

The Design and Validation of ICN-Enabled Hybrid Unmanned Aerial System

Manveen Kaur
School of Computing
Clemson University
Clemson, SC, USA
mkaur@clemson.edu

Rahul Amin
Tactical Networks Group
MIT Lincoln Laboratory
Lexington, MA, USA
rahul.amin@ll.mit.edu

Jim Martin
School of Computing
Clemson University
Clemson, SC, USA
jmarty@clemson.edu

Abstract—This work presents a measurement study that evaluates a novel Information Centric Networking (ICN)-enabled Hybrid Unmanned Aerial Vehicle (UAV) System called IH-UAS. IH-UAS leverages ICN along with an innovative system model integrating broker-based publish-subscribe message dissemination with a decentralized architecture to form an ad hoc (infrastructure-less) UAS to carry out military missions. The overarching research goal that drives this study is to design a system that pushes decision-making to the UAV swarm on the battlefield such that mission tasks are completed more reliably and in less time than traditional centralized UAV-based missions. We use theoretical and measurement-based analysis to validate the system. Through experiments conducted using a simplified variant of a Coordinated Search and Tracking (CSAT) application in IH-UAS, we demonstrate that IH-UAS performs better than the same application operating in a traditional centralized solution. We also show that the broker placement and the number of brokers are critical to application performance.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) provide pivotal assistance for tactical missions. A UAV on the battlefield communicates with a ground control station (GCS) using a beyond line of sight satellite link or a line of sight tactical data link. This system is collectively referred to as an Unmanned Aerial System (UAS). The US Department of Defense (DOD) classifies UAVs into five categories that help identify similar types of UAVs across several dimensions such as size, operational limitations, and physics-based mobility capabilities [1]. A large UAV such as the MQ-9 Reaper is classified as group 5 UAV while a smaller UAV such as the Wasp III is classified as group 1 UAV. Group 1 UAVs are comparatively resource-constrained in terms of computation, memory, communications, and battery power. However, they offer scalable and flexible deployment for battlefield missions in urban areas.

In centralized UAV missions, the GCS assigns a mission task to the UAV and analyzes the collected data using a computational system and a human operator. This closed-loop or human-in-the-loop decision-making requires frequent communication over a wireless link incurring high communication latency. Recent research recommends the implementation of machine learning (ML) algorithms on the UAVs to conduct some data processing locally in order to reduce communication with the GCS and overall mission time [2]. While group 5 UAVs can support the computation required for

ML algorithms by provisioning additional hardware such as a high-performance embedded computer, group 1 UAVs utilize a distributed implementation by forming a UAV swarm and implementing group decision-making. Group decision-making algorithms in a UAV swarm critically depend on well-timed, synchronous, and reliable reception of data from all relevant sources at the decision-making node within the swarm.

Therefore, a current focus in the research community is to optimize communication latency and reliability in a UAV swarm subject to the limiting characteristics of the UAVs. Recently proposed solutions to address this problem make use of technologies like Software-Defined Networking (SDN) [3], edge computing [4], and Information Centric Networking (ICN) [5]. ICN, specifically, is considered a promising solution for dynamic networks such as UAV swarms that require reliable, data-centric communication with low communication latency. However, the relevance of these technologies in the UAV swarm is established through their demonstrated benefits in other ad hoc networks, e.g., mobile (MANET) or vehicular (VANET) ad hoc networks. Contrary to these ad hoc networks, a UAV swarm may require three-dimensional mobility, more frequent topology changes, and a higher concentration of nodes in a given area [6]. Hence, an essential precursor to future UAV swarm system design is the measurement-based analysis of the design components in highly specific swarm scenarios.

