mmWave UAV-assisted Information-Centric Wireless Sensor Network for Disaster-Resilient Smart Cities: Preliminary Evaluation and Demonstration

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Abstract—**This paper presents an information-centric wireless sensor network-based ecosystem for smart-city applications. The proposed scheme aims for an integrated non-terrestrial wireless network using unmanned aerial vehicles with higher frequency bands for future broadband wireless communication in disaster-resilient smart cities. To demonstrate the feasibility of the proposed scheme, we performed a preliminary evaluation in terms of network performance, including throughput and jitter in the application and TCP layers. In addition, as one of the scenarios to be applied for disaster-information sharing systems, we demonstrated a video-streaming test through an on-site experiment, which will explore a new wireless networking technology in promising mmWave bands.**

Keywords—millimeter-wave; unmanned aerial vehicle; information-centric wireless sensor networking

I. INTRODUCTION

Emerging technologies, such as the Internet of Things (IoT), metaverse, and artificial intelligence, enable crowd sensing in central city areas. Thanks to the massive amount of valuable information they provide, problems related to urbanization, social needs, and governmental structures can be mitigated. Smart cities are a new paradigm that can lead to the provision of smart services centered around healthcare, transportation, energy, and natural disasters. This makes cities greener, safer, and friendlier for residents [1]. To take advantage of one of the essential elemental technologies underpinning the social infrastructure, we propose Wireless Sensor Networking (WSN) technology for disaster-resistant smart cities. Such technologies usually provide daily services, but in our approach, disaster-related information is shared using the same system when a disaster occurs. This approach brings two advantages: economic efficiency (i.e., we can eliminate the necessity of an exclusive disaster-communication and networking system) and availability improvement (i.e., the system can be available in emergencies because it is already in place for performing daily operations). At the same time, we need to make sure the proposed scheme can provide a high data rate and low latency with stable connectivity to establish a new sustainable smart-city ecosystem.

Millimeter-Wave (mmWave) communications have been recognized as a revolutionary new research domain in future mobile networking technologies, which can support a wider bandwidth compared to current mainstream spectrums, such as ultra-high frequency and microwave bands. Due to the vast spectrum bandwidth, mmWave communication enables a multi-gigabit data transfer [2], and the spectrum is globally assigned (for example, in 28, 38, and 60 GHz in the cellular network utilized in the 3GPP-FR2 [3]). Therefore, mmWave communication is positioned at the forefront of the global frontier and is an essential element in any discussion on next-generation wireless communications. As a global standardized system, one of the most important technology is a Wireless Local Area Network (WLAN), which helps smartphone users connect to the local network. In contrast to other mmWave communication systems, such as local 5G or private 5G, the IEEE 802.11 family has the advantage of widespread user terminals, which yields economic benefits in common device usage in the phase of smart-city deployment. IEEE 802.11 ay is the latest version of mmWave communications and operates under the point-to-point and point-to-multi-point topologies in indoor and outdoor environments on the unlicensed 60-GHz bands. IEEE 802.11 ay has been specified to improve the legacy IEEE 802.11 ad while guaranteeing backward compatibility for legacy users.

IEEE 802.11 ay supports mesh networks, which can provide a cost-efficient broadband wireless solution to replace fiber optical networks in city areas. The IEEE 802.11 ay-compliant mesh network can be deployed using a combination of Distribution Nodes (DNs) and Client Nodes (CNs), i.e., multiple DNs are linked to each other to form a backhaul mesh network, and end-users can access the network via CNs. The mesh network is structured and works based on multi-hop communication and dynamic controls, such as finding the most efficient path for information en route, i.e., if one DN goes down, another can immediately take over its role, thereby improving the network's availability. As such, the mesh network has suitable features for a network that supports disaster-resistant smart cities. As a commercial product, Meta (Facebook) offer Terragraph (TG) as an IEEE 802.11 ay-compliant mesh network [4]. TG aims to provide an alternative low-cost solution for operators to provide a similar cellular network or regional internet service on the unlicensed 60-GHz band.

Natural disasters (earthquakes, typhoons, hurricanes, floods, and other geologic processes) can potentially cut or destroy the existing territorial wireless network infrastructure in a disaster area. In this situation, it is a serious challenge to provide quick and temporary alternative wireless connectivity, but one solution is to use Unmanned Aerial Vehicles (UAVs),

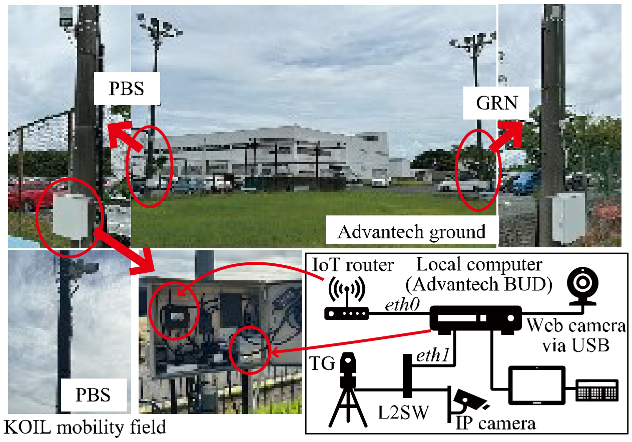

Figure 1. Overview of the test field developed in [12][13][14].

