Extending Kubernetes to Provide Federated and Adaptive Tactical Edge Clouds

Alessandro Amato*, Masoud Bozorgi**, Harrie Bastiaansen†, Willem Datema†, Mattia Fogli‡,
Johan van der Geest†, Thomas Kudla§, Pablo Sanchez¶, Niranjan Suri*‖, Susan Watson**
* *Florida Institute for Human and Machine Cognition (IHMC)*, Pensacola, FL, USA,
** *Defence Research and Development Canada*, Ottawa, Canada,
† *The Netherlands Organisation for Applied Scientific Research (TNO)*, The Hague, The Netherlands
‡ *University of Ferrara*, Ferrara, Italy,
§ *Fraunhofer Institute for Communication, Information Processing and Ergonomics*, Wachtberg, Germany
¶ *University of Cantabria*, Santander, Spain,
‖ *US Army DEVCOM Army Research Laboratory (ARL)*, Adelphi, MD, USA
{aamato, nsuri}@ihmc.org, {masoud.bozorgi, susan.watson}@forces.gc.ca,
{harrie.bastiaansen, willem.datema, johan.vandergeest}@tno.nl, mattia.fogli@unife.it,
thomas.kudla@fkie.fraunhofer.de, sanchez@teisa.unican.es, niranjan.suri.civ@army.mil

***Abstract*—This demonstration will show extensions to Kubernetes that leverage and extend cloud computing capabilities to the tactical edge, creating federated and adaptive tactical edge clouds for efficient data processing at the edge.**

***Index Terms*—Kubernetes, Network Emulation, Tactical Edge Computing, Tactical Clouds**

I. INTRODUCTION

The proliferation of ubiquitous sensing in the battlefield has resulted in a significant increase in the volume and velocity of data being generated. However, the challenge remains for commanders and decision-makers to be able to exploit this large volume of data in an effective and timely manner. The Denied, Disrupted, Intermittent, and Limited (D-DIL) nature of Tactical Networks (TNs) implies that this volume of data cannot be moved to an enterprise cloud environment for processing and exploitation. This reality has stimulated a growing interest in federated and adaptive edge–cloud architectures that can balance computational load between forward-deployed edge nodes and more robust rear-echelon clouds. Such architectures promise improved processing efficiency, enhanced survivability of mission-critical services, and reduced latency to generate actionable information from the raw sensor data, resulting in measurable gains in overall mission effectiveness.

Within the North Atlantic Treaty Organization (NATO) Science and Technology Organization (STO), two successive Research Task Groups (RTGs) have systematically addressed these challenges. The Information Systems Technology (IST)-168 RTG *Adaptive Information Processing and Distribution to Support Command and Control* measured the performance of Kubernetes (K8s), Lightweight Kubernetes (K3s), and Kubernetes Native Edge Computing Framework (KubeEdge) over emulated tactical networks and determined their limitations in terms of control traffic and ability to operate in environments prone to disconnection. Building upon those empirical insights, the IST-193 RTG *Edge Computing at the Tactical Edge* has developed an adaptive and federated tactical edge computing framework that orchestrates services in accordance with dynamic variations in workload demand, compute availability, and network performance across the federation [1].

II. SYSTEM DESIGN AND ARCHITECTURE

The demo environment is built using six tightly coupled elements. Such an environment consists of five tactical edge clouds operated by different nations, each runing Kubernetes on a collection of tactical nodes, which range from vehicle-mounted servers to edge devices carried by soldiers. A set of resource discovery, management, and orchestration services are deployed in each cloud so that workloads can be instantiated, managed, and, if necessary, migrated across national boundaries. A set of policy services ensures that security rules are not violated [2], [3].

Unity provides an interactive 3D visualization layer that renders the city, handles aerial and on-ground vehicles' trajectories, and the dynamic links between edge nodes, thereby allowing observers to assess system behaviour in real time. Moreover, Unity acts as a network controller. When a node is repositioned in the virtual environment, Unity recalculates the corresponding RF path loss and propagates the updated link to EMANE [4], ensuring that the virtual network reflects the current tactical geometry. Lastly, Unity functions as a synthetic data generator. Radar, roof-top microphone arrays, a network of Closed-Circuit Television (CCTV) cameras, and a roaming first-person camera that represents a soldier's mobile phone, are embedded in the scene and generate MQTT messages or expose an RTSP video stream whenever a drone traverses their coverage area.

EMANE provides an emulated radio network that links the five clouds. The connectivity between the nodes is modified based on the pathloss calculated by EMANE.

The Unmanned Aerial System (UAS) is modeled as a hostile quadcopter whose position, orientation, and acoustic signature are published over MQTT. Operators can fly the UAS along scripted or ad-hoc paths to generate realistic sensor stimuli.

At the edge, containerized Artificial Intelligence (AI) services subscribe to the audio and video topics, perform inference close to the data source, and publish detection messages that include target IDs, bearings, and confidence scores. The MQTT brokers in the three clouds exchange messages whenever connectivity is available, which means that analyzed results propagate even when raw data cannot.

Finally, a web-based dashboard gives the audience a single view of all the cluster states, federation events, network link health, and drone-detection alerts. From the Unity interface, an operator can throttle a link, disconnect a cloud, or redirect the drone, thereby provoking a measurable response from the federated and adaptive tactical cloud framework.

