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Review

Communication and networking of UAV-based systems: Classification and associated architectures☆

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ABSTRACT

Many advancements have been taking place in unmanned aerial vehicle (UAV) technology lately. This is leading towards the design and development of UAVs with various sizes that possess increased on-board processing, memory, storage, and communication capabilities. Consequently, UAVs are increasingly being used in a vast amount of commercial, military, civilian, agricultural, and environmental applications. However, to take full advantages of their services, these UAVs must be able to communicate efficiently with each other using UAV-to-UAV (U2U) communication and with existing networking infrastructures using UAV-to-Infrastructure (U2I) communication. In this paper, we identify the functions, services and requirements of UAV-based communication systems. We also present networking architectures, underlying frameworks, and data traffic requirements in these systems as well as outline the various protocols and technologies that can be used at different UAV communication links and networking layers. In addition, the paper discusses middleware layer services that can be provided in order to provide seamless communication and support heterogeneous network interfaces. Furthermore, we discuss a new important area of research, which involves the use of UAVs in collecting data from wireless sensor networks (WSNs). We discuss and evaluate several approaches that can be used to collect data from different types of WSNs including topologies such as linear sensor networks (LSNs), geometric and clustered WSNs. We outline the benefits of using UAVs for this function, which include significantly decreasing sensor node energy consumption, lower interference, and offers considerably increased flexibility in controlling the density of the deployed nodes since the need for the multihop approach for sensor-to-sink communication is either eliminated or significantly reduced. Consequently, UAVs can provide good connectivity to WSN clusters.

1. Introduction

Rapid advancements in the design and development of unmanned aerial vehicles (UAVs) of different sizes, shapes and capabilities have been taking place recently with new improvements in flight control and integrated circuit (IC) technologies. These important devices can enhance the operation of many environmental, commercial and military operations. Originally, UAVs were mainly used in military applications. However, recently many civilian ones have emerged. Their is involved in many areas such as search and rescue, agriculture, monitoring of large infrastructures, border monitoring, shipping and delivery of packages. For example, UAVs have been used in Japan in the agricultural industry for crop spraying (Newcome, 2004). They are also used in many types of disasters including meteorological, geological, ecological ones. For example, they were used in the aftermath of hurricane Katrina (katrina, 2012), L'Aquila earthquake (Adams and Friedland, 2011), Typhoon Marakot (Typhoon morakot, 2012), Tohoku Earthquake (Tohoku earthquake and tsunami, 2012), and Haitia earthquake (Haiti earthquake, 2012). UAVs can also provide significant services for image collection for disaster areas, which can be used to create hazard maps. UAV systems are characterized by several advantages such as low-cost operation, rapid placement, safe access to dangerous areas, flexible and scalable deployment to achieve many tasks, which are needed in many areas of today's society.

In addition to the above functions and applications, UAVs can also be used to monitor and track long linear structures (Jawhar et al.,

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2011, 2013). One example where an autonomous UAV was developed to address the problem of searching and mapping a stretch of a river is presented in Rathinam et al. (2007). While the coordinates of the river are not known, the UAV is equipped with GPS components. The UAV uses visual feedback and its GPS to determine the boundaries of the river. In another example, multiple UAVs have been proposed to perform border or perimeter patrolling (Girard et al., 2004). Multiple UAVs can collaborate on their mobility organization and navigation functions. Collaborative UAVs can provide effective, fast, and flexible monitoring of borders compared to other existing systems. For example, one UAV can follow one noticed target to collect more information. While another can collaborate in providing general monitoring for different border regions. Moreover, UAVs can be used to inspect and monitor linear infrastructures such oil or gas pipeline, roads, bridges, and power grids to ensure the reliable timely maintenance (Rathinam et al., 2005) and to extend the life of these civilian systems.

Although the above mentioned UAV applications are very useful, implementing, testing, and operating such applications are not trivial as a number of technical challenges are faced in designing these applications. The challenges include the need for good coordination and collaboration among UAVs; effective control mechanisms; 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 scheduling of tasks. These challenges present the main obstacles in effectively utilizing the UAV technology for future potential applications. In order for UAV-based systems to be effective in several applications, it is essential to have a capability to communicate efficiently among each other as well as with existing on-ground infrastructure networks and the Internet.

In this paper, we investigate the various needs and functions essential for communication in UAV-based systems. We propose various architectures that can be used for such systems including UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) communication. We also, study the services that can be provided by the middleware layer in order to provide efficient and seamless networking between the various UAV nodes. Finally, we provide a case study of the use of UAVs for data collection in WSNs.

The rest of the paper is organized as follows. Section 2 summarizes related work. Section 3 overviews the main functions, services and requirements of UAV-based networking architectures. Section 4 presents some UAV-based networking architectures. Section 5 outlines the services that can be provided by the middleware layer. Section 6 offers a case study that focuses on using UAVs for data collection in WSNs. Section 7 presents a performance evaluation of the various proposed protocols, and Section 8 concludes the paper.

2. Related work

UAVs have been used in many applications in recent years. Such applications involved river searching and tracking (Rathinam et al., 2007), border patrol and surveillance (Girard et al., 2004), generating real-time hazard maps (Suzuki and Miyoshi, 2008), forest-fire fighting before, during, and after the accident (Ollero and Merino, 2006), monitoring gas transmission pipelines (Hausamann et al., 2003), operational oil spill surveillance, monitoring and assessment (Allen and Walsh, 2008), structure inspections (Pratt et al., 2006), and imagery collection in disaster research and management. The teams that have handled the projects involving these applications have had to address many issues and challenges in using UAV systems.

Researchers have been working on inventing, and developing techniques to resolve technical issues and challenges in UAV systems. Some of these techniques involve the control of single and multiple UAVs. In Ryan et al. (2007), the authors focused on the use of multiple UAVs to perform sensing missions. The paper in Vachtsevanos et al. (2004), developed a system to control and avoid collision of multiple UAVs using a game theoretical approach. The authors in Bruggemann et al. (2011), address the issues involved in controlling UAVs used to inspect linear infrastructures such as oil and gas pipelines, power transmission grids, as well as roads. On the other hand, the paper in Rathinam et al. (2005) proposes a strategy that uses visual feedback to control an autonomous UAV that is used to monitor linear structures.

Another important aspect in UAV systems is the communication and networking. Such research involves areas such as reliability, mobility, self-configuration, delay, and bandwidth requirements. Depending on the applications, UAV systems have varying communication and networking requirements (Frew and Brown, 2008, Frew and Brown, 2009; Saleem et al., 2015). Such requirements include delay-tolerant networking (Brown and Henkel, 2006), command and control communication (Richards et al., 2002), and mobility support. At the link level, connections include relay, direct, and ferrying communication (Dixon et al., 2006). Platform safety also constitutes another important area in UAV systems. In addition, communication between the UAV and the ground control station is also required. In order for the operator to stay "on the loop", constant communication with the UAV is essential. Another platform communication safety that is required is one which supports detection, sensing, and avoidance (DSA) mechanism (Weibel and Hansman, 2005).

