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Data Communication in Linear Wireless Sensor Networks Using Unmanned Aerial Vehicles

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Abstract— **Unmanned Aerial Vehicles (UAVs) technology is evolving very quickly. New advancements in this important area of research have led more efficient and superior UAVs of all sizes, which have a vast amount of on-board command, control, processing, storage and networking capabilities. Such devices promise to be very useful and efficient in a wide variety of applications. In order to successfully and efficiently achieve their functions and accomplish their tasks, UAVs must communicate with each other using UAV-to-UAV (U2U) communication. They also must communicate with other systems using UAV-to-Infrastructure (U2I) communication. Furthermore, in addition to the numerous tasks and services that would be greatly improved using UAVs, these useful devices can be used to enhance the data collection process in wireless sensor networks (WSNs), which have a large number of environmental, military, and commercial monitoring and surveillance applications. In this paper, we offer an overview of UAV system services, functions, and requirements that are involved in the design of UAV-based systems at the various networking layers. We also present some of the various types of networking architectures, frameworks, and networking protocols that can be used for U2U and U2I communication. In addition, the paper outlines the services that can be performed by the middleware layer to provide increased networking system efficiency and seamless handling of communication between heterogeneous UAV nodes as well as ground and satellite communication units. In addition, we discuss the use of UAVs for data collection in WSNs. Such use of UAVs can be very effective in reducing WSN energy consumption, and communication interference, which can lead to a highly scalable and efficient networking framework.**

Keywords: Unmanned aerial vehicle (UAV), mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), routing, delay-tolerant networks (DTNs).

I. INTRODUCTION AND RELATED WORK

Unmanned aerial vehicles (UAVs) of different sizes, shapes and capabilities have been evolving rapidly with new advancements in flight control and integrated circuit (IC) technology. These important devices are expected to be used to enhance the operation and processes in many environmental, commercial and military operations. A few years ago military applications were the main driving force behind the development of UAVs and UAV-based systems. However, recently, a number of civil applications have emerged and participated in driving the development of UAV technologies further ahead. UAVs have been used or proposed for use for agriculture purposes, search and rescue operations, security and surveillance operations, environmental monitoring, large infrastructure monitoring, and terrain mappings. For example, In Japan, researchers produced UAVs for agricultural purposes such as crop spraying. They achieved around one third of the total agricultural aviation in Japan [1]. UAVs are used for different types of disaster research and management. They have also been utilized for research and management in meteorological, geological, hydrological, ecological, and human-induced disasters [2]. Furthermore, UAVs have been utilized with different capacities for detecting damages caused by the 2005 Hurricane Katrina [3], the 2009 Typhoon Morakot [4], the 2009 L'Aquila earthquake [5], the 2010 Haiti earthquake [6], and the 2011 Tohoku Earthquake and tsunami [7]. Images collected by UAVs were analyzed and used to produce hazard maps for the disaster areas. UAVs provide a low-cost, fast, flexible and safe means for imagery collection in disaster events. UAVs can also help in search and rescue support operations.

In addition to the above functions and applications, UAVs can also be used to monitor and track long linear structures [8][9]. One example is where an autonomous UAV was developed to address the problem of searching and mapping a stretch of a river [10]. In this application, the UAV is equipped with GPS components while the coordinates of the river are not known. UAV uses visual feedback and its GPS to find and map the boundaries of the river. In another example, multiple UAVs were proposed to perform border or perimeter patrols [11]. UAVs can collaborate on the organization of the motion and navigation functions. Collaborative UAVs can provide effective, fast, and flexible monitoring of borders compared to other proposed systems. For example, one UAV can follow one noticed target to provide more information about it while another can collaborate in providing general monitoring for different regions on the border. Moreover, UAVs can be used to inspect and monitor linear infrastructures such oil or gas pipeline, roads, bridges, and power grids to ensure the reliability and to extend the life of these civilian systems by enabling the process of providing proper and timely maintenance [12].

