Design and Evaluation of an Application-Oriented Data-Centric Communication Framework for Emerging Cyber-Physical Systems

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

Abolfazl Razi
School of Computing
Clemson University
Clemson, SC, USA
arazi@clemson.edu

Long Cheng
School of Computing
Clemson University
Clemson, SC, USA
lcheng2@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

2023 IEEE 20th Consumer Communications & Networking Conference (CCNC) | 978-1-6654-9734-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/CCNC51644.2023.10060823

***Abstract*—Emergent Cyber-Physical Systems (CPSs) like VANETs and UAV swarms are expected to fulfill essential roles in critical infrastructure domains. This increasing utility and the present nurturing economic conditions that enable their cost-effective deployment herald a period of significant growth and adoption. In addition, these systems are increasingly required to support complex data-intensive and QoS-sensitive applications in challenging operating conditions. However, the growth of these systems is limited by current Internet protocols that do not comprehensively meet the communication requirements of these systems. In this work, we present the design and evaluation of Software-Defined NAmed-data enabled Publish-subscribe (SNAP) communication framework that can effectively meet the communication requirements of demanding applications in emergent CPSs.**

I. Introduction

The evolution of Cyber-Physical Systems (CPSs) has led to an emergent class of mobile and heterogeneous systems relevant to society's critical infrastructure sectors, e.g., Vehicular Ad-Hoc Networks (VANETs) and Unmanned Aerial Vehicle (UAV) swarms. These systems are characterized by ad-hoc communication, mobility, and resource constraints of the participating nodes. Nodes typically support limited compute, memory, and communication capabilities. Due to advancements such as sensor technologies and lightweight machine-learning for Internet-of-Things (IoT), applications that these systems support are now trending towards data and compute-intensive cooperative tasks requiring distributed collection and analysis of substantial amounts of sensor data [1]–[3]. Applications relevant to critical infrastructure are also expected to have strict application-specified Quality-of-Service (QoS) requirements.

Further, these emergent CPSs are expected to support a diverse group of data-intensive and QoS-sensitive applications applications successfully. Therefore, they require flexible communication methods that can adapt to meet applications' unique, diverse, and dynamic QoS requirements subject to the system's resource constraints and network disruptions due to mobility. Traditional Internet communication protocols currently utilized within these CPSs do not comprehensively meet these communication requirements. For example, UDP-based methods, typically utilized for these systems, are based on rigid layered communication models that make CPS adaptation challenging.

In this work, we present a communication framework called **S**oftware-Defined **NA**med-data enabled **P**ublish-subscribe (SNAP) framework that can effectively meet the communication requirements of emergent CPSs. The two fundamental attributes of SNAP are Information-Centric Networking (ICN) and a decentralized control plane. ICN offers named-data-based resilient and lightweight communication in disruption prone ad-hoc networks [4]. The control plane offers system-level decision-making guided by the application's requirements. The SNAP communication framework utilizes an underlying decentralized architecture that commonly represents emergent CPSs using a system abstraction that we refer to as the APPlication SYStem (APPSYS). SNAP offers resilient, lightweight, and application QoS-focused flexible communication within a system to effectively support data-intensive and QoS-sensitive applications. The APPSYS design creates a scalable, cohesive, and unified system representation that promotes interoperability among diverse CPSs and integration with the Internet.

We present the initial design and evaluation of SNAP through an exemplar UAV swarm APPSYS on the battlefield supporting a Coordinated Search and Tracking (CSAT) application. CSAT utilizes the integrated sensing and computational capabilities of participating UAVs within the swarm to locate evasive targets of interest [5]. The evaluation showcases the ability of SNAP framework's control plane to support an application's QoS requirements, specifically in application and network conditions where traditional communication protocols suffer from severe performance degradation. The framework is extensible to any resource-constrained and mobile CPS supporting a data-intensive and QoS-sensitive application.

The rest of the paper is organized as follows. In Section II, we discuss related work and open challenges related to the development of communication methods for emergent CPSs. In Section III, we present design elements of the SNAP communication framework. In Section IV, we discuss the performance evaluation. We conclude our work in Section V.

