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# ▶ To cite this version:

Jun Li, Rahim Kacimi, Tianyi Liu, Xiaoyan Ma, Riadh Dhaou. Non-Terrestrial Networks-enabled Internet of Things: UAV-centric architectures, applications, and open issues. Drones, 2022, Special Issue Security, Privacy and Reliability of Drone Communications for beyond 5G Networks, 6 (4), pp.1-24. 10.3390/drones6040095. hal-03633507

# HAL Id: hal-03633507 https://hal.science/hal-03633507

Submitted on 7 Apr 2022

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# Article Non-Terrestrial Networks-enabled Internet of Things: UAV-centric architectures, applications, and open issues

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Abstract: Although Unmanned Aerial Vehicles (UAVs)-aided wireless sensor networks (WSNs) 1 have gained many applications, it is not long that research works have been put to design effective 2 algorithms and protocols. In this article, we address the UAV-enabled WSN (U-WSN), explore the 3 performance and the capability of the UAV, define the UAV functionalities as a communication 1 node, and describe the architectures and the relevant typical technologies that emerge from this new 1 paradigm. Furthermore, this article also identifies the main factors which influence the U-WSN design 2 and analyzes the open issues and challenges in U-WSN. These insights may serve as motivations and 2 guidelines for future designs of UAV-enabled WSNs. 2

**Keywords:** Wireless sensor networks; unmanned aerial vehicles; network architecture; mobility; trajectory planning

# 1. Introduction

Non-Terrestrial Networks (NTN), including drones and nano-satellites, bring consid-12 erable solutions for collecting data in future internet of things. Indeed, wireless sensor 13 networks (WSNs) have attracted exponential research growth due to their broad range 14 of applications ranging from military [1,2], environmental [3,4] to agriculture [5,6]. The 15 main function of a WSN is to collect as much data as possible and transmit it to the data 16 center, where it is observed, analyzed and processed. Multi-hop is a widely accepted 17 option to improve data collection in applications where sensors are statically deployed 18 and battery-powered. However, it brings sensors that act as intermediate nodes to die 19 faster than simple nodes because they consume a lot of energy to relay messages. As a 20 result, mobile sinks are introduced into WSN to balance network energy consumption by 21 moving between sensors. The mobility of the sink brings new issues including dynamic 22 topology, synchronization, network lifetime, etc ([7-9]). In existing research, most of the 23 network typologies utilize static or quasi-static (move on the ground at a low speed) nodes. 24 However, it is hard to be implemented in harsh terrains, such as snowberg or forests, which 25 are dangerous for humans. In such applications, Unmanned Aerial Vehicles (UAVs) are 26 more widely accepted due to their great flexibility and no need to involve humans. 27

UAVs can be drones, quadcopters, gliders, and balloons. Due to different application requirements, they could be equipped with various sensors, e.g., cameras, super-sonic sensors, etc. UAV-enabled WSN (U-WSN) comprises an air platform and a ground platform. The air platform could be composed of several UAVs. UAVs should be well controlled to keep a safe flight distance and a proper distance with the ground control center to make them under control. The ground platform could be composed of many sensor nodes, base stations, and data center according to applications. In applications, e.g., UAVs are

**Citation:** Li, J.; Kacimi, R.; Liu, T.; Ma, X.; Dhaou, R. Review of UAV-enabled WSN: from Categories, Applications, to Issues. *Journal Not Specified* **2022**, *1*, 0. https://doi.org/

Received: Accepted: Published:

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Version April 7, 2022 submitted to Journal Not Specified

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dispatched for aerial photography, no ground sensors needed to be deployed. Thus, the 35 ground sensors are not mandatory in a U-WSN. 36

The design of U-WSN applications requires wireless networking techniques. Although 37 many protocols and algorithms have been proposed for traditional WSN applications, they 38 can no longer meet up with the unique features and application requirements of U-WSN. 30 The main differences between WSN and U-WSN are outlined below: 40

- The topology of a U-WSN changes more frequently.
- The sensors are prone of being out of the range of the UAV if they have high relative velocities.
- The scale of the area of a U-WSN can be several orders of magnitude higher than the scale of a WSN.
- The UAVs are very limited in power compared to the ground sensor nodes and the base station.
- The UAVs need to be dispatched to maintain a safe flight and other issues.

Many researchers are currently engaged in developing schemes that fulfill these 49 requirements. This paper presents a review of UAV-centric architectures, applications, and 50 open issues. We aim better to understand the current research issues in this field. We 51 also attempt to investigate design constraints and outline specific tools to meet the design 52 objectives.

The main contributions of this paper are summarized as follows:

- analyze the performance and the capabilities of the UAV, based on which, we summarize the U-WSN applications.
- refine the UAV functionalities as a communication node in a U-WSN.
- compare and draw the network architecture and the standard technologies in U-WSN.
- evaluate the main factors which influence the U-WSN design.
- review and analyze the open issues and challenges in U-WSN.

The organization of this article is as follows: In Section 2, summarize the performance and capability of the UAV, and the relative applications of the U-WSN, and the functionalities of the UAV as a communication node. Section 3 analyzes the factors that influence the U-WSN design. Section 4 presents open issues and challenges in U-WSN. Section 5 gives a conclusive remarks of this work. Finally, Section 6 concludes this work.

# 2. Applications of U-WSN

Using UAVs is much more diverse in our daily life because of its significantly deploy-67 ment possibilities. Applications of U-WSN may either be traditional ones such as military 68 monitoring and reconnaissance, environmental disaster detecting and industrial control or 69 completely new application types such as smart city. 70

There are extensive surveys that have been done on the applications of U-WSN. For 71 example, authors in [10] give a review on the task using mobile robots. Shakhatreh et 72 al., provide a survey on civilian applications [11]. These research mainly focus on the 73 application fields when studying the application of the UAV. In this section, we will study 74 U-WSN applications through the performance and the capabilities of the UAV. 75

# 2.1. UAV Categorization

UAV is known as an aircraft or a drone without human on board. Humans control the 77 UAV in a variety of ways, such as ground control center, pre-programmed flight trajectory 78 and more complex and autonomous systems. Due to its different performances, capabilities and restrictions, the UAV encompass a wide range of different platforms.

One of the detailed and widely used schemes has been proposed in [12], as shown in 81 Table 1. In which, the UAVs are classified based on the mass, range, altitude, and endurance. 82 Moreover, another scheme based on Mean Take off Weight (MTOW) and the ground impact 83 risk has also been proposed [12], as illustrated in Table 2. 84

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Category	Mass (kg)	Range (km)	Flight alt. (m)	Endurance (h)
Micro	< 5	< 10	250	1
Mini-UAV	$< 20/25/30/150^{1}$	< 10	150/250/300	< 2
Tactical				
Close range (CR)	25-150	10-30	3,000	2–4
Short range (SR)	50-250	30-70	3,000	3–6
Medium range (MR)	150-500	70–200	5,000	6–10
MR endurance (MRE)	500-1,500	>500	8,000	10–18
Low altitude deep penetration (LADP)	250-2,500	>250	50-9,000	0.5–1
Low altitude long endurance (LALE)	15–25	>500	3,000	>24
Medium altitude long endurance (MALE)	1,000-1,500	>500	3,000	24-48
Strategic				
High altitude long endurance (HALE)	2,500-5,000	>2,000	20,000	24-48
Stratospheric (Strato)	>2,500	>2,000	>20,000	>48
Exo-stratospheric (EXO)	TBD	TBD	>30,500	TBD
Special task				
Unmanned combat AV (UCAV)	>1,000	1,500	12,000	2
Lethal (LET)	TBD	300	4,000	3–4
Decoys (DEC)	150–250	0–500	50–5,000	<4

Table 1. UAV categorization for differentiation of existing systems.