In this paper, we provide a measurement-based analysis of ICN through a novel UAV swarm system called ICN-enabled Hybrid-UAS (IH-UAS). IH-UAS supports battlefield missions through a hybrid swarm comprising of group 1 and 4/5 UAVs that utilize ICN to jointly provide sufficient computational capability and flexible deployment for decision-making algorithms and mission tasks respectively. The ability to conduct localized decision-making can be extended to support infrastructure-less operations. IH-UAS uses a decentralized communication architecture that incorporates ICN through the publish-subscribe middleware using multiple brokers. We investigate the performance of IH-UAS using a simplified variant of the Coordinated Search and Tracking (CSAT) application [2]. The main contributions of this work are:

- 1) A measurement study of ICN in a UAV swarm scenario focused on communication latency, reliability, and the

benefits of strategic and decentralized broker placement.

- 2) Early validation results for a novel UAV system, IH-UAS, that can support infrastructure-less operations through a decentralized ICN communication architecture.

Through theoretical and measurement-based analysis, we demonstrate that the CSAT application in IH-UAS can complete mission tasks more reliably in lesser time than a system using traditional, centralized unicast communication. Strategic broker placement close to the senders in the swarm and decentralized architecture with multiple brokers instead of a single broker further amplify the performance benefits.

The rest of the paper is organized as follows. Recent relevant literature and essential terminology referred to in this work are summarized in Section II. The IH-UAS system model and its theoretical analysis are discussed in Section III. The experimental methodology is presented in Section IV and results and analysis are presented in V. Section VI provides conclusions and identifies the future scope of this work.

II. BACKGROUND AND RELATED WORK

A UAV swarm refers to a heterogeneous group of UAVs that utilize its collective capabilities to achieve mission tasks cooperatively. Swarm communication can be infrastructure-based, ad hoc, or a hybrid between an infrastructure-based and an ad hoc approach where at least one UAV can communicate with an infrastructure node and UAVs within the swarm form an ad hoc network [7]. Connectivity within the swarm can be established through various standards, such as IEEE 802.11, IEEE 802.15.4, and Bluetooth Low Energy (BLE) [8]. Compared to other ad hoc networks like MANETs and VANETs, UAV swarms may be distinguished by three-dimensional mobility resulting in intermittent link outages, high node density resulting in reduced communication bandwidth, lack of constant infrastructure support, especially when operating in remote regions, and limited battery power [6]. Therefore, an important research area is the development of routing protocols and communication architecture to support demanding applications specifically in UAV swarms.

Research related to UAV swarm communication architecture primarily focuses on reliable communication with low latency. Some recent solutions propose the use of emergent cellular technologies to reduce communication latency. The architecture proposed in [9] utilizes a group of UAVs equipped with multi-access edge computing (MEC) facilities to provide 5G cellular connectivity with low latency to a UAV swarm. However, this solution is infrastructure-dependent and not suitable for all applications. In [3], an SDN controller is used to construct and maintain low latency routing paths for UAV communication. In [10], a hierarchical three-dimensional architecture is proposed where the first layer comprises sensor-equipped UAVs closer to the ground and the second layer comprises UAVs consolidating sensing information from the first layer. In [4], edge computing is used in conjunction with the UAV swarm to meet the strict quality of service requirements.

Recent research advocates for the use of ICN to support the data exchange requirement in a dynamic swarm subject to frequent network changes [5]. In ICN, data is exchanged in the form of Named Data Objects (NDOs), which are messages whose content is identifiable through string-based identifiers. Data transmission and forwarding is based on the NDOs instead of IP addresses or hostnames. ICN can be implemented through a broker-based publish-subscribe message dissemination. The three primary components of the publish-subscribe middleware are publishers, subscribers, and brokers. Messages are identified through string values called topics. Publishers (senders) transmit messages tagged with a specific topic to the subscribers (receivers) through a broker that facilitates this exchange. The broker maintains a data structure of subscribers and the topics of interest to them, and uses this reference structure to correctly forward messages received from the publishers.