Although the above mentioned UAV applications are very useful, implementing, testing, and operating such applications are not trivial processes. This is due to a number of technical challenges facing the design of these applications. The challenges includes the need for good coordination and

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collaboration among UAVs; good and effective control mechanisms; effective, secure, and reliable communication among UAVs and between UAVs and Ground Control Station (GCS) (or base station as referred to in the networking research community); safe actions; and good planning and scheduling in achieving the task. These challenges present the main obstacles in effectively utilizing the UAV technology for such mentioned applications and other future potential ones. In order for UAV-based systems to be effective in many applications, it is essential to provide them with the capability to communicate efficiently among each other as well as with existing on-ground infrastructure networks and the Internet. In this paper, we identify the main functions, and needs of UAV-based system communication. We also present different networking architectures that can be used in UAV-based systems for the purposes of UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) communication. In addition, we discuss the services that can be provided by the middlware layer, which is essential to provide efficient networking interface between heterogenous UAVs and various protocols used to communicate with the ground and satellite gateway units. Finally, we provide an overview of a model for using UAVs for data collection in WSNs.

The rest of the paper is organized as follows. Section II overviews the main functions, services and requirements of UAV-based networking architectures. Section III offers some UAV-based networking architectures. Section IV discusses middleware support for UAV systems. Section V presents a case study of data collection in WSNs using UAVs, and section VI concludes the paper.

II. UAV SYSTEM FUNCTIONS, SERVICES, AND REQUIREMENTS

In this section, the most important functions, services and requirements involved in the design of UAV-based networking systems and architectures are presented. We emphasize the collaborative networking nature of the communication system requirements since this is an essential part of internetworking of such system and their applications.

A. Communication Among UAVs

Collaborative communication is an important part of the functions in UAV systems is the networking support and services component. This is important since UAVs can be equipped with different networking technologies for communication among multiple UAVs and also between the UAVs and other systems such as the GCS, WSN, and on ground robots. Furthermore, not all UAVs can directly communicate with each other or with the base station. From an operational point of view, UAV systems have a wide range of applications, which have varying communication and networking requirements. In addition, different communication links can be available. Example of these communication links are cellular, satellite, line of sight, real-time mobile ad hoc networking, and delay-tolerate networking capabilities with data ferrying links.

B. UAV-Assisted Sensing

A range of UAV applications require multiple UAVs to collaborate to sense an area or to inspect an infrastructure using one or more types of sensors like cameras, heat sensors, radiation readers and different gases monitors. These applications will require efficient collaborative sensing among multiple UAVs to complete the required sensing task. As individual UAVs could handle some of the sensing tasks, it is more efficient and reliable if multiple UAVs could work together to organize the operations and collectively gather more accurate and more reliable information.

C. UAV-Assisted Acting

Some applications require acting devices such as the UAVs used for agricultural and military purposes. In these types of applications, multiple UAVs can collaborate to achieve the required tasks. For example, in agriculture, several UAVs could work together to effectively spray large fields with pesticides or to quickly determine the seeds over large areas. The autonomous collaboration should help complete the tasks faster and eliminate (or minimize) overlaps without human intervention.

D. UAV-Based Data Storage

While some UAV applications will send any collected data directly to the base station, other applications may require the UAVs to store the collected data due to three reasons. The first reason is that the collected data needs high communication bandwidth to be transferred from the UAVs to the base station that may not be available at all times. The second reason is that there is no need to transfer the collected data to the base station immediately as it will be used and processed after the operation. In this case, the collected data will be saved in the available on-board storages. The third reason is that the collected data need to be processed and aggregated instantaneously during the operation and then moved to the base station after the operation. UAVs can be homogenous or heterogeneous in terms of both storage capacities and data collection capabilities. UAVs can collect equal amounts of data or different amounts of data. This depends on the type of the application. If the collected data is not equal among UAVs or the used UAVs are equipped with heterogeneous storage capacities, then a collaborative data storage mechanism is needed among multiple UAVs to efficiently store the collected data among the UAVs.

E. UAV-Based Data Processing

Some UAVs can be equipped with high-end computer units that can be used by collaborative UAVs for some applications that need high-performance computing such as high-resolution image processing, video processing, pattern recognition, stream data mining, and online task planning. A high-performance data processing task can be achieved using one computer unit in one UAV or multiple computer units available in multiple UAVs. In the latter case, there is a need to use one of the distributed processing approaches to effectively utilize the available processors in the sky.