<sup>1</sup> Varies with national legal restrictions.

Table 2. Classification of UAVs based on the MTOW and the ground impact risk.

Number	$T^1_{GI}$	MTOW	Name	Note
0	10 <sup>2</sup>	Less than 1 kg	Micro	Most countries do not regulate this category since these vehicles pose minimal threat to human life or property
1	$10^{3}$	Up to 1 kg	Mini	These two categories roughly correspond to R/C model aircraft
2	$10^{4}$	Up to 13.5 kg	Small	
3	10 <sup>5</sup>	Up to 242 kg	Light/ultralight	Airworthiness certification for this category may be based either on ul- tralights (FAR <sup>2</sup> bpart 103), LSA <sup>3</sup> (Order 8130), or even normal aircraft (FAR Part 23)
4	10 <sup>6</sup>	Up to 4332 kg	Normal	Based on MTOW these vehicles correspond to normal aircraft (FAR Part 23)
5	107	Over 4332 kg	Large	These vehicles best correspond to the transport category (FAR Part 25)

<sup>1</sup>  $T_{GI}$  is the minimum time between ground impact accidents.

<sup>2</sup> Federal Aviation Regulations.

<sup>3</sup> Light Sport Aircraft.

# 2.2. Applications of U-WSN

Hereafter, we summarize and group the applications of U-WSN as in Table 3. If we consider the area where the sensors are deployed, the applications can be classified as in Table 4.

In aforementioned applications, both UAV and WSN play different roles and have different functionalities. We will detailed the functionalities of UAV in the next sub-section.

# 2.3. Functionalities of UAV as a Communication Node

In WSN applications, one of the objective is to obtain meaningful information through sensors deployed in the region of interest. Traditionally, the data gathering issues were implemented in multi-hops in which the sensors that are closer to the base station will selected as the relay nodes for those sensors that deployed far away from the base station. As a result, these relay nodes consume energy much faster than other nodes. As the network connectivity depends on these relay nodes, this will result in a shorter network life-time. To address these issues, mobile vehicles were introduced.

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Category	Application fields	Applications
	Aerospace	e.g., UAVs are used for aircraft maintenance in air-
		lines. In Jun. 2015 EasyJet began testing UAVs in
Industry Grade		the maintenance of their Airbus A320s. And in 2016,
·		Airbus demonstrated that using UAVs for the visual
		inspection of an aircraft on Farnborough Airshow.
	Reconnaissance	e.g., product quality monitoring and Smart-Grid
		measurements [13].
	Environmental	e.g., agriculture application [5].
	Urban	e.g., traffic monitoring, urban surveillance and civil-
		ian security [14].
	Others	e.g., military communication and surveillance [2].
	Recreational	e.g., filming and photographing recreational activ-
Consumer Grade		ity.
	Hobby	e.g., toys.
	Others	e.g., journalists using UAV for news gathering.

**Table 3.** Classifications of the applications of U-WSN according to the performance and the capability of the UAV.

Table 4. Classifications of the applications of U-WSN according to the sensor deployment.

Category	Subcategory	Applications
Ground On-ground		e.g., sensors are deployed on ground for environmental monitoring [8].
	Under-ground	e.g., the nodes are deployed underground for pipelines safety and monitoring [15]
Water	On-water	e.g., filming and photographing recreational activity.
Water	Under-water	e.g., use acoustic communications [16]
Hybrid	Combination of the	e.g., sensors are floating on the surface of the sea to moni-
	above	toring marine disasters [17].

Generally, it has limited conditions, such as limited velocity, and obstacles due to actual movement environment, when the mobile vehicles move on the ground. It would be a huge challenge if the traditional mobile vehicles are used in specific applications that are dangerous for human participation. Thus, UAV which has high extensive and flexible and do not need human on board, is a better choice in these similar applications. In this section, we will analyze and study the functionalities of UAV when it works as a communication node in WSN.

As previously described, UAV has been extensively applied in many areas. In this section, we analyze the existing applications and propose the main functionalities of the UAV in WSN.

#### 2.3.1. Maintaining Connectivity and Relaying

Maintain connectivity is one of the key problem in wireless networks. The failures 110 occurrence leads to the disconnect of the networks. The solution of such issues is to provide 111 a reliable multi-hop path to maintain the connectivity through other kinds of nodes, such 112 as mobile vehicles. However, it cannot maintain the wireless network connectivity all the 113 time. That is because the mobility of the mobile sink, based on which a node is within the 114 transmission range of the mobile sink at this moment may out of its range at next moment. 115 And the motion trajectory of the mobile sink is also restricted by the network deployment. 116 Thus, UAV, which trajectory could be predefined or randomly, is introduced to work as 117 mobile sink. 118

Extensive investigations have been conducted on maintaining connectivity in the context of U-WSN. Research in [4] address the city-scale video monitoring in WSNs. Multiple UAVs ride buses in a noisy 3-D environment were considered. The UAVs could recharge through moving bus, thus, it could maintain the connectivity of the network. However,

their study addressed on static objective nodes. In our previous works, [18–20], we address the dynamic wireless networks in which both the mobility of collectors and nodes were considered. The simulation results in [19] present that the moving of UAV can maintaining the connectivity of the wireless network. The sensor nodes that are without the transmission range of the base station could have an opportunity to communicate with the UAV through create connection path to the connected neighbours.

However, our previous works fail to consider the case that the UAV and the sensor moving in opposite directions. In section 4.2, we not only study the mobility of the UAV and the sensor, but also consider the case where they move in different directions, and the relationship between them also considered.

In Table 5, we summarize and compare the use of UAV for maintaining connectivity 133 in wireless networks. 134

Pof	Functionalities		NI 4	Portormon co Objective		
Kel.	<b>M.C.</b> <sup>1</sup>	D.C. <sup>2</sup>	<b>Loc.</b> <sup>3</sup>	INuav	r enormance Objective	
[5]	Yes	Yes	No	Multiple	Optimization of the photogrammetry process.	
[4]	Yes	Yes	No	Multiple	Maximization of data delivery.	
[13]	Yes	Yes	Yes	Multiple	Smart view in smart grid.	
[14]	Yes	Yes	Yes	Multiple	Civil security and disaster management.	
[15]	Yes	Yes	Yes	Multiple	Monitoring and mapping optimization of the oil or	
					gas pipelines.	
[18]	Yes	Yes	No	1	Maximization of packet delivery ratio and network	
					fairness.	
[19]	Yes	Yes	No	1	Maximization of packet delivery ratio, system fair-	
					ness and throughput.	
[20]	Yes	Yes	No	1	Maximization of packet delivery ratio and network	
					fairness.	
[21]	Yes	Yes	Yes	Multiple	Practical deployment.	
[22]	Yes	Yes	No	1	Optimization of the UAV flying path.	
[23]	Yes	Yes	No	Multiple	Maximization of data delivery.	
[24]	Yes	No	Yes	1	Optimization of localization	
[25]	Yes	Yes	No	1	Minimization of system energy consumption.	
[26]	Yes	Yes	No	Multiple	Maximization of data delivery.	
[27]	Yes	Yes	No	Multiple	Optimization of the speeds of UAVs.	
[28]	Yes	Yes	No	Multiple	Maximization of data delivery.	
[29]	Yes	No	Yes	Multiple	Optimization of localization in three-dimension	
					space.	
[30]	Yes	No	Yes	1	Optimization of real-time localization.	
[31]	Yes	Yes	Yes	Multiple	Maximization of data delivery.	
[32]	Yes	Yes	Yes	Multiple	Energy efficiency maximization.	
[33]	Yes	Yes	Yes	1	Maximization of data delivery.	