In many applications, image data is required to be sent from on-board radar systems to the operator. Additionally, in order to avoid collisions between multiple UAVs, cooperative sharing is required. In some systems, a data rate of 1 Mbps or more is needed if full visual situational awareness is required by the operator (Frew and Brown, 2008). On the other hand, smaller UAVs operating individually and flying in uncontrolled space would not require a high data rate, since only limited communication with the main control station would be needed. Small UAVs operating in emergency situations and deployed in heavier air traffic areas would require constant and frequent communication with the control stations in order to coordinate flights and avoid possible collisions with other aircrafts. The communication messages in such an environment are usually small requiring a limited amount of bandwidth. However, due to the real-time nature of the communication, the reliability and delay requirements in this case would be stringent. In other applications such as ones involving payload management, the needed communication bandwidth can range from low rates in the case of simple sensor readings to considerably higher rates (several Mbps) in the case of high-quality images or video. In the latter case, some UAV platforms use line-of-sight (LOS) microwave links with higher data rates.

Mission tasks constitute another important area that involve collaborative strategies among multiple UAVs as well as between UAVs and other systems. Some limited research has been done to design and evaluate various frameworks for such systems. In Teacy et al. (2009), the authors focused on combined sensing by multiple UAVs. In another paper (Chaimowicz et al., 2005), collaboration between Air-Ground multi-robots was addressed.

3. 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 collaborative networking nature of the system requirements since this is an essential part of communication in such system and associated application.

3.1. Communication among UAVs

Collaborative communication is an important part of the UAV systems for networking support and service components. This is important since UAVs can be equipped with different networking technologies for communication with multiple UAVs and between UAVs and other systems such as the GCS, WSN, and on-ground robots.

Furthermore, all UAVs cannot directly communicate with each other or with the base station. From an operational point of view, UAV systems have a wide range of applications with varying communication and networking requirements. In addition, many 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 devices.

3.2. UAVs as communication relay nodes

UAVs can act as relay nodes, which connect disconnected mobile ad hoc network (MANET) clusters. In this case, nodes belonging to different disconnected clusters can communication with each other by using a UAV, which can be placed in a strategic position between the two clusters. For this matter, one or more UAVs can provide this function in large MANETs providing communication efficiency, and flexibility. Using this strategy a MANET can extend over very large geographic area, where the nodes might have to be clustered in different regions due to land topology, node location, and mobility requirements imposed by the application. In this case, if multiple UAVs are needed, it is important to design efficient algorithms that optimize UAV node placement in order to minimize the number of required UAVs and still provide robust and reliable connectivity for all of the clusters in the MANET.

3.3. UAVs as network gateways

In remote geographic or disaster stricken areas, one or more UAVs can provide connectivity to backbone networks, communication infrastructure, or the Internet by acting as gateway nodes. This function can play an essential role to restore highly or even desperately needed cellular, Internet, or satellite coverage in such locations. This connectivity can support search and rescue, life saving, and reconstruction efforts. UAVs can be rapidly and efficiently deployed to perform this task in a very dynamic, and cost-effective manner.

3.4. UAV-assisted sensing

A range of UAV applications require multiple collaborative UAVs to sense an area or to inspect an infrastructure using one or more types of sensors like cameras, heat sensors, radiation readers and different gas monitors. These applications will require efficient sensing among multiple UAVs to complete a comprehensive sensing task. As individual UAVs could handle some of the sensing tasks, an efficient and reliable solution is to use multiple UAVs together in organizing the operations and collectively gathering accurate and reliable information.

3.5. UAV-assisted acting

Some applications such as agricultural and military purposes require acting devices such as UAVs. 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 distribute the seeds over large areas. The autonomous collaboration helps completing the tasks faster and minimize (or eliminate) overlaps without any human intervention.

3.6. UAV-based data storage

While some UAV applications will send any collected data directly to the base station, others may require UAVs to store collected data due to three reasons. The first is that the collected data needs high communication bandwidth may not be available at all times for transferring from UAVs to the base station. The second reason is that there is no need to transfer collected data immediately to the base station as it will be used and processed after the operation. Collected data can be saved in the available on-board storages as well. The third reason is that the collected data need to be moved to the base station only after data is processed and instantaneously aggregated during the operation. UAVs can be homogenous or heterogeneous in terms of both storage capacity and data collection capability. UAVs can collect equal or different amounts of data depending 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 desirable among multiple UAVs to efficiently store the collected data.

3.7. UAV-based data processing

Some UAVs can be equipped with high-end computer units that can be used by collaborative UAVs for those 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, one of the distributed processing approaches need to be effectively utilized by 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 when the results are needed instantaneously to trigger a suitable action. 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 try to destroy immediately. Such process cannot wait for information to be relayed to a distant base station and wait for the feedback. It has to be done on site immediately. Therefore, the UAVs in the area could work together to complete the analysis and react accordingly.

3.8. Distributed versus centralized control

Efficient and safe operations of multiple UAVs require unique real-time controls. Different control mechanisms are needed in coordinating among multiple UAVs that achieve a specific task, and effectively use the UAV resources, provide safe operations, and maintain the fault tolerance mechanism. It is difficult to do these using a centralized approach. This is due to three reasons: (1) A centralized control system suffers from single-point of failure problem, (2) Not all UAVs are connected to the GCS at all times, as control signals may not always reach the UAV, and (3) A centralized control could be a bottleneck for communication and security. For all these reasons, it is better to use distributed and collaborative controls.

4. UAV-based networking architectures

In order to perform various tasks and services, flying UAVs must be able to communicate with each other as well as with networking backbones and infrastructures. Figs. 1, and 2 illustrate U2U and U2I communication, as discussed in more detail here.

4.1. UAV-to-UAV (U2U) communication architectures

Since in-flight UAVs are highly mobile, UAVs can communicate with each other as a MANET. Each UAV constitutes a mobile node in a MANET. Research usually follows the Open System Interconnection (OSI) model, including the physical, data link, networking, transport and application layers (this layer typically includes the session and presentation layers).

