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UAS – WSN SYSTEMS, A PERSPECTIVE ON COMMUNICATION SYSTEM ARCHITECTURE

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Unmanned systems, artificial intelligence and affordable wireless technologies represent the main drivers for the digital transformation that could have a positive impact for the rural areas development. This article presents today's options for wireless communications technologies for UAV applications. Available solutions, advantages and limitations of implementing UAV precision farming for medium and large scale WSN were reviewed and compared for the reader's benefit. The authors proposed and simulated an optimum cost-efficient communication system architecture and presented its conclusions to validate the proposed communication system.

Keywords: UAV, UAS, WSN, wireless communication system architecture, datalink

1. Introduction

Digital technologies are bringing significant value to enhance the performance of the crops and to reduce the costs of agri-food production. Wireless Sensor Networks (WSN) are allowing farmers to monitor a wide range of parameters such as humidity, temperature or soil moisture to get precise information that will allow taking the best crop efficiency improvement measures.

We noticed a growing need for implementing Unmanned Aerial Systems (UAS) for precision farming applications in which the data collection from medium or large scale WSN is optimized in terms of time and effort. An UAS is usually composed of many Unmanned Aerial Vehicles (UAVs) and its related Command and Control (C2) system and datalink that allows the collection of real-time data. The need for implementing hybrid UAS - WSN systems is generated mainly by the poor coverage of today's wireless communication technologies in rural areas that is not allowing the data collection via terrestrial networks like GPRS/Cellular or WiFi that are particularly the best choice for small scale WSN. Medium or large scale WSN are composed of ground sensors that are usually deployed in mesh networks that are transmitting data to the Unmanned Aerial

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Vehicle (UAV) through gateways (GW) or base stations (BS) distributed on the ground.

This article' main hypothesis is that UAS - WSN systems seems to be the solution in rural areas with sparse agriculture fields, where the availability and affordability of high-speed broadband services and the need to increase the performance of the crops are the key issues with big impact to the development of those regions. The authors of this paper systematically approached multiple data sources and conducted a research synthesis based on UAV legislation, governance and regulatory frameworks. There are several sources providing a comprehensive overview of UAV flight regulations, implementation status and forecast. A reliable source of information regarding UAV development [1] is providing free access to accurate description of each country' applicable regulations and standards aiming to minimize the implication in the civilian air traffic operations.

Various studies like [2] that have compared the documents meant to regulate the UAV operations are concluding that there is no general approach of the conditions, drone classification or standards applicable to UAVs and therefore reviewing the scientific literature presenting the characteristics considered by various countries enabled the authors to have realistic predictions of future trends.

Further on, by reviewing the scientific literature analyzing the relationship between legal framework, available technologies and innovation needs, the authors had the opportunity to have a clear picture of the main issues to deal with for the adoption of guidelines, roadmaps, principles or codes of conducts. The dynamism of the UAV sector is, however, a blocking point for running a complete and coherent analysis of the worldwide situation but the development status or regulation status of pioneer-states are the main influencer on future standards to be taken into account.

The main contributions of this paper are summarized as follows:

- Today's options for wireless communications technologies for UAV applications were investigated.
- Available solutions, advantages and limitations of implementing UAV precision farming for medium and large scale WSN were reviewed and compared.
- An optimum cost-efficient communication system architecture was proposed and analyzed.

All the uncertainties related to regulatory framework are hampering the economic development of this market towards a solid, harmonized and coherent market. In Europe, European Union Aviation Safety Agency (EASA) is working to provide a common regulatory framework to support the competitiveness and leadership in the drone sector, to deliver new employment and business opportunities, and, at the same time, to give other European citizens who could be affected by drones' activity more safety and security [3].

While the UAS are using dedicated spectrum for the governmental applications, for the civilian usage, ITU defines the industrial, scientific and medical (ISM) frequency bands [4] that are, most likely, to be used also for WSN.

2. Materials and Methods

2.1. Today's options

The authors of [5] are analyzing the interference issue for several communication systems and technologies. For short range sensor networks, the ECC Recommendation 70-03 [6] allows devices radiating less than 100mW to use unlicensed spectrum for ranges less than few-hundred meters, without causing harmful interference to other radio equipment using the same bands. ISM bands are being shared with license-free communications applications like wireless sensor networks operating in 915MHz or 2.4GHz bands. The unlicensed devices are designed to be tolerant with any ISM emission in these bands, therefore unlicensed low power equipment is able to operate in these bands without any harm to other ISM users.

