Unmanned Aerial Vehicles for Agriculture: an overview of IoT-based scenarios

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Abstract

The agricultural sector is experiencing a new revolution, giving birth to the so-called Agriculture 4.0 paradigm. It brings digital technologies in the field to support the farmers' work, enhancing the productivity of farms. In this chapter, the attention is focused on the role that both Internet of Things (IoT) and Unmanned Aerial Vehicles (UAVs) can play in this regard, whether used in a joint manner or not. We analyse the work being done both in recent research projects and in the literature on those topics, taking into account the role of long-range wireless communications to enable such scenarios, and the potential of 5G and the upcoming Multi-Access Edge Computing (MEC) technology, especially in rural areas, where the lack of connectivity is still hampering the process of digital transformation.

Keywords: agriculture, IoT, UAV, LPWAN, 5G, edge computing

1. Introduction

Smart Farming (SF) refers to the application of Information and Communication Technology (ICT) to agriculture. Data collected and analysed through

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ICT techniques support efficient production processes, thus motivating scientists, practitioners, private and public companies to work towards the goal of developing and encouraging the use of innovative technologies to support farmers on the ground. The most relevant technologies and techniques to be fully exploited are the satellite imagery, the use of agricultural robots, a larger use of sensor nodes to collect data, and the potentialities of UAVs for remote sensing and actuation [1]. Remote sensing, especially UAV-based, is used in a plethora of different scenarios, as for instance forestry [2]. Choosing what sensors to be installed on remote sensing systems depends on the scenario. Satellites represent a long-standing solution for remote sensing, and IoT scenarios can be found also applied to the satellite field [3]. Contrarily to satellites, anyway, UAVs provides great flexibility from the point of view of payloads, because those can be changed at every flight. UAVs must be considered as a breakthrough technology, a game changer [4, 5]. The potential is tremendous, especially when combined with IoT and Low-Power Wide Area Networks (LPWANs). A categorization of the scenarios enabled by the combined use of these paradigm sees data acquisition and data analysis to develop and feed Decision Support Systems (DSSs), or even semi-autonomous solutions. The most common types of IoT sensors used in agriculture can gather data on water in the soil, moisture content, electrical conductivity, and acidity; along with those, solutions well established also in other fields are used, like wind, temperature, humidity, and solar radiation sensors. A case of special interest is the detection of weeds through optical components combined with machine vision systems [6].

UAVs in agriculture can provide support on various issues. For instance, in reconstructing 3D models of crops, determining the crop height, or estimating the value of agricultural indexes, as the Leaf Area Index (LAI) or the Normalized Difference Vegetation Index (NDVI), taking advantage of e.g. multispectral cameras. Very precise imagery can be collected, and large fields can be monitored through the use of swarms [7, 8] that can be used as Flying Ad-Hoc Networks (FANETs) [9]. This opens to the detection of diseases, yield estimation, pest monitoring, and creation of virtual plantations, for instance. It is also worth citing phenotyping, and UAVs have shown potential in this scenario, because collected imagery can be used by image analysis techniques to improve the throughput.

The aim of this work is to present and discuss both research initiatives and scientific literature on the topic of IoT-based SF, especially looking at the use of UAVs in this field. The rest of this work is structured as follows: in Section 2, we analyse how UAVs are used in research projects and what are the considered application scenarios. In Section 3, the analysis on the application scenarios is deepened, taking into account also selected scientific works from the literature, highlighting the role of unmanned vehicles. In Section 4, both requirements and solutions for networking are presented, briefly comparing existing protocols supporting IoT scenarios in agricultural settings. Then, Section 5 opens to the potential future role of a joint use of MEC and 5G networks, presenting network architectures to connect smart farms through satellites and UAVs. Finally, the conclusions can be read in Section 6.

2. The perspective of research projects

In this section, we will survey relevant research projects recently funded in the EU in the field of SF, especially those exploiting UAVs. The main goal is to highlight the increasing attention towards those activities and to analyse the involved technologies, further than describing the application scenarios of interest.

In the last years, the EU has been actively undertaking R&I activities laying the ground for the digitisation of the European agriculture, also taking into account the potential role that UAVs can play. Strategic interventions have been funded to support the uptake of digital technologies and to develop new solutions. In Table 1, we show the most recent EU projects that exploit UAVs, detailing the project name and its starting date, the objective to be achieved from the point of view of the application scenario, and the exploited digital paradigms. The aim is in highlighting the projects explicitly taking into account the use of UAVs for different goals. As you may expect, most projects rely on the use of multiple techniques and technologies in an integrated manner; herein we highlight the most prominent ones.

Table 1 – The most relevant EU-funded R&I projects exploiting UAV technology in the farming sector in the last years.

project	**start date**	**goal(s)**	**cloud/edge**	**data serv.**	**sensing**		**unmanned v.**		**data analysis**	
	ended *(yes/no)*		**computing**	**inform. sys.**	*terr.*	*sat.*	*aerial*	*terr.*	*big data*	*ML*
Sweeper	February 2015 (y)	Harvest Robot			X		X	X		
Flourish	March 2015 (y)	Crop Monit.	X		X		X	X		X
RUC-APS	October 2020 (n)	Agric. Prod.	X				X			
IoF2020	January 2017 (n)	Crop Monit. Livestock Farm. Dairy Monit.	X	X	X		X	X	X	
APMAV	March 2017 (y)	Crop Monit.	X		X		X		X	X
Romi	November 2017 (n)	Crop Monit.					X	X		X
Pantheon	November 2017 (n)	Orchard Monit. Water Use			X		X	X	X	
Swamp	November 2017 (n)	Water Use	X	X	X		X		X	
BigDataGrapes	January 2018 (n)	Crop Monit.	X	X	X		X		X	X
Dragon	October 2018 (n)	Crop Monit. Skill Acquisition	X	X	X	X	X		X	X

The use of unmanned vehicles is a trend of great interest, as also confirmed by looking at the projects in Table 1. In the following, we describe more extensively each initiative. The *APMAV* project consists of an intuitive solution for agricultural management based on UAV technology and an intelligent cloud-based platform that provides farmers valuable, actionable and real-time recommendations for driving down costs and improving crop performance. The *Flourish* project leverages on UAVs as well, aiming at surveying a field from the air, then at performing a targeted intervention on the ground with an Unmanned Ground Vehicle (UGV). The idea is to develop a DSS targeting Precision Farming (PF) applications with minimal user intervention. The *SWAMP* project develops IoT-based methods and approaches for smart water management in the precision irrigation domain, in order to utilize water more efficiently and effectively, avoiding both under- and over-irrigation.