II. Related Work

Numerous recent works propose solutions to meet the communication requirements of emergent CPSs. Solutions can be classified as network QoS-oriented solutions and data-dissemination solutions. Network QoS-oriented solutions aim to meet standard network QoS requirements. For example, several solutions leverage fifth-generation (5G) cellular communication and mmWave links to support high data rates, increased throughput, and low latency [6]. Data-dissemination solutions provide QoS-aware methods for data dissemination in CPSs. Group communication solutions based on the MQ Telemetry Protocol (MQTT) or modified implementations of standard multicast protocols have been applied in UAV swarms and VANETs to reduce the impact of network disruption and utilize resources more optimally [7], [8]. Some works propose solutions that utilize Software-Defined Networking (SDN) for effective resource-management within resou constrained emergent CPSs. Hybrid solutions such as use of decentralized SDN in conjunction with MQTT ir provide optimized routing and forwarding paths based o application's latency QoS requirement. Recently, Informa Centric Networking (ICN) has been used as a resilient lightweight communication solution suitable for resou constrained and disruption-prone networks dominantly changing application defined data. The use of various ICN plementations, including Named Data Networking (NDN) and publish-subscribe based implementations, e.g. HoP-Pull (HoPP) [10] have been proposed within emergent C

While beneficial, no existing solution meets the CPS c munication requirements comprehensively. Some soluti e.g. those using 5G cellular communication, are infrastruc dependent and unsuitable for remote scenarios. Solutions that follow end-to-end path semantics result in high overhead from frequent re-transmissions in disruption-prone networks [11]. Similarly, SDN-based solutions and multicast protocols have high overhead from substantial control information exchange. Existing SDN-based solutions do not address the challenge of SDN communication overhead and maintaining consistency among decentralized controllers in dynamic networks. ICN is currently limited by challenges like efficient management of the forwarding plane and topic look-up tables.

III. SNAP Communication Framework

The architectural underpinnings of SNAP communication framework are provided through the APPSYS system abstraction. APPSYS is designed to be an application of the Internet that represents an emergent class of CPSs. It provides a standard high-level architectural template that is modular, scalable, and applicable to a broad class of CPSs. SNAP supplements the benefits of the APPSYS design with an efficient communication framework that can dynamically support the needs of a diverse group of applications subject to the system's operational constraints, i.e., limited communication resources and expected network disruption from mobility. We discuss SNAP and APPSYS through an example of a traditional UAV swarm reorganized as a UAV swarm APPSYS.

APPSYS - The UAV swarm APPSYS utilizes a multi-star topology where a traditional flat-mesh UAV swarm is divided into groups known as *clusters*. Nodes within a cluster are within broadcast range. Each cluster communicates with the backend Control Station (CS) through one or more specially designated nodes. Intra-cluster communication uses existing and emerging Radio Access Technologies (RATs) or custom Software Defined Radios (SDRs) that offer further degrees of agility. Each cluster is hierarchically organized, and top-level nodes across clusters form a rich multi-path mesh network that facilitates inter-cluster communication using SNAP. Clusters include sensing and compute nodes. Sensing nodes are equipped with relevant sensors and collect sensing data. Compute nodes conduct application data analysis on collected sensor data. APPSYS clusters are scalable and dynamic. Further discussion on the APPSYS can be found in our prior