In [5], the authors propose an ICN architecture called ICN-IoT to support an Internet of Drones (IoD). ICN-IoT uses publish-subscribe infrastructure to exchange relevant data between ground-based sensors and a group of flying UAVs. The ICN implementation in [5] is infrastructure dependent and communication among UAVs is not considered. Additionally, the use of ICN in this work is derived from its applicability in other ad hoc networks and not through measurements conducted in a UAV swarm. To the best of our knowledge, work presented in this paper is the first measurement-based study that investigates the performance impact of ICN through broker-based publish-subscribe transmission within the UAV swarm, devoid of complexity from additional design elements. Additionally, IH-UAS, proposed in this work, is novel in its hybrid composition aimed at computational and operational benefits on the battlefield.

III. SYSTEM MODEL

IH-UAS comprises a hybrid UAV swarm using a leader-follower model. The leader connects to the GCS through a long-haul wireless link and is a group 4 or 5 UAV with multiple transceivers and sufficient compute, memory, and power resources. The followers are group 1 UAVs with a single transceiver and limited resource availability. The swarm communicates as an ad hoc network using standards-based IEEE 802.11a. Each node directly communicates with its one-hop neighbors within 802.11a's communication range and multi-hop communication is supported through routing protocols, e.g. Open Shortest Path First (OSPF). The GCS assigns tasks to the leader which allocates them to a suitable set of followers and analyzes the data collected. Allocating tasks to followers entails strategic resource assignment to best utilize the collective sensing capabilities of the swarm. The leader can also utilize this property to extend the swarm's reach by flexibly deploying followers anywhere within its communication range. The leader may analyze the data collected from the followers locally without GCS support.

IH-UAS implements ICN through one or more brokers to exchange data. Multiple brokers allow decentralized commu-

nication. It is scalable in terms of adding followers as required, flexible in mission-specific deployment, and provisioned with resources required to reduce closed-loop communication with the GCS. The use of ICN ensures communication without much prior knowledge of the swarm network and thus results in low latency. The characteristics of the broker, including temporary local information caching, result in high reliability. Overall, these factors make IH-UAS well-suited for battlefield missions.

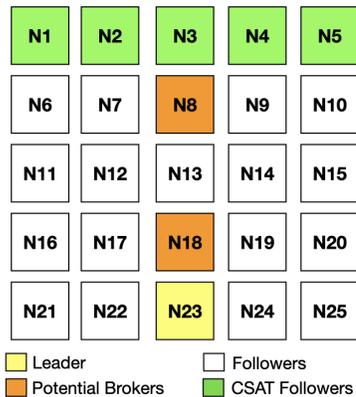


Fig. 1. UAV swarm topology for IH-UAS

We make certain simplifying assumptions for the early validation of IH-UAS presented in this work. We assume static operations and a simplified $n \times n$ swarm topology. The exemplar use-case involves IH-UAS supporting a search and tracking mission task through the CSAT application middleware. The CSAT application uses the integrated capability of sensing UAVs to locate an evasive target on the battlefield [2]. A simple CSAT scenario involves multiple followers deployed for searching and tracking within a region of interest, sending CSAT data to the leader for data processing and analysis. The leader uses a machine-learning algorithm similar to [2] for data aggregation, processing, and video analytics. The analysis helps complete the mission task by successfully sending a target location to the GCS or driving the followers' video-sensing efforts. The CSAT data from various followers must be received synchronously at the leader to improve the convergence time of the employed algorithm, and thus, the accuracy of the analysis. We refer to the set of nodes in the UAV swarm as U , the set of nodes participating in the CSAT application as C , and the leader node as u_l . C is a subset of U . Fig. 1 illustrates the IH-UAS system model and the CSAT nodes used for the study.

A. Theoretical evaluation of publish-subscribe transmission

We theoretically isolate and characterize the latency impacts of ICN and unicast using a wired system. These results are applicable to radio access systems that use a scheduled medium access control such as TDMA or a random access scheme such as IEEE 802.11a radios where there are no or minimal packet collisions. We measure latency as the

application delay experienced by an application. This exercise helps in quantifying and understanding the rate of growth for ICN and unicast for UAV swarms in different operating scenarios which is important for future low-level design of IH-UAS.