Data-driven activities are proposed in the *Dragon* project, whose main efforts are directed towards skill transfers to ease the adoption of PF techniques.

Several data sources are considered and the data flows are analysed through the use of Big Data techniques to provide agricultural knowledge and to develop information systems. This projects leverages on the joint use of several techniques in an ambitious manner. The *PANTHEON* project, by taking advantage of the technological advancements in the fields of robotics, remote sensing and Big Data management, aims at designing an integrated system where a limited number of heterogeneous unmanned robotic components (including terrestrial and aerial robots) move within the orchards to collect data and perform some of the most common farming operations. The *SWEEPER* project has proposed a robotic system to harvest sweet peppers in greenhouses, leveraging on machine vision techniques to acquire both colour and distance information, and then storing the collected items in an onboard container. Another robotic platform has been developed in the *ROMI* project in an open and lightweight fashion. Assisting in weed reduction and crop monitoring, these robots reduce manual labour and increase the productivity. Land robots also acquire detailed information on sample plants and are coupled with an UAV that acquires complementary information at the crop level. The *BigDataGrapes* project focuses on grapes and wine production, using Machine Learning (ML) to support decisions. Data are collected also through UAVs, as for instance canopy characteristics. The *RUC-APS* project is centered on management approaches aiming at enhancing SF solutions in agriculture systems, applying operational research to optimise farm production. The *IoF2020* project is a very large initiative from the point of view of SF digital technologies: in particular, this project aims at accelerating the adoption of IoT, in order to secure sufficient, safe and healthy food and at strengthening competitiveness of farming and food chains in Europe. It aims at fostering a symbiotic ecosystem of farmers, food industry, technology providers, and research institutes. As visible in Table 1, unmanned vehicles can be used to cover different scenarios, like monitoring, harvesting, and supporting decisions in uncertain conditions. Their use is typically coupled with the use of sensors on the ground, and with cloud solutions to collect, store, and analyse the data to extract actionable information. In Section 3, IoT scenarios in the agricultural field are presented, highlighting the role that UAVs can play.

3. IoT scenarios in agriculture

The use of UAVs in rural areas is less constrained by regulations than in urban areas [10], and thus their use is increasing at a faster rate [11]. This is mainly due to the lower density of both people and buildings, which also translates into less obstacles for the vehicle itself. On the other hand, the degree of connectivity is lower, forcing to prefer the use of dedicated solutions instead of relying on existing networks, like the cellular ones. Distance from airports is likely greater than in urban areas, thus yet posing less constraints on flights, which can be performed in a complete preprogrammed way, requiring a minimal intervention from the pilot. Anyway, the presence of the pilot is a requirement almost everywhere in the world, limiting the scope of Beyond Visual Line of Sight (BVLoS) flights. The use of UAVs, as well as other technologies, is transforming agricultural practices, giving birth to smart farms. In what follows, we concentrate on the scientific literature concerning the use of UAVs in several agricultural scenarios, especially with IoT-based setups. The results are presented in Table 2 and Table 3, the former providing details on the considered works, and the latter detailing the agricultural scenarios of interest.

Higher mechanization in agricultural processes has been fueled by the large diffusion of low-cost sensor nodes and the increasing use of actuating solutions. Real-time stream processing, analysis and reasoning are key concepts towards automation in this field [23], i.e., towards a larger use of robots that can adapt to space and time-varying conditions with minimal delay. Robots can perform very precise operations, and can operate in fleets, as proposed in [24], which considers both UGVs and UAVs. Moving systems rely on Global Navigation Satellite System (GNSS) techniques for precise positioning, and PF applications need large accuracy: because of this, the Real-Time Kinematic (RTK) technique is used to improve the location accuracy. Several commercial systems integrate a GNSS receiver and use one or more fixed RTK reference base stations [32] for

Table 2 – Surveyed literature in the field of SF, especially considering the use of unmanned vehicles in IoT scenarios.

work(s)	main objective(s)
[6]	survey on machine vision on board autonomous agr. vehicles
[7]	autonomous inspections for PF operations
[8]	Farm Management Information System (FMIS) for PF
[12]	survey on UAVs applications for agr.
[13]	remote sensing and image analysis for agr. UAVs
[14]	UAVs to determine management zones for soil sampling purposes
[15]	application scenarios and known limitations of agr. UAVs
[16]	survey on IoT use in agr. scenarios
[17]	UAV to estimate plowing depth with an RGB-D sensor
[18]	UAV to distinguish sugar beets from weeds
[19]	UAV and terrestrial sensing to measure leaf temperature
[20]	UAV for precision spraying
[21]	802.15.4 channel modeling for UAVs use in fields
[22]	UAV in viticulture to find missing plants
[23, 24]	aerial and terrestrial robots in agr. and forestry
[25]	survey on commercial UAVs platforms for SF
[26]	long-range networking for IoT scenarios in agriculture
[27]	IoT greenhouse management system
[28, 29]	IoT irrigation system with long-range networking
[30]	IoT monitoring system in agr.
[31]	yield and response to fertilizers with UAVs

providing accuracy up to centimeters. Further than precise positioning, robots depend on machine-vision systems to navigate the environment [6]; according to the technology and the scenario under consideration, specific spectral signatures are of interest (for instance, Normalized Difference Vegetation Index (NDVI)), and hyperspectral imagery is today a reality for both local and remote sensing. Commercial devices, to be used on board, can already capture both RGB and