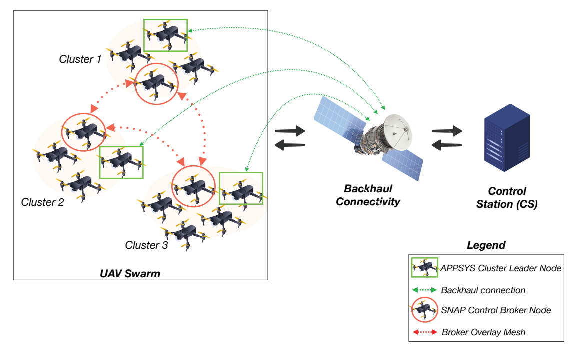


Fig. 1: UAV Swarm APPSYS using SNAP Communication Framework

SNAP Framework - SNAP implements publish-subscribe ICN communication through decentralized software brokers (*control brokers*) located within the APPSYS. Control Broker (CB) software is implemented on the top-level nodes in each cluster. Nodes within a cluster communicate via the cluster's CB. CBs use a pull-based communication primitive where subscribers initiate communication by sending subscribe requests for specific topics to the CBs. A CB forwards all received subscribe requests to other CBs. All CBs have a topic look-up table of topics associated with incoming subscribe requests and the associated interface. The topic look-up table is used to form a reverse path for dissemination of published messages to the subscribers. SNAP uses ICN communication over underlying IP connectivity for backward compatibility with IP-based systems. Nodes publish messages through their cluster's CB. Fig. 1 illustrates the UAV swarm APPSYS communicating using SNAP framework. The CBs collectively form a decentralized control plane that is capable of taking data dissemination decisions based on an application's QoS requirements and current QoS state. Each CB executes independent control-plane decisions that are implemented in the form of applied data services. Data services refer to the set of data-oriented actions that the control pl CB may apply in response to an application's requi Each CB includes software modules that allow it t relevant application and system state information, a data services in response to state awareness. For exa CB control plane collects current application QoS st nodes participating in an application.

Illustrative Data Service: Intelligent Data Fusion an exemplar data service relevant to a data-intensive a sensitive application with strict data-dissemination requirements. IDF is applicable where the volume of l application data being disseminated may result in congestion and failure to meet latency requirements. IDF, the CB reduces application traffic being diss through its outbound interface by intelligently ag sensing data at the broker. The CB considers messa each sensing node to have a different sensor noise level. The sensor noise level is available as state information to the CB control plane. The CB fuses messages from all sensing nodes at each time-step prioritized by the associated sensor noise-level. At a given time-step, higher number of messages are aggregated from a sensing node with high associated noise as compared to a sensing node with comparatively lower associated noise. The number of messages to be fused from each sensing node is formulated as a Maximum Likelihood Estimation problem formulation. The complete details of the IDF formulation are omitted here due to space limitations. They can be found in [13].

IV. Evaluation and Results

To assess the efficacy of a UAV swarm using SNAP, we examine the impact of SNAP's IDF data service in supporting the QoS requirements of a CSAT mission. The experimental network conditions reflect high utilization due to high CSAT traffic load. Our prior work illustrates that traditional methods like UDP-based unicast and centralized publish-subscribe communication in a flat-mesh UAV swarm experience prohibitively high latency at high offered loads from applications; thus, severely impacting application performance [14]. Further, traditional methods do not incorporate standardized measures to detect and mitigate network impairment, causing further application performance degradation. The SNAP control plane detects network impairment using constant QoS state monitoring and applies data services as mitigation measures to improve QoS. We conduct our evaluation in a hardware testbed implementation of a two-cluster UAV swarm APPSYS comprising of hardware-constrained Intel NUC NUC5i5RYK mini-PCs and Raspberry Pi 2 devices. Three sensing nodes, S1, S2, and S3, in Cluster 1 transmit sensing data to a compute node C1 in cluster 2. Fig. 2 illustrates this setup. The sensing nodes transmit the data through their cluster's CB (B1). Control plane state monitoring and the subsequent decision to apply a data service (IDF) are taken by B1. The hardware testbed used wired connectivity to decouple the evaluation from the complexities of specific wireless communication protocols. However, results from the evaluation hold true for wireless

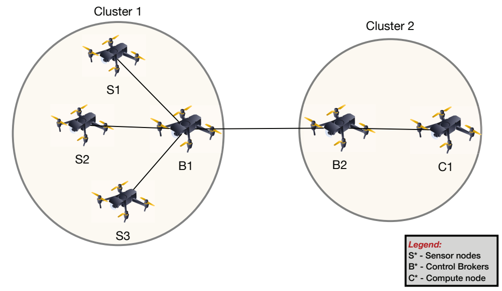
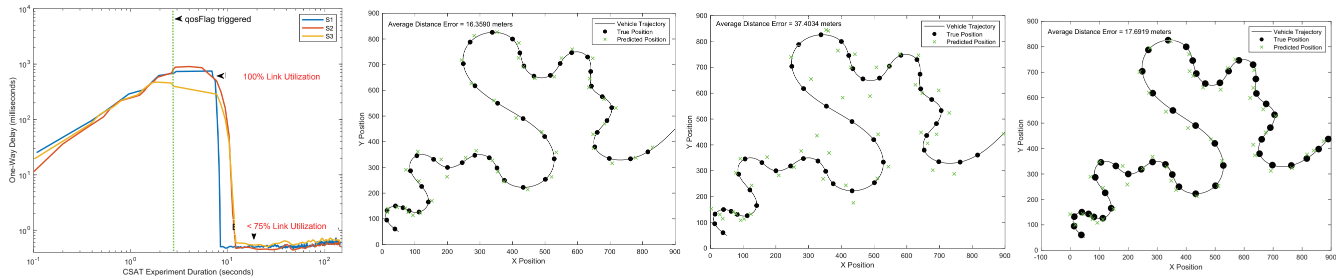