The physical and data link layers 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

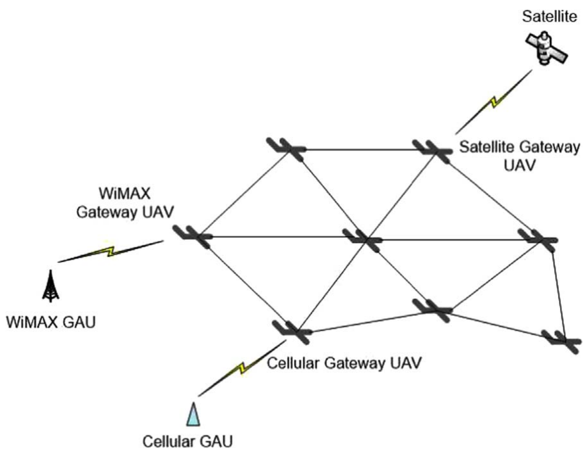


Fig. 1. UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) Communication.

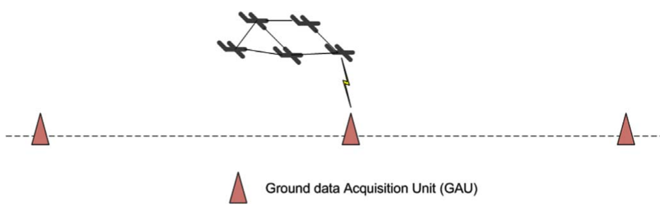


Fig. 2. UAV-fleet communication with ground data acquisition units as they come within range.

extensions of the IEEE 802.11 such as IEEE 802.11n have been developed with longer communication ranges and relatively high data rates (Olenewa, 2014). Such version can be used with U2U communication. The IEEE 802.11 protocol supports carrier sense multiple access with collision avoidance (CSMA/CA) at the data link layer which is also 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 (Jawhar et al., 2010, Jawhar and Wu, 2005a, 2005b).

Routing protocols for MANETs can be categorized into six different classes (Tareque et al., 2015):

- Static protocols: In these protocols, the routing table is programmed into each one of the nodes (UAVs in this case) before the mission.
- Proactive protocols: In these protocols, the routing table is built and maintained periodically by each node in a proactive manner before any demand for data transmission.
- Reactive protocols: In these protocols, the path between a source node and a destination node is discovered only when data needs to be transmitted in an on-demand basis. Later on, the discovered path can be used by further transmissions if the topology of the related nodes does not change.
- Hybrid protocols: These protocols include both the proactive strategy for certain paths or path segments and the reactive strategy for other paths or path segments. For example, if the network is divided into clusters, communication between the cluster heads (inter-cluster communication) can use a proactive strategy, and communication inside the cluster (intra-cluster communication) can use the reactive strategy.
- Position/Geographic Based protocols: These protocols rely on the availability of node locations using GPS or other location determination methods to find a path between the source and destination.
- Hierarchical protocols: In these protocols, multiples hierarchical levels for the nodes exist and communication between the nodes in the lower levels of the hierarchy is achieved using nodes in the upper levels. Typically, this kind of structure is efficient in very large networks/providing increased scalability.

The choice of the appropriate networking protocol for U2U communication depends on the nature of the application which determines the following specifications (Stallings, 2005, Olenewa, 2014; Lilien et al., 2014):

- Number of UAVs in the network: Some routing protocols provide good performance for small networks but do not perform well in a large network where other protocols can be more effective.
- On-board processing capabilities: This includes microprocessor that has 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 is large. This is true in UAV-based networks with small size UAV.
- Energy and power capability of the UAVs: Some energy-aware routing protocols are more appropriate, especially for small size UAVs.
- GPS capability of the UAV: This allows designers to use geographic routing protocol, which provides good performance with large UAVs and high mobility networks. Many routing protocols have been developed for VANETs, with similar characteristics.
- Connection to backbone infrastructure network: Appropriate mapping of networking parameters between U2U routing protocol and the infrastructure network is important and must be considered.
- Transmission robustness and security: These are also important factors to consider depending on the application.
- Collocated networking protocols: In environments where other networked devices are used, it is important to guard against interference when the same frequency range is being used.
- License-free operation: This is an issue that needs to be considered when choosing an appropriate protocol since some operating frequencies require proper licensing.
- Handoff and roaming: As UAVs move in and out of communication range of various 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 good quality imagery and video, while lower data rates can be tolerated when the exchanged data is limited. In this case, while high data rates are not essential, low delay becomes critical for such real-time data traffic.
- Degree of UAV mobility: Some routing protocols provide good performance but suffer from a prohibitively large number of control message overhead when the nodes are highly mobile. This is true as discovered routes constantly break and new routes must be discovered. Other protocols, such as geographic-based ones are appropriate for such an environment since they have reduced overhead.

The latter item, which is node mobility, identifies a very important characteristic that differentiates Flying ad hoc networks (FANETs) from MANETs or vehicular ad hoc networks (VANETs). A UAV has a speed of 30–460 Km/h, which result in several related communication and networking issues and challenges (Clapper et al., 2007, Han et al., 2009). Generally, MANET nodes move on a particular territory, and VANET nodes move on fixed roads, while FANETs or UAV networks fly in the sky. Multi-UAV fleets normally do not have a fixed flight plan since they often have to update their flight paths in reaction to the environmental feedback and mission updates (Tareque et al., 2015). This property must be taken into consideration in UAV mobility modeling research.

Based on the characteristics of each class of MANET routing protocols, in the following discussion we identify the appropriateness of each MANET routing protocol class for UAV-based networks.

Due to the fact that they require a significant amount of setup time, static protocols would be appropriate for smaller networks of UAVs. They have low complexity, and do not use bandwidth to establish routes. They also do not exhibit communication latency since the routes are predetermined. They are suitable for applications where the topology of the UAVs and the corresponding mission are fixed.

Proactive protocols have medium complexity, can adjust to topology changes, and require a larger amount of memory for the routing table and consume more bandwidth for signalling as the number of UAVs grows. On the other hand, the routes are proactively discovered and maintained, this does lead to communication latency when data needs to be transmitted. Therefore, this class of routing protocols would be appropriate for applications a which have a smaller number of UAVs, and require faster real-time communication.

Reactive protocols have average complexity, and low memory usage for the routing table. They are efficient for larger networks since the routing table entries are only created on-demand. However, due to the need to find a route for the first time when two UAVs need to communicate, they exhibit higher communication latency. They also adjust well to topology changes. Unlike proactive routing protocols, they do not constantly use a large amount of signalling, bandwidth, and energy to find and maintain routes. This is only done when a new session is needed or the related topology of an existing path is changed. Consequently, they are appropriate for applications with medium or large networks of UAVs, which have smaller on-board memory capacities, and can tolerate the higher communication latency when new routes need to be discovered.