This is usually very important if the UAVs are operating in areas that are far from the base stations and also when the processing results are needed instantaneously to trigger some types of suitable actions. For example, in a battlefield, a UAV may need to identify an enemy unit that may be within close proximity with some friendly units. In this case image processing and pattern recognition are required to find the enemy and destroy it on sight. Such process cannot wait for information to be relayed to a distant base station and wait for result. It has to be done on site. Therefore, the UAVs in the area could work together to complete the analysis and react accordingly.

F. Distributed Versus Centralized Control

Efficient and safe operations of multiple UAVs require different real-time controls. Different control mechanisms are needed to coordinate among multiple UAVs to achieve a specific task, to effectively use the UAV recourses, to provide safe operations, and to control the fault tolerance mechanisms. It is difficult to control all these and other aspects using a centralized approach. This is due to three reasons: (1) A centralized control system suffers from the single-point of failure problem, (2) Not all UAVs will be connected to the GCS at all times, which means the control signals will not always reach the UAV in time, and (3) A centralized control will increase the communication performance and security requirements as all control signals must be sent securely in real-time. For all these reasons, it is better to use distributed and collaborative controls.

III. UAV-BASED NETWORKING ARCHITECTURES

In order to perform their various tasks and services, UAVs that are in flight must be able to communicate with each other as well as with networking backbones and infrastructures. Figures 1, and 2 illustrate U2U and U2I communication, which will be discussed in more detail in this section.

A. UAV-to-UAV (U2U) Communication Architectures

Since in-flight UAVs are highly mobile networks, UAVs can communicate with each other using mobile ad hoc networking (MANET) networking protocols. Each UAV constitutes a mobile node in a MANET. Research in this challenging area of networking and communication has been very active at each of Open System Interconnection (OSI) model. This includes the physical, data link, networking, transport and application layers (this layer typically includes the session and presentation layers). The physical and data link layers are considered the underlying network, which can use the popular IEEE 802.11 protocol. This protocol has a reasonable communication range of several hundred meters in the line-of-sight communication. Recent extensions of the IEEE 802.11 such as IEEE 802.11n have been developped with longer communication ranges and relatively high data rates [13]. Such version would can be used with U2U communication in applications where the UAVs might have longer distances between each other. The IEEE 802.11 protocol supports carrier sense multiple access with collision avoidance (CSMA/CA) at the data link layer which can also be appropriate for U2U communication. It can provide support for best effort (BE) data traffic using the distributed coordination function (DCF) and quality of service (QoS) data traffic such as multimedia and real-time using the Point Coordination Function (PCF). The latter employs a guarantee-based approach for data exchange within a super frame.

At the networking layer, which typically handles end-to-end routing of data packets, a wide variety of routing protocols have been proposed. The lack of a fixed topology and central control in MANETs poses a great challenge to the routing process in this environment [14][15][16]. Routing protocols designed for ad hoc networks such as the Dynamic Source Routing protocol (DSR) [17], Ad hoc On-Demand Distance Vector (AODV) protocol [18], Temporally Ordered Routing Algorithm (TORA) [19], and many others [20][21][22][23][24][25][26] work very well under certain conditions where nodes are reliable, they all behave correctly and there are no misbehaving nodes in the network. However, in reality different nodes exhibit different measures of reliability and ability to effectively and correctly participate in the routing and data transmission process. Routing protocols were investigated and modified and new protocols were introduced to enhance the routing process in mobile ad hoc networks (MANETs).

The choice of the appropriate networking protocol for U2U communication depends on the nature of the application that is used, which determines the following specifications [27][13]:

- Degree of UAV mobility: Some routing protocols have good performance however suffer from a prohibitively large number of control message overhead when the nodes become highly mobile. This is the case since discovered routes constantly break and new routes must be discovered. Other protocols, such as geographic-based ones are more appropriate in such environments since they tend to have reduced overhead in such circumstances.
- Number of UAVs in the network: Some routing protocols have good performance in small networks but do not perform well in large size networks where other protocols can be more effective.
- The on-board processing capabilities: This includes the kind of microprocessor and its ability to do complex calculations.
- On-board memory and storage capacity: Some of the routing protocols require large space especially when the number of nodes in the network increases. This can be the case in a lot of UAV-based networks with small size UAV.
- Energy capacity and power consumption capability of the UAVs: Some energy-aware routing protocols would be more appropriate for use especially in small size UAVs.
- GPS capability in the UAV circuitry: This allows the designers to use geographic routing protocols, which