With the expansion of IoT and IEEE 802.15.4 standard [7], a growing number of electronic devices will get a big market share worldwide and most of them are supposed to work on the same or overlapping frequency spectrum. The original 802.11 standard released in 1997 operates within the 2.4 GHz ISM band and divides it into 78 channels (1MHz distance). The 802.11b [8] also uses the 2.4GHz ISM band and divides it into 14 channels (5 MHz distance).

New long-range technologies such as 802.11ah [9], LoRa [10], and SIGFOX [11] are providing high energy efficiency and fair data rates. In [12] the authors are proposing solutions for interference detection and avoidance mechanisms that could maintain the unlicensed frequency bands as the most used bands for drone' ground communication systems. Using frequency agility technique, multiple wireless sensor networks can communicate simultaneously without RF interferences. Various applications are more and more recommending the formation flight approach [13] and synchronized flight and maneuvers inside a multi-drone formation has to rely on a robust, safe and secure communication topology [14].

In 2016, [15] specified that a 5MHz LTE signal within 698-703MHz is the most likely deployment for Broadband Public Protection and Disaster Relief organizations in Europe. Since most of the countries are not allowing beyond line of sight (BLOS) flights and the fact that in rural/agricultural areas, the potential interference and hence the safety and security of the mission are considered with low risk, the 2.4GHz and 5.7GHz tends to be the only solution for the UAV datalink for UAS – WSN systems in rural/agriculture applications.

2.2. Typical UAS – WSN communication architecture

In the last years, the authors have noticed a high increase of related articles approaching the multiple UAV applications which analyzed several communication systems to handle the C2 of a swarm of drones. The authors of [16] reviewed the available communication technologies for the Control and Non-Payload Communications (CNPC) link, also referred as the datalink for multi-UAV. While the paper analyzed typical CNPC technologies as the wireless microwave backhaul for the primary CNPC link, it also presented the satellite communication system (SATCOM) as the best solution for the secondary CNPC link. For a similar architecture, [17] presents the security threats within the UAV communication system.

In [18] the authors are concluding that systems integrating WSN, UAVs and IoT are on an ascendant trajectory and will become ubiquitous in commercial applications. Recent papers like [19] proposed a hierarchical architecture of UAVs with multilayer and distributed features to facilitate the integration of different UAVs into the next-generation wireless communication networks.

The emerging 4G/5G/LTE technologies that seems to become a viable option for ensuring safe and secure communications to low and medium altitude flying UAVs and even for extending 4G/5G/LTE coverage due to the flexibility in forming dynamic connections of UAVs are analyzed in [20] and [21]. The UAS – WSN architecture was reviewed in [22] that concludes that 4G/ 5G terrestrial networks have a great potential to serve multi-UAV systems. Authors of [23] proposed a hybrid wireless communication scheme having WiFi 802.11 for ground-to-air communication and the low-power Bluetooth 802.15.1 for UAV-to-UAV communication. The paper describes an affordable communication solution that could be used for various UAV applications.

A hybrid UAS – WSN system is composed of one or more group of sensors connected to more gateways / base stations that will transmit data to one or more unmanned aerial vehicles (UAV), usually copter-type, an airborne data terminal (ADT), the payload and the airborne datalink module (ADM). Each UAV is controlled via the datalink system by the Ground Control Station (GCS) through the ground data terminal (GDT). The GDT is the ground component that together with the ADM forms the datalink system used for the C2 of the UAV and also to transmit the payload data and the information collected by the ADT. GCS is used to plan the mission, monitor and control the UAV or the payload. The GCS is basically a computer integrated into a ruggedized case that integrates the control commands and displays useful flight information. The IPBox plays the role of the data dispatcher and is connected to the GCSs and is responsible of the transmission of the commands to UAVs.

2.3. Advantages and limitations of UAS – WSN wireless communication systems for precision agriculture

Very low frequencies provide better coverage solutions for wireless sensor applications to cover large areas. Unlike HF or V/UHF bands, ISM offers tremendous advantages like small size antennas, high frequency reuse, and low power consumption. While lower frequency bands would help in extending the communications range due to low path loss attenuation, the inconvenient of antenna size is reducing the potential applications of the sensor. In addition, low frequency is not allowing high throughput. 900MHz and 868MHz wireless sensor networks provides a high performance, low power (and extremely low cost) alternative to similar products in the 2.4GHz space. 868MHz band can be used without any additional government approvals. An advantage of the 900MHz frequency is that it is not nearly as crowded as higher frequency bands.

