Aerial Monitoring with Drones: Experimental Insights on Communication Challenges

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***Abstract*—A system of unmanned aerial and ground vehicles is implemented and evaluated for autonomous monitoring of freight containers at a container terminal. Reliable operation of this system requires stable, high-throughput, and low-latency communications and networking. We present experimental results and insights from using multiple drones connected via 5G and Wi-Fi mesh to fulfill their monitoring mission and acting as relays to enhance the connectivity and latency of ground vehicles. The used technologies fulfill most requirements but have limited scalability.**

***Index Terms*—UAV networks, aerial connectivity, latency, relaying, hybrid robot systems**

I. INTRODUCTION

Aerial inspection and monitoring of large, complex, and dynamic environments is increasingly performed by semi-autonomous cyberphysical systems consisting of multiple drones. Application domains span transportation, agriculture, defense, industrial, and logistics. One of the key building blocks is the wireless communication required for tasks like command and control, sensing, coordination, and offloading of computation tasks. This is why significant research and development on communication and networking of drones has been made in recent years [1], [2]. Two core requirements are short round-trip latency for command and control as well as high uplink rates for delivery of payload data, including high-resolution images and video streams. The standardization body 3GPP has addressed the integration of drones into cellular networks and incorporated a range of drone-related features into its specifications [3]. Besides 5G, also Wi-Fi is employed to enable short-range and license-free communications and to form ad hoc mesh networks between drones.

Our own research on networked multi-drone systems has, for many years, concentrated on system-level and experimental work [4]–[7], often conducted in collaboration with practitioners to identify relevant requirements and approaches for real-world use cases. This paper continues this stream of hands-on research. Specifically, we report on communication-related insights gained from experiments with a monitoring system that we developed, implemented, deployed, tested, and evaluated in a container terminal. The system employs multiple aerial drones and a ground rover communicating via both 5G cellular and Wi-Fi mesh systems with a local ground control station (GCS) and a cloud server. The system is applied in two use cases, where drones use the network to (i) coordinate autonomously to identify and localize freight containers and (ii) support a rover on the ground to improve its connectivity.

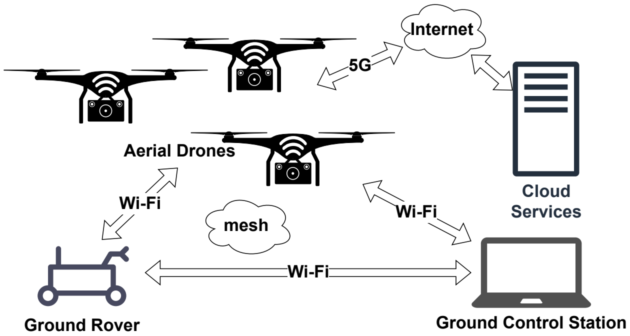


Fig. 1: System architecture with drones, rover, cloud services, and ground control station connected with Wi-Fi mesh and 5G

Using the system in real-world conditions, we gained insights on communication requirements and challenges. We report on the following functionality: service discovery (overhead, choice of protocol), visual monitoring (required data rate, scalability), and ground coverage extension via aerial relays (link quality, latency).

The paper is structured as follows: Section II describes the system components and their interaction, Section III presents measurement results. Section IV discusses the findings. Section V addresses related work. Finally, Section VI recaps.

II. SYSTEM DESCRIPTION

The system developed and assessed consists of several drones for aerial monitoring and a rover on the ground. These vehicles are supported by computing infrastructure both on-site for command and control and remote for data processing. The system architecture is shown in Fig. 1.

Wi-Fi and 5G are employed for wireless connectivity between the system entities. A Wi-Fi mesh network enables the exchange of control commands and telemetry data, facilitating low-latency local coordination without external infrastructure. At the same time, 5G is used to transmit payload data to remote cloud services for processing and analysis.