Since hybrid protocols have a combined strategy using proactive and reactive techniques. They constitute a compromise between the two classes. Consequently, they have average complexity, medium memory usage, and medium bandwidth consumption for signalling. They have a medium to high communication latency since the routes still need to be discovered at the beginning of a session between source and destination nodes. They can be used in small as well as larger networks. They are mostly appropriate for heterogeneous UAV networks where some nodes need their communication routes to be proactively discovered and maintained since they cannot tolerate communication delay, while other nodes need to communicate only on an on-demand basis and can tolerate larger delays.

Position/Geographic based protocols have higher complexity, require higher memory usage, do not use a lot of bandwidth for signalling, and have lower communication latency. This is the case since the routing is mostly determined based on location information, which is assumed to be readily available. They are appropriate for larger networks with bigger and more complex UAVs, which are equipped with location determination circuitry such as GPS.

Hierarchical protocols have higher complexity, lower memory usage, consume more bandwidth for signalling, and have higher communication latency. Their main advantage is that they are more flexible and highly scalable. They are appropriate for heterogeneous, larger networks with UAVs that have various sizes, processing and storage capacities, power, and communication capabilities. Each UAV type in such networks can have different functions and responsibilities based on their available resources and position in the hierarchy. For example, some nodes might act as cluster heads, and perform functions such as data fusion and compression. They can also have larger communication range and can provide connectivity to infrastructure networks while simultaneously using different types of protocols.

In addition to the considerations, it is important to note that routing protocols designed for ad hoc networks such as Dynamic Source Routing protocol (DSR) (Perkins, 2001), Ad hoc On-Demand Distance Vector (AODV) protocol (Perkins and Royer, 1998), Temporally Ordered Routing Algorithm (TORA) (Park and Corson, 1997), and many others (Barry and McGrath, 2003, De et al., 2002; Hwang and Varshney, 2003; Nelakuditi et al., 2002; Sobrinho and Krishnakumar, 1999; Xiao et al., 2000; Ye et al., 2003) usually assume that the various nodes in the network will willfully participate in the routing process in a reliable manner. However, this might not be the case in many applications and operating conditions. Consequently, additional research has been done to extend these protocols further to provide improved performance in certain situations and networking environments.

4.2. 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, 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. This can be used to collect U2U data from the other UAVs in flight, and exchange this data to and from the networking infrastructure using one of the existing WLAN and WWAN protocols (depending on the distance and type of service) that are available in that particular geographic area. We name the nodes as the *Gateway data Acquisition Units (GAU)*. This unit could be ground-based such as cellular or the IEEE 802.16 (WiMax), or they could be satellite-based systems.

4.3. Links between various nodes of the UAV system

Fig. 3 shows various protocols that can be used at the different links for U2U and U2I communication. In the U2U link, IEEE 802.11a/b/g/n protocol can be used, which is an established protocol that has evolved over the years. In addition, Table 1 shows various networking protocols that can be used in UAV systems (Olenewa, 2014, Stallings, 2005; IEEE, 2014). The table shows their main characteristics, the physical and data link layer specifications, their data rates, transmission range, and the corresponding UAV system communication and link types.

4.4. The networking layers in the nodes of the UAV system

Fig. 4 shows different OSI model layers that can be used at the basic UAV and gateway UAV nodes. In addition to the classic layers, we add the middleware, which resides between the application and transport

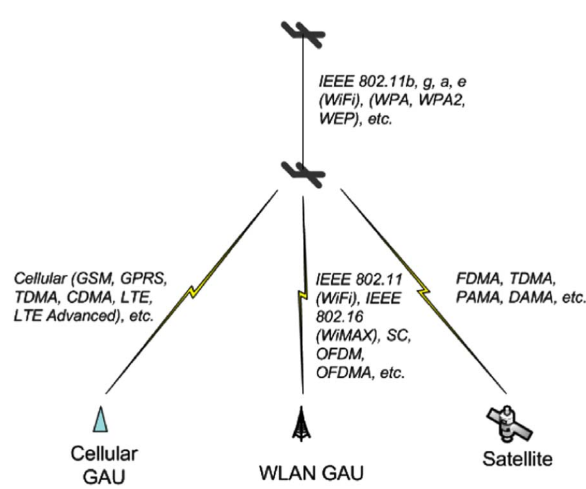


Fig. 3. Various protocols at different links of the UAV communication system hierarchy.

Table 1
The Various Networking Protocols that are Useful for UAV Systems. *OFDM: Orthogonal Frequency Division Multiplexing; TDD: Time Division Duplex; DSSS: Direct Sequence Spread Spectrum; CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance; DCF: Distributed Coordination Function; PCF: Point Coordination Function; HSDPA: High Speed Downlink Packet Access; LTE: Long Term Evolution (4G cellular technology); LEO: Low Earth Orbit; MEO: Medium Earth Orbit; GEO: Geostationary Earth Orbit; FDMA: Frequency Division Multiplexing; TDMA: Time Division Multiplexing.*

Protocol	Main Characteristics	Physical Layer Specs	Data Link Layer Specs	Data Rate	Transmission Range	UAV System Communication and Link Types
IEEE 802.15.1 (Bluetooth)	Cable replacement	2.4 GHz Band, FHSS/FSK	Master/Slave, TDD	1 Mbps	10 m	Data Communication Inside UAV.
IEEE 802.11a	Data Networking, Local Area Network	5 GHz Band, OFDM	CSMA/CA, DCF/ PCF Mechanisms	6, 9, 12, 18, 24, 36, 48, 54 Mbps	120 m outdoors	high data rate U2U and UAV-to-WLAN GAU, in 5 GHz range
IEEE 802.11b	Data Networking, Local Area Network	2.4 GHz Band, DSSS	CSMA/CA, DFS/ PFS Mechanisms	1, 2, 5.5, 11 Mbps	140 m outdoors	low to Medium Data Rate U2U and UAV-to-WLAN GAU, in 2.4 GHz range.
IEEE 802.11g	Data Networking, Local Area Network	2.4 GHz Band, DSSS, OFDM	CSMA/CA, DFS/ PFS Mechanisms	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1 40 m outdoors	Low to high Data Rate U2U and UAV-to-WLAN GAU, in 2.4 GHz range.
IEEE 802.11n	Data Networking, Local Area Network	2.4 GHz and 5 GHz Band, DSSS, OFDM	CSMA/CA, DFS/ PFS Mechanisms	15, 30, 45, 60, 90, 120, 135, 150 Mbps	250 m outdoors	medium to high Data Rate U2U and UAV-to-WLAN GAU, in 2.4 GHz range.
IEEE 802.16/rel 1/rel 1.5/rel 2(m) (WiMAX)	Metropolitan Area Network	2–66 GHz Band, MIMO-OFDMA	TDD, FDD	2 to 75 Mbps	Up to 35 miles (56 Km)	low to high data rate, long range/high altitude, small to large size UAV, U2U and UAV-to-WLAN GAU, in 2–66 GHz range.
Cellular 3G	Wide Area Network connectivity. Digital, packet switched for data; optional circuite switched or packet switched for voice	800–1900 MHz	CDMA, HSDPA	144 Kbps (mobile users) to 42 Mbps (for stationary users)	Depends on associated cell radius (1 Km to several Km's)	low to high data rate, range heavily dependent on local cell system size and architecture, small to large size UAV, UAV-to-WLAN GAU.
Cellular 4G/LTE	same as 3G	700–2500 MHz	LTE and LTE Advanced	300 Mbps to 1 Gbps	Depends on associated cell radius (1 Km to several Km's)	low to high data rate, range heavily dependent on local cell system size and architecture, small to large size UAV, UAV-to-WLAN GAU.
Satellite (LEO/MEO/ GEO)	Wide Area Network	1.53–31 GHz	FDMA and TDMA	10 Mbps (upload) and 1 Gbps (download)	Satellite used as repeater and can cover 100's of Km's to entire earth	low to high data rate, provides communication in areas where other services such as WiMAX or cellular are not available, small to large size UAV, UAV-to-WLAN GAU, end-to-end delay ranges from 20 ms (LEO) up to 250 ms (GEO).