We study a scenario where application data flows from X_1 to a set of receivers $\{X_4, X_5, \dots, X_n\}$ over a multi-hop wired network illustrated in Fig. 2. We make the system assumptions that all nodes and links in the system are identical; the application data size is uniform; and, the sender and receivers use the same topic for publish-subscribe transmission. The broker is initially located at X_3 . With unicast transmission, the transmission of 1 message from X_1 to n receivers requires transmission of n copies of the same message. Meanwhile, publish-subscribe transmission requires the transmission of 1 message from X_1 to the broker and n copies from the broker to n receivers. Thus, it can be hypothesized that the application delay experienced in this system will grow faster for unicast transmission than publish-subscribe transmission. Further, the growth rate will be slower when the hop distance between the broker and the receivers is minimized.

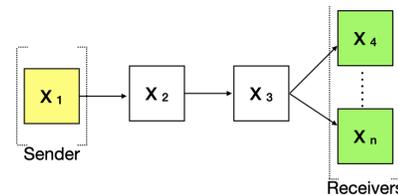


Fig. 2. Simple system model for theoretical analysis

The application delay experienced in this system is the sum of queuing (Q), processing (Pr), transmission (T), and propagation (P) delay at each link. We assume $Q = Pr = 0$ for traffic in the system. The total time taken for n receivers connected through l links to receive a unicast message can be expressed as $ln(P+T)$. For a publish-subscribe system where the broker is placed at the $(l-m)^{th}$ node, m hops away from the receivers, the total time taken for n receivers to receive a message can be expressed as $(l+mn-m)(P+T) + nP$. The component nP in this expression represents the one-time operation of subscription to the broker and is trivial. Therefore, as the number of receivers increases, the application delay for unicast and publish-subscribe transmission increases by ln and $(l+mn-m)$, respectively. Fig. 3 demonstrates the growth in application delay as n increases from 1 to 50 using the system illustrated in Fig. 2. We also show that the rate of growth increases as the distance between the broker and receivers is increased.

In a scenario with multiple senders and one receiver, the difference between unicast and publish-subscribe transmission is observable in the system's total number of message flows. For transmission of 1 message each from n senders to 1 receiver, n message flows exist for unicast transmission resulting in each message experiencing significant queuing and processing delays at each node in the shared path to

the receiver. For publish-subscribe transmission, the broker aggregates the message flows resulting in application traffic regulation within the system. With n message flows from n senders to the broker and one aggregated flow from the broker to the receiver, each message only experiences significant queuing and processing delays at nodes in the shared path to the broker. In the theoretical system model where $Q = Pr = 0$, both transmission methods would incur similar application delay. In a practical experimental system where $Q \neq 0$ and $Pr \neq 0$, lower application delay is expected with publish-subscribe transmission and the broker placement causes further impact. For publish-subscribe transmission, the application delay $D = P + T + Pr + Q$ experienced by n senders at each node would increase by tD where t defines the hop distance between the senders and the broker. Comparatively, the application delay for unicast transmission would be lD where $l > t$. We test this hypothesis in Section V.

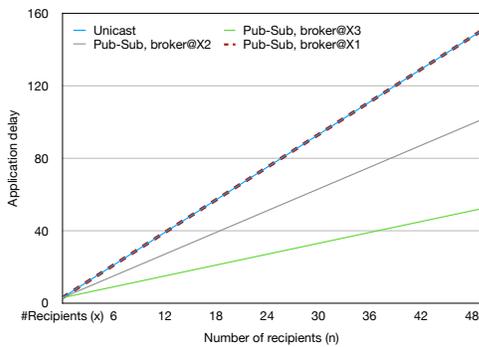


Fig. 3. Growth rate of application delay as total receivers increase.

