Ultra-Reliable IoT Communications with UAVs: A Swarm Use Case

Zhenhui Yuan, *Member, IEEE,* Jie Jin, Lingling Sun, *Senior Member, IEEE,* Kwan-Wu Chin,
and Gabriel-Miro Muntean, *Senior Member, IEEE*

***Abstract*—Unmanned Aerial Vehicles (UAV) are powerful Internet of Things (IoT) components, offering sensing, communications and data analysis in the air. Recently, 3GPP TS 22.261, TR 22.862, and TR 36.777 have specified performance requirements for communications between multiple UAVs in the 5G domain. This article discusses communications reliability challenges in a UAV swarm context. Recommendations for designing an ultra-reliable communications system for UAV swarms are introduced with focus on software protocol stack and RF hardware. For the purpose of demonstration, we developed EasySwarm, an open-source UAV swarming platform, which adopts the Long Range (LoRa) radio at physical layer and a low-latency channel access protocol at MAC layer. Real-life test-beds are built consisting of 10 UAVs and 20 robotics cars that produce background traffic. LoRa, WiFi and LTE networks are employed to provide broadband and cellular wireless network support. Results show that using LoRa leads to better reliability, in particular, allowing for higher swarm density and longer coverage distance, than when WiFi is used. In addition, LTE provides the best reliability and latency for UAV swarms with good network connectivity.**

Keywords*—*UAV, IoT, ultra- reliable, swarm.

I. EMERGING IOT WITH UAVS

LATELY the UAV market has seen an exceptional growth, with Compound Annual Growth Rates (CAGR) of over 30% since 2014 and huge demands in both the toy/hobby and industrial Internet of Things (IoT) applications areas. These sectors have market shares of approximately 30%/70%. This increasing trend is expected to continue and shipments of over 90 million of consumer UAVs to be recorded in 2025 alone[1]. Deploying a team of UAVs, or swarm, for industrial IoT services is becoming reality for applications involving public safety, delivery, search and rescue, surveillance, etc. Figure 1 presents typical UAV swarm use cases that can be deployed in urban and rural areas. In an urban area with good mobile network coverage, a UAV swarm is deployed at cloud and is remotely controlled via a mobile network, whereas in a rural area with poor network support, a UAV swarm is generally connected to a ground control station and employs unlicensed spectrum protocols such as LoRa and WiFi with limited communications range. Our previous research [1] demonstrated that collaborative UAVs would benefit public safety services, assuming UAVs have the support of new ad-hoc networking protocols.

Communications technologies are key to deploy successfully UAV swarm IoT services in both urban and rural areas. GSMA[2] has released recommendations on how mobile networks can support unmanned aircraft operations beyond-visual-line-of-sight (BVLOS). Mobile networks allow highly scalable, reliable and secure connectivity for UAVs, enabling fast deployment of new services. For instance, cellular connected UAVs are able to access real-time information from air traffic control and update the on-going flight plan. To address the requirement of using cellular technologies by UAV swarms, 3GPP[3] has produced studies on enhanced LTE support for UAVs. Existing 4G LTE networks are well suited to support the deployment of UAV swarms in urban areas and 3GPP working groups are putting effort towards further optimization of cellular networks that are dedicated to UAV usage. However, deploying a UAV swarm in rural areas is more challenging. In many cases, high density UAVs need inter-communications via a local wireless network and require reliable communications in response to dynamic network topologies. In this regard, non-3GPP technologies (i.e. WiFi, LoRa, ZigBee, etc) are needed to provide local wireless communications between UAVs. Nevertheless, there are many technical challenges when directly applying these local wireless technologies [2] [3], including related to routing protocol, energy saving, traffic model analysis, etc.

This article overviews for the first time the challenges related to the usage of both 3GPP and non-3GPP communications technologies by UAV swarms. Then the paper presents recommendations for designing an ultra-reliable communications system, targeting urban and rural areas alike. The recommendations include both software (i.e. communications protocols,

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Z. Yuan is Associate Professor at the Key Laboratory of RF Circuits and Systems (Hangzhou Dianzi University), Ministry of Education, China (email: yuanzhenhui@hdu.edu.cn).

J. Jin is CEO at RobSense Technology, http://www.robsense.com (email: jie.jin@robsense.com).

L. Sun is Professor and Director at the Key Laboratory of RF Circuits and Systems (Hangzhou Dianzi University), Ministry of Education, China (email: llsun@hdu.edu.cn).

K.W Chin is an Associate Professor at the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Australia. (email: kwanwu@uow.edu.au).

G.-M. Muntean is an Associate Professor and Director of the Performance Engineering Lab, School of Electronic Engineering, Dublin City University, Ireland (e-mail: gabriel.muntean@dcu.ie).