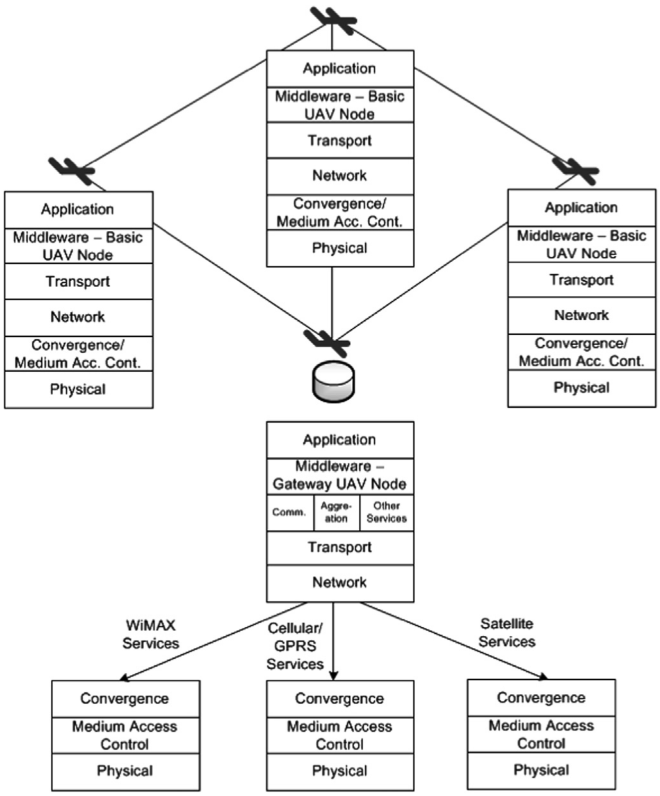


Fig. 4. The networking protocol layers at the basic UAV (BU) and gateway UAV (GU) nodes.

layer of each node. 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.

4.5. Classification of UAV data traffic

The UAV-based networking systems must consider different types of data traffic and their QoS characteristics. The associated networking protocols must support stringent data requirements for U2U and U2I communication. Table 2 presents a classification of the various types of UAV-based network data traffic, data traffic types, their delay, delay jitter, and bandwidth (data rate) requirements.

4.6. Emerging standards

Due to the several challenges of the new aeronautical applications including emerging UAV applications, there are high needs to define new communication solutions which can effectively support these new applications. The National Aeronautics and Space Administration (NASA) in the United States and the European Organization for the Safety of Air Navigation (EUROCONTROL) are leading the development of new communication systems. A standard for UAS Control and Non-Payload Communication (CNPC) links is being developed in the United States to enable safe integration of UAS operations within the National Airspace System (NAS) (Kerczewski and Griner, 2012). NAS is the main aviation system in the United States that involves, the US airspace, airports, and monitoring and control equipment and services that implement the enforced rules, regulations, policies, and procedures. This system covers the airspace of the United States and large portions of the oceans. Some of its components are also shared with the military air force. For safe integration of UAS operations in NAS, sense and avoid techniques, aircraft-human interface, air traffic management policies and procedures, certification requirements, and CNPC are being studied (Unmanned aircraft systems, 2012). This integration allows UAVs to function within the airspace used for manned aircrafts used for passenger-carrying and cargo.

CNPC links are defined to provide communication connections to be used for aircraft safety applications and to enable remote pilots and other ground stations to control and monitor the UAVs. This involves several issues including communication architecture types, rate requirements, bandwidth requirements, frequency spectrum allocation, security requirements, and reliability requirements. Two communication architecture types were proposed including line-of-sight (LOS) communication which provides communication with unmanned aircrafts through ground-based communication stations and beyond-line-of-sight (BLOS) communication which provides communication with unmanned aircrafts through satellites. The communication rates requirements for both uplink (ground-to-air) and downlink (air-to-ground) were defined based on the size of unmanned aircrafts as shown in Table 3. The uplink rates are much lower than downlink rates as the uplink communication will be mainly used to send small messages to control the unmanned aircrafts while the downlink communication is used for different types of communication including video transmission. The uplink rate was determined to support transmission of 20 individual control messages per second. This rate is required to provide a complete real-time ground control for a UAV using a joystick (Kerczewski and Griner, 2012).

The supported density requirements of unmanned aircrafts that use CNPC to the year 2030 are also specified (Unmanned aircraft systems, 2012) and shown in Table 4. The third column shows the numbers of unmanned aircrafts (of different sizes) that can be supported if a terrestrial-based communication link of radius 100 km is used.

Based on the defined UAV density, the required bandwidth for CNPC links is 90 MHz divided into 34 MHz for the terrestrial-based LOS CNPC links and 56 MHz for the BLOS CNPC links (Kerczewski and Griner, 2012). Two frequency spectrum ranges were assigned by the 2012 International Telecommunications Union World Radio Communications Conference (WRC-12) to be used by CNPC to provide reliable and real-time data transmissions. These frequency spectrums are from 960 MHz to 1164 MHz (L-Band) and from 5030 MHz to

Table 2
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

Table 3
CNPC Data Communication Rates.

Aircraft Size	Uplink Rate	Downlink Usages	Downlink Rate
Small (<= 55 kg)	2424 bps	Basic services only	4008 bps
Medium and Large (> 55 kg)	6925 bps	Basic services only	13,573 bps
Medium and Large (> 55 kg)	6925 bps	Basic and weather radar	34,133 bps
Medium and Large (> 55 kg)	6925 bps	Basic, weather radar and video	234,134 bps

Table 4
CNPC supported aircraft density.