As drones, we use twinFOLD GEO hexacopters by the Austrian company twins. They are controlled by an ArduPilot flight control unit (FCU) and a Raspberry Pi 4b onboard companion computer running Ubuntu 22.04 with the Robot Operating System 2 (ROS2) Humble. This allows drones to operate autonomously while coordinating each other and allowing remote command and control. The drones use the Quectel RM500Q 5G UE to connect to the Internet. The Wi-Fi mesh is based on Wallys DR4029 wireless access points providing Wi-Fi 5 (802.11ac) in the 5 GHz band. They run the OpenWrt firmware that implements the Meshmerize multipath routing protocol [8].

The GCS controls the mission by sending commands to all or individual drones. To do so, it receives and visualizes the MAVLink telemetry and ROS2 topics forwarded by the onboard companion over an IP-based network. It can be placed on-site or at a remote site connected via the Internet.

The ROS2-based flight stack on board the companion computer sends high-level navigation commands over a local MAVLink connection to the FCU, which then performs the low-level control to maneuver the drone. Specifically, for aerial monitoring, we implement a distributed approximation of the multiple traveling salesman problem (mTSP) [9]. The drones coordinate using ROS2 topics (publish-subscribe) and services and actions (request-response).

III. System Evaluation

The system is evaluated in a container terminal, where containers are transferred between road vehicles and train wagons. Containers are typically temporarily stored in grouped stacks before being transported further.

A. *Use Cases*

The communication capabilities are evaluated in two use cases: aerial monitoring and aerial relaying. These address different combinations of vehicles: aerial vehicles only, mixed teams of aerial and ground vehicles, and ground vehicles only.

The **aerial monitoring** use case is illustrated in Fig. 2. It consists of three drones that coordinate in a distributed way to scan a set of container stacks. They are supported by an on-site GCS that controls the mission and monitors the status of the drones and by a cloud server that processes images and identifies and localizes containers. Once the GCS initiates the mission, each drone selects a container stack and performs a circular flight around it while capturing pictures periodically. The drones upload the pictures compressed with JPEG over the 5G network to a cloud server using the secure file transfer protocol. They constantly share their scanning progress to the GCS and other drones. Once a stack has been fully scanned, the drone proceeds to the next stack (or returns to its takeoff location once all stacks have been scanned).

The **aerial relaying** use case is illustrated in Fig. 3. Its goal is to demonstrate the ability of drones to provide networking services to ground users. The focus is to offer reliable low-latency communication for real-time services such as remote operation. Specifically, using Wi-Fi mesh, we stream a video from an autonomously operating ground rover to a GCS. A drone follows the rover's path in the air to provide wireless relaying functionality, thus improving the quality of the video if required. In good conditions, the rover transmits the video stream directly to the GCS. However, whenever the radio signal experiences strong shadowing, the stream is transmitted in a multihop way via the drone.

Fig. 2: Aerial view of a container stack as seen by a drone with detected container IDs in green

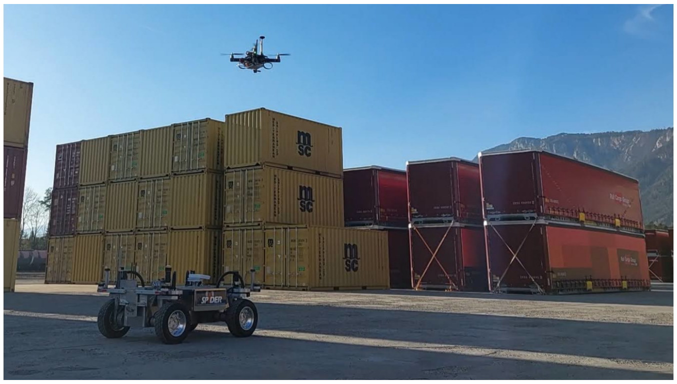


Fig. 3: Rover and drone operating between the container stacks

We perform several experiments for both use cases and present selected results and insights.