Table 3 – Agricultural scenarios covered by the described works and use of unmanned vehicles.

scenario	work(s)	use of unmanned vehicles	
		aerial	*terrestrial*
plowing evaluation	[17]	✓	
spraying	[20, 24]	✓	✓
monitoring	[13, 15, 16, 7, 8, 22]	✓	
soil/field mapping and analysis	[23, 14, 15]	✓	✓
seeding/planting	[15]	✓	
weeding	[23, 18, 6]	✓	✓
irrigation/water management	[15]	✓	
health assessment	[12, 13]	✓	
yield estimation	[31]	✓	

Near Infrared (NIR) bands, and stereovision systems can be used to build 3D maps of the environments [6].

UAVs can be used as data mules to collect data from nodes in open fields [21] or to assess whether an area has been subject to plowing and the plowing depths [17]. The authors consider the use of UAVs as an alternative to satellites. In fact, according to the authors, even high-resolution satellites cannot classify the roughness of the terrain, thus motivating the use of UAVs. A RGB camera is installed onboard and collected georeferenced data are analysed to assess the plowing depths. RGB and NIR are collected by means of an UAV also in [18], with the aim of classifying plants and weeds. The proposed system makes use of the Excess Green Index (ExG) [18] in the case of RGB-only, which depends on the green, red, and blue color components in the images; if NIR is exploited as well, NDVI can be used because of the richer information it provides. By combining these results with geometric features, sugar beets can be recognised even in the case of overlapping plants; furthermore, weed detection is reported as accurate in the space among the rows of sugar beets. NDVI has been used also in the segment of viticulture for precision applications [22]: in fact, when an UAV platform is used to collect very detailed images in a vineyard, plant rows can be discriminated from inter-rows, so being able to identify missing plants with very good precision.

UAVs can be seen as part of a Wireless Sensor Network (WSN), acting as mobile nodes [19], thus being able to analytically characterize the channel model between a moving UAV and fixed terrestrial nodes becomes of interest [21]. In particular, PF is taking advantage of UAVs (several commercial systems are already available [25]) ranging from fixed to rotary wing machines, able to fly at different speeds and altitudes. Lots of uses are already in place for UAVs, like the aforementioned monitoring scenarios, further than pesticide spraying, which is a key application for PF [20]. Heavy and large UAVs can be used for such a purpose in the case of large fields, joint with the use of multispectral techniques in order to firstly generate an NDVI map, and then using this information to efficiently spray pesticides and fertilizers. The idea of a more accurate use of resources, avoiding any waste and using the right amounts, has been around for quite some time.

3.1. Use of data and data ownership

As highlighted in the previous section, data are at the very core of the transformation of the agricultural process. Nowadays, the right to access and use the collected data is at the center of the discussion: Europe has recently made steps towards granting the data originator (i.e., the farmer) a leading role in controlling the access and the use of data by means of the so-called *Code of Conduct on Agricultural Data Sharing* by COPA-COGECA.

4. Wireless communication protocols

Wireless data transfers from both sensors and vehicles in smart agriculture scenarios play a key role, as mostly application scenarios are based on the use of wireless sensor networks. This section provide an overview on the most adopted wireless technologies in this field.

Regarding agriculture, short and long range communication standards can play different roles: they may be used in an integrated manner in complex scenarios, or separately according to the specific application. From a different perspective, communication standards can be classified according to the data rate that can enable a certain type of application demanding or not for bandwidth. Analogously, data rate has a relative impact of energy requirements, that is, high data rates like those used for imaging and videos, as well as large bulk of data, entail high energy consumption; differently, in case of long-time monitoring and small volumes of data, wireless protocols with lower data rates assure a long lasting operation both in the case of long and short range communications.

Considering the large set of wireless communication protocols and the necessities in smart agriculture applications, the use of LPWAN protocols is widespreading. Such a protocol family is designed to provide affordable connectivity on large coverage areas and with a relatively low energy profile. Long Range Wide Area Network (LoRaWAN), Sigfox, and NarrowBand Internet of Things (NB-IoT) are the leading technologies nowadays [33]. LoRaWAN has been created by the LoRa Alliance and takes advantage of the LoRa modulation with Chirp Spread Spectrum modulation [34], which is easy and affordable to implement on LoRa chips. LoRa transceivers operates at sub-GHz frequencies (e.g., 868 MHz in Europe, 915 MHz in USA). LoRaWAN uses a star topology to interconnect the nodes, and to collect sensing data through a central *concentrator*. It converts these data in order to be transferred through the Internet. It is specifically designed for IoT applications to connect thousands of sensors, modules, and appliances over a large network. LoRaWAN is commonly utilized in variety of agriculture application areas including weather forecasting [35], irrigation control [28], and farm monitoring [26]. Sigfox is an ultra-narrowband wireless protocol for low data rate applications, thereby making this technology appropriate for IoT and machine-to-machine (M2M) systems [36]. Sigfox implements the Differential Binary Phase Shift Keying (D-BPSK) modulation and operates in unlicensed ISM bands, i.e. 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia. It is an LPWAN network protocol that offers an end-to-end IoT connectivity solution based on its patented technologies. Sigfox is also suitable for agricultural applications, such as: monitor silo and tank levels, measure the temperature of grain stocks, protect remote farmhouses and outbuildings, secure gates and deter livestock thieves, optimize colony health with remotely monitored beehives, monitor food temperatures along the entire cold chain[1]. Finally, NB-IoT is considered as the latest radio access technology that emerges from 3rd Generation Partnership Project (3GPP) to enable support for IoT devices. Differently from LoRaWAN and Sigfox, NB-IoT coexists with Global System for Mobile (GSM) and Long-Term Evolution (LTE) under licensed frequency bands 900 MHz [37] with a frequency bandwidth of 200 kHz [38]. Thanks to long battery life, large coverage, and its low cost, NB-IoT is a very suitable solution for various agriculture applications such as livestock tracking, greenhouse monitoring [39], and precision farming [40]. For the sake of completeness, other technological solutions for the smart agriculture - aside from such dedicated protocols - have been implemented on top on very diffused wireless protocols, i.e., WiFi and Zigbee.