Aircraft Size	Density of UAVs in Space (km^3)	No. of UAVs within Radius of 100 km
Small	0.000802212	1680
Medium	0.000194327	407
Large	0.00004375	91

5091 MHz. However, a portion of the first range will be shared with other legacy applications for surveillance and navigation purposes. Another issue of CNPC links is the high security requirements. Good security mechanisms should be used on CNPC links to avoid any possibility of spoofed control or navigation signals that may allow unauthorized persons to control the UAVs (Zeng et al., 2016). For meeting future communication capacity requirements in aeronautical communications, a new air-ground communication system, called L-Band Digital Aeronautical Communication System (L-DACS), is being developed in Europe with funding from EUROCONTROL. L-DACS is the system in the Future Communication System (FCS) for L-band, 960–1164 MHz. L-DACS comprises of L-DACS1 (Sajatovic et al., 2009) and L-DACS2 (Fistas, 2009). L-DACS1 is multi-carrier broadband Orthogonal Frequency-Division Multiplexing (OFDM)-based system while L-DACS2 is narrow band single-carrier with Gaussian Minimum Shift Keying (GMSK) modulation system. More information about L-DACS1 and L-DACS2 including their benefits with the current aeronautical system and their physical and medium access layers can be found in Neji et al. (2013).

5. Middleware support for UAV systems

5.1. The importance of the middleware layer in the UAV networking stack

Middleware technology has become an essential part of any distributed environment that offers essential features and functionalities. It simplifies and expedites distributed application process as compared to the traditional approach. Thus, in simple words "middleware offers a set of functionality components in a distributed environment." 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 their heterogeneity, security, and reliability challenges with other distributed systems. Based on our previous research, middleware generally offers many advantages for mobile ad hoc environments and networked robots such as UAV systems. MuniSocket allows the device using it to simultaneously utilize all available network interface cards (NIC) available. This can serve two purposes: (1) Increasing bandwidth and (2) enhancing reliability. When multiple UAVs need to accomplish a large task that involves heavy communication, it is possible to have several MuniSocket-UAVs in the formation to carry that load. This adds to better handling of communication loads and adding the capability to achieve the required QoS requirements for the applications.

5.2. Services provided through middleware support

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

- Runtime support: As an UAVs system is viewed as a set of services provided for supporting applications, SOM should provide mechanisms to deploy, load, and execute these services.
- Support for service: For different communication techniques among consumers, services, registries and brokers that enable reliable and efficient local and remote service utilization.
- Support for consumer services: SOM should enable client applications to discover and use registered services.
- Service transparency: SOM should allow client applications to transparently use available services without exposing the implementation details or in some situation its detailed components locations.
- Hiding heterogeneity: All heterogeneity details of UAV hardware and network should be hidden from the applications.
- Configurable services: This requirement is to address 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.
- Self-organization: This can include self-x properties such as self-management, self-healing, self-configuration, auto-discovery, self-adaptation, and self-optimization of service providers. UAVs provide a dynamic distributed environment where UAVs can fail and new UAVs can be added anytime. In addition, other mobile nodes with some services can be available momentarily. Availability of services in these nodes is also dynamic. Therefore, SOM should support self-management, auto-discovery, auto-change, self-optimization and auto-change mechanism for efficient utilization of available services.
- Interoperability: Some UAV applications require variety of devices to be operated. This requirement addresses heterogeneity challenges mentioned in the previous section. SOM for UAV can be designed to be interoperable with different devices such as different types of sensors, RFID, and actors.
- Handling of volumes of data: This requirement helps in hardware and network organization mentioned in the previous section. Some UAV applications involve large volumes of data and high communication loads.
- Secure communication: 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.
- QoS requirements: Mechanisms are needed to configure and satisfy QoS requirements in a UAV environment. Example of QoS requirements in UAV could be reporting a critical reading within certain time frame and error level. In some situations, the QoS requirements can come from multiple considerations such as safety and collaborative sensing.
- Integration with other systems: As UAVs system usually do not operate in isolation, SOM should enable integration of UAV systems

with others such as WSN, enterprise or web systems. For example, some web applications rely on UAV for their current information such as weather and traffic conditions. In this case, SOM should enable such integration for these applications to fulfill their goals.

In our previous work, we proposed a SOM architecture that can satisfy the development and operations of such services (Mohamed et al., 2014). This architecture consists of multiple layers that provide the main common functionalities required by any type of collaborative UAV applications. This SOM allows for integrating basic services for service discovery, registry and invocation as well as more advanced UAV and application specific services that may be incorporated to build different advanced collaborative UAV applications. More information about this architecture can be found in Mohamed et al. (2014).

5.3. Middleware support for heterogeneous network interface UAVs

As indicated earlier, in some UAV networking models, it is possible to have UAVs as a particular fleet to have multiple network interface sockets (MuniSocket) (Mohamed et al., 2010). For example, a UAV might have simultaneous networking access to cellular, WiMAX, as well as satellite communication infrastructures. We name this UAV a MuniSocket-UAV. The related networking layer architecture of this type of node is shown in Fig. 5. Depending on the application and the size and type of UAV network, one or more MuniSocket-UAVs might exist in a particular UAV-based network. In MuniSocket-UAV node, the middleware layer can manage the connectivity between the upper layers and various network interface ports. These services can be provided in U2U and U2I communication. For example, in the U2U case, if communication among UAVs is using a multihop routing protocol, depending on the data traffic requirements, a specific path might be selected that meets certain QoS requirements such as bandwidth, and end-to-end delay. In this case, the path can include MuniSocket-UAVs that provide communication through particular network interfaces to meet such QoS requirement. This QoS path selection is shown in Fig. 6. The same strategy can be adopted in the U2I case. The following section discusses Self-configured MuniScoket-UAV model and provides some insight into existing work and new things that can be done.

MuniSocket-UAV: Utilizing multiple interconnections among several computers, or UAV on-board computers in our case, to improve communication performance and reliability is not straightforward in a the dynamic environment which characterizes UAVs. Different strategies have been used to use multiple network interfaces to achieve efficient communication between nodes. In Mohamed (2006) and Mohamed et al. (2010) the MuniSocket model is introduced. This strategy relies on the use of different network interfaces in order to enhance transfer time, throughput, and reliability. The architecture proposes a user-level socket over several network interfaces. Using this mechanism flexible, effective, and reliable data transfer can be achieved among multiple UAVs, especially in situations where huge amounts of data must be transferred among different UAVs as well as from UAVs to ground networking infrastructures. In Mohamed et al. (2010), the authors propose a self-configured MuniSocket, which uses multiple homogeneous and heterogeneous network interfaces and networks. In this case, the MuniSocket is able to apply effective self-management techniques with the goal to achieve better performance, and reliability (Mohamed et al., 2005) with different interconnection scenarios.