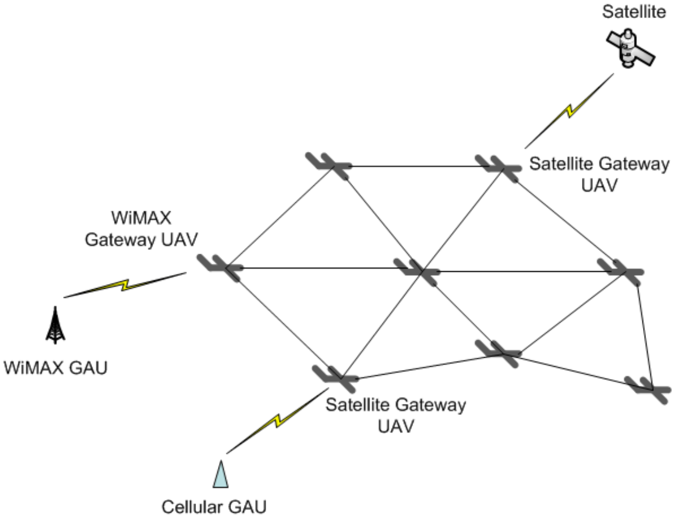

Fig. 1: UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) Communication.

have good performance with large and highly mobility networks. A good amount of such routing protocols have been developed for vehicular ad hoc networks (VANETs), which exhibit similar characteristics as some UAV applications.

- Connection to the backbone infrastructure networks: Appropriate mapping of networking parameters between the U2U routing protocol and the networking protocol used in the infrastructure network is important and must be considered.
- Transmission robustness and security: These are also important factors to consider depending on the application that is being used. Several secure routing protocols have been proposed in the literature.
- Collocated networking protocols: In environments where other networked devices are used, it important to guard against interference when such devices and associated networking protocols use the same frequency range.
- License-free operation: This is an issue that needs to be considered when choosing the appropriate protocols since some operating frequency ranges require the acquisition of proper licensing in some areas or geographic regions.
- Handoff and roaming: As UAVs move in and out of range of various communication gateways, appropriate and timely handoff and roaming strategies must be used to ensure seamless switching between cells.
- Throughput: This is also an important component that needs to be considered in light of the data traffic that is required to be supported by the UAV-based network. High throughput and data rates are essential for high quality imagery and video, while lower data rates can be tolerated when the data that is being exchanged is more limited such as pure command and control or telemetric sensor data. In such case, while high data rates are not essential, low delay becomes critical for such real-time data traffic.

B. UAV-to-Infrastructure (U2I) Communication

Another important component of the UAV networking model is U2I communication. Collaborative UAV fleets are expected to be able to communicate with each other using U2U communication described previously. In addition, typically there is a need to exchange data with networking infrastructure and the Internet. For this purpose, one of the UAVs can play the role of a gateway node, which can be used to collect U2U data from the other UAVs in flight, and communicate this data to and from the networking infrastructure using one of the existing wireless local area network (WLAN) and wireless wide area networks (WWAN) protocols (depending on the distance and type of service) that are available in that particular geographic area. We name the nodes that are used to provide this networking interface with the existing infrastructure the *Gateway data Acquisition Units (GAU)*. These units might be ground-based using WLAN or WWLAN protocols such as cellular or the IEEE 802.16 (WiMax) protocols, or they could be satellite-based using one of the different satellite systems and protocols that are available.

Figure 3 shows the various protocols that can be used at the different links for U2U and U2I communication. Futhermore, Figure 4 shows the different OSI model layers that can be used at the basic UAV node and the gateway UAV node. In addition to the classic networking layers, we show the middleware layer, which resides between the application and transport layer of each node. More details about the services and functions of this important layer are presented in a later section. However, it is important to note that the middleware layer at the gateway node has additional functions such as data aggregation, UAV-to-Infrastructure QoS mapping, and other interface services that might be needed with the type of communication services it provides.