Wi-Fi is the most commonly utilized protocol in many indoor and outdoor applications: it is considered as the main option for various IoT applications for the smart agriculture like data collection and the connection to cloud. Nevertheless, the high power consumption level of Wi-Fi makes it poorly suitable for agriculture scenarios, despite being still largely adopted. Wi-Fi operates at the 2.4GHz or 5GHz frequency bands. Its transmission range is almost limited, up to 1 km, but it provides a nominal minimum bit rate of 1Mb/s at 2.4GHz and can scale up for a large set of bandwidth-demanding applications. ZigBee is a Wireless Personal Area Network (WPAN) communication technology that was specifically developed by ZigBee Alliance based on the 802.15.4 for low cost and low power solutions for home automation [41]. Nevertheless, thanks to the low cost and the great diffusion of Commercial Off-the-Shelf (COTS) chips, Zigbee has firmly imposed in various applications like greenhouse monitoring [27, 21], water saving [29], and yield improvement [30].

There are other features of wireless network protocols to be considered be-

[1]Scenarios at: `https://www.sigfox.com/en/agriculture`

cause they can be more significant than others in terms of requirements. Indeed, some smart agriculture applications might need adequate data transfer rates and large coverage ranges due to high numbers of sensors spread over the field. Besides, it is typically unpractical to provide fixed power to the sensors, thus justifying the use of batteries. Anyway, a frequent replacement of batteries would not be desired. Hence, power consumption is another key parameter for sensors, and the power used for wireless transmissions must be carefully weighted. Considering these key features, Fig. 1 provides a qualitative comparison among the cited network protocols in terms of range and transmission rate (axes), and of power consumption (bubble size).

5. Multi-access edge computing and 5G networks

The scope of this section is to discuss the potential advantages brought by the exploitation of the MEC paradigm in the SF context.

The cloud computing paradigm enables the offloading of data and data processing to remote servers. Such an approach, intrinsically centralized, is showing its limits with respect to the needs of today's services and applications. In particular, many IoT applications require mobility management, location awareness, low latency, and scalability; those requirements cannot be fully satisfied by centralized approaches. Several challenges should be taken into account, such as single point of failure, lack of location awareness, loss of reachability, and latency, which can severely impact on the expected performance level [42]. Furthermore, centralized servers can be overwhelmed by huge amounts of traffic, thus adding further delays and suffering efficiency loss: as a matter of fact, the very rapid growth of cloud-based applications and services is putting the central infrastructure under pressure [42]. Because of those reasons, edge computing has been proposed as the candidate for filling the gap, meaning that intermediate entities are placed among the end-devices and the cloud. On-site MEC servers process the data collected from close sensors, thus removing the need of upload to a remote cloud service. By doing so, the overall delay is reduced, and

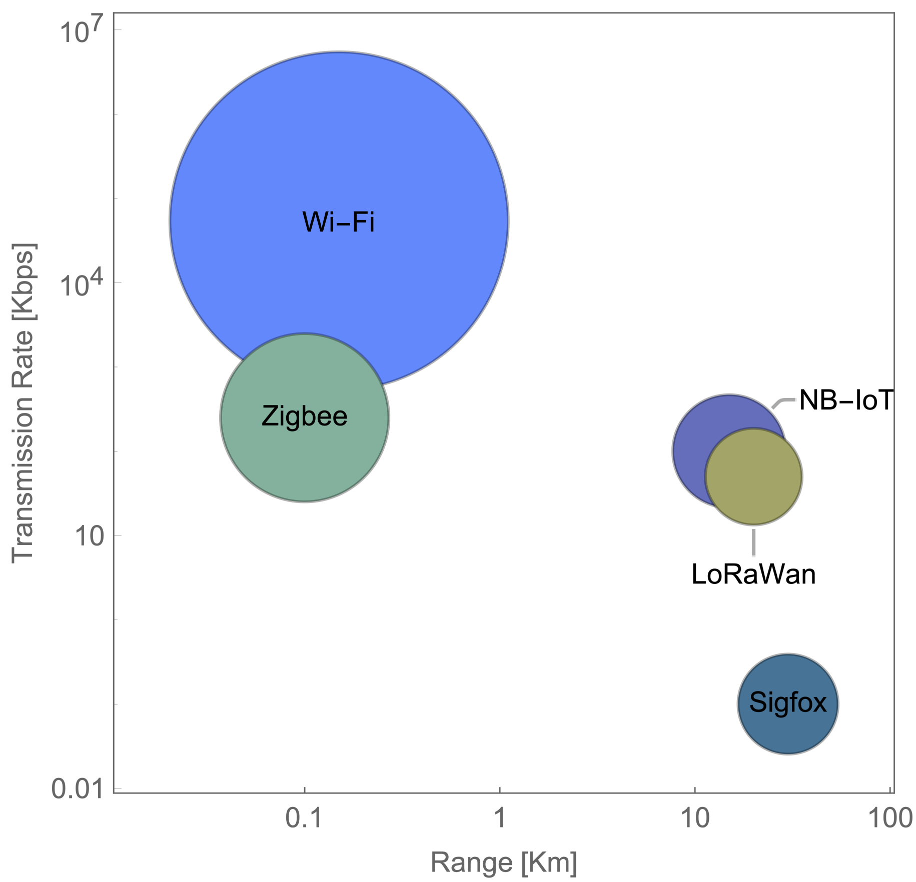

Fig. 1 – Qualitative comparison of the most diffused wireless communication protocols in smart agriculture presented in terms of transmission rate and range (axes) and power consumption (bubble size).