B. *Aerial Monitoring*

During the **initialization phase**, each drone advertises the services it provides and queries the services it requires to establish a local network for direct, low-latency coordination. This generates a significant traffic volume in a short period. This traffic burst places high demands on the network and can even break the communication when causing queue overflows.

To address this problem, we analyze the communication middleware of ROS2, which is based on data distribution services (DDS) for distributed discovery, serialization, and transportation. We set up a testbed consisting of two drones and one GCS connected via a Gbit-Ethernet switch. We start the GCS software to control the mission, and on each drone we start the complete ROS2 flight stack consisting of 32 nodes, 62 topics, 210 services, and 5 actions. The resulting number of packets over time is shown in Fig. 4.

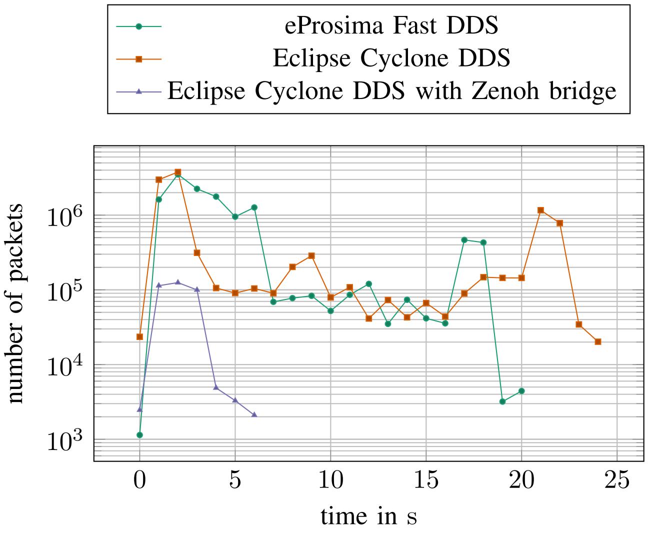


Fig. 4: ROS2 discovery overhead

There are different vendors providing middleware. Our comparison of the standard option, eProsima Fast DDS, with an alternative middleware, Eclipse Cyclone DDS, shows only minor differences. However, when we replace the inter-drone communication with the Eclipse Zenoh protocol, we experience significant improvements in a way that the number of packets decrease by more than an order of magnitude and the discovery time reduces to fraction of its previous value. This is achieved by the design of Zenoh's discovery mechanism and more efficient messaging in comparison to DDS: Instead of advertising all publishers and subscribers, only the desired subscriptions are advertised and grouped by drones (as opposed to the individual several dozen ROS2 nodes per drone) for compression [10].

During the **monitoring mission**, the drones regularly take pictures and offload them using the on-board 5G UE to cloud services for post-processing. The associated traffic volume depends on the flight speed and spacing between capture locations. Our experiments are with $2\,\mathrm{m}$ and $5\,\mathrm{m}$ spacing, resulting in 38 to 111 capture locations for one container stack, depending on its size (see Fig. 5). Flights with a maximum speed of $5\,\mathrm{m/s}$ lead to a capturing period of $3\,\mathrm{s}$ to $4\,\mathrm{s}$ with an average picture size of about $10\,\mathrm{MB}$. The resulting payload data rate is shown in Fig. 6. The average value is between 20 and $30\,\mathrm{Mbit/s}$, depending on the waypoint spacing.

To generalize these experimental results and study the scalability of the system, we express the payload data rate as $r = \bar{S}/\Delta t$ with average image size $\bar{S}$ and capture interval Δt. The aggregated rate produced by N drones is then $L = \sum_{i=1}^{N} r_i = N\,\bar{S}/\Delta t$, which is shown in Fig. 7 for $\bar{S} = 10\,\mathrm{MB}$. In our experiments, the rate remained below $100\,\mathrm{Mbit/s}$, but increasing the number of drones or capture rate quickly raises the demand to several hundred $\mathrm{Mbit/s}$. This means that care must be taken when scaling the aerial monitoring system, not to exceed the network's capacity.