The lack of regulations in the air-to-ground communication systems and the hesitation of the UAV flight certifying authorities, are the biggest threats or challenges of the deployment of hybrid air-ground sensor networks.

Related work studying wireless technologies used in precision agriculture applications were reviewed and compared to allow our readers to have a better understanding of today’s options in terms of range, power consumption, latency and maximum data rate.

In [24] the authors are presenting an extensive comparison of most common wireless communication technologies like IEEE 802.15.4/e, Bluetooth low energy (BLE), IEEE 802.11ah, LoRa and SIGFOX focusing on the lifetime of the devices used within the WSN. The challenges of the emerging 802.11ah devices are presented in [25]. Communication devices built on standards like GPRS, LTE, WiMAX, are providing reliable connections over long distances, high throughput but there is a big drawback: they consume energy and need a fixed infrastructure of base stations to transmit its data. In [26] the authors present an analytical model to estimate the current consumption of a device, using empirical data. Table 1 briefly presents the results of the main parameters comparison of today’s wireless communication technologies that are used for connecting the nodes within the WSN.

Table 1

Most popular WSN communication technologies

	Parameters						
	Standard	Frequency band	Tx power	Max. data rate	Typical latency	Max. range	Cost
ZigBee	IEEE 802.15.4	868/2400MHz	100 mW	250 kbps	200 ms	100 m	Low
Bluetooth	IEEE 802.15.1	2.4 GHz	100 mW	3 Mbps	100 ms	50 m	Low
BLE	IEEE 802.15.1	2.4 GHz	10 mW	1 Mbps	6 ms	10 m	Low
LoRa	IEEE 802.15.4g	868 MHz	100 mW	30 kbps	1 s	10 km	Medium
SigFox	IEEE 802.15.4g	868 MHz	122 mW	100 bps	2 s	40 km	Medium

WiFi a	IEEE 802.11a	5 GHz	100 mW	54 Mbps	50 ms	10 m	High
WiFi b/g	IEEE 802.11b	2.4 GHz	100 mW	11/54 bps	50 ms	140 m	High
WiFi n	IEEE 802.11n	2.4/5 GHz	100 mW	450 Mbps	50 ms	250 m	High
WiFi HaLow	IEEE 802.11ah	900 MHz	100 mW	40 Mbps	50 ms	1 km	High
GPRS/GSM	3GPP	900/1800 MHz	560 mW	114 kbps	1 s	10 km	High
3G/4G LTE	3GPP	700/1700-2100/ 1900/2500-2700 MHz	500 mW – 1W	80 Mbps	50ms	6 km	High

When focusing on the limitations of the reviewed WSN communication technologies, the authors concluded that the LOS between the sensor and the BS is mandatory for ZigBee. Classic Bluetooth has a limited range while BLE is more usable for indoor-WSN due to its very short range. If its network size (scalability), interference risk and data rate are managed, LoRa seems to be a good option for WSN applications for precision agriculture. Although SigFox is more robust to interference, the low data rate represents its biggest weakness in comparison with LoRa. However, the communication range makes it a great option for low data rate applications. IoT is seen as having a very important role on the roll-out of the WSN and its connected devices. Integration of WSN into IoT will enhance the process automation and optimize the operational costs.

WiFi has too high-power consumption for setting up a WSN, however, if the energy is available, it is a great technology to manage high throughput needs and it is also a versatile mobile technology. HaLow WiFi is an emerging technology that could solve the range issue of WiFi but still, the power consumption brings limitations. Ancillary GPRS/GSM technology brings a high-power consumption but still is the most available technology in rural and hilly areas.