reliable services are provided with high availability. IoT, which is considered one of the key use cases of MEC [43], is expected to greatly benefit of it. In some ways, MEC, standardized by ETSI, can be seen as a new era of the cloud, where a decentralized infrastructure opens new markets and enables real-time critical applications, such as Vehicle to Anything (V2X) scenarios. When coupled with the features offered by 5G, such as the network slicing [44] highlighted in Fig. 2, and the increasing softwarization process, MEC and Software Defined Networking (SDN) together bring efficient network operation and service delivery [45].

The popularity of SDN is speeding up the adoption of MEC, and we propose in what follows a high-level network architecture of interest in the context of SF.

When looking at rural contexts, where internet connectivity still suffers from poor coverage in several geographic areas, aerospace networks play a role in filling the gap [9] since long time. The advent of mega-Low Earth Orbit (LEO) constellations and nano-satellites, as complementary to geosynchronous (GEO) backbones [46], is expected fuel the massive introduction of digital technologies in the SF context[2]. Along to connectivity via satellites, MEC-based architectures exploiting satellites have been proposed in [46, 47], in order to take advantage of MEC even in contexts with poor terrestrial coverage, or to deliver multimedia flows with the desired Quality of Experience (QoE). In Fig. 2, which depicts a plausible scenario, two possible reference architectures are considered, according to the scenario under consideration. In the case of small-scale agriculture, a local MEC server could be economically unfeasible, thus remote offloading [46] represents the best option: while the satellite delay must still be payed, relying on LEO satellites greatly reduces such a value (one-way delays can be lowered to less than 50ms, well below the average 270ms in the case of GEO satellites) and the presence of edge servers close to the terrestrial satellite gateway (or to the radio network controller site [48]) shrinks to the minimum both the terrestrial network and the processing delays. In the case of large-scale agriculture, where larger investments are expected because of the potential larger revenue, proximal offloading [46] becomes economically feasible; such a solution offers very low delay and computational power close to where it is needed.

In [49], the authors propose UAVs with on-board MEC functionalities, taking into account the constraint due to limited batteries capacity. The tasks to be performed are split in two parts: a fraction to be run on board the UAV, and the other fraction to be migrated towards terrestrial stations. MEC is exploiting the advent of 5G, and designing those functionalities on board UAVs benefit

[2]See the case of the Starlink constellation of LEO satellites by SpaceX.

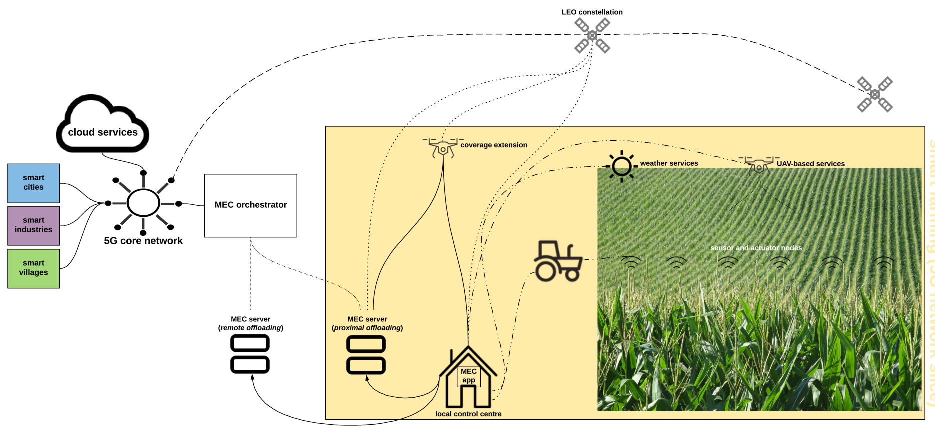

Fig. 2 – Plausible network architectures, highlighting the use of MEC in *proximal offloading* and *remote offloading* configurations [46].

of large commercial interests, but it needs a careful design analysis. Mobile-enabled and wireless infrastructure aerial drones are considered in [50], i.e., drones exploiting 5G connectivity in the former case and drones relaying or providing 5G connectivity in the latter one. The authors are convinced that, although integrating drones into cellular networks is a rather complicated issue, 5G standard has progressed in building the fundamental support mechanisms.

Referring to Fig. 2, we assume that 5G connectivity is offered via LEO satellites, and that a MEC server acts as an intermediate entity for satisfying the aforementioned requirements of a real-time IoT network, for instance relying on autonomous vehicles and operations, such as coverage extension and agricultural services. Connectivity can be provided in two different manners: through a direct connection to satellites, which means that the latter have on-board transparent interfaces; or through the use of relay nodes. In Fig. 2, both options are considered: the case of a direct connection of the control center to the satellite transparent payload [51], and the case of an UAV, acting as a relay node for coverage extension [52]. At this time, the use of relay nodes is the most doable solution for both technical and economical reasons.