Table 5. Summarising and comparison of the UAV functionalities in the existing U-WSN.

<sup>1</sup> M.C. is the abbreviation of "Maintain Connectivity".

<sup>2</sup> D.C. is the abbreviation of "Data Collection".

<sup>3</sup> Loc. is the abbreviation of "Localization".

<sup>4</sup>  $N_{uav}$  is the number of UAVs.

#### 2.3.2. Data collection

In traditional data collection protocols, sensors were usually assumed to be static and densely deployed. Sparse and mobility were not considered because they cannot maintain connectivity of the network. Thus, the nodes may not be connected through multi-hop paths. After the introduction of mobile nodes, how to collect data from the mobile nodes becomes a new challenge.

Data collection has been addressed extensively in the literature. In [34,35], the authors proposed an energy conservation scheme to extend the network lifetime, and the data collecting time is extended accordingly. In reference [25], the authors attempt to make full use of integrating small-scale UAV in a ground wireless network for information collecting

and environmental monitoring and surveillance. The cost-reducing and energy-saving were conducted through using small-scale UAVs.

In [26], the authors address the data gathering problem of how to efficiently utilize 147 the battery power for the maximizing data collection performance in rechargeable WSN. 148 The rechargeable sensor network can provide enough energy to maintain the system 149 connectivity. In [27], the authors propose the optimal speed control of the UAV which 150 could helps the system to collect data efficiently. Both of them are based on a single UAV. 151 Authors in [28] address the data collection issue through multi-UAVs, in which both the 152 packet received ratio and packets tracking ratio were evaluated. However, the fairness and 153 collisions between UAVs are failure to considered in this work. And this is one of the main 154 contributions that the authors in [23] have done. The authors concentrate on the problem 155 of data gathering from scattered sensors through integrating several UAVs in the context of 156 large scale sensor networks. A heuristic algorithm based on a column generation approach 157 was proposed and the results perform well.

The main idea of these research is to extend the data collection time through extending the network life time. They pay little attention on the impact of the network topology on data collection. In U-WSN, the dynamic topology has a critical influence on the connectivity of the wireless network. It will directly affect whether a route is created between two nodes and the endurance of the connection.

However, most of existing works address the static network topology. The authors concentrated on the dynamic topology in [18–20], both the mobility of the UAV and sensors are considered. The authors fail to present all the relationships between the mobility and the data collection because of space limitations. In section 4.2, we address the impact of the dynamic topology on the connection. In Table 5, we give a summarisation and comparison of using UAV for data collection in the existing applications.

#### 2.3.3. Localization

Location-based services in variety of applications, such as weather forecasting, traffic 171 monitoring, smart home [36] and rescue application. Global Positioning System (GPS) [37] 172 is a solution in such applications. GPS works well on localization when the applications 173 are implemented outdoor. It is better for the GPS to be used far enough from buildings 174 or obstacles otherwise GPS signals become unreliable. However, GPS has high power 175 consumption, especially in large scale networks, and poor performance when applied 176 indoors. Thus, a large number of works have been done to optimize the location-aware 177 performance. 178

Various types of categories of existing localization methods have been introduced according to different standards, range-based and range-free, coarse-grained and fine-grained, cooperative and cooperative-free, networking centric positioning and self-positioning. Among these classifications, the Range-Based and Range-free algorithms are the typical one according to whether to use range information. Typical Range-Based algorithms like Time of Arrival (ToA), Time Difference of Arrival (TDoA) and Received Signal Strength (RSS). Range-free methods calculate the location information from the connectivity information.

There is a huge scope of application offline training for localization. Thus, it is critical for the localization mechanisms to implement the training step for taxonomic hierarchy in the infrastructure of internet of things. The localization algorithms are classified into two categories, self determining and training dependent methods, if we take into account the internet of things scenario.

Localization methods with mobile nodes are the best solutions regarding these issues. <sup>191</sup> Vehicles moving in the interesting area and broadcasting 'beacons' messages, through which vehicles can self-localize via combining with appropriate methods. Nodes that have <sup>193</sup> received the 'beacon' messages are within the transmission range of the mobile vehicles. <sup>194</sup> Through combining with proposed technologies, the sensor nodes can give an estimation <sup>195</sup> about their locations after enough 'beacons' messages are received. The vehicle-aided <sup>196</sup> localization algorithms are classified into two categories, static vehicle-aided localization <sup>197</sup>

and mobile vehicle-aided localization. In static vehicle-aided localization algorithms, 198 e.g., in [38], the localization accuracy depends on many factors, the number of vehicles, 100 the deployment and the trajectory of the vehicles, etc. It can be predicted that uniform 200 deployment in high densely will bring a high localization accuracy. However, it also leads 201 to high hardware cost and energy consumption. The UAV, which moves at a high speed and 202 has high flexibility, works as a mobile vehicle which is the best choice in such applications. 203

In the context of U-WSN, the authors in [29] address the issue of how to achieve three-204 dimensional localization using a UAV. In this work, sensors are deployed in the monitoring 205 area without equipped a GPS while UAV is equipped with a GPS. UAV flies over the 206 area and broadcasts 'beacon' messages which include the geographical information of the 207 UAV. The nodes that received the 'beacon' messages are able to estimate their geographical 208 positions through combing with appropriate technologies. However, it is not a real-time 209 algorithm. Authors in [30] proposed a real-time localization algorithm using Extended 210 Kalman Filter which is based on time difference of arrivals. The proposed algorithm works 211 well on the estimation of sensors positions. In section 4.2, we focus on the dynamic topology 212 wireless network and give a definition on the relationship between the UAV and the mobile 213 nodes, based on which the nodes positions could be well estimated. In [39], the authors 214 give a summary on mobility-assisted localization algorithms in wireless networks.

In Table 5, we summarizes the use of UAV for localization in the existing applications. 216 Thereafter, the functionalities of UAV as a communication node are detailed in Table 5. 217

# 3. Factors Influencing U-WSN Design

A U-WSN design is influenced by many factors, including architecture of U-WSN; 219 relative motion between the UAV and the Sensors; fault tolerance; scalability; production 220 costs; operating environment; hardware constraints; transmission media; and power con-221 sumption. These factors are addressed by many researchers as surveyed in this paper. 222 However, none of these studies has a full integrated view of all factors that are driving 223 the design of sensor networks and sensor nodes. These factors are important because they 224 serve as a guideline to design a protocol or an algorithm for sensor networks. In addition, 225 these influencing factors can be used to compare different schemes.