IV. EXPERIMENTAL METHODOLOGY

Experiments conducted in this work serve the dual purpose of validating the high-level IH-UAS system model and providing a measurement-based study showing the performance impact of ICN in a UAV swarm. The scenario of interest is the transmission of CSAT application messages from nodes in C to u_l to support a search and tracking mission. Successful mission execution depends on synchronous, timely, and reliable reception of CSAT messages from all nodes in C to u_l . Various system attributes could potentially impact successful mission execution. The experimental methodology involves studying the impact of these attributes on a set of application performance metrics, referred to as control metrics, for CSAT using publish-subscribe transmission. The two aspects of this study are the comparison of publish-subscribe and unicast transmission, and optimizing ICN architecture. We emulate the UAV swarm illustrated in Fig. 1 using CORE [11] and EMANE [12]. Each emulated node has an isolated network stack and independent processes, and the swarm uses IEEE 802.11a EMANE radio model with a Modulation and Coding Scheme (MCS) that supports 6 Mbps data rate. Using a receiver bandwidth of 20 MHz and transmit power of 0 dBm, the maximum inter-node distance is set to 500 meters. OSPF-MDR is used as multihop routing protocol.

The control metrics comprise one-way delay (OWD) and packet error rate (PER). For a CSAT message transmitted from a sender in C to u_l , OWD is measured as the difference between the sender's transmission and the u_l 's reception times. We consider two relevant measures of OWD, OWD_{avg} and OWD_{max} . For n CSAT messages sent at the same time-step from n nodes in C , OWD_{avg} and OWD_{max} are the mathematical average and the maximum value computed from n OWD samples received at u_l respectively. The significance of OWD_{max} derives from the CSAT machine learning algorithm's requirement to receive CSAT data from all sensing UAVs synchronously. Packet Error Rate (PER), measured at u_l for each sender, is the ratio of CSAT application messages not successfully received at u_l to the total messages transmitted from a given node in C .

We decompose the system attributes that can impact the CSAT application performance into video attributes and swarm attributes. Video attributes include video resolution and frame size. For reference, a video resolution of 360p with 30 frames per second (fps) requires an application transmission rate of 1 Mbps from the sender [13]. It can use the Maximum Transmission Unit (MTU) of the sender's outbound interface as the maximum packet size [14]. Swarm attributes include the number of nodes in C , the distance between nodes in C and u_l , and the placement and number of the brokers in publish-subscribe transmission. In our experiments, the number of nodes belonging to C range from 1 to 5, and the complete set consists of $\{N1, N2, N3, N4, N5\}$. The distance is measured as the number of hops between a given pair of nodes. We vary the broker placement for different experimental settings.

Evaluation Toolset

The performance evaluation toolset comprises of two in-house applications, perfTool, and simplePubSub, developed for this study. These applications operate in client-server mode and are respectively used for performance evaluation of unicast and publish-subscribe transmission. The perfTool client functionality comprises of transmission of unicast constant bit rate (CBR) traffic to the server over a UDP socket with a user-defined message size, transmission rate, and the duration of transmission defined as the number of messages transmitted. The client message includes the packet sequence number, transmission timestamp, and a user-defined payload determined by the message size. The perfTool server can receive the incoming messages from multiple senders and log the contents of each message along with the sender's IP address and reception timestamp. The transmission and reception timestamps are used to compute OWD for the message, and the sequence numbers are used to calculate PER. Clients can use synchronized transmission start times for multiple simultaneous clients to create realistic swarm transmission conditions. The nodes in C run perfTool client code while u_l runs the server code.