Looking more closely to the use of IoT in the example proposed in Fig. 2, both short and long-range sensor nodes are deployed in the field, as for instance those exploiting the Long Range (LoRa) protocol, which covers long distances even in difficult conditions. The data collected by sensors are then delivered towards a server for analysis and storing purposes. Several heterogeneous data sources, i.e., sensors placed in the soil and measuring e.g. the use of water, satellite/UAV imagery, and weather-related data coming from stations placed in the field, are collected altogether. Being heterogeneous sources, both in the data type and in the generation time-scale, there is the need to integrate and analyse raw data at a software level, with the clear purpose of deriving useful information to be used by a farmer or by autonomous vehicles. In the former case, such a system act as a DSS for the farmer's needs; in the latter case, such a system acts as an (un)supervised centralized intelligence, guiding the autonomous vehicles during their operations or sending commands to the deployed actuators. The UAVs and UGVs can be pre-loaded with the needed information before departing, as common nowadays, or can exchange data, to be used by the central intelligence as real-time feedback while guiding the vehicle. Given the requirements of the aforementioned autonomous case, the availability of a MEC server is crucial to achieve very low delays, and to efficiently elaborate large quantities of raw data, as in the case of large-scale agriculture. Thus, UAVs can efficiently support environmental monitoring [53] and agriculture applications [4, 21]. As already discussed, civil applications require that the human pilot, still needed for security reasons, has Visual Line of Sight (VLoS) with the UAV, thus somewhat limiting the scope of their use because of the reduced operating range. The possibility of using cellular networks to extend the range to use UAVs through 4G/5G links has been subject of studies in the literature [54, 55], in order to characterize the quality of the signal received at flying altitudes [55]. In [56], the authors test the possibility of using LTE networks for piloting an UAV in a rural area in Denmark. The preliminary measurement campaigns, aimed at characterizing the path loss model, are then backed by simulation results confirming that LTE networks can be used for such a purpose. In [57], the authors proposed the use of a UAV-to-ground video feed to support a remote pilot on the ground through visual context while piloting in BVLoS conditions. The video feed and the telemetry are supposed to be complementary and mixed together in the data flow coming from the UAV to the Ground Control Station (GCS). Such a study is framed in the wider context of using swarms of drones for different purposes, like either monitoring of power lines, or of cultural heritage sites, or for agricultural applications.

6. Conclusion

Agriculture is experiencing a new revolution, but the potential for such a phenomenon to succeed depends on several factors. In this work, we focus on the technological factors, such as IoT; unmanned systems for data gathering, coverage extension, and for agriculture-specific application scenarios; long and short-range networking solutions for data collection; 4G/5G cellular networks and satellite solutions for connectivity; and on the potential of MEC in the field. This short survey has aimed at providing an holistic view of all the technologies turning around such a digital revolution in Agriculture 4.0.

References

[1] M. Bacco, P. Barsocchi, E. Ferro, A. Gotta, M. Ruggeri, The Digitisation of Agriculture: a Survey of Research Activities on Smart Farming, Array 3 (2019) 100009.

[2] C. Torresan, A. Berton, F. Carotenuto, S. F. Di Gennaro, B. Gioli, A. Matese, F. Miglietta, C. Vagnoli, A. Zaldei, L. Wallace, Forestry applications of UAVs in Europe: A review, International Journal of Remote Sensing 38 (8-10) (2017) 2427–2447.

[3] M. Bacco, L. Boero, P. Cassara, M. Colucci, A. Gotta, M. Marchese, F. Patrone, IoT Applications and Services in Space Information Networks, IEEE Wireless Communications 26 (2) (2019) 31–37.

[4] M. Bacco, A. Berton, E. Ferro, C. Gennaro, A. Gotta, S. Matteoli, F. Paonessa, M. Ruggeri, G. Virone, A. Zanella, Smart Farming: Opportunities, Challenges and Technology Enablers, in: IoT Vertical and Topical Summit on Agriculture-Tuscany (IOT Tuscany), IEEE, 2018, pp. 1–6.

[5] M. Bacco, G. Brunori, A. Ferrari, P. Koltsida, E. Toli, IoT as a Digital Game Changer in Rural Areas: the DESIRA Conceptual Approach, in: 2020 Global Internet of Things Summit (GIoTS), IEEE, 2020, pp. 1–6.

[6] G. Pajares, I. García-Santillán, Y. Campos, M. Montalvo, J. Guerrero, L. Emmi, J. Romeo, M. Guijarro, P. Gonzalez-de Santos, Machine-Vision Systems Selection for Agricultural Vehicles: a Guide, Journal of Imaging 2 (4) (2016) 34.

[7] D. Doering, A. Benenmann, R. Lerm, E. P. de Freitas, I. Muller, J. M. Winter, C. E. Pereira, Design and Optimization of a Heterogeneous Platform for Multiple UAV use in Precision Agriculture Applications, IFAC Proceedings Volumes 47 (3) (2014) 12272–12277.

[8] Z. Zhai, J.-F. Martínez Ortega, N. Lucas Martínez, J. Rodríguez-Molina, A Mission Planning Approach for Precision Farming Systems based on Multi-Objective Optimization, Sensors 18 (6) (2018) 1795.

[9] M. Bacco, P. Cassara', M. Colucci, A. Gotta, M. Marchese, F. Patrone, A Survey on Network Architectures and Applications for Nanosat and UAV Swarms, in: International Conference on Wireless and Satellite Systems (WISATS), EAI, 2017, pp. 1–10.

[10] M. Reger, J. Bauerdick, H. Bernhardt, Drones in Agriculture: Current and future legal status in Germany, the EU, the USA and Japan, LANDTECHNIK 73 (3) (2018) 62–79.

[11] P. Patel, Agriculture Drones are Finally Cleared for Takeoff, IEEE Spectrum 53 (11) (2016) 13–14.

[12] P. Radoglou-Grammatikis, P. Sarigiannidis, T. Lagkas, I. Moscholios, A compilation of UAV applications for precision agriculture, Computer Networks 172 (2020) 107148.