#### 3.1. Architectures of U-WSN

In the architecture design, the main objective is to impose few requirements to the 228 execution capabilities of the UAV. Basically, the UAV is able to move to a given location 229 and activate their payload when required. Then, according to different applications, UAV 230 is integrated in different architectures. The global picture of the main architectures in 231 U-WSNs is shown in Fig. 1. The general architecture could be mapped to various specific 232 scenarios. In the following, we introduce the links and the relevant technologies with their 233 application fields in Fig. 2. 234

# 3.1.1. Sensor-Sensor Link (S-S)

The communication between sensors is the basic one included in other links. A low 236 energy and data rate protocol can be used. The standard IEEE 802.15.4 [40], along with the corresponding upper layers which are compliant with the ZigBee [41] protocol stack, is 238 typically used at this link layer. Generally, the data-rate is less than 1 *Mbps*. 239

# 3.1.2. UAV-Sensor Link (U-S)

In the link between UAV and sensor, the UAV usually acts as a mobile sink. The 241 distance between the UAV and a sensor is ranging from several meters to hundred meters. 242 In the case of close range, the U-S links could apply the technologies as in S-S link. The 243 connection between UAV and sensors is able to use the IEEE 802.15.4 (ZigBee) and IEEE 802.11ah (WiFi) [42] protocols. These protocols have the medium range that could achieve 245 several hundred meters. 246

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Figure 2. Links, technologies and applications of UAV-assisted WSNs.

# 3.1.3. UAV-Smart Phone Link (U-SP)

In some applications, the UAV is connected to smart-phone in order to collect data from the phone. The commutation range between them is medium. Thus, the U-SP link basically uses the medium range protocols such as IEEE 802.11ah (WiFi) and IEEE 802.16p (WiMAX), which are adapted for machine to machine communication. Adaptations of LTE-Advanced (LTE-A) are also experimented [43].

# 3.1.4. UAV-GateWay Link (U-GW)

Similarly to U-SP, the connection between UAV and gateway used to collect informa-254 tion. Thus, their communication range are at the same level. The U-GW link use medium range protocols such as IEEE 802.16p (WiMAX) for real-time data delivery and LTE/LTE-A 256 for transmitting large data (e.g. video) in real-time monitoring. 257

# 3.1.5. UAV-UAV Link (U-U)

In this category, the data transfer between UAVs, and the UAV create link with UAV. 259 The protocols, e.g. IEEE 802.11, IEEE 802.16p (WiMAX), with medium range can be used to 260 achieve the connectivity between the UAVs. In real-time applications, the U-U links can 261 apply LTE/LTE-A. 262

# 3.1.6. UAV-Satellite Link (U-SL)

In some applications, the UAV is connected to satellite. The communication range is 264 long. To achieve the long distance connectivity, the Random Access (RA), hybrid schemes and Demand Assignment (DA) schemes are usually used. In Fig. 2, we give a summary 266 and comparison of their technologies and applications. 267

# 3.2. Scalability

The number of sensor nodes may be in the order of hundreds or thousands, or reach 269 an extreme value of millions. The network topology is dynamic The new schemes must be 270 able to work with this number of nodes and utilize the high density of the network. The 271 density gives by the number of nodes within the transmission radius of each node in region 272 A, and it can be calculated according to [44] as 273

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$$p(R) = \frac{N\pi R^2}{A} \tag{1}$$

where *N* is the number of sensors in region *A*, and *R* is the radio transmission range. 274 In general, the density can be as high as 20 sensor nodes per  $m^3$  [45]. The node density 275 depends on the application. For the vehicle tracking application is around 10 sensor nodes 276 per region [45]. A home may contain around two dozens of home appliances containing 277 sensor nodes [46], but this number will grow if sensors are embedded into furniture and 278 other miscellaneous items. For human motion tracking application is around 5 nodes per 5 279  $\times$  5 m<sup>2</sup> [31]. For habitat monitoring application, the number of sensor nodes ranges from 280 25 to 100 per region [47]. 281

# 3.3. Fault Tolerance

Some sensor nodes may fail or be blocked because of power exhaustion, the UAV's 283 motion, or environmental interference. The failure of sensor nodes should not affect the 284 overall task of the U-WSN. This is the reliability or fault tolerance issue. Fault tolerance is the ability to sustain sensor network functionalities without any interruption due to sensor 286 node failures [48,49]. The reliability  $\gamma(t)$  or fault tolerance of a sensor node is modelled in 287 [49] using the Poisson distribution to capture the probability of not having a failure within 288 the time interval (0, t): 289

$$\gamma(t) = \exp(-\lambda_k \cdot t) \tag{2}$$

where  $\lambda_k$  and t are the failure rate of sensor  $S_k$  and the time period, respectively. 290 Note that protocols and algorithms may be designed to address the level of fault tolerance 291 required by the applications. If the studied environment has little interference, then the 292 protocols can be more relaxed. For example, if sensor nodes are being deployed in a house 293 to keep track of humidity and temperature levels, the fault tolerance requirement may be 294 low since this kind of sensor networks is not easily damaged or interfered by environmental 295 noise. On the other hand, if sensor nodes are being deployed in a battlefield for surveillance 296

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# 3.4. Power Consumption and Network Lifetime

The wireless nodes and the UAV are powered by battery which has limited power source. Both the lifetime of the sensors and the UAV show a strong dependence on the micro-electronic device lifetime. Therefore, power conservation and power management take on additional importance. It is for these reasons that researchers are currently focusing on the design of power-aware protocols and algorithms for sensor networks.

and detection, then the fault tolerance has to be high because the sensed data are critical and sensor nodes can be destroyed by hostile actions. As a result, the fault tolerance level

depends on the application of the U-WSN, and the schemes must be developed with this in

The main task of a sensor node in a sensor field is to detect information and forward 307 them. And the main task of the UAV is to load sensors or devices. Hence, the power 308 consumption of the sensors includes three phase: UAV flying, sensing, communication, and 309 data processing. The main power consumption of the UAV is the movement consumption 310 [31]. It cost a lot when it flying at an altitude [31]. And there is a big gap between the 311 energy consumption during different UAVs [31]. The sensing unit and the data processing 312 are the same as in traditional WSN [50]. For the communication unit, it was noticed that, in a U-WSN, the communication contains two phase, the communications between sensors 314 on the ground and the communications between the on-ground sensors and the air sensors 315 that deployed in the UAV. And the communications between the ground sensors is able 316 to adopt the model as presented in [50]. In this section, we will focus on the air-ground 317 communication. 318

# 3.4.1. Power Consumption during Air-ground Communication

The Signal-to-Interference-and-Noise Ratio (SINR) is used to measure the achievable throughput and link quality. Suppose that, the SINR is denoted by  $S_{inr}$ , then, 321

$$S_{inr} = \frac{P_r}{P_{s,r} + P_{n,r}},\tag{3}$$

where  $P_{s,r}$  is the interference power summing at the receiver,  $P_{n,r}$  is the receiver noise power,  $P_r$  is the received power from the serving transmitter. For a particular application, in order to achieve the required throughput, the SINR is set at a given throughput (denoted by  $S_{inr,0}$ ) through adjusting the transmitter power. The energy consumption involved in the process of delivering a message (from a ground node) towards an aerial collector over a session interval  $\Delta t$ , can be given as the following [51], 322

$$E_{S_i} = S_{inr,0} \cdot (\overline{P_{I,a}} + P_{n,p}) L_{S_i^i} \cdot \Delta t, \tag{4}$$

where  $\overline{P_{I,a}}$  is the average aerial interference power, and  $P_{n,p}$  is the platforms noise power. Then, the total energy consumption is obtained <sup>1</sup>, <sup>329</sup>

$$E_{all} = \Sigma_{i=1}^N E_{S_i}.$$
(5)

# 3.4.2. Network Lifetime

Network lifetime is a key design consideration for battery-powered U-WSNs. There exist number of research focus on the lifetime maximization issues [52,53] or on the prediction of the remaining lifetime [54,55]. Other research focus on the energy-efficiency issues so as to extend the network lifetime [56–59], and the trajectory planning of the UAV is one of the most consideration among these schemes [32,60,61]. Although a number of studies have been done for network lifetime, U-WSN still face some issues, e.g., the collisions and