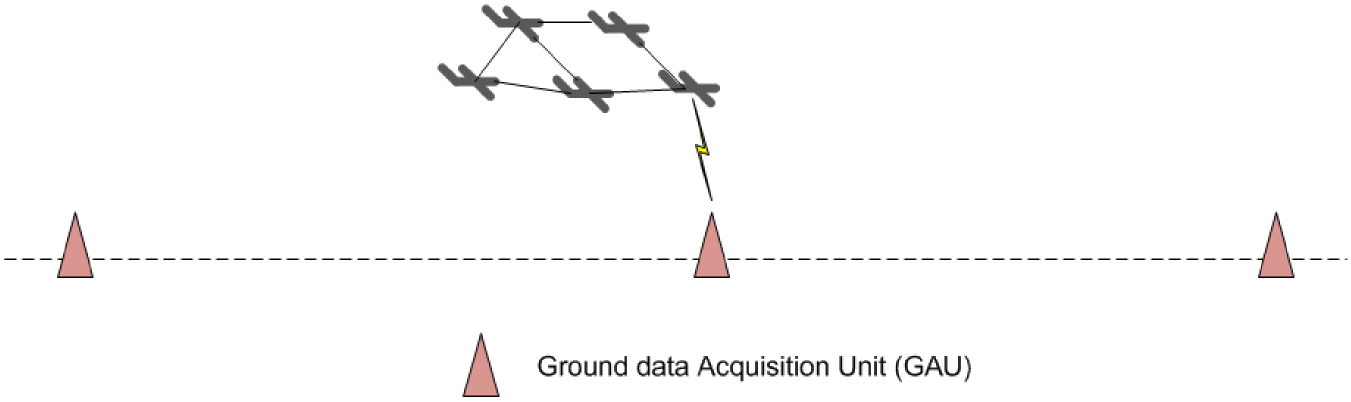

Fig. 2: UAV-fleet communication with ground data acquisition units as they come within range.

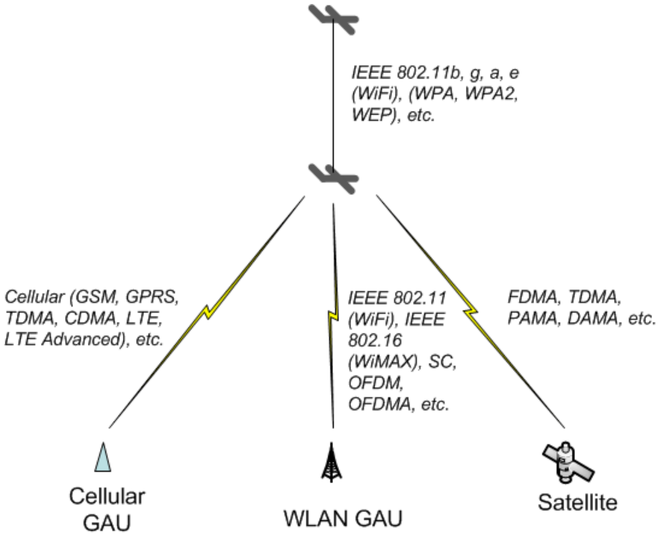

Fig. 3: The various protocols at the different links of the UAV communication system hierarchy.

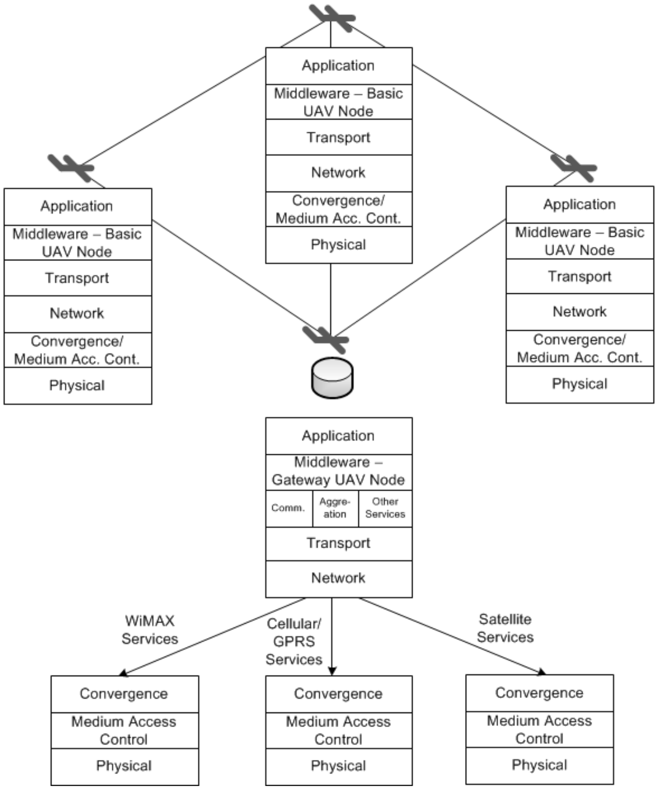

Fig. 4: The networking protocol layers at the basic UAV (BU) and gateway UAV (GU) nodes.