[13] M. Kulbacki, J. Segen, W. Knieć, R. Klempous, K. Kluwak, J. Nikodem, J. Kulbacka, A. Serester, Survey of Drones for Agriculture Automation from Planting to Harvest, in: 2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES), IEEE, 2018, pp. 000353–000358.

[14] J. Huuskonen, T. Oksanen, Soil Sampling with Drones and Augmented Reality in Precision Agriculture, Computers and electronics in agriculture 154 (2018) 25–35.

[15] C. Yinka-Banjo, O. Ajayi, Sky-Farmers: Applications of Unmanned Aerial Vehicles (UAV) in Agriculture, in: Unmanned Aerial Vehicles, IntechOpen, 2019.

[16] A. D. Boursianis, M. S. Papadopoulou, P. Diamantoulakis, A. Liopa-Tsakalidi, P. Barouchas, G. Salahas, G. Karagiannidis, S. Wan, S. K. Goudos, Internet of Things (IoT) and Agricultural Unmanned Aerial Vehicles (UAVs) in Smart Farming: A Comprehensive Review, Internet of Things (2020) 100187.

[17] P. Tripicchio, M. Satler, G. Dabisias, E. Ruffaldi, C. A. Avizzano, Towards Smart Farming and Sustainable Agriculture with Drones, in: Intelligent Environments (IE), International Conference on, IEEE, 2015, pp. 140–143.

[18] P. Lottes, R. Khanna, J. Pfeifer, R. Siegwart, C. Stachniss, UAV-based Crop and Weed Classification for Smart Farming, in: International Conference on Robotics and Automation (ICRA), IEEE, 2017, pp. 3024–3031.

[19] T. Moribe, H. Okada, K. Kobayashl, M. Katayama, Combination of a Wireless Sensor Network and Drone Using Infrared Thermometers for Smart Agriculture, in: 15th Annual Consumer Communications & Networking Conference (CCNC), IEEE, 2018, pp. 1–2.

[20] U. R. Mogili, B. Deepak, Review on Application of Drone Systems in Precision Agriculture, Procedia computer science 133 (2018) 502–509.

[21] M. Bacco, A. Berton, A. Gotta, L. Caviglione, IEEE 802.15.4 Air-Ground UAV Communications in Smart Farming Scenarios, IEEE Communications Letters 22 (9) (2018) 1910–1913.

[22] A. Matese, S. F. Di Gennaro, Practical Applications of a Multisensor UAV Platform Based on Multispectral, Thermal and RGB High Resolution Images in Precision Viticulture, Agriculture 8 (7).

[23] J. J. Roldán, J. del Cerro, D. Garzón-Ramos, P. Garcia-Aunon, M. Garzón, J. de León, A. Barrientos, Robots in Agriculture: State of Art and Practical Experiences, in: Service Robots, IntechOpen, 2017.

[24] P. Gonzalez-de Santos, A. Ribeiro, C. Fernandez-Quintanilla, F. Lopez-Granados, M. Brandstoetter, S. Tomic, S. Pedrazzi, A. Peruzzi, G. Pajares, G. Kaplanis, et al., Fleets of Robots for Environmentally-Safe Pest Control in Agriculture, Precision Agriculture 18 (4) (2017) 574–614.

[25] V. Puri, A. Nayyar, L. Raja, Agriculture Drones: A Modern Breakthrough in Precision Agriculture, Journal of Statistics and Management Systems 20 (4) (2017) 507–518.

[26] B. Citoni, F. Fioranelli, M. A. Imran, Q. H. Abbasi, Internet of Things and LoRaWAN-Enabled Future Smart Farming, IEEE Internet of Things Magazine 2 (4) (2019) 14–19.

[27] Z. Tafa, F. Ramadani, B. Cakolli, The Design of a ZigBee-based Greenhouse Monitoring System, in: 2018 7th Mediterranean Conference on Embedded Computing (MECO), IEEE, 2018, pp. 1–4.

[28] P. Fraga-Lamas, M. Celaya-Echarri, L. Azpilicueta, P. Lopez-Iturri, F. Falcone, T. M. Fernández-Caramés, Design and Empirical Validation of a LoRaWAN IoT Smart Irrigation System, in: Multidisciplinary Digital Publishing Institute Proceedings, Vol. 42, 2020, p. 62.

[29] W. Ma, Y. Wei, F. Sun, Y. Li, Design and Implementation of Water Saving Irrigation System Based on Zigbee Sensor Network, in: IOP Conference Series: Earth and Environmental Science, Vol. 252, IOP Publishing, 2019, p. 052086.

[30] Z. Zhou, K. Xu, D. Wu, Design of Agricultural Internet of Things Monitoring System based on ZigBee, Chemical Engineering Transactions 51 (2016) 433–438.

[31] A. G. Schut, P. C. S. Traore, X. Blaes, A. Rolf, Assessing Yield and Fertilizer Response in Heterogeneous Smallholder Fields with UAVs and Satellites, Field Crops Research 221 (2018) 98–107.

[32] J. A. Thomasson, C. P. Baillie, D. L. Antille, C. R. Lobsey, C. L. McCarthy, Autonomous Technologies in Agricultural Equipment: A Review of the State of the Art, American Society of Agricultural and Biological Engineers, 2019.

[33] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, A comparative study of LPWAN technologies for large-scale IoT deployment, ICT express 5 (1) (2019) 1–7.

[34] D. Bankov, E. Khorov, A. Lyakhov, On the limits of LoRaWAN channel access, in: 2016 International Conference on Engineering and Telecommunication (EnT), IEEE, 2016, pp. 10–14.

[35] M. Bacco, P. Barsocchi, P. Cassará, D. Germanese, A. Gotta, G. R. Leone, D. Moroni, M. A. Pascali, M. Tampucci, Monitoring Ancient Buildings: Real Deployment of an IoT System Enhanced by UAVs and Virtual Reality, IEEE Access 8 (2020) 50131–50148.