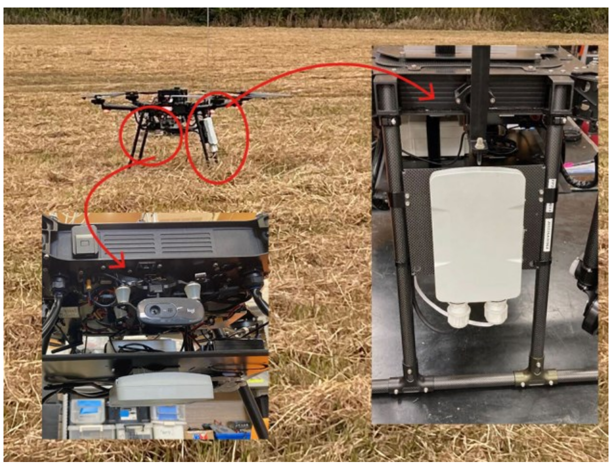

Figure 2. Overview of developed ARN device.

which improve the coverage by acting as aerial base stations [5][6]. Recall for a moment the characteristics of mmWave communications: the radio propagates straightforwardly, and therefore is significantly attenuated by penetration, atmosphere (oxygen), heavy rain, and moisture-containing material. Fortunately, UAVs can establish more reliable Line-of-Sight (LoS) links for ground end-users, which leads to a better communication channel. Therefore, UAV-assisted mmWave wireless networks can provide a broadband wireless network offering wide-area coverage even if a disaster strikes.

As we look at the network layer, the protocol suite must be designed based on an autonomous and decentralized network architecture. Information-Centric Networking (ICN) is a remarkable candidate for a future network architecture that shifts from host locations to content data [7]. This is beneficial in data-intensive applications optimized for content retrieval in an autonomous-decentralized ad-hoc network environment. ICN names the data instead of the address, i.e., the end-users can discover and obtain the data via names, and this naming-based retrieval achieves a location-free structure. Another vital feature of ICN is in-network caching, i.e., the data are copied and stored in the cache memories on the network nodes, which can be helpful for further data retrieval. In ICN systems, the data are handled separately by individual content units, i.e., the data can be self-certified and encrypted by their producer, which contributes to security improvement. Applying ICN to WSN, which yields Information-Centric Wireless Sensor Network (ICWSN) [8], positively affects network performance, such as boosting data delivery and improving data fetching delay. Therefore, ICWSN has the potential to solve the challenges arising from the case where most WSN devices are resource-constrained with radio frequency, processing resource, energy, and memory limitations. To provide information related to disasters through ad-hoc wireless networks, the data abstraction resulting from ICN design contributes to easy data spreading.

For mmWave UAV communications, Sanchez et al. [9] formulated a stochastic channel model for mmWave UAV communications under hovering conditions. Gapeyenko et al. [10] investigated the use of aerial relay nodes for dynamic routing to mitigate the effect of obstacles on the radio links. Masaoka et al. [11] investigated mmWave UAV-assisted communications for remotely operating and flying unmanned devices regardless of ground conditions, achieving high-speed data transmission. The use of mmWave bands is growing, and this study is positioned as a prior effort to them.

Consequently, this paper investigates an ecosystem to support application services for disaster-resilient smart cities. The proposed scheme is constructed based on the mmWave UAV-assisted ICWSN architecture. As part of our ongoing work [12][13][14], we have been developing a test field for ICWSN in the mmWave band. In this work, we describe the developed test field and aerial node using an industrial UAV. As a contribution of this paper, to illustrate the effectiveness of the proposed scheme, we evaluate network performance and the feasibility of the scheme. The demonstration includes a real-time video streaming application on the mmWave UAV-assisted ICWSN system as a scenario that shares a disaster-area information.

The remainder of this paper is organized as follows. Section II of this paper gives a brief overview of the development of the proposed ICWSN test field. Section III describes the proposed scheme. Section IV presents the evaluation results and discussion. Section V discusses related work. We conclude in Section VI with a brief summary and mention of future work.