<sup>&</sup>lt;sup>1</sup> Generally, the main focus is in the energy consumption of the sensor nodes, and, it assumes that the network is not constrained by the possible limitation in the aerial platforms energy. Accordingly, its energy consumption is not account.

re-transmissions during communications, which cannot fully avoided in applications that 337 degrade the lifetime. 338

# 3.5. Security and Regulation

Security and regulation of the data collected from a U-WSN, either while stored inside 340 the UAV or during their transmission from the UAV to a gateway, is a major unsolved con-341 cern. Furthermore, as thousands of businesses could receive clearance to fly drones in the 342 near future, UAVs will face with various security issues such as loss of data, authentication, 343 access control, and intrusion attacks. In U-WSNs, security solutions are required for data 344 confidentiality, authentication and integrity at low cost. 345

Moreover, there are still many regulation issues to be resolved in the coming research. 346 Indeed, there are many requirements from the governments to regulate where the drones 347 fly and what is done with the torrents of data collected from aerial surveillance [62]. In 348 fact, numerous civilian drone manufacturers claim that the main barrier in U.S. and Europe 349 is not the technology, but the regulation. For instance, the U.S. FAA (Federal Aviation 350 Authority) provide some basic regulations and restrictions of the airspace that will govern 351 who can fly drones in the United States and under what conditions. A standard that is 352 formulated by 2016 will permit unmanned aircraft systems (UAS) to interoperate with manned aircraft using an "electronic means" to see and avoid potential aerial disasters. Due 354 to the UAV is flying in the same national airspace, it is crucial for the world to comply with 355 a same safety regulations and restrictions. 356

# 4. Open Issues and Challenges

This section summarizes and discusses the open research issues and challenging future directions. L. Gupta et al. give a survey on important issues in U-WSN [63]. 350

#### 4.1. Synchronization Issues

The synchronization issue was a thorny subject in U-WSN, considering the limited communication time. In the past, many synchronization algorithms have been investigated 362 to keep the synchrony of networked systems. The perfect time synchrony, Time-Diffusion Protocol (TDP) [64], was proposed by Su and Akyildiz. In the synchronization process, 364 the TDP applies an iterative and weighted averaging mechanism built on the collected 365 messages from the whole network. In reference [65], the authors through enhancing the 366 TDP scheme to adapt to the particular applications (e.g., tracking and surveillance) that 367 require global time synchronization and fault-tolerance. However, most of these research 368 are based on traditional wireless networks. In the context of U-WSN, especially in dynamic 360 topology, the beaconing mechanism is usually used for the network synchronization [18– 370 20,66,67]. In [68], the authors give a survey on the synchronization in U-WSNs. 371

#### 4.2. Relative Motion between the UAV and the Sensors

Both UAVs and targets are moving in U-WSN applications, such as animals monitoring. 373 The topology of the network changes as the node and the UAV move. At this point, one node 374 is within the range of the UAV, while at another time, it may be outside the transmission 375 range. Thus, mobility directly affects the connectivity of the network. It has a significant 376 impact on the data transmission performance of the network. 377

The duration that the mobile node is within the transmission range of the UAV has an 378 essential impact on the performance of the network, which is defined as contact duration [18–20,31]. However, it only considers the case of mobile nodes and the same mobile 380 direction as the UAV, the static case and opposite mobile direction with the UAV are not 381 considered. In the following, we will give a complete definition. 387

### 4.2.1. Contact Duration between the UAV and the Sensor

In U-WSN with mobile sensors, the node has an opportunity to communicate with the UAV when they are within range of each other. The link duration is named as *contact* 385

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duration [18–20,31]. As the "one UAV and one sensor" is the min-unit in U-WSN, we take this scenario where the UAV moves along a predefined path to maintain the network 387 connectivity, for example, to calculate the *contact duration* (which is denoted as  $T_{cd}$  in this 388 article). 389

According to the existing research, we refined the scenario into two categories: (a) 390 both the UAV and the sensors move along a straight path, and (b) they move along a 391 curved path. The other cases, e.g., the "trajectories" of the UAV and the sensors have some 392 intersections,  $T_{cd}$  still need further study. 393

#### (a) Straight Path

When the trajectory of the UAV is a straight path, the scenario can be further refined 305 as: sensor is static (Fig. 3), sensor and the UAV are move at the same direction (Fig. 4), and 396 in the opposite direction (Fig. 5). 397

The relative movement distance between sensor and the UAV is denoted by  $d_r$ . UAV 398 fly at a height h with constant velocity v. The range of the sensor is denoted by r. The 399 original distance between UAV and node is  $d_x$ . Then, we will discuss the calculation of the 400 contact duration time as follows: 401

The node is static (Fig. 3). In this case, the relative velocity between the node and the 402 UAV is v. The relative movement distance between them is  $d_r = A_s B_s$ , i.e. 403

$$d_r = 2(r^2 - h^2 - d^2)^{\frac{1}{2}}.$$
(6)

when the UAV is out of the range (Fig. 3(a)). In Fig. 3(b), when the UAV is within the 404 range of the node,  $d_r = D_s B_s$ , i.e. 405

$$d_r = (r^2 - h^2 - d^2)^{\frac{1}{2}} + d_x.$$
(7)

The *contact duration* between the UAV and the static node,  $T_{cd}$  can be given by,

$$T_{cd} = \frac{d_r}{v} \,. \tag{8}$$

This is based on an assumption that the flying height of UAV is smaller than the range 407 of the node (h < r) and the UAV is out of the range of the node in the beginning 408  $(d_x > r)$ . The relative movement distance will be different if their topologies are changed (as illustrated in Fig. 4 and Fig. 5). 410



(a) UAV is out of the range of the sensor

(b) UAV is within the range of the sensor

Figure 3. Simple scenario with one UAV and one Sensor (Static).

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(b) UAV is within the range of the sensor

Figure 4. Simple scenario with one UAV and one Sensor (Same direction).

The node and the UAV move at the same direction (Fig. 4). The sensor velocity is ٠ 411  $v_s$ . The contact duration time depends on the original deployment of the UAV if the 412 sensor and the UAV have the same speeds ( $v_s = v$ ). The relative velocity between 413 the node and the UAV is 0. Let the moving time and distance of node are T and L414 respectively. The relative movement distance between the UAV and the sensor is 415  $d_r = 0$  when the UAV is out of the range of the UAV ( $d_x > r$  in Fig. 4(a)).  $d_r = L$  when 416 the UAV is within the range of the node ( $d_x \leq r$  in Fig. 4(b)). 417 418

When  $v_s \neq v$ , similarly to static case, the relative distance between them can be given <sup>418</sup> by,

$$d_{r} = \begin{cases} 0 & v_{s} > v, d_{x} \ge r, \\ A_{s}B_{s} & v_{s} < v, d_{x} \ge r, \\ A_{s}D_{s} & v_{s} > v, d_{x} < r, \\ D_{s}B_{s} & v_{s} < v, d_{x} < r. \end{cases}$$
(9)

Then, according to equation (8) and Fig. 4(b), the  $T_{cd}$  between the UAV and the mobile sensor (moving at the same direction), can be given as in,

$$T_{cd} = \begin{cases} T & v_s = v, \, d_x \le r \,, \\ 0 & v_s = v, \, d_x > r \,, \\ 0 & v_s > v, \, d_x \ge r \,, \\ \frac{2A_sC_s}{v - v_s} & v_s < v, \, d_x \ge r \,, \\ \frac{A_sC_s - d_x}{v_s - v} & v_s > v, \, d_x < r \,, \\ \frac{A_sC_s + d_x}{v - v_s} & v_s < v, \, d_x < r \,, \end{cases}$$
(10)

where  $A_s C_s = (r^2 - h^2 - d^2)^{\frac{1}{2}}$ .