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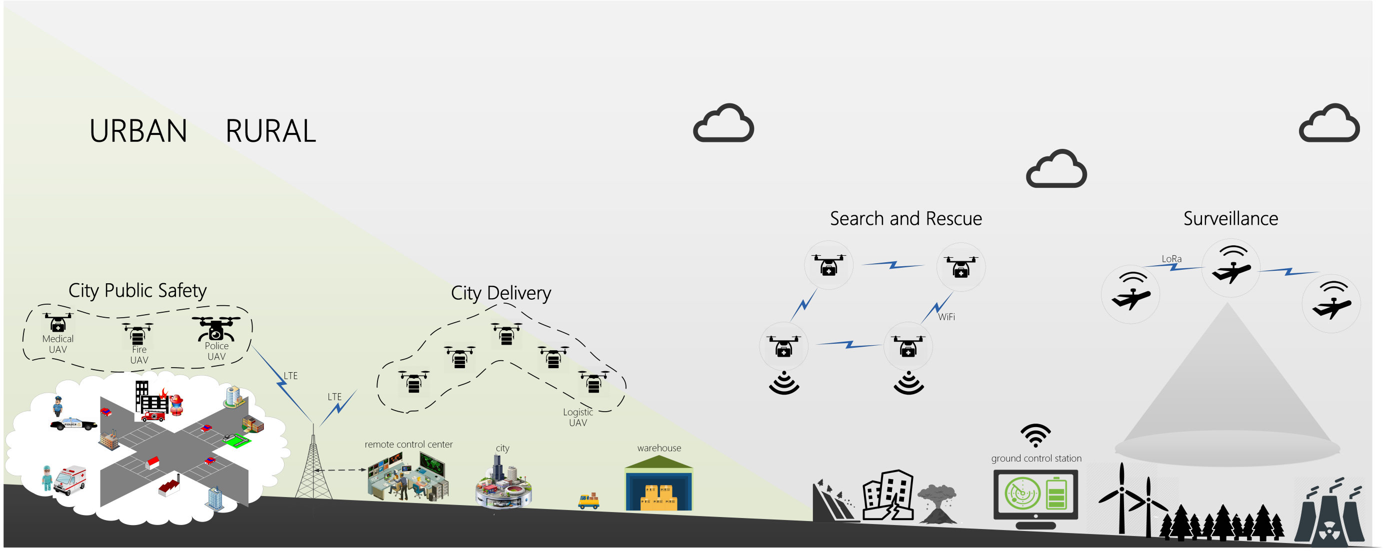

Fig. 1: Industrial use cases using UAV swarm at urban (in-mobile network) and rural area (out-of-mobile network): 1. city public safety service using medical UAV, fire UAV and police UAV that are coordinated by LTE network; 2. city delivery service using logistic UAVs that are controlled by LTE network; 3. search and rescue service using UAV swarm via WiFi mesh network; 4. surveillance service using UAV swarm via LoRa mesh network.

embedded operating system and UAV cloud) and hardware aspects (i.e. anti-interference modulation, low power long range radio frequency and embedded computing processor). In particular, we developed a novel wireless local communications solution, EasySwarm, which is an open-source platform using LoRa as radio frequency (RF) radio and a novel MAC-layer low latency communications protocol. Real-life test-beds were setup and tests were performed to show the communications performance comparison when LoRa, WiFi and LTE are employed. The article aims to save time and resources of UAV service providers and clients when deploying industrial IoT applications in either urban or rural areas. Also, standards community is suggested to support the emerging UAV swarm use cases with optimized networking technologies, in particular in the non-3GPP realm.

II. ULTRA-RELIABLE COMMUNICATIONS AND CHALLENGES

A. *Ultra-reliable Communications*

Ultra-reliable communications (URC) refer to achievement of certain level of service almost 100% of the time. Examples of URC are provided in [4] and include reliable cloud connectivity, critical connections for industrial automation and reliable wireless coordination for vehicles-to-vehicles communications. There is trade-off between maintaining the desired service level and the actual service level when referring to reliability or ultra-reliability (e.g. data rate, capacity, etc. vs time). For instance, a reliable wireless system supports 100 Mbps data rate 95% of the time or an URC system guarantees 100 Kbps data rate 99.999% of the time. Lately, URC was extensively researched including in the EU-funded project METIS[4], which focused on the operation of mobile and wireless systems.

5G PPP[5], the largest European stake-holder consortium on ICT infrastructure which includes European Commission, manufacturers, telecommunications operators, service providers, SMEs and research institutions, has specified URC as a key requirement for future networked communications with focus on IoT or involving critical machine-type communication (uMTC). Among others, URC allows for reception of immediate feedback from remotely controlled autonomous vehicles, including UAVs. Technically, network reliability refers to the capability of successfully delivering packets within a given latency bound. According to 3GPP TR 22.862, 50ms and 5ms are upper bound latencies for air-to-ground (or *UAV Node to Node*) and air-to-air (or *UAV Node*) radio links, respectively, so that the flight controller can have good responsiveness for gesture control.