Fig. 2: UAV swarm setup for performance evaluation

CSAT Application - The CSAT application variant we developed continuously tracks a vehicle of interest (V_T) using vehicle position predictions computed using Kalman Filtering (KF). CSAT sensing nodes in the UAV swarm APPSYS transmit V_T's positions in the XY Cartesian plane at each time-step to the compute node within the APPSYS. C1 aggregates the data at each time-step and uses KF to produce V_T's expected position, V_{Te} at the next time-step. V_{Te} is transmitted back to the sensor nodes where it is used to inform the sensing nodes' flight plans. CSAT's success depends on the accuracy of V_T's predictions which depends on the timely reception of sensing messages at the compute node. Therefore, we consider One-Way Delay (OWD) associated with incoming messages at C1 as the CSAT QoS metric. Through an experimental run within the testbed, we empirically determine a OWD $\leq 2ms$ to be sufficient to meet the CSAT accuracy requirement.

Experiments - We conducted comparative studies where we first incrementally increased the CSAT offered load to create network impairment conditions that impacted the CSAT QoS. We increased the load by gradually increase message transmission rate and observed the impact on the compute node's V_{Te} position prediction accuracy at each time-step. We considered accuracy as the inverse of distance error, $D = \sqrt{(X_\tau - \hat{X}_\tau)^2 + (Y_\tau - \hat{Y}_\tau)^2}$, where (X_τ, Y_τ) and $(\hat{X}_\tau, \hat{Y}_\tau)$ are the coordinates of the V_T's true position and estimated position, V_{Te}, at time τ. We then applied IDF at B1 in response to the QoS degradation at high offered load and observed the impact of this data service. B1 collected application QoS state as a part of the CSAT feedback messages carrying the V_{Te} estimated position from C1 to the CSAT sensor nodes.

Results - Fig. 3a characterizes the OWD at C1 for each participating CSAT sensor node, S1, S2, and S3. We first observe a rapid increase in OWD observed at C1 as the aggregated offered load from all sensor node in increased to 100% of the link capacity at B1. Then, we observe that as B1 initiates the IDF data-service, the offered load is reduced by data aggregation and the OWD falls back within its QoS bounds of $\leq$ 2 ms. Without IDF, we can expect an increase in OWD bounded only by B1's maximum queue capacity leading



(a) **(b)** **(c)** **(d)**

Fig. 3: (a) Impact of applying IDF on OWD at 100% link utilization (b) Position prediction accuracy at 50% link utilization (b) Position prediction accuracy at 100% link utilization (c) Position prediction accuracy with IDF at 100% link utilization

to severe CSAT performance degradation. Figs. 3b, 3c, and 3b show the impact of OWD resulting from various operating conditions on the accuracy of predictions made by C1. Figs. 3b and 3c show the average distance error between V_T's and V_{Te}'s positions at 50% and 100% link utilization for B1. The average distance error increases by a factor of 2.28 due to OWD resulting from high link utilization in Fig. 3c. Therefore, CSAT prediction accuracy significantly decreases as OWD is impacted by network impairment. When B1 is made aware of the QoS degradation, it applies the IDF data service. Fig. 3d shows the impact of this service. We observe that the average distance error reduces by 52% as compared to Fig. 3c. This improvement can be attributed to the reduction in overall load offered by IDF's data aggregation as well as the 'intelligent' aggregation that considers the associated sensor noise levels of various sensing nodes.