(b) UAV is within the range of the sensor

Figure 5. Simple scenario with one UAV and one Sensor (opposite direction).



Figure 6. Simple scenario with one UAV and one Sensor (curve path).

• The node and the UAV move at opposite direction (as shown in Fig. 5). Similarly to the front case, the relative movement distance depends on the dynamic topology. Hence, it can be given by,

$$d_r = \begin{cases} A_s B_s & d_x \ge r, \\ A_s D_s & d_x < r. \end{cases}$$

Then, the  $T_{cd}$  between the UAV and the sensor (moving at the opposite direction) can be calculated by,

$$T_{cd} = \begin{cases} \frac{2A_sC_s}{v+v_s} & d_x \ge r, \\ \frac{A_sC_s-d_x}{v+v_s} & d_x < r. \end{cases}$$
(11)

As shown in Fig. 3, Fig. 4 and Fig. 5,  $T_{cd}$  achieves the maximum when the UAV flies on the top of the node. This conclusion is corroborated in equation (8), (10) and (11). The longer the  $T_{cd}$ , the higher opportunity for the sensor to communicate with the UAV.

# (b) Curve Path

When the trajectory of the UAV is a curve path (Fig. 6), the contact duration is obtained through a beacon based prediction mechanism [33].

The midline of the pre-defined path is y = f(x) (Fig. 7). At  $t_k$ , the UAV sends a 427 beacon message to its coverage, and S receives it and successfully sends the join message 428 to the UAV. The precise location and speed of the S which are recorded in join message are 429 obtained by the UAV. The location coordinates is denoted by  $S_{t_k}(x_{t_k}, y_{t_k}, 0)$ . The vehicles 430 are supposed to mobile on a flatland and it assumes that the altitude changes are negligible. 431 The distance between *S* and the midline of the path is denoted by  $a_0 = y_{t_k} - f(x_{t_k})$  (Fig. 432 7). Without loss of generality, we assume that the *S* moves along a line which is given by 433  $y = f(x) + a_0$  before the next beacon coming. This assumption is based on an estimation 434 that the influence brought by the lane change of bicycles is negligible compared to the path 435 length. 436

Suppose that, the  $m + 1^{th}$  beacon is sent at  $t_l$  (then, the  $IBD = t_l - t_k$ ). Then, the coordinates of *S* at  $t_j$  ( $t_k \le t_j < t_l$ ) is given by,

$$\begin{cases} v_i t_j \doteq \int_0^{x_{t_j}} \sqrt{(1 + (y')^2)} dx, \\ y_{t_j} = f(x_{t_j}) + a_0, \end{cases}$$
(12)

where  $\int_0^{x_{t_j}} \sqrt{(1+(y')^2)} dx$  is the curve length of  $y = f(x) + a_0$  when  $x \in [0, x_{t_j}]$ . Accordingly, the coordinates of the UAV at  $t_j$  can be obtained through,

$$\begin{cases} vt_j \doteq \int_0^{x_{t_j}^u} \sqrt{(1+(y')^2)} dx, \\ y_{t_j}^u = f(x_{t_j}). \end{cases}$$
(13)



**Figure 7.** An illustration of the trajectory of  $S_i$ . In this figure,  $l_k$  is the curve length.

Let  $T_{cd,t_k}$  be the *remaining contact duration* of the node *S* and the UAV at  $t_k$ . It means that the *S* will out of the range of the UAV after  $T_{cd,t_k}$ , and it can be obtained through,

$$T_{cd,t_k} \doteq \frac{1}{v} \int_{x_{t_k}}^{x_{t_\lambda}} \sqrt{(1+(y')^2)} dx \,, \tag{14}$$

with a boundary conditions  $d_{t_{\lambda}}(U_{t_{\lambda}}, S_{t_{\lambda}}) = R$  where  $t_{\lambda} = t_k + T_{cd,t_k}$  and R is the transmission range of the UAV.

#### 4.2.2. Summary and Insight

Through reviewing the relative motion between the UAV and sensors, the contact duration between the sensor and the UAV is one of the key factor in the U-WSN applications. The longer the contact duration, the higher opportunity for the communication between the sensor and the UAV. Conversely, the shorter the contact duration, the lower opportunity of the communication between them. Thus, the data transmission of the network can be better improved, if the contact duration is considered [18,33].

Furthermore, the fairness of the network can be enhanced if the contact duration is considered when designing the routing protocols [48] or MAC protocols [20].

# 4.3. Trajectory Planning of the UAV

As aforementioned, mobile vehicle based technologies are effective methods address-449 ing localization issue because of its mobility and flexibility. Path planning is object to 450 improve the localization accuracy with a best possible trajectory of the UAV. Proper path 451 planning can guarantee good coverage of the whole sensing field as well as keeping the 452 minimum path length. Study in [69] is an application to UAV path planning. An adaptive 453 operator quantum-behaved pigeon-inspired optimization algorithm along with logistic 454 mapping method were proposed in [69] for the application to UAV path planning. A 455 comparison result presents that the performance of their proposed algorithm is better than 456 parts of the existing algorithms in terms of convergence and accuracy. Indeed, according to different applications, many investigations with different objective functions and 458 optimization methods have been done (we summarize them in Table 6).

Moreover, according to whether there is interaction between UAVs and nodes, path planning of U-WSN has two categories. First is static path planning in which the path is predefined and second is dynamic path planning in which the path can be changed. The existing algorithms are summarized and compared in Table 7.

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Objectives	Detail	Applications
max C(𝔅)	Maximization of the coverage of the whole sensing field. In some applica- tions, tt is better to make sure that all the nodes within the interesting area to be covered.	In [70], the authors formulate an area cov- erage reliability issue. Their proposed al- gorithm quantifies the network likelihood that the network can be in an operating state where the coverage condition is sat- isfied.
min P <sub>UAV</sub>	Minimization of the UAV flying path. The whole path length should be con- trolled to reduce the localization delay and the system energy consumption.	Authors in [22] proposed an effective path length reduction algorithm for UAV path planning which has a low computational complexity. The proposed algorithm not only used in control center but also in UAV controller.
min D <sub>UAV</sub>	Minimization of the UAV's travel du- ration. This objective helps the system to save energy consumption.	In [23], the authors address the path plan- ning issue with the objective of the min- imization of UAV's flying duration. En- ergy, fairness, collision and tracking be- tween UAVs were considered.
$\max A(\mathbb{S})$	Maximization of the localization accuracy. This objective helps the sensors within the coverage be localized with high accuracy.	In [24], the authors address the path plan- ing accuracy problem on U-WSN. They proposed an novel algorithm which con- siders the accuracy of positioning and the efficiency of flight.
min E <sub>wsn</sub>	Minimization of energy consumption. This is the main problem in almost all of the applications.	In [71], based on genetic algorithm, the au- thors proposed an energy efficient mech- anism for autonomous UAV. In this algo- rithm, the authors considered the relief and obstacles.
max Q <sub>data</sub>	Maximization of the quality of data communication. The main objective in almost all of the application due to their research based on the collected data.	Authors in [72] proposed two data collec- tion protocols (IDGP and DDGP) based on infrastructure through plan the mobile path.
max L <sub>network</sub>	Maximization of the network lifetime. The longer the network lifetime, the more collections of the network.	Authors in [32,60,61] proposed trajectory planning algorithms to extend the net-work lifetime.
S is the sensor set	- -	

Table 6. The objectives of path planning in U-WSN.