B. *Challenges*

For UAV swarms, reliable control signal delivery is particularly important. In practice UAV swarms adopt either a mobile ad-hoc network (MANET) or a vehicular ad-hoc network (VANET) as the network infrastructure; however, both VANET and MANET are designed for mobile terminals at low speed (i.e. 0-2m/s for MANET nodes and 20-30m/s for VANET nodes) that operate in a two dimensional space. Additionally, the current communications protocol stack does not consider any UAV-specific mobile communications models or address

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[4] EU-funded project METIS, https://www.eit.uni-kl.de/en/wicon/projects/metis/ [Accessed on 25 Jul 2018].

[5] 5G-PPP Website, https://5g-ppp.eu [Accessed on 25 Jul 2018].

any QoS UAV-related aspects. For instance, the end-to-end latency sharply increases as more UAVs join a network and the highly dynamic topology causes frequent breaks in wireless connectivity. Therefore there is a strong motivation to study and propose new communication solutions that cater for UAV swarms and control data reliability.

3GPP TS 22.261 [5] has specified that UAV traffic needs dedicated priority and QoS treatment. Typically, UAV-IoT data consists of small and non-consecutive packets that require low bandwidth. Take downlink UAV traffic for instance, temperature sensors and GPS modules generate 2-byte and 36-byte packets at less than 10 Hz, respectively. The uplink UAV control traffic consumes around 0.8 kbps bandwidth only. Additionally the uplink UAV traffic needs higher reliability than that of the downlink traffic. In order to support high level UAV-IoT services, state-of-the-art research works are investigating diverse UAV emerging use cases.

3GPP Radio Access Network (RAN) working group recommends that UAVs must be controlled reliably and quickly. 3GPP TR 22.862 [6] focuses on enablers for critical communications and provides the first overview of communications for vehicle collaboration and connectivity. The report specifies that the latency for controlling UAVs does not need to be ultra low if a human operator is involved. This is because humans have limited reaction speed anyway and thus it makes little sense to have ultra-low latency. 3GPP TR 36.777 [7] provides an overview of the performance of LTE networks when used to serve aerial vehicles. In particular, among 5G Key Performance Indicators (KPI) are latency and reliability.

III. DESIGNING A UAV SWARM COMMUNICATIONS SYSTEM

This section makes fundamental recommendations for the design of ultra-reliable communications system for UAV swarms. In general, the quality of communications between UAVs mainly depends on the amount of traffic, networking protocol, wireless RF hardware and channel environment. Fig. 2 (a) presents a typical wireless subsystem for most IoT equipment regarding software and hardware aspects. The software of IoT communications subsystem should concern first traffic characteristics of applications, based on which appropriate communications protocols are then selected or designed. For instance, applications with large-amount data transfer (e.g. high definition (HD) video transmission) need a communication protocol with high bandwidth (e.g. IEEE 802.11n, mmWave), whereas applications featuring small packets, non-consecutive and energy-sensitive (e.g. sensor network on farm) are better served by low-bandwidth, but power efficient communications protocols (e.g. LoRa). Additionally, an embedded operating system is generally needed to mange computing and hardware resources of IoT equipment. The hardware aspect of IoT communications involves design and development of drivers, hardware abstraction layer (HAL) and communication transceivers.

Figure 2 (b) presents the recommended air-to-air communications system for UAV swarm. Details of the software and hardware design are discussed below.

A. Software Design

1) Data Encapsulation: Data generated by a UAV swarm includes control signal (e.g. GPS, speed, IP address, battery, etc) and IoT traffic (e.g. video, temperature, humidity, etc), etc. Typically, this data is carried by *MAVLink*[6] communication protocol, which has been widely deployed on commercial UAV platforms. A MAVLink frame allows customized definition in XML and then conversion to C/C++, C# or Python code. The minimum MAVLink packet length is 8 bytes without payload and the maximum MAVLink packet length is 263 bytes for full payload. MAVLink packs C-structs over serial channels and sends packets to the ground control station. The packet format of the proposed communications subsystem is byte aligned (8-bits). This makes the packet compatible with a number of on-the-shelf robotic platforms such as 8-bit MCU (e.g. Atmel, STM8, MSC-51) and serial I/O interfaces (e.g. RS232).