For the simplePubSub application, the server implements an in-house broker while the client supports the publish and subscribe functions. A client in publish mode (publisher) transmits

CBR traffic to the broker in the same manner as the perfTool client. A client in subscribe mode (subscriber) connects to the broker using a UDP socket and provides a message topic of interest. Any message identified with this message topic that the broker receives is forwarded using unicast UDP message to the subscriber. The message contents are similar to the perfTool message and are logged at the broker and the subscriber as they arrive. Message topics are string values separated by delimiters that provide insight into message contents. The topic format $\langle \text{nodeName/applicationName/messageType} \rangle$ is used in simplePubSub. For example, a CSAT message from the node $N1$ to the broker would be labeled with the topic $\langle N1/csats/videoStream \rangle$. The nodes in C and u_l run the client code in publish and subscribe mode, respectively. The broker in the system runs the server code. We model the CSAT application traffic in perfTool and simplePubSub by setting the transmission rate and message size. We also ensure that application code differences in both tools that could potentially impact the comparison of measurement are minimized.

V. RESULTS AND ANALYSIS

We present and analyze three key results from our experiments. Overall, these results illustrate the efficacy of ICN over centralized unicast transmission for low latency and reliable communication in a UAV swarm and serve as initial validation of the IH-UAS design.

A. Comparison of OWD for publish-subscribe and unicast transmission.

Fig. 4 presents the comparison of publish-subscribe and unicast transmission for the CSAT scenario where an increasing number of nodes belonging to C are transmitting application data to u_l located at $N23$. We present observations for three cases corresponding to $C = \{N3\}$, $C = \{N2, N3, N4\}$, and $C = \{N1, N2, N3, N4, N5\}$. The broker for the publish-subscribe transmission is placed at $N8$. The conducted experiment uses a message size of 500 Bytes and a transmission rate of 100 kbps. A nominal transmission rate is chosen to study the performance impact without incurring additional application delay from processing at the broker. The OWD_{max} observed at $N23$ for both transmission methods is comparable when C comprises only one sender. As the number of senders in C becomes > 1 , the median OWD_{max} value using publish-subscribe transmission becomes lower than unicast transmission. The difference between the two is 2.2 ms and 3.1 ms for 3 and 5 senders, respectively. The broker used for publish-subscribe transmission aggregates the message flows from all senders and reduces the system's total number of message flows. The reduced number of flows corresponds to reduced processing and queuing delays experienced at each intermediate node between the senders and u_l and results in lower OWD. Overall, Fig. 4 demonstrates the effectiveness of ICN for a UAV swarm with multiple, simultaneous senders.

B. Impact of the broker position on OWD.

In Section III, we presented theoretical results that indicated that strategic placement of brokers to minimize network

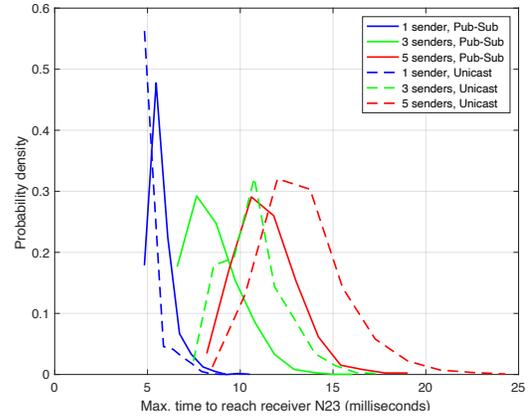


Fig. 4. Comparison of OWD with increasing number of senders.

traffic resulted in a lower OWD growth rate. Fig. 5 verifies this hypothesis in an experimental setting by comparing the OWD_{avg} observed at $N23$ for two broker positions using the CSAT application scenario described in Section V-A with 5 senders. In the first case, the broker is placed 1-3 hops away from nodes in C at $N8$. In the second case, the broker is placed 3-5 hops away from the nodes in C at $N18$. Fig. 5 shows significant difference in OWD_{avg} due to broker placement as the message size increases from 500 to 1250 Bytes. For a message size of 1250 Bytes, the difference in the median and 97th percentile value of OWD_{avg} observed when the broker is at $N8$ and $N18$ is 2.26 ms and 7.36 ms respectively. As analyzed in Section V-A, the placement of the broker closer to the senders reduces the total number of message flows, resulting in lower OWD. Further, it is possible for the sum of queuing, processing, and transmission delays to be significant enough to show meaningful impact only at the higher message size. Overall, Fig. 5 indicates that the distance between the brokers and senders in the UAV swarm must be minimized for lowering application latency.