[36] A. Lavric, A. I. Petrariu, V. Popa, Long Range SigFox Communication Protocol Scalability Analysis under Large-Scale, High-Density Conditions, IEEE Access 7 (2019) 35816–35825.

[37] A. Adhikary, X. Lin, Y.-P. E. Wang, Performance evaluation of NB-IoT coverage, in: 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall), IEEE, 2016, pp. 1–5.

[38] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, H. S. Razaghi, A primer on 3GPP narrowband Internet of Things, IEEE communications magazine 55 (3) (2017) 117–123.

[39] C. He, M. Shen, L. Liu, C. Okinda, J. Yang, H. Shi, et al., Design and Realization of a Greenhouse Temperature Intelligent Control System based on NB-IoT, Journal of South China Agricultural University 39 (2) (2018) 117–124.

[40] G. Castellanos, M. Deruyck, L. Martens, W. Joseph, System Assessment of WUSN Using NB-IoT UAV-Aided Networks in Potato Crops, IEEE Access 8 (2020) 56823–56836.

[41] P. Baronti, P. Pillai, V. W. Chook, S. Chessa, A. Gotta, Y. F. Hu, Wireless Sensor Networks: a Survey on the State of the Art and the 802.15.4 and ZigBee standards, Computer communications 30 (7) (2007) 1655–1695.

[42] P. Porambage, J. Okwuibe, M. Liyanage, M. Ylianttila, T. Taleb, Survey on Multi-Access Edge Computing for Internet of Things Realization, IEEE Communications Surveys & Tutorials 20 (4) (2018) 2961–2991.

[43] D. Sabella, A. Vaillant, P. Kuure, U. Rauschenbach, F. Giust, Mobile-Edge Computing Architecture: The Role of MEC in the Internet of Things, IEEE Consumer Electronics Magazine 5 (4) (2016) 84–91.

[44] S. Konstantinos, X. Costa-Perez, V. Sciancalepore, From Network Sharing to Multi-Tenancy: the 5G Network Slice Broker, IEEE Communications Magazine 54 (7) (2016) 32–39.

[45] B. Blanco, J. Fajardo, I. Giannoulakis, E. Kafetzakis, S. Peng, J. Pérez-Romero, I. Trajkovska, P. Khodashenas, L. Goratti, M. Paolino,

E. Sfakianakis, Technology Pillars in the Architecture of Future 5G Mobile Networks: NFV, MEC and SDN, Computer Standards & Interfaces 54 (4) (2017) 216–228.

[46] Z. Zhang, W. Zhang, F.-H. Tseng, Satellite Mobile Edge Computing: Improving QoS of High-Speed Satellite-Terrestrial Networks Using Edge Computing Techniques, IEEE Network 33 (1) (2018) 70–76.

[47] C. Ge, N. Wang, I. Selinis, J. Cahill, M. Kavanagh, K. Liolis, C. Politis, J. Nunes, B. Evans, Y. Rahulan, et al., QoE-Assured Live Streaming via Satellite Backhaul in 5G Networks, IEEE Transactions on Broadcasting.

[48] M. Patel, B. Naughton, C. Chan, N. Sprecher, S. Abeta, A. Neal, et al., Mobile-Edge Computing: Introductory Technical White Paper, MEC Industry Initiative (2014) 1089–7801.

[49] M. Hua, Y. Huang, Y. Sun, Y. Wang, L. Yang, Energy optimization for Cellular-Connected UAV Mobile Edge Computing Systems, in: International Conference on Communication Systems (ICCS), IEEE, 2019, pp. 1–6.

[50] I. Bor-Yaliniz, M. Salem, G. Senerath, H. Yanikomeroglu, Is 5G Ready for Drones: A Look into Contemporary and Prospective Wireless Networks from a Standardization Perspective, IEEE Wireless Communications 26 (1) (2019) 18–27.

[51] A. Guidotti, A. Vanelli-Coralli, M. Conti, S. Andrenacci, S. Chatzinotas, N. Maturo, B. Evans, A. Awoseyila, A. Ugolini, T. Foggi, et al., Architectures and Key Technical Challenges for 5G Systems Incorporating Satellites, IEEE Transactions on Vehicular Technology.

[52] L. Amorosi, L. Chiaraviglio, F. D'Andreagiovanni, N. Blefari-Melazzi, Energy-Efficient Mission Planning of UAVs for 5G Coverage in Rural Zones, in: International Conference on Environmental Engineering (EE), IEEE, 2018, pp. 1–9.

[53] M. Bacco, F. Delmastro, E. Ferro, A. Gotta, Environmental Monitoring for Smart Cities, IEEE Sensors Journal 17 (23) (2017) 7767–7774.

[54] B. Van der Bergh, A. Chiumento, S. Pollin, LTE in the sky: trading off propagation benefits with interference costs for aerial nodes, IEEE Communications Magazine 54 (5) (2016) 44–50.

[55] X. Lin, V. Yajnanarayana, S. D. Muruganathan, S. Gao, H. Asplund, H.-L. Maattanen, M. Bergstrom, S. Euler, Y.-P. E. Wang, The sky is not the limit: LTE for unmanned aerial vehicles, IEEE Communications Magazine 56 (4) (2018) 204–210.

[56] H. C. Nguyen, R. Amorim, J. Wigard, I. Z. Kovacs, P. Mogensen, Using LTE Networks for UAV Command and Control Link: A Rural-Area Coverage Analysis, in: Vehicular Technology Conference (VTC-Fall), 2017 IEEE 86th, IEEE, 2017, pp. 1–6.

[57] M. Bacco, P. Cassara, A. Gotta, V. Pellegrini, Real-time multipath multimedia traffic in cellular networks for command and control applications, in: 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), IEEE, 2019, pp. 1–5.