2) Embedded Operating System: Computing resources on UAV are limited in terms of CPU, RAM and flash capacity. Traditional operating systems such as Linux and Windows are not appropriate for use due to their high resource consumption. Lightweight operating systems have been designed for IoT equipment with specific concerns on real-time capabilities, network connectivity and protocol support, energy efficiency, hardware agnostic, security, etc. In this article, it is recommended to deploy OpenWRT[7] as the embedded operating system for hosting UAV swarm-aware networking protocols. OpenWRT is an open-source Linux distribution for embedded systems and has been widely used in many wireless routers. OpenWRT supports a variety of wired (serial, Ethernet, etc.) and wireless (WiFi, LoRA, cellular, etc.) protocols, and also low bandwidth web protocols such as Constrained Application Protocol (CoAP)[8] and Message Queuing Telemetry Transport (MQTT)[9].

3) Low Latency Communications Protocol: Many research works have tried to reduce the latency by designing proper communications protocol at network and link layers of the OSI network model.

- *MAC Layer Protocol* is critical for a UAV swarm using *star* network topology, e.g. a UAV communicates with a group of ground robots and sensors. In this case, latency and packet collisions need to be reduced by the MAC layer protocol. In [8], a combination of CSMA/CA and TDMA medium access protocols was proposed for super dense UAV swarm scenarios, where UAVs are used to sense and collect real-time data from a disaster area. The new MAC solution allows UAVs to transmit simultaneously packets without any delay or collisions. A data collection protocol [9] in a UAV-based wireless sensor network was developed to better collect data transmitted from large number of ground sensors. It

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[6] Micro Air Vehicle Communication Protocol, http://www.qgroundcontrol.org/mavlink/start [Accessed on 25 Jul 2018].

[7] OpenWRT Wireless Freedom, http://openwrt.org/ [Accessed on 25 Jul 2018].

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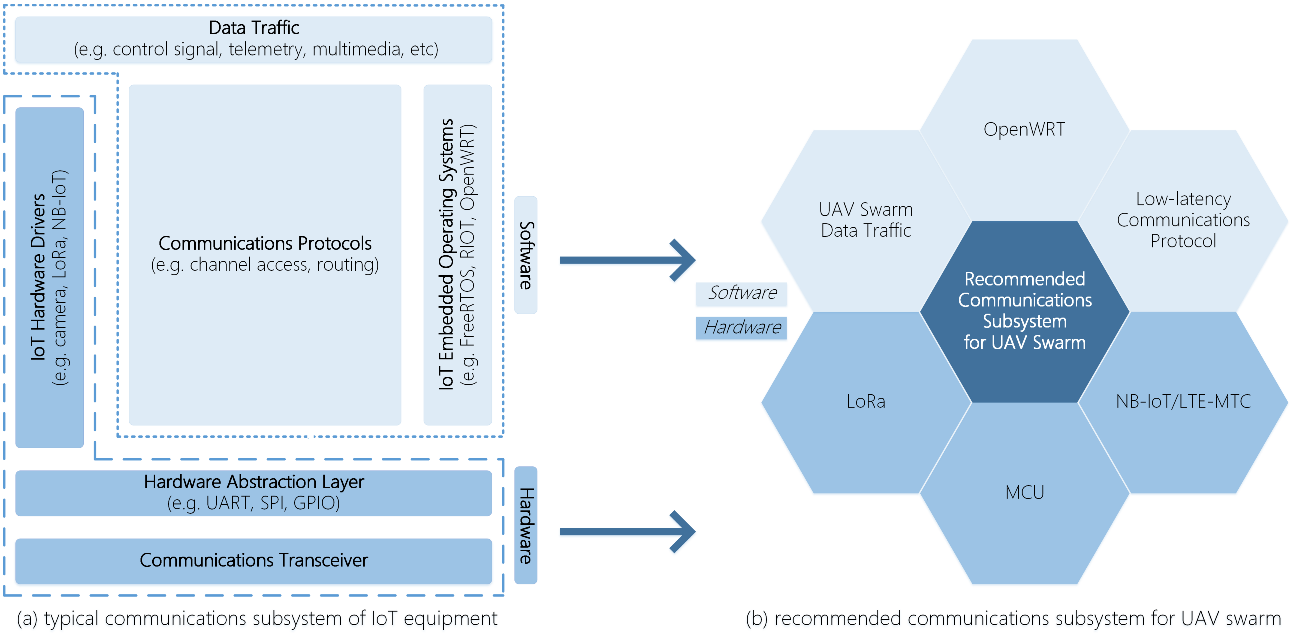

Fig. 2: Typical wireless subsystem of IoT equipment and recommended design for UAV swarm communications

assigns different priorities to subframes of a UAV's beacon signal and defines a lower contention window to a higher transmission priority subframe.