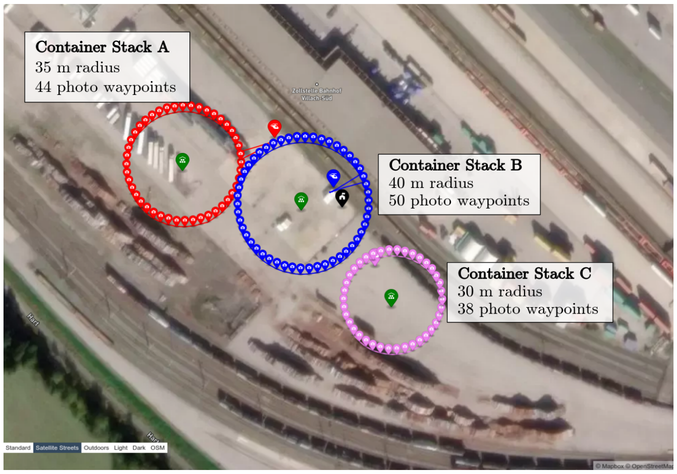
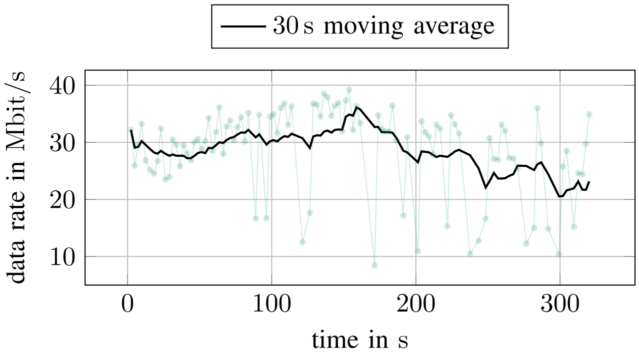
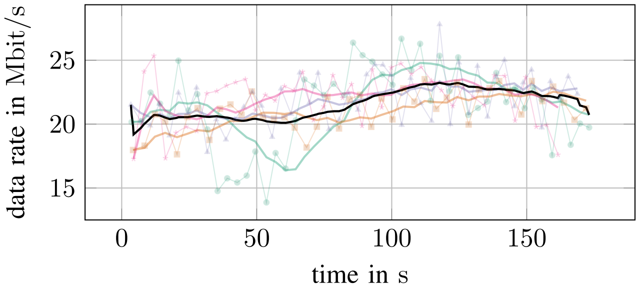


Fig. 5: Monitoring mission with three drones circling container stacks and taking pictures on marked photo waypoints (© Mapbox © OpenStreetMap)



a: $2\,\mathrm{m}$ waypoint spacing



b: $5\,\mathrm{m}$ waypoint spacing

Fig. 6: Measured data rate per drone for visual monitoring payload for different flights (colored) and average (black)

C. Aerial Relaying

Rovers working on the ground experience severe shadow fading due to the massive container stacks. The drones can improve their connectivity by acting as aerial relays. We measure the end-to-end latency of a video stream transmitted from a rover to a local GCS with Wi-Fi mesh. Fig. 8 shows the results both with and without aerial relaying.

Fig. 8a shows the distance between rover and GCS. The

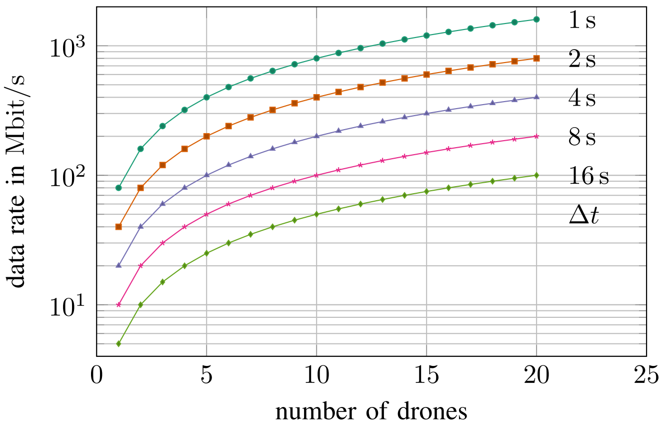


Fig. 7: Calculated aggregated payload data rate for visual monitoring over the number of drones for varying capture interval Δt