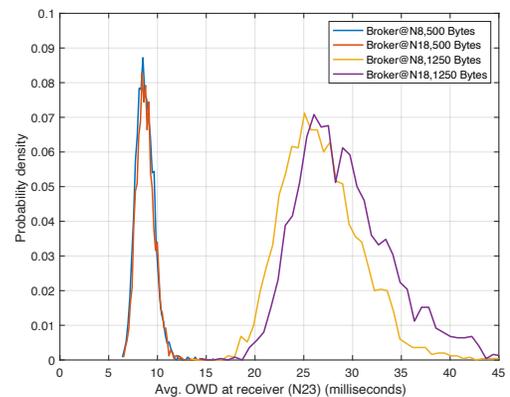


Fig. 5. Impact of broker position on OWD.

C. Comparison of centralized and decentralized ICN architecture.

It is established in many works that a centralized ICN architecture with a single broker results in a performance bottleneck as the application traffic handled by it increases [15]. Our experiments show that while a single broker system can successfully handle the transmission rate of 100 kbps with PER = 0% as demonstrated in Sections V-A and V-B, performance significantly degrades at higher transmission rates as the senders in C increases. Fig. 6 shows that in a centralized single broker system with five senders transmitting at 300 kbps, a rate higher than previous experiments, the OWD_{avg} increases linearly as the experiment progresses. The centralized broker is placed at $N8$ and the message size of 500 Bytes is used. The median value of OWD_{avg} observed in this case is 1.5s with a PER of 24%. However, significant improvement in OWD_{avg} is observed when the centralized broker is replaced by two brokers at $N7$ and $N9$. The brokers at $N7$ and $N9$ handle application traffic from $\{N1, N2, N3\}$ and $\{N4, N5\}$ respectively. The median value of OWD_{avg} observed in this case is 17.78 ms, and the PER is 0%. It should be noted that the combined transmission rate from 5 senders transmitting at 300 kbps is lower than the effective throughput between C and u_i . The linear increase in OWD_{avg} can be attributed to the performance bottleneck created by a single broker. Overall, Fig. 6 indicates that a decentralized multiple-broker system can accommodate a higher number of senders and transmission rates with lower application latency and higher reliability than a centralized single-broker system.

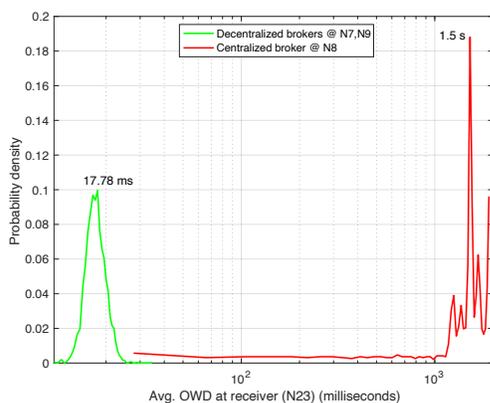


Fig. 6. Impact of centralized vs decentralized brokers on OWD.

VI. CONCLUSION

In this work, we presented a novel UAV swarm system, IH-UAS, through which we conducted a measurement-based analysis of ICN in a particular battlefield scenario involving a search and tracking mission. Through theoretical and simulation results, we demonstrated that an ICN implemented through a broker-based publish-subscribe message dissemination method achieves lower application delay and quicker completion of group communication reliant mission tasks than

a centralized, unicast system. Furthermore, our study informs some key design considerations for an ICN-based swarm system. First, the time to complete a mission task is optimized by minimizing the distance between the broker and the UAVs in the swarm that are collecting application data. Second, a decentralized broker architecture with multiple brokers can facilitate a more reliable exchange of a higher volume of application data than a centralized architecture with a single broker. For video-sensing swarm applications like CSAT, the use of decentralized brokers allows higher video resolution and arguably better video analytics at the leader in IH-UAS. The future scope of our work involves further measurements-based analysis to quantify the point at which ICN becomes more beneficial than unicast. It additionally involves extending the presented IH-UAS system design to support advanced broker functions including dynamic initialization, optimized location, and appropriate broker-to-broker forwarding mechanisms.