- *Network Layer Protocol,* or routing protocol, is fundamental for a UAV swarm using *mesh* network topology. The dynamic topology of the UAV swarm leads to frequent connection breaks which impact performance of the routing protocol. In [10], the authors proposed the optimized link-state routing protocol (P-OLSR) to adapt to topological changes of UAV ad-hoc networks. P-OLSR uses GPS information to predict the quality of the wireless links so that the routing adapts to topology changes with minimum interruptions and delays. In [11], the authors overviewed and compared the performance of state-of-the-art position-based routing protocols when deployed in UAV ad-hoc networks. In particular, a comprehensive analysis of routing performance was conducted in terms of delivery rate, path dilation and scalability. For a UAV swarm with pre-defined flight path (e.g. GPS is known), it is recommended using routing protocols [10] [11]. If the UAV swarm topology is random with non-static mobility model, low-cost flooding is probably much better and more efficient.
- *Cellular Network* use is recommended for wide area controlling of a UAV swarm in urban areas. Our previous research [12] introduced a novel software defined network (SDN)-based mobile sensor networking architecture, UCANET, for UAV swarms. UCANET location is at the cloud and maintains the global swarm topology. Each UAV monitors the wireless link conditions including received signal strength index (RSSI), round-trip delay (RTT) of single hop, link life time and flight speed. These statistics are then sent back to the UCANET cloud over cellular network for advanced network resource planning. A cloud robotics platform called Rapyuta is reported in [13]. It is designed to offload heavy computation from UAVs to the cloud. It outsources part of a UAV's onboard computational processes to a commercial data center. For instance, a pre-installed Amazon Machine Image (AMI) has been provided to enable fast deployment. The Rapyuta cloud platform offers centralized networking architecture and helps computing resource limited devices such as micro UAVs. However, it should be noted that,deployment of such cellular network-based UAV swarm relies on the actual operator network coverage.

B. Hardware Implementation

UAVs for IoT are typically equipped with many sensors such as infra-red cameras, mmWave radar, barometers, cameras. These sensors are continuously generating data which needs real-time processing and analysis.

- *LoRa*[10] technologies allow long range communications at low data rate and low battery consumption as well as massive connections access in one LoRa gateway. These features make LoRa an ideal option for outdoor UAV swarm communications. In this article, we designed a new LoRa gateway to provide support for local *star* topology network for UAV swarms.
- NB-IoT/LTE-MTC, specified in 3GPP Release 13, are cellular technologies offering reliable wireless communications, in particular supporting massive number of

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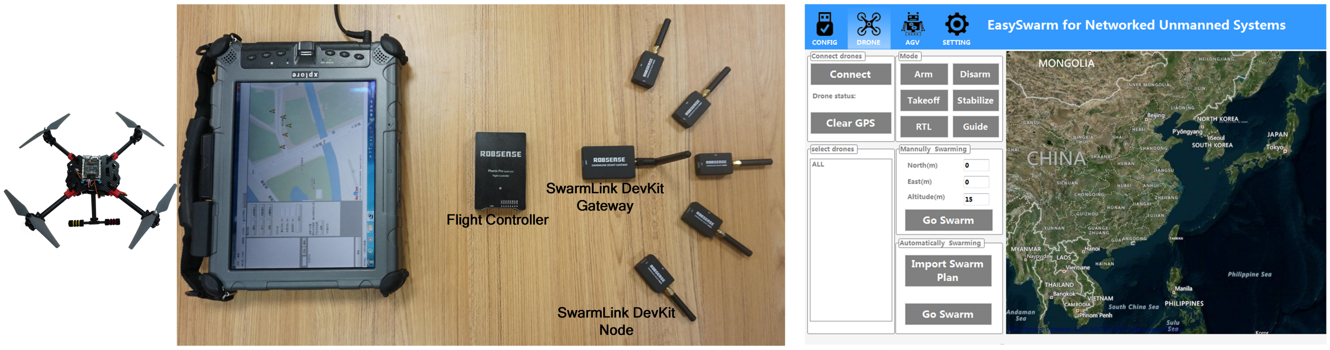
[10] LoRa, https://www.lora-alliance.org [Accessed on 25 Jul 2018].



North(m) 0
East(m) 0
Altitude(m) 15

EasySwarm Hardware
(a)

EasySwarm Ground Control Software
(b)

Fig. 3: EasySwarm: an open-source platform for UAV swarming. (a) EasySwarm hardware including gateway and nodes, and (b) EasySwarm ground control software

low throughput IoT devices. NB-IoT offers new radio added to current LTE platforms and is optimized for the IoT market. LTE-MTC delivers various additional LTE enhancements for Machine Type Communications. Note that deploying NB-IoT or LTE-MTC based UAV swarm test-bed requires more expensive experimental hardware in comparison to that of LoRa.

- *MCU* modules have been widely used by most UAVs in flight controllers. However, MCU is limited in terms of computing resources and performs poor when running complex algorithms. For instance, for applications that need fast on-board processing (i.e. fast channel access protocol [14], SLAM[11], HD video transcoding), field-programmable gate array (FPGA) or GPU chips are better solutions, rather than a MCU chip. Xilinx[12] has released a specific hardware platform for UAVs video transmission called Zynq UltraScale, that affords low latency, real-time UltraHD video compression/decompression and transmission with integrated H.265 video codec.