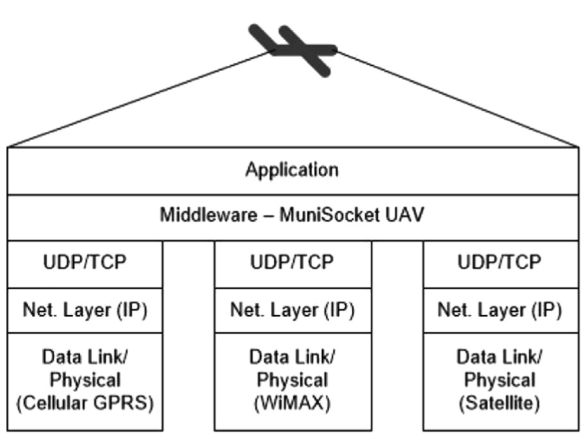


Fig. 5. MuniSocket-UAV networking protocol layers.

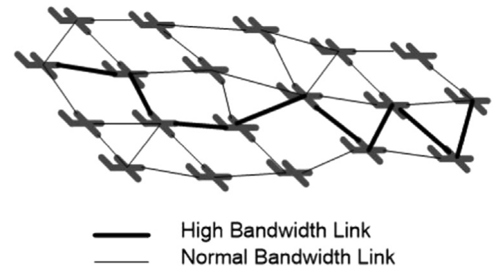


Fig. 6. QoS-path selection in a MuniSocket-UAV fleet.

6. Case study: data collection in WSNs using UAVs

WSNs have evolved quickly and they are found in many applications such as military, environmental, border and infrastructure monitoring. In some applications, UAVs can be used to collect data from WSNs in order to significantly reduce energy consumption by allowing the sensor nodes to transfer their collected data to the sink without having to rely on the traditional multihop approach (Say et al., 2016, Fadlullah et al., 2016; Sotheara et al., 2016; Li et al., 2016; Dong et al., 2014). This section presents an overview of a framework that can be used for data collection in WSNs using UAVs.

Some research has been done to use UAVs in order to enhance the deployment, operation, communication, and energy efficiency of WSNs. In Dorling et al. (2012) the authors studied aerial deployment of sensors through cooperative communication. In de Freitas et al. (2010), the use of UAVs to function as relays in order to enhance the communication in WSNs was investigated. On the other hand, the paper in Oliveira et al. (2010) provided a framework for using a UAV that is moving at a high speed to act as a sink for the WSN. Three data query algorithms were presented to accomplish this task. The authors in Giorgetti et al. (2011) addressed the use of cooperative communication for WSNs to transmit collected data to a distant UAV. Furthermore, some work has been done to provide efficient medium access control (MAC) protocols that can be used to support effective communication between WSNs and UAVs moving at high speeds (Ho et al., 2010, Ho et al., 2011; Ho and Shimamoto, 2011). In addition, some researchers have investigated the use of mobile devices to collect data from WSNs. In Shah et al. (2003), mobile entities that were called *MULEs* are used to collect data from sparse WSNs. In this models, sensors buffer the collected data until a MULE comes within range. In Jea et al. (2005) multiple MULEs that are moving in parallel lines are used to collect data from randomly deployed sensors in a WSN. Consequently, the field is divided into parallel regions depending on whether the sensors are within range of the moving MULEs or not. In Zhao and Ammar (2003), the authors used a moving node called *ferry* to collect data from nodes in a highly partitioned ad hoc network. The ferry, which is a special mobile node with added resources such as increased storage capacity, and renewable power, transports messages between nodes in the network that do not have multihop path between them. In Zhao et al. (2004), an extension of this approach is presented which identifies two types of ferries: *task-oriented*, and *message-oriented*. In the task-oriented case, the ferry is a moving node where the path is determined for non-messaging reasons such as a campus buss. In the message-oriented case, the ferry path is optimized in order to provide efficient communication between the disconnected nodes in the network. in Zhao et al. (2005), the model was further extended to support multiple ferries with a focus on optimizing and synchronizing the ferry routes in order to achieve increased efficiency. In Tariq et al. (2006), the ferry model was used to support communication in sparse ad hoc networks that contain mobile nodes.

The above algorithms are designed for MANETs, multi-dimensional WSNs, or rely on a multihop approach for data communication. However, in this framework, a UAV is used to collect data from the nodes. As mentioned earlier, this approach leads to significant energy consumption reduction, and reduced interference when data is communicated. Also, unlike the multihop strategy which requires the nodes to be within range of each other in order to allow for a connected topology, using the UAV does not require a connected network. This leads to significant increased flexibility in node density and placement. This allows the deployment of the nodes to be mainly dictated by the specific needs of the application.

In this framework, four types of nodes are defined: sensor nodes (SNs), relay nodes (RNs), UAVs and a sink. The SNs in each WSN cluster send their data to the RN node that is acting as a cluster head using one of the multi-dimensional WSN routing algorithms. The RN node stores the data collected from the SNs until the UAV comes within its range which causes the RN to transmit its buffered data to the UAV. The UAV moves from one cluster to another on its way to the sink where it communicates all of the collect data. In the case of larger networks and a higher number of clusters, additional sinks can be placed at certain intervals. This leads to the following advantages:

- Increased scalability of the network, which is essential for very long or large WSN networks.
- Increased efficiency due to parallel transmission of the data from the RNs to the UAVs.
- More reliability, since failure in communication in one of the segments due to malfunction of the UAV or the sink only affects the corresponding segment.
- Reduced end-to-end delay that is experienced by the collected data from the SNs to the sink.

We name this framework as UAV-based WSN (UWSN), which is illustrated in Fig. 7. Typically, a WSN has a multi-dimensional topology, which includes geometric placement of the nodes in a predefined manner or as a deployment where the nodes are placed randomly in the area that is being monitored (e.g., dropping the SNs from a UAV). However, in many applications, the structure that is monitored can be linear in nature such as oil, gas, and water pipelines, rivers, sea coasts, borders, roads, and bridges, which leads to a linear sensor network.

6.1. Linear sensor networks

We classify LSNs into *thin* and *thick* ones (Jawhar et al., 2011). In the thin LSN case, the sensors are aligned in a linear form making a thin line, where each SN only has one forward and one backward neighbor along the line. On the other hand, in the thick LSN case, the sensors are placed either geometrically (in a symmetric and predefined manner) or randomly between two parallel lines. In addition, LSNs are also classified into additional categories from a hierarchical point of view.