REFERENCES

- [1] "Cjcsi 3255.01 - joint unmanned aircraft systems minimum training standards," tech. rep., 2009.
- [2] T. Zeng, O. Semiari, M. Mozaffari, M. Chen, W. Saad, and M. Bennis, "Federated Learning in the Sky: Joint Power Allocation and Scheduling with UAV Swarms," in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, (Dublin, Ireland), pp. 1–6, IEEE, June 2020.
- [3] A. Ramaprasath, A. Srinivasan, C.-H. Lung, and M. St-Hilaire, "Intelligent wireless ad hoc routing protocol and controller for uav networks," in *Ad Hoc Networks*, pp. 92–104, Springer, 2017.
- [4] W. Chen, B. Liu, H. Huang, S. Guo, and Z. Zheng, "When uav swarm meets edge-cloud computing: The qos perspective," *IEEE Network*, vol. 33, no. 2, pp. 36–43, 2019.
- [5] P. Boccadoro, M. Losciale, G. Piro, and L. A. Grieco, "A standard-compliant and information-centric communication platform for the internet of drones," in *European Wireless 2018; 24th European Wireless Conference*, pp. 1–6, VDE, 2018.
- [6] L. Gupta, R. Jain, and G. Vaszkun, "Survey of Important Issues in UAV Communication Networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.
- [7] M. Campion, P. Ranganathan, and S. Faruque, "A review and future directions of uav swarm communication architectures," in *EIT*, pp. 903–908, 2018.
- [8] S. Khan, M. Zeeshan, and Y. Ayaz, "Implementation and analysis of multicode multicarrier code division multiple access (mc-mc cdma) in iee 802.11 ah for uav swarm communication," *Physical Communication*, vol. 42, p. 101159, 2020.
- [9] C. Grasso and G. Schembra, "A fleet of mec uavs to extend a 5g network slice for video monitoring with low-latency constraints," *Journal of Sensor and Actuator Networks*, vol. 8, no. 1, p. 3, 2019.
- [10] Q. Zhang, M. Jiang, Z. Feng, W. Li, W. Zhang, and M. Pan, "Iot enabled uav: Network architecture and routing algorithm," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3727–3742, 2019.
- [11] J. Ahrenholz, C. Danilov, T. R. Henderson, and J. H. Kim, "Core: A real-time network emulator," in *MILCOM 2008 - 2008 IEEE Military Communications Conference*, pp. 1–7, 2008.
- [12] J. Ahrenholz, T. Goff, and B. Adamson, "Integration of the core and emane network emulators," in *2011 - MILCOM 2011 Military Communications Conference*, pp. 1870–1875, 2011.
- [13] "Recommended upload encoding settings," <https://support.google.com/youtube/answer/1722171>. Accessed: 07-22-2021.
- [14] J. Wang, Z. Feng, Z. Chen, S. George, M. Bala, P. Pillai, S.-W. Yang, and M. Satyanarayanan, "Bandwidth-Efficient Live Video Analytics for Drones Via Edge Computing," in *2018 IEEE/ACM Symposium on Edge Computing (SEC)*, (Seattle, WA, USA), pp. 159–173, IEEE, Oct. 2018.
- [15] Z. Y. Thean, V. V. Yap, and P. C. Teh, "Container-based mqtt broker cluster for edge computing," in *2019 4th International Conference and Workshops on Recent Advances and Innovations in Engineering (ICRAIE)*, pp. 1–6, IEEE, 2019.