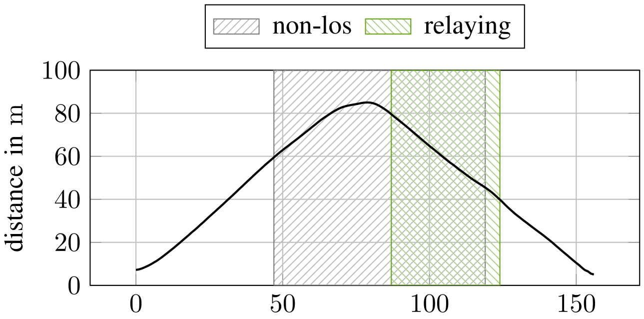
gray background marks the period during which there is no direct line-of-sight between them. Fig. 8b shows the end-to-end latency without an aerial relay. The average latency is about 100 ms in line-of-sight conditions. It increases to multiples of this value when the line-of-sight is obstructed. At some points in time, even link outages occur. This behavior is also seen in the sharp increase of the link metric in Fig. 8c, capturing the degradation of the underlying communication link. Fig. 8d shows the end-to-end latency if an aerial relay drone is employed during the period marked with a green background. The latency first increases (in the gray period) but then stabilizes once the relay becomes active (during the green period). The link metrics in Fig. 8e support this behavior.

IV. LESSONS LEARNED

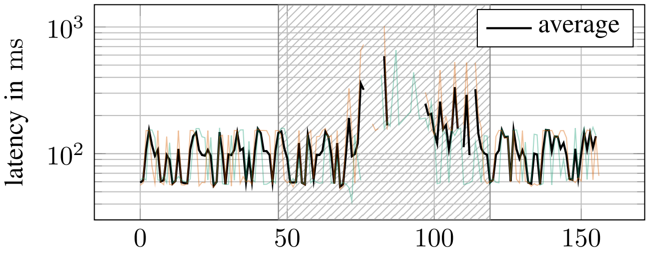
Let us share some of the lessons learned during our experiments intended for other researchers performing hands-on field work with multi-drone systems.

First, stable high-rate communication is absolutely crucial for autonomous operation. Control algorithms often provide a multitude of services that rely heavily on communication. This is especially critical during the initial service discovery phase, where rapid and reliable data exchange is needed to establish connections and functionality. In our system, which is rather small, we measured up to 3.8 million packets per second during the first three seconds of a mission, which makes the demand for powerful communication infrastructure evident.

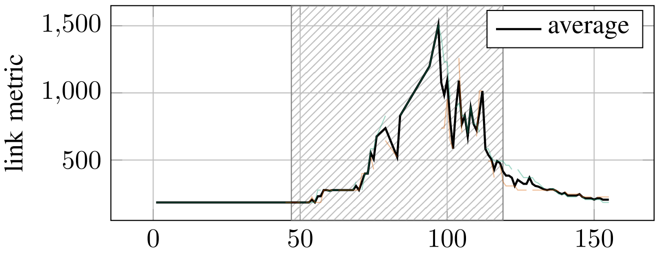
Second, the integration of visual monitoring with multiple drones significantly amplifies the volume of payload data generated. Each drone produces about 30 Mbit/s, and data volume increases linearly with the number of drones and capture rate. Current technologies can manage this volume up to about ten drones and capture intervals in the order of several seconds. However, challenges arise if the number of drones exceeds ten or if the capture interval is below two seconds.