The authors have reviewed existing technologies to provide a reliable air-to-ground connectivity considering an outdoor setup in which energy and high gain antennas are bringing obvious advantages in terms of data rate and communication range. The advantages and limitations are listed hereafter:

- Wi-Fi in ISM bands provides ~100 Mbps data rate within 3 km range and has a major spread in civilian UAV applications. Despite its limitations of latency and exposure to interference it is a cheap an affordable technology to be used in rural areas.
- Point to point VHF/UHF equipment are providing a decent 300 kbps data rate for a range of 15km in direct LOS and however, the power consumption, equipment weight and antenna size are providing limitations to the UAV autonomy and mission time.
- 4G/5G/LTE is an emerging technology that seems to be easy to deploy and brings high throughput (30Mbps) and full mobility for low altitude UAVs however the fixed terrestrial infrastructure and poor coverage in rural areas is not yet deployed/implemented.

- SATCOM allows reliable BLOS connectivity for data rates up-to 200kbps but the weight of the airborne satellite modem and cost are clear showstoppers for a cost effective UAS datalink for precision farming.

2.4. Proposed communication system architecture

The authors proposed an optimum cost-efficient communication system architecture described in Fig. 1 after analyzing various wireless technologies applicable for UAS-WSN integrated systems. The ground sensors are connected via LoRa standard radio communications. GDT1 ensures the control and reception of telemetry data from UAV1 via a 5.7GHz band datalink. UAV1 flies at low altitude and uses the 2.4GHz frequency for communication with the BS. GDT2 ensures the control and reception of telemetry data from UAV2 via a 5.7GHz band datalink. UAV2 flies at medium altitude and transmits payload data to the C2 center.

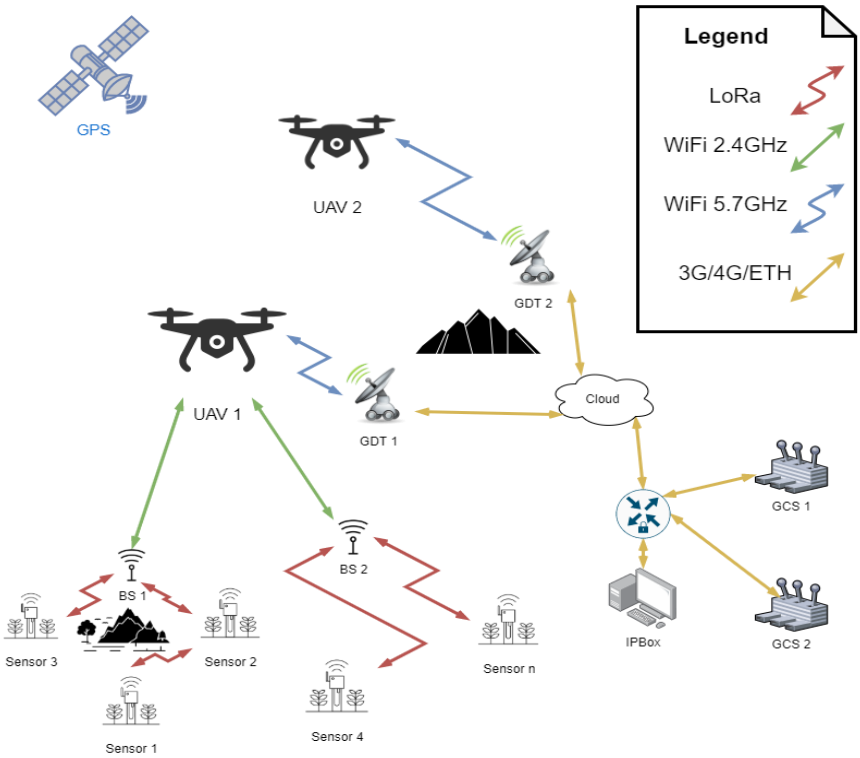

Fig. 1. Proposed hybrid UAS – WSN communication architecture

The main challenge in developing a cost effective UAS – WSN system for improving the crop efficiency in rural areas with sparse crop fields consists of:

- Deploying the WSN sensors and its main nodes that will transmit data to the UAV. The attenuation of ground and diffraction losses caused by vegetation or forest plays a significant role in planning the WSN.

- Deploying a network of GDT to ensure proper connectivity with the UAVs. The main constraint is to identify locations that will ensure direct line of sights (LOS) from the GDT to the UAV at specific flight altitude. Moreover, the interference analysis is needed when several GDTs will have to connect to more UAVs.
- Calculating the optimum trajectory for the UAV to make sure it collects all the information from the nodes in its area of interest.

