

UAV-based IoT

Subjects: [Computer Science](#), [Artificial Intelligence](#)

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The Internet of Things (IoT), which consists of a large number of small low-cost devices, has become a leading solution for smart cities, smart agriculture, smart buildings, smart grids, e-healthcare, etc. Integrating unmanned aerial vehicles (UAVs) with IoT can result in an airborne UAV-based IoT (UIoT) system and facilitate various value-added services from sky to ground. In addition to wireless sensors, various kinds of IoT devices are connected in UIoT, making the network more heterogeneous. In a UIoT system, for achieving high throughput in an energy-efficient manner, it is crucial to design an efficient medium access control (MAC) protocol because the MAC layer is responsible for coordinating access among the IoT devices in the shared wireless medium. Thus, various MAC protocols with different objectives have been reported for UIoT.

UAV-based IoT

Throughput

MAC protocol

1. Introduction

Internet of Things (IoT) applications have become increasingly popular in various civil and industrial domains owing to their easy integration with wireless-sensor networks, cost-effectiveness, easy deployment, low energy consumption, etc. In an IoT system, thousands of devices can be connected to each other as well as to the Internet for sharing information. IoT is widely utilized in fields such as healthcare monitoring [\[1\]](#), environmental monitoring [\[2\]](#), remote patient monitoring [\[3\]](#), precision agriculture [\[4\]](#), energy monitoring [\[5\]](#), indoor monitoring [\[6\]](#), dam monitoring [\[7\]](#) and transportation. Moreover, IoT is fundamental for building smart cities [\[8\]](#), whose building blocks include smart metering, smart building, smart agriculture, smart homes, and smart health. The IoT devices can be controlled remotely to perform the desired functionality. The information exchange among the IoT devices occurs through the network that employs the standard communication protocols.

Recently, unmanned aerial vehicles (UAVs) have been used in various military and civil applications. UAVs are lightweight aircraft that can be operated remotely or in a preprogrammed manner. Generally, a UAV is equipped with various sensors, computational units, cameras, a global positioning system, transceivers, etc. UAVs have practical applications in surveillance and monitoring [\[9\]](#), precision agriculture [\[10\]](#), search and rescue operations [\[11\]](#), road traffic monitoring [\[12\]](#). Conventional communication systems focus on the infrastructure-based networks (such as cell-tower-based LTE and access-point-based Wi-Fi) that have spread to every corner. However, the lack of mobility hinders their adaptation to dynamic mobile environments. Moreover, their high cost and comprehensive deployment procedure render them unsuitable for remote and emergency situations. Therefore, nonconventional communication systems, such as Project Loon [\[13\]](#) and Facebook drone project [\[14\]](#), have appeared. Small-scale

UAVs have gained more popularity for more dynamic and ad-hoc scenarios owing to their maneuverability, ease of deployment, hovering ability, and cost-effectiveness.

The integration of UAVs with IoT networks is a new direction for research and industry. The concept of IoT enables things to be connected anywhere anytime using any network, to provide any service. This characteristic feature of IoT allows UAVs to become an integral part of IoT infrastructure. In UAV-based IoT (UIoT), UAVs can be utilized for different purposes, such as UAV trajectory planning [15], data collection from ground IoT devices [16], data sampling and reconstruction [17], energy-efficient device discovery [18]. The usage of drones can enhance the various aspects of smart cities, such as data collection, privacy and security, public safety, disaster management, energy consumption, and quality of life. In UIoT, UAVs generally collect data from ground sensors and devices through peer-to-peer connections. Therefore, data transmission to neighboring nodes is not required, which can reduce energy consumption.

In UIoT, a medium access control (MAC) protocol is essential because it manages the coordination among different IoT devices during data transmission. However, several challenges need to be addressed at the MAC layer to provide high network throughput, low energy consumption, and low latency. The high mobility of UAVs is one of the most important challenges, resulting in a highly dynamic network topology. The IoT devices can only get access to a UAV when the UAV is within their communication range. The UAV is usually equipped with directional antennas for energy-efficient transmission. In this case, the IoT devices located in different areas can communicate with the UAV at different times. This causes unfair access opportunities in the network. On the other hand, reducing the energy consumption of the devices is very important in the UIoT network. In UIoT, three types of energy consumption should be considered: the energy consumption of battery-powered UAVs, energy consumption of onboard sensors, cameras, and other IoT devices, and energy consumption of ground IoT devices and sensor nodes. Therefore, how to select or design an appropriate MAC protocol for the uplink channel by handling these issues is a challenging problem.

The UIoT is a relatively new research area but can solve well-known IoT problems such as data collections from an infrastructure-less remote area, non-line-of-sight (NLoS) communication, energy wastage due to long-distance transmission, and providing network coverage to disaster areas. The main purpose of this article is to summarize the existing MAC solutions in UIoT, which will work as a starting point for researchers and engineers in this area. The rigorous comparison and discussion will help them to get a good insight into existing works in this field.