Note that, most off-the-shelf UAVs use WiFi for both air-to-ground and air-to-air communications. However, WiFi communication protocols enable limited amount of wireless data exchange and commercial WiFi RF hardware gives short communication distance, i.e. typically less than 100m. Therefore, WiFi is not considered as the best option for outdoor UAV swarm in industrial IoT applications.

IV. EASYSWARM: OPEN-SOURCE PLATFORM FOR UAV SWARMS

An open-source UAV networking platform, EasySwarm[13] (shown in Figure 3), was specifically designed according to the recommendations presented in Section III. It includes ground control software (Figure 3 (b)) which facilitates easy and fast addition of new UAVs. The EasySwarm platform adopts a dedicated UAV-IoT gateway, SwarmLink, from RobSense Technologies. SwarmLink uses LoRa modulation to provide superior anti-interference as well as long-distance communications. A proprietary packet collision avoidance algorithm is integrated with the SwarmLink firmware to provide low latency channel access even in high density UAV scenarios. SwarmLink has implemented a FreeRTOS real-time embedded operating system on a ARM7 CPU. Developers are free to use off-the-shelf flight controllers, set up dynamic waypoint plans, and execute pre-configured swarming plans.

V. REAL-LIFE TESTING USING LORA, WIFI AND LTE

This section presents real-life tests involving UAV swarm deployment. ***Reliability*** and ***polling delay*** are measured to assess communications quality. The reliability is defined as the probability of successful delivering packets with a latency threshold of 125 ms. The latency threshold is indicated in 3GPP TR 22.862 and includes the round-trip delay of a UAV control packet and the actual packet processing time (*e.g., MCU, RF module, socket processing*) at gateway and node. Polling delay refers to the overall time that a downlink packet was distributed from the gateway to the nodes in a polling access way.

The test-bed considers both urban (in-mobile network) and rural (out-of-mobile network) areas. In rural area, a LoRa gateway (*RobSense SwarmLink*) and a WiFi gateway (*TP-Link TL-WR742N*) are used to provide centralized local network access. Swarm configurations (i.e. height, distance between drones, speed, direction) are distributed to UAVs through the gateways. In an urban area, UAVs are connected to *China Mobile* LTE network via a 4G dongle (*HUAWEI E8372h-155*). Polling delays are measured and compared for LoRa, WiFi and LTE access. Two scenarios are considered:

- **Scenario One: Reliability**. To evaluate single link reliability of LoRa and WiFi, a single UAV flies away from the LoRa and WiFi gateway separately from a distance of 10 meters to 2500 meters at a speed of 3 m/s. For

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[11] OpenSLAM for simultaneous localization and mapping, https://www.openslam.org [Accessed on 25 Jul 2018].

[12] Xilinx ZYNQ UltraScale, https://www.xilinx.com [Accessed on 25 Jul 2018].

[13] EasySwarm GitHub, https://github.com/RobSenseTech/SwarmLink.git [Accessed on 25 Jul 2018].

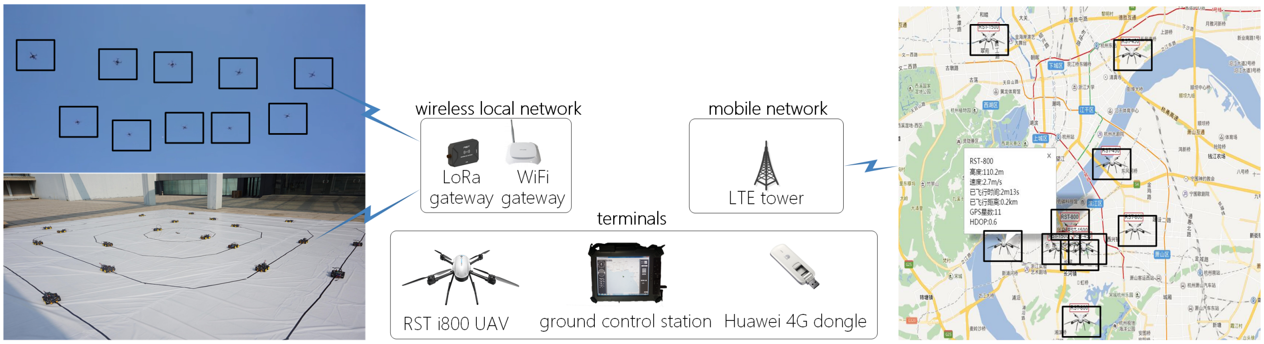

Fig. 4: Real-life testbed: (1) a wireless local network including 10 UAVs and 20 robotic cars that are connected via LoRa and WiFi, respectively; (2) LTE network including 10 UAVs that are distributed within 2.5 km x 2.5 km area in Hangzhou city.