C. *Classification of UAV Data Traffic*

The UAV-based networking systems must consider the different types of data traffic and their QoS characteristics. The associated networking protocols must support stringent requirements of the exchanged U2U and U2I data. In table I, a classification of the various types of UAV-based network data traffic is presented. The table presents the data traffic types, their delay, delay jitter, and bandwidth (data rate) requirements along with some sample applications that might use this kind of data.

IV. MIDDLEWARE SUPPORT FOR UAV SYSTEMS

A. The Importance of the Middleware Layer in the UAV Networking Stack

Middleware technologies have become an essential part of any distributed environment and offer essential features and functionalities. It simplifies and expedites the distributed application process compared to many traditional development approaches. Thus, to put it in simple terms “middleware connects any set of components in a distributed environment to offer better functionality.” That component could be an application, a task within an application, a platform, a communication network, a piece of hardware (e.g. robot, sensor, microcontroller, UAV, etc.), a server, a client, a service, a grid node, and so on. UAV systems are complex distributed systems that share with other distributed systems their heterogeneity, security, and reliability challenges in addition to their own unique challenges such as high speed mobility and high safety requirements. Based on our previous research, middleware generally offers many advantages for developing

TABLE I: Classification Table of UAV-Based Network Data Traffic and their QoS Requirements

Data Traffic	Delay Tolerance	Delay Jitter Tolerance	Bandwidth Requirement	Sample Applications
Real-time Sensing	Low	Medium	Low	Environmental telemetric data monitoring, pipeline monitoring, traffic monitoring
Store-and-forward sensing (archival/off-line storage)	High	High	Low	Habitat monitoring, seismic activities, volcano monitoring
Command-and-control	Low	Medium	Low	UAV-to-UAV, Ground to UAV, military flights
Real-time video	Low	Low	Very High	Border monitoring, interactive military surveillance, disaster recovery
Store-and-forward pictures	High	High	High	Military surveillance, environmental surveillance pictures
Store-and-forward video	High	High	Very High	Disaster recovery, long term military surveillance

and operating mobile ad hoc environments and networked robots such as UAV systems. This great advantage helps simplify the implementation and operations of collaborative UAV applications.

B. Services Provided Through Middleware Support

A new and advanced approach in middleware technologies is the use of service-oriented middleware (SOM). This approach has already been proven to simplify the implementation and operations of a number of industrial domains in SOC. It was used for wireless sensor networks, telecommunications, manufacturing, collaborative workflow systems, business process applications, and distributed monitoring and control systems. Generally, a service oriented middleware (SOM) for UAVs should support a number of requirements some of which (e.g. the first three in the list) are common for any SOC application, while the rest are enforced by the characteristic of the UAVs environment and the challenge of implementing and operating applications on that environment. The requirements include the support for:

- Runtime support for services deployment and execution: As an UAVs system is viewed as a set of services provided for supporting some applications, SOM should provide mechanisms to deploy, load, and execute these services.
- Support for different communication methods among service consumers, services, service registries and brokers that enable reliable and efficient local and remote service utilizations.
- Support for service consumers to discover and use registered services: SOM should enable client applications to discover and use registered services.
- Service transparency to client applications: SOM should allow client applications to transparently use available services without exposing the services implementation details or in some situation its detailed components locations.
- Abstractions to hide the heterogeneity of underlying sensor environments: all heterogeneity details of UAV hardware and network should be hidden from the applications.
- Configurable services: This requirement is to help solve the hardware resources and application knowledge challenges mentioned in the previous section. SOM should provide mechanisms for client applications to configure UAV services to meet specific application requirements such as QoS, security or reliability.
- Support for self-organization mechanisms: This can include self-x properties such self-management, self-healing, self-configuration, auto-discovery, self-adaptation, and self-optimization of service providers. WSN are dynamic distributed environments where nodes can fail and new nodes can be added anytime. In addition, mobile nodes with some services can be available for some time. The availability of services in these nodes is also dynamic. Therefore, SOM should support self-management, auto-discovery, auto-change, self-optimization and auto-change mechanisms for efficient utilization of available services.
- Interoperability with a variety of devices: This requirement helps solve the heterogeneity challenges mentioned in the previous section. Some sensor applications require variety of devices to be operated. SOM for UAV can be designed to be interoperable with different devices such as devices with different types of sensors, RFID, and actors to enable easy application development and operation.
- Efficient handling of large volumes of data and high communication loads: This requirement helps in solving the limited hardware resources and network organization challenges mentioned in the previous section. Some UAV applications involve large volumes of data and high communication loads.
- Secure communication and execution: As UAVs are being widely deployed in domains that involve sensitive and critical information, secure communication and execution becomes a very important aspect in SOM for UAV. SOM should provide mechanisms to secure the utilization and operations of UAV services. All communication and execution for supporting these services should be also secured.
- Support for QoS requirements: A large range of UAV applications have QoS requirements. Mechanisms are needed to configure and satisfy these requirements in UAV environments. Example of QoS requirements in UAV can be reporting a critical reading within a certain time frame and within a certain error level. In some situations, the QoS requirements can come from multiple applications such as safety and collaborative sensing.
- Support for integration with other systems: As UAVs

system usually do not operate in isolation, SOM should enable the integration of UAV systems with other systems such as WSN, enterprise or web systems. For example, some web applications rely on UAV for their current information such as information on weather conditions and traffic conditions. In this case, SOM should enable that integration such that these applications can fulfill their goals.

V. CASE STUDY: DATA COLLECTION IN WSNS USING UAVS

The WSN technology have been evolving very quickly in recent years. Sensors are constantly increasing in sensing, processing, storage, and communication capabilities. As an example of using UAV-based systems to enhance the performance, capabilities and efficiency of some application, UAVs can be used to provide efficient data collection in WSNs. In this section, we present and overview of the work that has been done in this area and offer a framework for data collection in WSNs using UAVs.

There is some effort to utilize UAVs for enhancing the deployment, operation, connectivity, and life span of WSNs. Dorling et al. investigated improving aerially deployed sensor networks by using cooperative communications [28]. De Freitas et al. proposed using UAVs to function as a relay network to support WSN connectivity [29]. Horacio et al. proposed and evaluated the performance of three algorithms for data query in WSNs when the sink such as an UAV is moving at high speed [30]. Giorgetti et al proposed an energy-efficient cooperative transmission scheme for WSNs where data gathered by sensor nodes need to be collected and sent to a far away UAV receiver [31]. In addition, as UAVs can move in high speeds, there is some investigation to study and design of new medium access protocols for communication between WSNs and UAVs [32][33][34]. On the other hand, utilizing mobile entities for gathering information from WSN were studied in some research. Shah et al. provided an architecture to provide connectivity of sparse WSNs using existing mobile entities in the environment named MULEs [35]. Sensors are assumed to continuously generate sensing data and buffer it until a MULE comes within its transmission range. Another architecture where multiple MULEs are used to collect data is presented in [36]. In this model, the MULEs are set in motion along straight parallel lines in a field, with randomly deployed sensors. This divides the field into parallel regions of two types, depending on whether they have sensors, which are in range of a MULE or not. Zhao et al. introduced a message ferrying scheme which uses a mobile node called a ferry to provide communication between nodes in a highly partitioned ad hoc network [37]. The ferry is a special node with increased resources including renewable power, large memory and processing capabilities, and is used to transport messages between nodes, which otherwise might not have a multihop path between them. An extension of the ferry scheme was introduced in [38]. They determine that the mobility of the ferry can be task-oriented, where its route is determined for non-messaging reasons, such as a campus bus, or it can be message-oriented, where ferry mobility is specifically designed to improve messaging performance. In addition, the model was extended to multiple ferries with emphasis on designing ferry routes in [39]. This model allows the possibility of interaction between the ferries, and address the problem of ferry route synchronization in order to increase efficiency. Later in [40], the ferry model is further extended to sparse ad hoc networks with mobile nodes.