2. Application Scenarios

2.1. UAV-Based Wireless Networks for IoT Devices

The use of UAVs as a flying BS is attracting considerable attention among researchers and in the industry [19]. UAVs can function as a mobile aerial BS to provide reliable downlink and uplink communications for ground users and enhance the capacity of wireless networks. With LoS communication, the UAV can establish strong communication links with the ground devices by mitigating the signal blockage and shadowing. By adjusting its

altitude, and speed, the UAV can fly toward potential ground users and establish a reliable connection with low energy consumption. Owing to the energy limitations of IoT devices, they cannot transmit data over long distances. In such IoT scenarios, a UAV can function as a flying BS, collecting data and transmitting it to the devices that are outside of the communication range of the transmitters. In a previous study [20], the energy consumption of IoT devices was significantly reduced via the optimized deployment of multiple UAVs as flying BSs compared with a case in which stationary aerial BSs were deployed. Another study is focused on minimizing the distance between UIoT devices while keeping the UAV connected to the terrestrial base station [21]. Moreover, a technique to optimize the deployment of UAV and user association is addressed in [22].

Associated challenges: One of the design challenges regarding the UAV-based wireless networks is to model air-to-ground (A2G) channels. Compared to air-to-air communications, A2G channels are more prone to signal blockage. Therefore, the optimal design and deployment of UAV-based communication systems require an accurate A2G channel model.

2.2. UAVs as Relays for Data Collection from IoT Devices

Recently, the use of UAVs to gather data from IoT devices has attracted research attention. In many IoT applications, IoT devices are deployed in a remote and rural area without ground network infrastructure. These devices produce important data that must be collected periodically. Timely delivery of fresh information is a critical step for data-analytics applications. Because UAVs can provide LoS communication, it is possible to collect data energy efficiently.

Associated challenges: Although UAV's mobility provides promising opportunities, the trajectory of UAVs needs to be optimized for faster data collection, better throughput, less energy consumption, and lower delay. Generally, optimizing the flight path of UAVs is challenging because it should consider many physical constraints and parameters such as channel variation due to the mobility, UAV's dynamics, the energy consumption of UAVs, and flight constraints.

2.3. UAVs in 5G Communication for IoT Devices

The UAV is an important component of the fifth generation mobile network (5G) and beyond 5G (B5G) communication because of its capability of flexible deployment, strong LoS communication links, and freedom with controlled mobility [23]. 5G must support a larger number of users/devices requiring internet connectivity with different performance requirements and a larger number of applications and use cases. In many situations, terrestrial BSs are inadequate with regard to the 5G key performance indicators because the BS of the cellular network always remains powered. For example, the terrestrial infrastructure may be unable to cover certain areas, such as oceans and rural and remote areas. Most importantly, it may have limited coverage when a disaster occurs and terrestrial BSs become inoperative. In a 5G network, ground IoT devices can increase the available bandwidth that UAVs and satellites can provide. In such scenarios, UAV-based communication is promising for regions outside the coverage of operational ground BSs.

Associated challenges: Due to size, power, and weight constraints, different types of UAVs may be limited to different operational altitudes. The higher altitude of UAVs promotes higher LoS connectivity because reflection and shadowing are reduced, whereas lower altitude ensures a reduction in path loss. In 5G communications, different urban or rural scenarios require different altitudes of UAVs. Thus, optimizing the UAV altitude according to the requirements is a challenging task due to different blockages and obstacles.

2.4. UAVs as Energy Harvester for IoT Devices

UAVs can not only collect data but can also wirelessly transfer energy to energy-constrained IoT devices [24]. Most UAVs are rechargeable and can store more energy than an IoT device. Most IoT devices are very small and have a low battery capacity. Thus, UAVs can transfer energy to IoT devices via wireless power transfer (WPT) technology, which can increase the network lifetime.

Associated challenges: As UAVs mainly rely on rechargeable battery power, energy harvesting, and flying duration affect the energy consumption of UAVs significantly. Therefore, it is crucial to prolong the service duration of UAVs during the mission via advanced charging technologies.

2.5. UAVs in Mobile Edge Computing (MEC) for IoT Devices

Recently, the use of UAVs in conjunction with MEC has become a popular research topic [25]. Most IoT devices use several IoT applications and must perform several computational tasks. Because of their limited computation capability and energy, IoT devices offload their tasks to a nearby UAV, which is equipped with an MEC server. The UAV performs some of the tasks by itself and offloads the most critical portion to the ground station. After the tasks are completed, the results are transmitted from the UAV to the ground IoT devices.

Associated challenges: Due to the limited computation capability of UAVs, to handle complex offloaded tasks is difficult and also wastes a lot of UAV energy.

2.6. UAV-IoT in Crowd Surveillance Using IoT Devices

In general, UAVs exhibit outstanding characteristics compared to manned airplanes. Using suitable IoT devices, cameras, and communication devices, countless use cases can be defined for UAVs. For example, using high-resolution cameras and a suitable communication system such as LTE (Long Term Evolution), UAVs can be used for crowd surveillance [26]. This use can obviously be applicable for security reasons to monitor any suspicious activity among crowds of people. In traditional patrol systems, there is a need for many security guards and a huge amount of human effort to provide the necessary safety for people. In this aspect, UAVs can be used to assist security guards by remotely surveilling people at places of interest. UAVs can also help to track, detect, and recognize criminals adopting face recognition methods.

Associated challenges: UAV-IoT in crowd surveillance may face malicious attacks due to the open links and dynamic topologies by intentional jamming and disruption. To avoid malicious modification, there is a need for a

secure and lightweight mechanism to prevent attacks such as eavesdropping, man-in-the-middle attack, and so on.

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