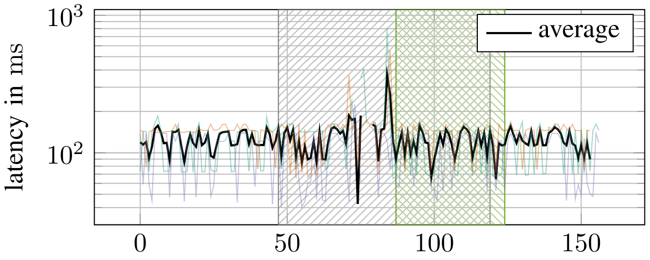
a: Distance between ground nodes



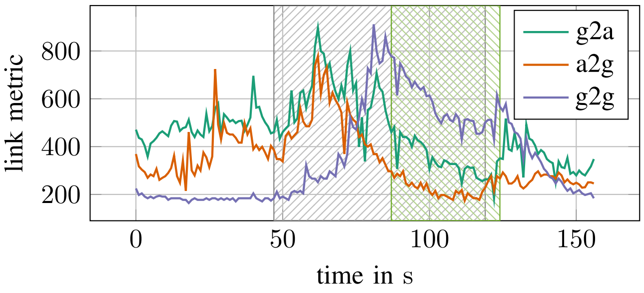
b: End to end latency without aerial relay



c: Link metric without aerial relay



d: End to end latency with aerial relay



e: Average link metrics g2a (ground to air), a2g (air to ground), and g2g (ground to ground)

Fig. 8: Latency of communication link with and without aerial relay for different experiments (colored) and average (black).

Third, communication breakdowns of ground vehicles in complex environments with massive objects that are being moved around can be effectively mitigated by aerial relays, yielding reasonable latency values. The use of ad hoc routing protocols further enhances the connectivity by switching between direct links and multi-hop paths. This adaptability is crucial for maintaining reliable communication in dynamic environments with changing shadowing constellations.

V. RELATED WORK

Recent work explored communication performance using ROS2 as middleware in multi-robot systems. Park et al. [11] conducted an empirical study of the real-time characteristics of ROS2, evaluating scheduling and message latency in 5 GHz Wi-Fi systems. However, their work was performed in controlled environments and did not address aerial components or scalability under high-throughput payloads. Similarly, Castillo-Sánchez et al. [12] presented a testbed and methodology to analyze ROS2 wireless communication in robot swarms, focusing on DDS quality-of-service (QoS) tuning and messaging reliability over Wi-Fi. Results highlighted performance limitations of ROS2 with up to 25 nodes using CycloneDDS. However, they did not investigate more efficient middleware such as Zenoh. Erős et al. [13] proposed a ROS2 communication architecture for collaborative industrial automation focusing on indoor environments and deterministic control without addressing wireless mesh or air-to-ground integration. In contrast to these works, our study provides an experimental evaluation of aerial and ground robots operating in an outdoor container terminal under real-world conditions.

A complementary line of research investigates drone-based data collection and monitoring. Messaoudi et al. [14] provide a comprehensive survey of drone-based data collection schemes and associated challenges. Xu et al. [15] review drone applications in smart city management. Zhang and Li [16] study a drone-enabled IoT relay system for environmental monitoring in remote areas without public networks. Bhat and Venkitaraman [17] propose a hybrid V2X and drone-based system for road condition monitoring. These papers highlight the growing interest in drone-based monitoring and relaying but do not provide an analysis of communication middleware or aerial relaying in industrial environments, as addressed here.

VI. CONCLUSIONS

Our experiments with a multi-drone system capable of autonomous aerial monitoring of freight containers in a container terminal demonstrated some communication challenges and approaches. The drones identify and localize containers and act as aerial relays to enhance connectivity for ground vehicles. Measurements underscore the importance of careful system dimensioning to prevent exceeding the network capacity.

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