All of the algorithms that are mentioned above are designed for multi-dimensional WSNs or ad hoc network architectures, or use a multihop strategy. In order to significantly reduce the energy consumption used in data transmission and extend the network lifetime, we present an preliminary overview of a framework for data collection and transmission is done using UAVs. The system defines four types of nodes, which include: sensor nodes (SNs), relay nodes (RNs), UAVs, and sinks. The SNs use a classic WSN multihop routing approach to transmit their data to the nearest RN, which acts as a cluster head for its surrounding SNs. A UAV moves back and forth along the network, which can be partitioned in many cases, and transports the data that is collected by the RNs to the sinks located at both ends of the WSN. Additional sinks can be located at certain distances to constitute more segments in the case of very long and large WSNs. In this case, one or more UAVs can be used in each segment. This provides for added efficiency through parallel operation and collection of data, increase reliability, since each segment is relatively independent and the failure of nodes (UAV, or sink) in one segment does not affect the others, and scalability since large networks with a high number of nodes can be efficiently supported. We name this network architecture a UAV-based WSN (UWSN). Figure 5 presents an brief illustration of this model. We are currently working on designing efficient UAV movement algorithms and related networking protocols for this UAV-based architecture.

VI. CONCLUSION

UAV technology has been evolving very quickly leading to highly mobile and capable devices, which can be used in numerous commercial, military and environmental applications. U2U and U2I communication is an essential component, which is vital to enable these devices to perform many collaborative tasks and services. In this paper, we stated the different functions and requirements that are important to be addressed by researchers in order to provide robust, efficient, and energy-aware communication in UAV-based systems. We presented an overview of the different U2U and U2I networking architectures and the different communication protocols that can be used at the various layers of the OSI networking model. In addition, we offered a case study where UAVs are used for efficient data collection in WSNs. As the UAV-based applications are rapidly growing, it becomes essential for researchers to solve many open problems in this area in order to provide efficient, and seamless U2U and U2I

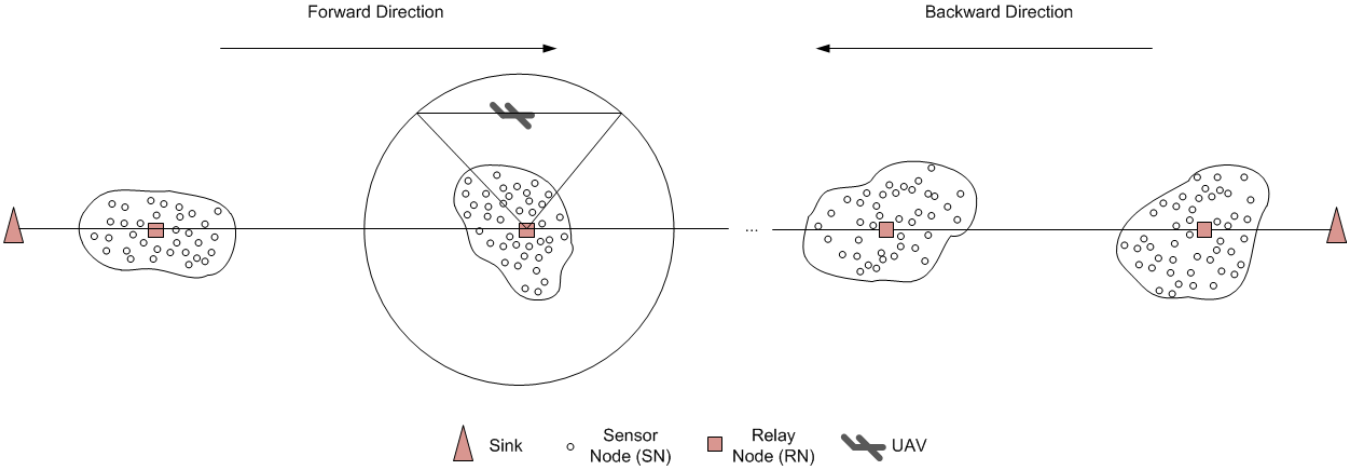

Fig. 5: UAV-based Data Collection in WSNs. The figure shows two sinks with a UAV collecting data from each RN node which acts as a cluster head as it comes within its range. The UAV moves back and forth between the sinks and uploads the data to each sink when it reaches it.

communication, which is a critical component for effective UAV system design and successful deployment.

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