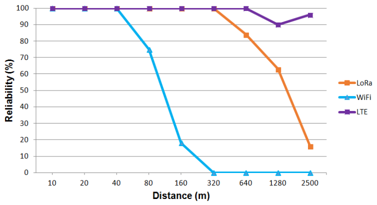

Fig. 5: Network reliability of a single UAV via LoRa, WiFi and LTE, respectively.

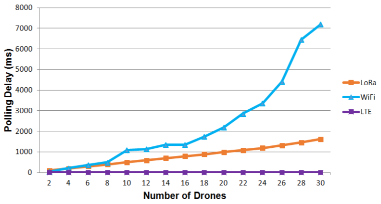

Fig. 6: Polling delay of a UAV swarm via LoRa, WiFi and LTE, respectively.

LTE, it is difficult to know exactly which cellular tower the UAV is connected to. For consistency, the UAV is first connected to the LTE network then flown away in a random direction from 10 meters to 2500 meters.

- **Scenario Two: Polling Delay**. First, the polling delay of a ten UAV swarm connected via LoRa and WiFi is studied. Twenty auto-guided vehicles (AGV) are also connected to the same gateway with UAVs in order to generate background traffic, as shown in Figure 4. The distance between LoRa/WiFi gateways and UAVs is restricted within 80 meters, which has been demonstrated to have the best single link reliability (100%) in Scenario One. To avoid collisions of drones, the EasySwarm software uses the *Pathway Mobility Model* that predefines flight routes for all drones. To avoid collisions of AGVs, a line tracking system is used to keep the AGVs moving following circular paths. Secondly, the polling delay of ten UAVs connected via a LTE network is studied. Twenty AGVs are also connected to LTE and generate background traffic. Note that these AGVs use the same operator as the UAVs. All UAVs and AGVs are uniformly distributed within a 2.5km x 2.5km area in Hangzhou city, China. Each UAV flies up to a height of 100 meters and stays hovering until the test ends.

Note that *Scenario One* had to be implemented first in order to find out the appropriate range within which both LoRa and WiFi provide the same 100% network reliability. In both scenarios, beacon messages are exchanged between drones and gateways transmitting speed and GPS information at one Hz. Each UAV and AGV generate an eight byte control packet at one Hz containing GPS information and remaining power value.

Figure 5 illustrates the results from *Scenario One*. In case (1), a single UAV is used via LoRa and WiFi network. It is shown that the reliability of LoRa solution is decreasing linearly from 100% to 20% as the communication distance increases to 2500m. The reliability of WiFi reduces sharply to 20% and 0% at 160m and 320m, respectively. Note that, 100% network reliability is achieved as far as 320m and 40m for LoRa and WiFi, respectively. In case (2), a single UAV is connected via LTE. Results show that LTE network in urban area offers ultra-reliable (100%) communications within movement of 2500m, except occasionally performance drop due to handover between cellular stations. For instance, the reliability decreased to 90% at a distance of 1280m.

Figure 6 presents the results from *Scenario Two*. In case (1) ten UAVs are connected via LoRa and WiFi network. Following a two tailed t-test analysis it can be said with 95% confidence level that there is no statistical difference between the LoRa results and those in the WiFi case, when the number of nodes (drones and AGVs) was below eight. However, the polling delay of LoRa was 54.5% and 77.5% lower than that of WiFi when the number of nodes was 10 and 30, respectively. Note there are statistical significant differences between these results (95% confidence level). In case (2) ten UAVs are connected via LTE network. Tests demonstrate that LTE provides the best polling delay in comparison with both LoRa and WiFi, with average latency of 19ms.

VI. CONCLUSIONS AND FUTURE WORKS

This article reviews state-of-the-art communications technologies for deployment of UAV swarms in both urban and rural areas. Recommendations for designing ultra-reliable communications systems are first presented regarding both software and embedded hardware aspects. We found that the communication range of LoRa is eight times higher than that of WiFi and provided maximum reliability (100%). The paper shows how LTE network offers the best performance in terms of reliability and polling delay in comparison with that of LoRa and WiFi. Consequently, it is suggested that LTE is used by UAV swarm when cellular coverage is available. For cases when there is no cellular network support, like in rural areas, LoRa is preferred to WiFi.

Future works will concern self-organized UAV swarms, in which communications protocol needs to be adapted to dynamic swarm topology. For swarms with high dynamic mobility, the routing protocol should avoid frequent route breaks and re-build a route as fast as possible. For swarms with large number of UAVs, fast channel access with low packet collisions at MAC layer should be the focus. Additionally, cybersecurity of UAV swarms is essential to be considered, e.g. dynamically establish or refresh of credentials and subscriptions.