# 4.3.1. Static path planning

In static case, the trajectory for mobile vehicles is determined in advance. Vehicle 465 moves along the pre-determined trajectory strictly. The simplest case is that the vehicles move in Lines [73]. The vehicle moves in a predefined line and broadcasts gradient signals 467 to localize the unknown node. The trajectory is a x-rays. Based on this, the algorithms can 468 be SCAN, DOUBLE SCAN, and HILBERT [74]. In SCAN algorithm, the vehicle moves in 469 one direction while it moves in both directions in DOUBLE SCAN method. In HILBERT 470 SCAN scheme, the vehicle moves in the Hilbert pattern. They all have the same objective 471 that is to maximize the network coverage, even in the corner. It can be noticed that some 472 areas are visited frequently because of the linearity of the trajectory. Thus, curves were 473 introduced. Circle and s-curve [75] are the critical methods to reduce localization col-474 linearity [75]<sup>2</sup>. However, this types of scan leave the corner of the region. Thus, mobile 475 anchor node centroid localization (MACL) algorithm [76] was introduced. In MACL, the 476 mobile vehicle traverses the interesting area following a spiral trajectory and periodically 477

<sup>&</sup>lt;sup>2</sup> In Statistics, the co-linearity refers to the fact that the explanatory variables in the linear regression model are distorted or difficult to estimate accurately due to the existence of precise correlation or high correlation between the explanatory variables. Thus, in the localization mechanism, the localization could be well estimated if the col-linearity could be reduced.

broadcasting beacon packets which contain its current position. More algorithms and their characteristics are summarized and compared in the Table 7.

 $E_c^2$  $N_{mv}$   $^1$  $A_{l}^{3}$ Algorithms Advantages Disadvantages Static Path Planning 1 High Lines[73] Low The simplest path planning. Shorter communication range. SCAN. Double 1 Medium High These algorithms are object to maximize They waste much of col-linearity. SCAN, Hilbert<sup>[74]</sup> the coverage. Circle, S-curve [75] 1 Medium Medium No col-linearity These algorithms leave the corner of the interest area. MACL [76] 1 Medium Low In MACL, the vehicle moves along a spi-The accuracy of the localization ral path and broadcasts 'beacon' (includis about 50%. ing the current location information) periodically. PI [77] 1 High Perpendicular Intersection (PI) is used to Energy consumption for turns are Medium localize nodes. Vehicle moves in zigzag not considered. line with an angle within  $(0, \frac{\pi}{3})$ . LMAT [78] The authors fail to consider the 1 Medium Medium In this algorithm, the vehicle moves along an equilateral triangle line to send energy consumption for turns. 'beacons', through which, the sensors positions are well estimated even if the "beacon" are col-linear. S-type [79] 1 High High This algorithm achieves the shortest path Much energy consumed for turns and low vehicle utilization. through making the vehicle moves in 'S'. The interesting area is divided into small square (with each has a size of  $\frac{R}{\sqrt{2}}$ ), based on which the col-linearity problem is solved. WCL [80] 4 High High In WCL algorithm, four mobile vehi-Due to 3D localization, this alcles were used. They form a threegorithm consume much energy. dimensional space and move in 3D-space, Beacon col-linear problem are fail thereby, a 3D space network could be covto sloved. ered. **Dynamic Path Planning** MBAL [81] 1 Medium Low MBAL works better when the sensors are This algorithm fail to consider the irregularly deployed. obstacle case. BRF, BTG [82] 1 High Medium In the two algorithms, the network topol-Both the two algorithms have ogy was regard as a connected indirectly high real-time requirements. graph. And they are able to localize all the sensors if they are densely deployed. MBL(ndc) [83] 1 It is a dynamic trajectory planning algo-The algorithm complexity is high High High rithm. when the network size is large. MALS [84] 1 Medium High This algorithm is proposed based on clus-Due to it is based on clustering, tering mechanism. And it is designed for thus, high localization delay is non-uniform and irregular deployment brought. scenarios. DREAMS [85] 1 Medium High In DREAMS, the sensory field informa-It performs normal when the tion are not required in advance. node failure is presence. Virtual Ruler [86] 2 High High In virtual ruler, it can be measured in dif-In this algorithm, all unknown ferent values from different point of view. nodes are required to deploy an It is applicable for obstructed networks. ultrasound receiver or "beacon".

Table 7. Comparison of existing path planning algorithms based on mobility.

<sup>1</sup>  $N_{mv}$  is the number of mobile vehicles.

<sup>2</sup>  $E_c$  is the energy consumption. Here, we have three levels: "Low", "Medium" and "High" which are from the original references that the algorithms are defined.

 $^{3}$   $A_{l}$  is the localization accuracy.  $A_{l}$  has three levels: Low:  $A_{l}$  < 70% ; Medium:  $A_{l} \in$  [70%, 90%); High:  $A_{l} \ge$  90%.

Static path planning algorithm works well when the unknown nodes are assumed 481 to be uniformly deployed. However, it may not be a better solution when the nodes are 482 deployed disarray. Due to the disarray deployment, it spends a lot of localization time and 483 moves long path if the system use the static path planning algorithms. Some researchers 484 concentrate on the work of dynamic case to fully utilize the distribution information and 485 minimize the energy consumption and path length. In dynamic case, none of the mobile 486 path is defined in advance. All of the trajectories are determined based on the real-time 487 information. 488

A large number of investigations have been done on dynamic path planning. Due to the dynamic characteristics, one of the central issues is whether to consider obstacles. Thus, the existing dynamic path planning algorithms can be classified into two categories, with and without obstacle.

Authors in [81] proposed a movement mechanism, mobile beacon-assisted localization (MBAL). It is a low computational complexity algorithm among movement path planning algorithms. However, the obstacle case is not considered. In [82], the authors proposed two algorithms, Breadth-First (BRF) and Backtracking Greedy (BTG) algorithms, based on which all nodes could be localized. However, it requires very high real-time condition. We give a summarizing and comparison in Table 7.

# 4.3.3. Summary and Insight

Through reviewing the static and dynamic path planning of mobile vehicles (as presented in Table 7), we notice that few algorithms use extra hardware to plan the trajectory. Most of the existing algorithms use col-linearity principle [75] of mobile vehicles. A single mobile vehicle would be cheaper. However, it may bring more col-linearity or longer localization time issues. Multiple mobile vehicles could help to reduce the localization time, especially in 3-dimension scenarios.

Compared to the dynamic case, static path planning algorithms fail to fully utilize 506 the real-time information that obtained. In practical applications, the environment where 507 the sensors are deployed is full of uncertainties, and therefore, dynamic path planning 508 performs better than pre-defined one because it can consider more real-time information. 509 The main issues in dynamic path planning are adaptability and computational complexity. 510 In the existing dynamic path planning algorithms, which applied in obstructed scenarios, 511 it is assumed that the nodes are equipped with hardware (such as cameras, radar, infra-red, 512 sonar, etc) for detecting obstacles. Based on these, the dynamic algorithms are recognized to 513 fully use the real-time information and they are more accepted for areas with uncertainties. 514

#### 5. Discussions

In this section, we introduce a working example to discuss the aforementioned factors and issues. 517

# 5.1. A Working Example

Without loss of generality, take the UAV trajectory as a curve. In the following, we take the scenario as presented in Fig. 6, which has one UAV and multiple sensors, as an example. As shwon in Fig. 6, the data center is set at the original center point of the path, sensors are deployed in the front part of the predefined path and move along the path. The UAV takes-off from the data center and flies to the given height *h*, and then, flies along the path with a given speed *v* to collect data from sensors. 520

The main energy consumption of such scenario is the energy consumption of the battery [31]. Thus, the network lifetime depends on the UAV flying time. We set is as 300 seconds in the simulation.