II. Development of ICWSN Test Field

We have been developing the testbed device and test field to evaluate a mmWave ICWSN framework [12][13][14], as shown in Figure 1. The test fields were constructed at the KOIL mobility field (Kashiwa, Chiba) and the baseball field in Advantech Japan (Nogata, Fukuoka). In this paper, we focus more on the baseball field because this is where we conducted the experiment. The framework is composed of a group of Sensor Nodes (SNs), Relay Nodes (RNs) (classified into Ground RN (GRN) and Aerial RN (ARN)), and a Private (self-operated) Base Station (PBS). We implemented the PBS and RN devices, and the control computer used an industrial

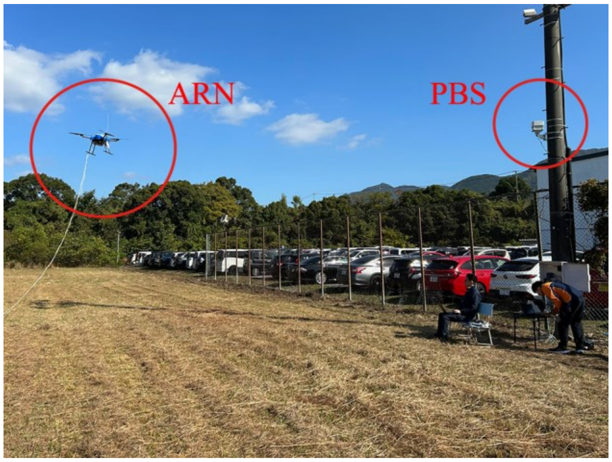

Figure 3. Field view of experimental site

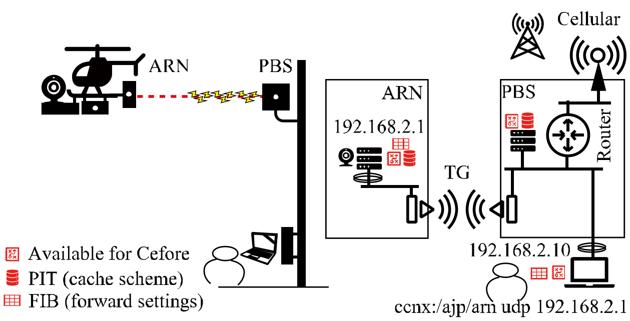

Figure 4. Network model of experimental site.

Advantech BUD (two-core 1.8 GHz Intel Atom CPU, 4 GB RAM, Ubuntu 20.04 OS, and extended processing and communications modules) device for reliability and robustness.

For the mmWave TG communication system, we used the BeMap MLTG-DN for PBS and MLTG-CN [15] for RN and SN. Note that MLTG-DNs can transmit up to distances of about 300 m, and all routes must be LoS with no foliage, walls, or other obstacles in the link. Their maximum transmission power, i.e., Effective Isotropic Radiated Power (EIRP), is 45 dBm, and the antenna consists of a phased array with 64 elements. In the beamforming method, the steering angle is [–45°, 45°] in the azimuth plane and [–25°, 25°] in the elevation plane, and it selects an index of direction among predefined beams. The MLTG-DN and MLTG-CN support the SC-PHY mode with the adaptive rate control of 1–12 in IEEE 802.11 ad/ay and have four channels, consisting of 58.32, 60.48, 62.64, and 64.80 GHz (central) frequency bands with 2.16-GHz bandwidth.

III. Development of ARN device

The ARN device consists of a control computer, camera, and MLTG-CN mounted on the UAV, as shown in Figure 2. The control computer used the BUD device, the same as the previously mentioned testbed device. The camera and MLTG-CN were connected to the computer via the Universal Serial Bus (USB) and Ethernet (wired LAN) cables, respectively. As shown in Figure 3, due to Japan's Radio Act and Civil

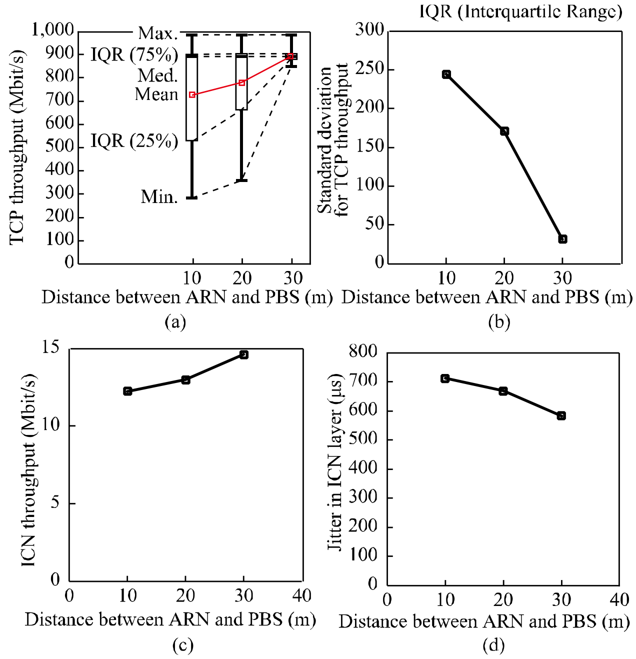

Figure 5. Experimental results of network performance: (a) TCP throughput. (b) Standard deviation for TCP throughput. (c) ICN throughput. (d) Jitter versus distance between nodes.