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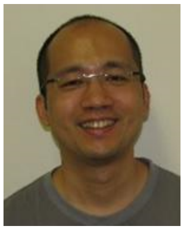
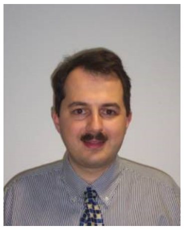
Zhenhui Yuan (M'12) received his B.Eng. degree in software engineering from Wuhan University, china in 2008 and PhD degree in electronic engineering from Dublin City University, Ireland in 2012. His research focuses on wireless communications with robotics. He was a postdoc researcher (2012-2014) on project funded by Ericsson and Enterprise Ireland which aimed at developing a next generation telecommunication management system. He was a visiting scholar at Network Research Lab, UCLA, USA in 2014. He was 3GPP researcher on 5G (2014-2015) at Huawei (Shanghai) Technologies.Co. Ltd. Since 2015, he is Associate Professor at Key Laboratory of RF Circuits and Systems (Hangzhou Dianzi University), Ministry of Education, where he founded the intelligent Robotics Communications Group (iRoC Group). He is the co-founder and chief scientist at RobSense (Hangzhou) Technology Co. Ltd. He has published over 20 papers at international journals and conferences. He won best paper awards at IEEE ICCRE 2016 and IEEE BMSB 2014. His research website is at www.zhenhuiyuan.com.

Jie Jin received the B.S. degree in electronics engineering from Hangzhou Dianzi University, China, in 2010 and the M.S. degree in mechatronics from University of Southern Denmark, Sonderborg, Denmark, in 2012. Currently, he is pursuing a Ph.D. degree in electronics engineering at Dublin City University, Dublin, Ireland, where he also was a research assistant with the RINCE Institute, since 2015. His research interests include system-on-chip design, FPGA based reconfigurable computing, multicore embedded system design with energy efficiency and safety. Recently, he dedicates himself to the IoT field with focus on UAV systems and applications, in terms of hardware/software co-design. Since 2015, he founded RobSense Technology co. ltd and focused on designing a SoC-based flight controller for industrial drones.



Kwan-Wu Chin obtained his Bachelor of Science with First Class Honours and the PhD degree from Curtin University, Australia, in 1997 and 2000, respectively. He was a Senior Research Engineer at Motorola, where he developed zero configuration home networking protocols and designed new medium access control protocols for wireless sensor networks and next generation bandwidth managers. In 2004, he joined the University of Wollongong as a Senior Lecturer before being promoted to the rank of Associate Professor in 2011. His current research areas include medium access control protocols for wireless networks, and resource allocation algorithms/policies for communications networks. He holds four United States of America (USA) patents, and has published more than 100 conference and journal articles.

Lingling Sun (SM'97) received the B.S. degree from Nanjing University of Posts and Telecommunications, Nanjinag, China, in 1982, and the M.S. degree from the University of Electronic Science and Technology, Chengdu, China, in 1985. She joined the Electronics and Information Department, Hangzhou Dianzi University (HDU), Hangzhou, China, as an Assistant Professor, and became a Professor in 1999. Since 1997, she has been with the Microelectronic Computer-Aided Design (CAD) Center, HDU, as Vice-Director and Director. Her major research interests includes the design and CAD of RF/microwave integrated circuits and systems. She is also very interested in smart hardware systems and medical electronic equipment. She was principal investigator for over 40 national projects funded by national ”863” and ”973” projects, NSFC. She has published over 80 papers at international peer-reviewed journals and conferences. Currently she is Director of the Key Lab of RF Circuits and Systems, HDU, Ministry of Education. She is Chairperson of the IEEE EDS Hangzhou branch. Prof. Sun is a Senior Member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) and the IEEE Circuits and Systems Society (IEEE CAS).



Gabriel-Miro Muntean (SM'17) received the BEng and MSc degrees in Software Engineering from the Computer Science Department, ”Politehnica” University of Timisoara, Romania and the PhD degree from Dublin City University (DCU), Ireland, for research in the area of quality-oriented adaptive multimedia delivery in 2003. He is an Associate Professor with the DCU School of Electronic Engineering and co-Director of the DCU Performance Engineering Laboratory. His research interests include quality, performance and energy saving-related issues of multimedia and multiple sensorial media delivery, personalized technology-enhanced learning and other data communications over wired and wireless networks. He has published more than 300 papers in top-level international journals and conferences and has authored three books and sixteen book chapters and edited six additional books. Dr. Muntean is Associate Editor for the IEEE Transactions on Broadcasting and Multimedia Communications Area Editor for the IEEE Communications Surveys and Tutorials and reviewer for important international journals, conferences, and funding agencies. He is project coordinator for the EU Hrizon 2020-funded project NEWTON (http://newtonproject.eu).