We used periodic beacon mechanism to synchronize the network. The UAV sends a beacon message to its surrounding coverage to announce its coming. The sensors that received the beacon send a join message which contains the location and the speed to the 530

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**Figure 8.** The number of sensors ( $N_{node}$ ) that participate the communications. The  $T_{sync,i}$  (i = 1, 2, 3, 4, 5) are the synchronization intervals.

UAV. After the reception of the join messages from the sensor nodes, the data collection phase starts. The interval between adjacent beacons is named as synchronization intervals, and denoted as  $T_{sync}$ .

Fig. 8 presents the scalability and the data collection performance of the network in different synchronization intervals and network size. It shows that the shorter the  $T_{sync}$ , the larger the  $N_{node}$ . This is because, the shorter  $T_{sync}$  brings larger number of nodes that are detected. Thus, the number of nodes that participate the communication increased. It is also able to enhance the fairness of the network when appropriate  $T_{sync}$  was selected. This is because the appropriate  $T_{sync}$  brings the communication opportunity of those nodes that will never be detected in other case.

### 5.2. Extension of the U-WSN use-case to NTN-Aided IoT

The current state of the art shows the need for 3D modeling and simulation of NTN, 542 including moving in space connected objects. Problems studied in the case of UWSN could 543 be extended to general non-terrestrial network use cases. Opportunistic routing under 544 energetic constraints is challenging, particularly in autonomous crewless vehicles and 545 nano-satellites. Even though recent works on energy harvesting show the opportunity 546 to optimize the overall system either through flying ad-hoc networks deployment [87] 547 and drones trajectory control [88] or by using efficient data collection [89] combined with 548 fast wireless power transfer [90]. The system control could be via centralized, distributed, or multi-tier architectures. Designed for WiFi devices, crowd-based schemes [91] allow 550 autonomous adaptive placement without exploiting the device's location. The applicability 551 of those distributed schemes raises energy optimization needs when it is a matter of things 552 with low-power. The self-organization of the NTN is particularly challenging, to efficiently 553 collect and send data via the network on intermittent connection to infrastructure to the 554 cloud. Autonomy and placement to maintain permanent connectivity [92] dictate revisiting 555 communications from UAVs to the cloud, which are investigated in the context of 5G and beyond [93]. 557

Furthermore, in addition to the issues mentioned in this paper, there are wide open challenges in U-WSN applications. For example, the charging challenges, collision avoidance and swarming, etc.

The UAV missions necessitate effective energy management for battery-powered UAVs. Reliable, continuous, and intelligent management can help UAVs achieve their missions and prevent loss and damage. The UAV's battery capacity is a crucial factor in enabling sustainable missions. But as the battery capacity increases, its weight increases, which causes the UAV to consume more energy for a given task. The main directions in the literature to mitigate the limitations in UAV batteries are UAV battery management [94], wireless charging for UAVs [95], and solar powered UAVs [96].

UAVs can collide with obstacles by moving or stationary objects in indoor or outdoor environments. Therefore, during UAV flights, it is vital to avoid accidents with these obstacles. Thus, the development of UAV collision avoidance techniques has gained research interest.

#### 5.3. Future Edge flying Servers

Edge computing is an optimization method that consists of processing data at the 573 edge of the network, close to the data sources, i.e., near the sensors (at the border of the 574 IoT perception layer). Basics of Mobile Edge computing are provided in [97]. Drones 575 with more computing capacity than sensors can thus play the role of Mobile Edge Servers. 576 Therefore, it would be possible to minimize the bandwidth requirements between the 577 sensors and the data processing centers by undertaking the analyses as close as possible to 578 the On-ground data sources. There are several advantages to placing computation at the 579 drone level. Indeed, this makes possible the placement of functions to reduce the volumes of data to be transmitted, perform complex tasks in particular for reconfigurable sensor 581 architectures, correlate data from heterogeneous sources, etc. Furthermore, UAV-enabled 582 Edge computing in IoT helps to avoid the transmission of irrelevant data to data centers or 583 the cloud, thus bringing fluidity and speed of analysis and decision-making.

UAV-enabled edge server approaches require mobilizing resources that may not be permanently available. Consequently, the same networking challenges highlighted above are raised: the intermittency of the links, the Air-Ground contact duration, and the energy consumption, but also computing ones such as responsiveness and prioritization of task execution. Several issues can be considered in UAV-enabled edge computing for IoT, particularly those of data and task offloading.

# 6. Conclusions

In this article, we provided the main basics and features of UAV-enabled wireless sensor networks. Compared to traditional WSN, UAV-enabled WSNs present different issues and challenges. Through detailed analysis of the existing U-WSN applications, we refined the performance and the capability of the UAV and its functionalities when used as a communication node. In addition, the architectures, standard technologies, open issues, and challenges that emerge from this new paradigm are also mined. These insights may serve as motivations and guidelines for future designs of U-WSN.

The high flexibility of the UAV and the high dynamic topology of the network create new problems that cannot be ignored, the *contact duration*. In the future, the remaining contact duration between the UAV and the sensor would be a key criterion when addressing the issues in U-WSN, especially in the context where the sensor nodes are mobile. Because of the relative movement of the UAV and the sensors, the factors that influence the U-WSN design show difference from WSN. The UAV trajectory planning has become a link that cannot be crossed in the design of a U-WSN.

Author Contributions: Conceptualization, X.Ma, R. Kacimi and R. Dhaou; methodology, X.Ma, R.Kacimi and R. Dhaou; software, X.Ma; validation, X.Ma, R. Kacimi and R. Dhaou; formal analysis,X.Ma, R. Kacimi, T. Liu, J. Li and R. Dhaou; investigation, X.Ma, R. Kacimi, T. Liu, J. Li and R. Dhaou;resources, X.Ma, R. Kacimi and R. Dhaou; writing—review and editing, X.Ma, R. Kacimi, T. Liu, J. Li and R.X.Ma, R. Kacimi and R. Dhaou; writing—review and editing, X.Ma, R. Kacimi, T. Liu, J. Li and R.Dhaou; visualization, X.Ma, R. Kacimi and R. Dhaou; supervision, R. Kacimi and R. Dhaou; fundingacquisition, R. Dhaou. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shanghai Pujiang Talent Program (2020PJC107), and ZhejiangProvince Qianjiang Talent Program (QJD2002010).

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Institutional Review Board Statement: Not applicable. 615 Informed Consent Statement: Not applicable. 616 Data Availability Statement: Not applicable. 617 Acknowledgments: The authors would like to thank all reviewers and editors who helped improve 618 the manuscript. 619 Conflicts of Interest: The authors declare no conflict of interest. 620 References 621 1. Gupta, P., Pareek, B., Singal, G. et al. Edge device based Military Vehicle Detection and Classification from UAV. Multimed Tools 622 Appl, 2021, https://doi.org/10.1007/s11042-021-11242-y. 623 S. H. Lee, S. Lee, H. Song, and H. S. Lee. Wireless sensor network design for tactical military applications: Remote large-scale 2. 624 environments. 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