3. Experimental results

To evaluate the proposed communication system architecture, we have used as a test-case, an UAS - WSN hybrid network, deployed in a hilly region, composed of 17 ground sensors distributed in 5 sparse areas, 5 Base stations (BS) that are collecting data from ground sensors.

For validating the UAS – WSN communication system architecture, the authors have used an RF propagation software (ICS Telecom, produced by ATDI) that allowed the propagation calculation based on the proposed system's RF technical parameters of the wireless communication technologies. The simulation environment estimates the propagation losses based on the digital cartography maps and analyze the reliability of the radiocommunication links of the equipment modelled in the tool according to their technical parameters. Ground, vegetation (forests or even the crops), man-made structures or rain are causing attenuation or diffraction losses and therefore the RF simulations can deliver relevant data needed for deploying the WSN, for planning the UAS - WSN mission and for determining the optimum locations for the BS and GDT.

The steps performed to validate the model are:

- High-resolution digital cartography setup – needed for accurate prediction of radio connectivity.
- Equipment modelling (ground sensors, BS and UAV).
- BS coverage analysis is needed to determine the optimum flight level for UAV1 that collects data from BS. ITU R-525 propagation model was used to calculate the propagation losses and attenuations and Tx/Rx signal level for different flight altitude.
- GDT1 and GDT2 site optimization to ensure sufficient coverage for the flight altitudes determined in point 3 above.
- GDT1 and GDT2 coverage calculation with ICS Telecom and ITU R-525 propagation model.
- UAS – WSN coverage and datalink analysis.

The GDTs technical parameters and antenna diagram allowed the authors to simulate the RF composite coverage of the two ground data terminals used in the proposed test-case. GDT 1 will establish the connectivity with the UAV 1 flying at 600m while GDT 2 will ensure the datalink with UAV 2 that surveys the whole area at a flight altitude of 1500m ASL. The UAS – WSN system modelled in ICS Telecom is presented in Fig.2 below. The ground sensors are represented by red arrows, the BS are the grey squares, the GDTs are the green squares, while the UAVs are marked with red triangles.

Fig. 2. Simulated UAS - WSN system and WiFi links

The studied WSN is formed by a network of 5 ground sensor clusters distributed in sparse orchards and Fig. 3. presents the location details of the simulated UAS – WSN components extracted from the modelling tool.

a. b.

Fig. 3. UAS – WSN details: a-BS2 and its 4 ground sensors; b-UAV1 and the 5 BS.

The BS coverage was simulated for various flight altitude and the optimum altitude to collect the information and to avoid obstacles has been determined. RF coverage maps (providing the signal strength) and best server coverage maps (providing indications of the best server received in a specific area) are used to calculate the flight path of the UAV. The mission planning and RF simulation of the UAS – WSN system allowed the authors to validate the proposed model as a cost-effective and easy-to-implement solution and to determine the optimum flight altitude of the UAVs to properly cover and collect the WSN data. Our proposed UAS – WSN architecture was validated from the RF connectivity point of view. Fig. 4 presents the coverage maps for 600m respectively 900m flight altitude above sea level (ASL). The coverage was analyzed and the selected coverage maps are showing that the higher the flight level (with reference to 600m) the lower the area in which the UAV will get a reliable connectivity to the ground sensors in the surveyed area.