III. DEMO

The demonstration is based on a Counter UAS (C-UAS) scenario. In the demo, we show five national Kubernetes-based edge clouds connected into a single, federated deployment running over EMANE-emulated tactical radio links. The Unity-based simulation of the Anglova military scenario is used to generate a variety of sensor feeds, including acoustic sensors, tripwire sensors, CCTV cameras, and mobile phone cameras. Containerized AI services for audio and video drone detection will be deployed, orchestrated, and migrated across the tactical edge clouds, dynamically adapting when service requirements are not met anymore. Viewers will see Unity's simulated audio and video sensor data flowing to the nearest national cloud, where containerized analytics pick out drone signatures. When network links degrade, the federated orchestration mechanism automatically redeploys those analytics to a better-connected cloud, and detections continue without interruption—illustrating end-to-end sensing, analysis, and resilient service migration.

The demonstration unfolds as a narrative with four key stages that each emphasize both facets of the contribution: the operation of the federation and the resulting analytics.

First, the demo begins with the default situation where there is **no federation**. One of the nations deploys an audio classifier, a video object detector, and a fusion service. However, this nation does not have sufficient resources of its own in theater to process the incoming sensor streams timely, resulting in overloaded resources and network links.

Then, we establish the **federation** with the developed framework, where the five national clouds register through common APIs. The objective is to show that a federation of tactical edge clouds can be established quickly.

Subsequently, a **federated deployment** occurs, where we deploy an audio classifier, a video object detector, and a fusion service across the federation. The federation layer selects two of the clouds according to available compute and link quality. At the same time, a UAS is launched within Unity.

Next, we cause **link degradation and migration**. EMANE is instructed to reduce the bandwidth and raise the latency on the path between two clouds. The federated and adaptive tactical edge computing framework detects that service-level objectives are in danger of being violated, and it requests Kubernetes to migrate the video detector to the third cloud, which still has a healthy connection to the sensors.

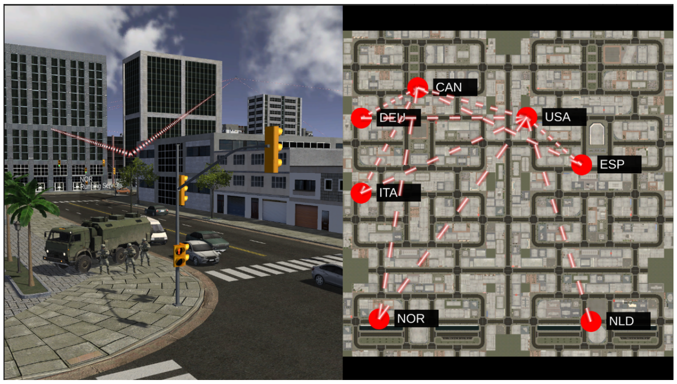

Fig. 1: Unity simulation for demo.

Lastly, there is **multi-UAS scaling**, where we introduce two additional UASs that follow distinct trajectories. Processing demand rises and the developed framework adapts by starting a further instance of the audio classifier in the previously lightly loaded cloud.

Throughout the demonstration, the metrics for backhaul traffic, CPU load, detection latency, and service availability are updated in real time. A web dashboard lists every analytic service that can be provided and displays the real-time resource state of every cloud. At the end of the session, we compare these measurements with those gathered from a control run in which all analytics reside in a single cloud, thereby quantifying the benefits of adaptive federation.

ACKNOWLEDGMENT

This demonstration builds on work produced under NATO IST-168, IST-193, and related multinational research programs. We thank all contributing organizations for their continued collaboration and support.

REFERENCES

[1] H. Bastiaansen, J. v. d. Geest, C. v. d. Broek, T. Kudla, A. Isenor, S. Webb, N. Suri, M. Fogli, B. Canessa, A. Masini, R. Goniacz, and J. Sliwa, "Federated control of distributed multi-partner cloud resources for adaptive c2 in disadvantaged networks," *IEEE Communications Magazine*, vol. 58, no. 8, pp. 21–27, 2020.

[2] A. Amato, H. Bastiaansen, W. Datema, M. Fogli, J. v. d. Geest, T. Kudla, P. Sanchez, N. Suri, and S. Watson, "A performance cost/benefit analysis of adaptive computing in the tactical edge," *2024 International Conference on Military Communications and Information Systems (ICMCIS)*, 2024.

[3] A. Amato, H. Bastiaansen, W. Datema, M. Fogli, R. Fronteddu, R. Galliera, J. v. d. Geest, T. Kudla, P. Sanchez, N. Suri, and S. Watson, "Adaptive computing in federated tactical clouds - overview, results and follow-up for ist-193 rtg 'edge computing at the tactical edge'," *Proceedings of the NATO Research Symposium 'Towards the convergence of Edge Computing, Adaptive Networking, and Information Management at the Tactical Edge' (IST-208 RSY)*, 2024.

[4] A. Amato, R. Fronteddu, and N. Suri, "Dynamically creating tactical network emulation scenarios using unity and emane," in *MILCOM 2023 - 2023 IEEE Military Communications Conference (MILCOM)*, 2023, pp. 201–206.