces the traffic control messaging overhead in the proactive routing in the mesh network between the nodes.

Secondly, we compare the connectivity of the system using CLAN algorithm that enables multi-hop transmission of the UAV messages and the system using individual MAVLink links to connect each node to the ground control station with a direct link. Connectivity of a node is "1" if a node can reach to the GCS and "0" if the node cannot. Total connectivity is the ratio of connected nodes over the total number of nodes, shown in Eq. 1 where N represents the number of total UAVs in the network. Both methods are simulated in order to get the average connectivity with the same initial node positions in each simulation run. Each simulation is run for 100 seconds and the simulation is run 1000 times to get the average results. The average percent of the connectivity is shown in varying area size, number of nodes and number of jammers are shown in Figs. 5–7 within the range of 95% confidence interval.

$$Connectivity = \frac{\sum_{i=1}^{N} c_i}{N} \tag{1}$$

It can be seen that when the operation area of the group of drones is small, CLAN framework outperforms the single-hop communication by merely 10%. However, as the area increases, our proposed algorithm performs better by up to 50%. In the presence of standing jammers -that are randomly distributed in each simulation- the improvement is larger since the network nodes in CLAN relocate themselves in order to maintain connectivity while the communication in single-hop MAVLink is disrupted.

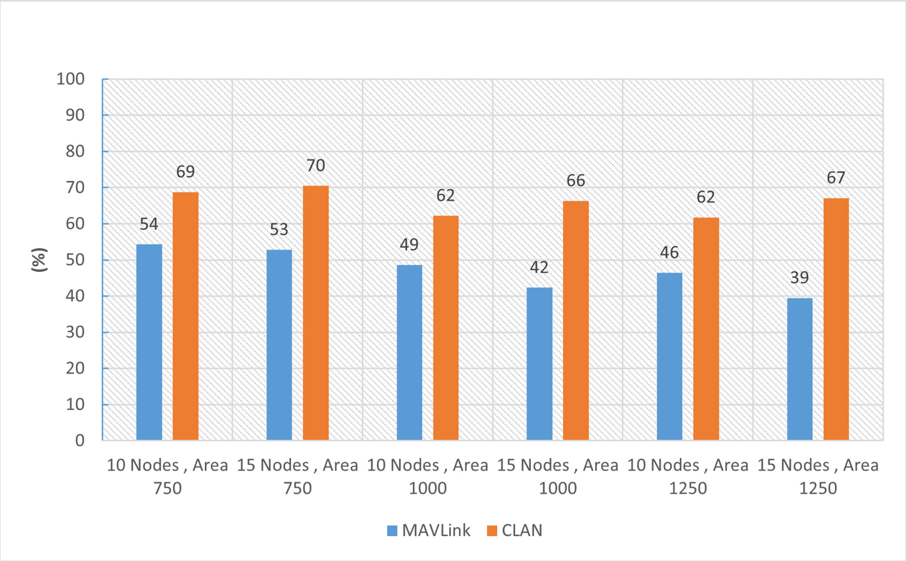

Fig. 7. Average connectivity (3 Jammers)

5 Conclusion

In this paper, we proposed an algorithm in order to increase the connectivity of multiple UAV systems by dividing the nodes into branches with respect to their distance to the ground control station and form a ad-hoc mesh network between the nodes. In our approach, we used an proactive ad-hoc routing in order to combat highly dynamic network topology due to the nature of UAV networks. We modified the B.A.T.M.A.N. algorithm to reduce the number of traffic control messages and according to our simulations we reduce these messages by up to 90%. With the reduced overhead of the traffic control messages, this ad-hoc mesh network is used to provide communication between the UAVs and the ground control station. The messages are sent over multiple hops and over possible multiple paths which increases the operation range and connectivity of multiple UAV systems. Our heuristic algorithm to relocate the node relies on local information and allows the node to act faster to broken links and possible jamming attacks. According to our results, CLAN algorithm does perform 10% better where the both the operation area and the number of nodes is smallest when no jammers are present and the improvements go up to 72% compared to single-hop communication using individual MAVLinks for each drone.

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