V. Conclusion and Future Work

This work presented the initial design and evaluation of the SNAP communication framework as a solution that provides resilient, lightweight, and application-QoS-focused communication methods using an underlying robust and scalable APP-SYS system abstraction. Through an exemplar data service, IDF, we demonstrate that this framework has the potential to successfully meet the dynamic application-specific QoS requirements of a diverse range of data-intensive and QoS-sensitive applications that are expected to operate in emergent CPSs. In a UAV swarm APPSYS conducting the CSAT application, the SNAP control broker successfully detects QoS degradation and dynamically applies IDF to improve CSAT accuracy. While the IDF is a prototype of a useful data-service, the future scope of this work includes the development of a comprehensive set of modular 'intelligent' services that the control plane can apply in response to application performance requirements. We will especially focus on data-services that utilize machine-learning as a part of the control plane decision-making.

References

[1] "Tensorflow lite." [Online] https://www.tensorflow.org/lite. Accessed: 06-05-2022.

[2] S. Campbell, N. O'Mahony, L. Krpalcova, D. Riordan, J. Walsh, A. Murphy, and C. Ryan, "Sensor technology in autonomous vehicles: A review," in *2018 29th Irish Signals and Systems Conference (ISSC)*, pp. 1–4, IEEE, 2018.

[3] C. Grasso and G. Schembra, "A Fleet of MEC UAVs to Extend a 5G Network Slice for Video Monitoring with Low-Latency Constraints," *JSAN*, vol. 8, p. 3, Jan. 2019.

[4] A. Afanasyev, J. Burke, T. Refaei, L. Wang, B. Zhang, and L. Zhang, "A Brief Introduction to Named Data Networking," in *MILCOM 2018 - 2018 IEEE Military Communications Conference (MILCOM)*, (Los Angeles, CA), pp. 1–6, IEEE, Oct. 2018.

[5] P. Vincent and I. Rubin, "A framework and analysis for cooperative search using UAV swarms," in *Proceedings of the 2004 ACM symposium on Applied computing - SAC '04*, (Nicosia, Cyprus), p. 79, ACM Press, 2004.

[6] D. Mishra and E. Natalizio, "A survey on cellular-connected uavs: Design challenges, enabling 5g/b5g innovations, and experimental advancements," *Computer Networks*, vol. 182, p. 107451, 2020.

[7] F. Xiong, A. Li, H. Wang, and L. Tang, "An sdn-mqtt based communication system for battlefield uav swarms," *IEEE Communications Magazine*, vol. 57, no. 8, pp. 41–47, 2019.

[8] R. Muzaffar, E. Yanmaz, C. Raffelsberger, C. Bettstetter, and A. Cavallaro, "Live multicast video streaming from drones: an experimental study," *Autonomous Robots*, vol. 44, no. 1, pp. 75–91, 2020.

[9] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, K. Claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang, "Named data networking," *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 3, pp. 66–73, 2014.

[10] C. Gundogan, P. Kietzmann, T. C. Schmidt, and M. Wahlisch, "HoPP: Robust and Resilient Publish-Subscribe for an Information-Centric Internet of Things," in *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*, (Chicago, IL, USA), pp. 331–334, IEEE, Oct. 2018.

[11] C. Gündoğan, P. Kietzmann, M. Lenders, H. Petersen, T. C. Schmidt, and M. Wählisch, "Ndn, coap, and mqtt: a comparative measurement study in the iot," in *Proceedings of the 5th ACM Conference on Information-Centric Networking*, pp. 159–171, 2018.

[12] "Towards connecting the disconnected internet." [Online] https://people.cs.clemson.edu/ jmarty/papers/TowardsConnectingTheDisconnectedInternet.pdf. Accessed: 08-27-2022.

[13] M. Kaur, "Snap: A software-defined & named-data oriented publish-subscribe framework for emerging wireless application systems." [Online] https://tigerprints.clemson.edu/all_dissertations/3065/. Accessed: 11-14-2022.

[14] M. Kaur, R. Amin, and J. Martin, "The design and validation of icn-enabled hybrid unmanned aerial system," in *2021 IEEE Military Communications Conference (MILCOM)*, IEEE, 2021.