Aeronautics Act regulations, the UAV flew with a captive flight (not free). Note that the mooring rope is not only used to anchor the UAV to the ground but is also bundled with a LAN cable in parallel for power supply to the MLTG-CN via PoE. Figure 4 shows the network model of the experiment. As an end-user terminal, a PC (two-core 1.3 GHz Intel Core i5U CPU, 8 GB RAM, and Ubuntu 20.04 OS) was directly connected to the PBS, and the static IP addresses were assigned for ARN and the PC. The ICN platform used Cefore [16], which is a ccnx-compliant protocol stack. Note that we only install Cefore in the control computer of ARN and PC; the data can be exchanged via the "cefnetd" and "csmgrd" daemon processes from the application program. Namely, the system can perform based on the ccnx-based procedure, including naming, caching, and data management.

IV. Experimental Results

Let d denote the distance between ARN and PBS. To establish the link between two, UAVs hovered at the location where d = 10 m and at the height of 5 m, the same as that of PBS, and the antenna surfaces between SN and ARN and between ARN and PBS facing each other. Under this condition, the TG link can be reconstructed, including the beamforming direction, by restarting MLTG-CN (on the ARN). Note that this procedure can be accomplished by restarting MLTG-DN (on the PBS), but it takes more time to reconfigure than when using MLTG-CN. Figure 5 shows the results of network performance. TCP throughput was measured every 1 s for 30 s using iPerf3. ICN throughput was calculated based on the time intervals when the data provider commits static data using the "cefputfile" command from the control application, and then the receiver retrieves the data

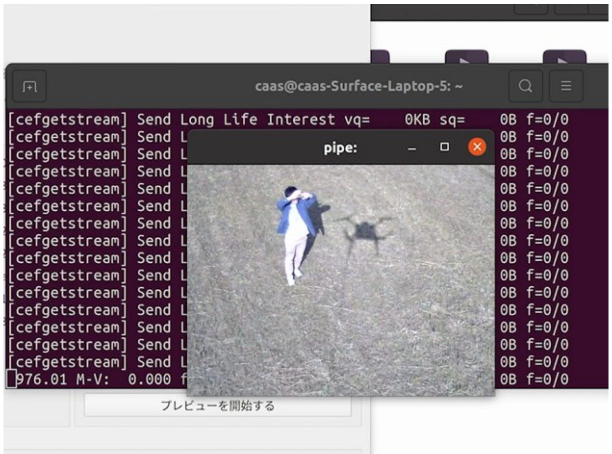

Figure 6. Demonstration of video streaming application.

using the "cefgetfile" command. The ICN throughput was the mean value of the three measures for three different file fetches.

As shown in Figure 5(a), the average TCP throughput is 891 Mbit/s (in median value) and 735, 787, and 899 Mbit/s (in mean value) in the cases where d = 10, 20, and 30 m, respectively. Note that, in the physical layer, the TG can support the data transfer rate up to 1,925–4,620 Mbit/s; nevertheless, MLTG only supports Gigabit Ethernet (GbE); so this wired interface causes a bottleneck. Figure 5(b) shows the variance of TCP throughput. The standard deviation decreases when d increases because the UAV moves vertically and horizontally (including roll and pitch), even if it is stably hovering in a fixed position. This movement affects the mmWave feature (i.e., straight radio propagation and directional beamforming), which can be relatively small for far distances of d. As shown in Figures 5(c) and (d), the average ICN throughputs are 12.2, 13.0, and 14.6 Mbit/s, and the average jitters are 712, 669, and 583 µs for d = 10, 20, and 30 m, respectively. These results have the same characteristics as that of TCP evaluations in Figures 5(a) and (b). The ICN throughput is much lower than that of TCP because the latency causing mmWave propagations will affect the ICN layer, and Cefore cannot optimally work, which is for wired LANs.

To demonstrate the provision of information on the disaster-stricken area, the ARN performed live video broadcasting from the sky to the PC (connected to ground PBS). On the basis of the literature [17], the ARN provided the streaming video from the camera mounted on the UAV using the "cefputstream" command, and the PC received it using the command of "cefgetstream" command. Figure 6 shows a screenshot of the PC during the demonstration, where it is clear that the streamed video can be received, although the static photo cannot represent its motion.

V. CONCLUSION

In this paper, we evaluated the network performance and demonstrated a high-capacity application of the video-streaming application. We can obtain the fundamental performance and show the scheme's feasibility. In future work, we plan to deploy the proposed eco-system in an actual city and we should construct stable mmWave-band networks.

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