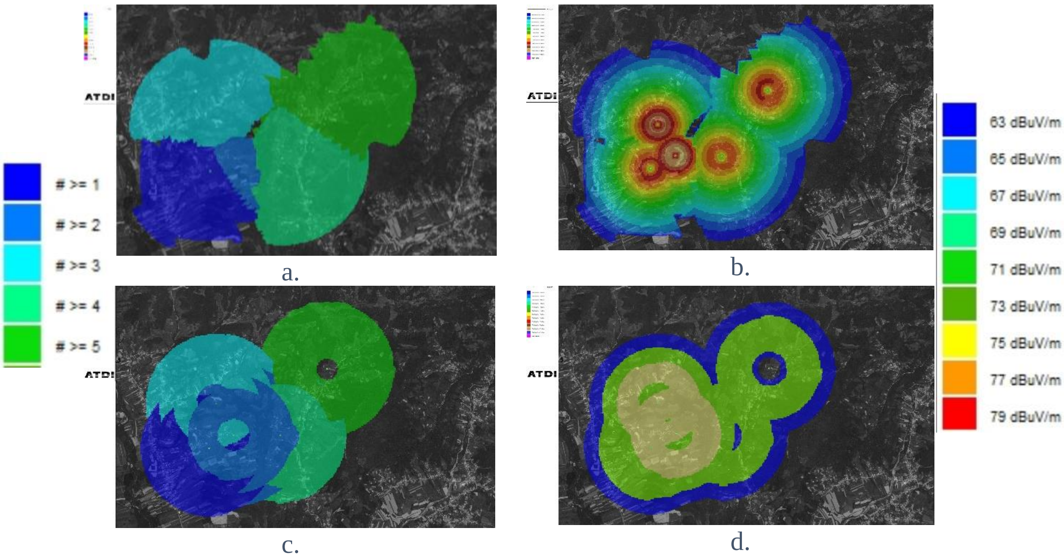

Fig. 4. Simulated Coverage maps: a-Best Server Coverage at 600m ASL; b-RF Coverage at 600m ASL; c-Best Server Coverage at 900m ASL; d-RF Coverage at 900m ASL.

The GDT RF coverage map was calculated, and Fig. 5 is presenting the simulated coverage maps for the network of GDTs that proofs that the GDT locations were properly selected to ensure radio connectivity for UAV1 flying at 600m ASL and UAV2 flying at 1500m ASL.

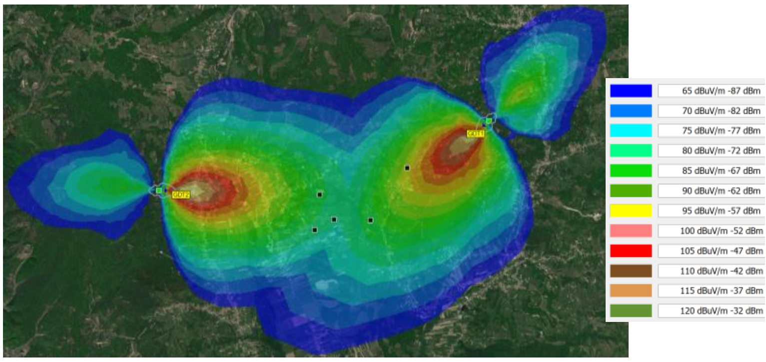

Fig. 5. – RF composite coverage for GDT1 at 600m and GDT2 at 1500m ASL

Table 2 presents the results of the simulated scenarios that allowed the authors to determine the optimum flight altitude of UAV1. When increasing UAV flight altitude, the side lobes of the ground BS are influencing the covered area, while a very low flight altitude is also having a negative impact due to diffraction loss caused by the ground surface (hills, peaks) or vegetation.

Table 2

Simulation results based on the composite coverage

Flight altitude [m]	100	200	400	600	900	1000
Cover area [sqkm]	68.24	80.64	82.30	82.58	74.66	54.30
Observations	Ground obstructions	Acceptable	Good	Best	Coverage gaps	Gaps

4. Conclusions

The paper starts with an analysis of available wireless communication technologies and standards. It moves on to identify challenges in implementing an optimum architecture of UAS – WSN communication system and concludes with a recommendation of a cost-effective solution to allow data collection and crop monitoring for an UAS – WSN system. With a variety of already published standards and having a big number of interested actors from both sectors – industry and regulatory agencies, different environments and multiple development scenarios, the review process, aimed to extract essential conclusions for briefing its readers in a reasonable manner, was extensive.

Future regulatory framework needs to provide the UAV solution developers the right to fly whilst ensuring flight security and the right to use dedicated/licensed spectrum to ensure reliable communications and secure interconnectivity. For the typical/commercial sensor networks, from safety and security reasons, licensed frequency bands are to be considered while unlicensed bands will always leave the reliability of the radio-links with poor leverages in handling protection to interference or jamming attacks, the unlicensed spectrum bands being widely used by current commercial drones and mostly used for limited line-of-sight applications.

Similar UAS-WSN deployments should consider as a general conclusion that the proposed architecture needs to be simulated in advance, as the terrain, crops and other obstacles could influence the roll-out of the UAS-WSN. The optimum locations of placing sensors/BS or UAS ground equipment needs to be validated to ensure that UAS collects WSN data in various scenarios. Latency and interference analysis have to be determined for each mission deployment scenario and a general approach could be subject of future works.

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