In order to provide additional motivation, some applications for LSNs are listed below:

6.1.1. Ground Oil, gas, and water pipeline monitoring

In many countries, commodities such as oil, gas and water use long pipelines in order to be transported between various places. For example, water needs to be transported from desalination plants to the cities. In addition, oil and gas use pipelines to be moved from refineries or production locations to ports and consumption destinations. Sensors that can be used to monitor the pipelines form an LSN.

6.1.2. Underwater pipeline monitoring

UAVs can be used to collect data about underwater pipelines, which can carry oil, and gas and extend to hundreds of kilometers (Jawhar et al., 2007). Langeled Pipeline constitutes a good example of this kind of important infrastructure. It is used to transfer natural gas from Norway to England under the north sea and has a length of 1200 Km and exists at a depth of 800–1100 m. The pipeline is equipped with sensors at regular intervals in order to sense vibrations, which can be caused by strong currents in the free spans. Such vibrations can subject the pipeline to dangerous pressure in the corresponding segments (Manum and Schmid, 2007). As shown in Fig. 8, in order to increase the reliability of the system, the pipeline is divided into multiple segments. The sensors at the ends of each segments are connected through wires to surface buoys. Individual sensors collect their data and transmit it using acoustic communication in a multihop approach to the nearest sensor that is connected to a surface buoy. The latter then stores the collected data from the underwater sensors. A UAV is used to fly over the sea surface and collect the data from the surface buoys as it comes within range using RF signals.

6.1.3. Railroad monitoring

Another important application of LSNs is railroad monitoring, where sensors can be used to collect important information the railroad that can be useful to predict any future failures and schedule preventive maintenance (Hartong et al., 2008).

6.1.4. Road-side network

Ad hoc networks of nodes along sides of roads can be used to

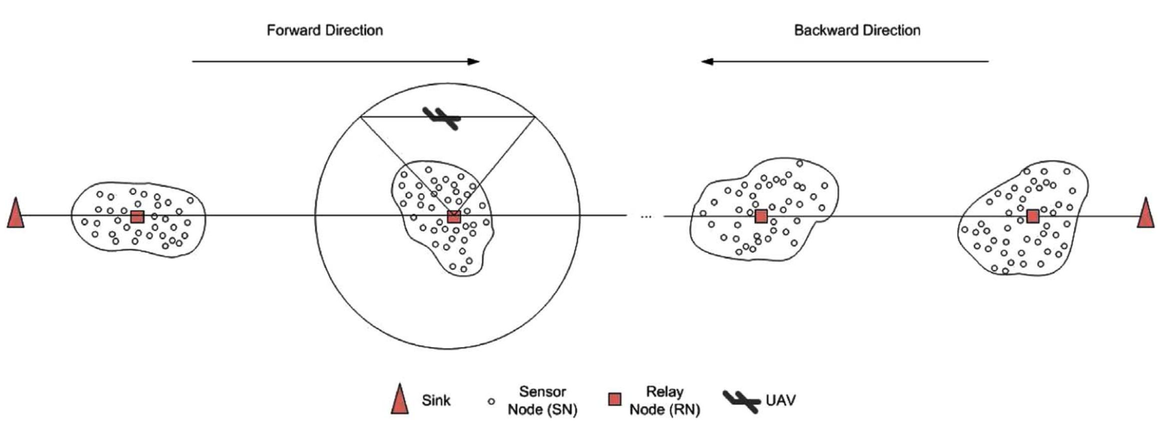


Fig. 7. UAV-based Data Collection in clustered WSNs where the clusters are aligned in a linear fashion.

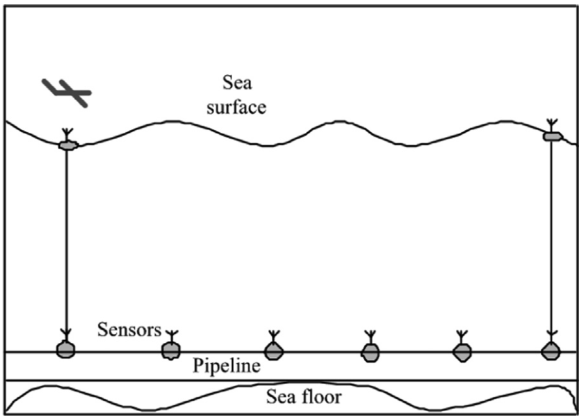


Fig. 8. Variation of proposed system showing UAV data communication with an LSN used for underwater pipeline monitoring.

monitor moving vehicle activities, and status such as speed, density, accidents, abnormal situations, and more. The data acquired by the nodes on the road side from speed detectors for example, or other sensing devices can be collected using a low-flying UAV. This can be especially effective in rural and remote areas where the roads can stretch for hundreds or thousands of kilometers.

6.1.5. Border monitoring

In order to monitor illegal crossing of people or vehicles or any other activities along borders between countries or any other geographic locations, sensors can be deployed. Such deployment can be done using a low flying UAV according to a pre-determined density. The resulting topology would be that of a thick LSN. The UAV can also be used to collect data from the sensors. As discussed in the underwater pipeline case, in order to provide for more scalability, reliability, and efficiency, multiple sinks can be installed at pre-determined locations forming different LSN segments. In that case each segment can be serviced using a different UAV. This would be desirable for very long borders that can stretch for hundreds or thousands of kilometers. In addition, in certain situations that require additional scalability for very long borders, each segment can be further divided into multiple clusters (or sub-segments). An RN node can be deployed to act as a cluster head in each cluster and the corresponding SNs can send their collected data to the RN. The UAV can then pass over the RN nodes to collect the data as it comes within range and transport it to the sink for that particular segment.

6.1.6. Other applications

The list of LSN applications that were discussed is not comprehensive. Many other applications exist such as river and seacoast monitoring, and more. In most of these LSN networks a low-flying UAV can be used to collect data from the various nodes on the ground and deliver it to the sink resulting in the advantages that were discussed earlier.

6.2. Clustered WSN

A variation of WSN topologies is clustered WSNs. Fig. 7 illustrates a clustered WSN where the clusters are formed in a linear fashion. Each cluster consists of multiple SNs along with one RN, which acts as a cluster head. The SNs in each cluster send their data to the RN node either using a multihop routing algorithm or with a single hop transmission depending on the size of the cluster and the transmission range. In the figure, a UAV that goes back and forth between two sinks at the ends of the WSN, is used to collect the buffered data in each RN as it comes within range and delivers the collected data to the sink that is in the direction of its movement. Another variation of clustered WSNs is shown in Fig. 9 with a UAV collecting data from each RN node

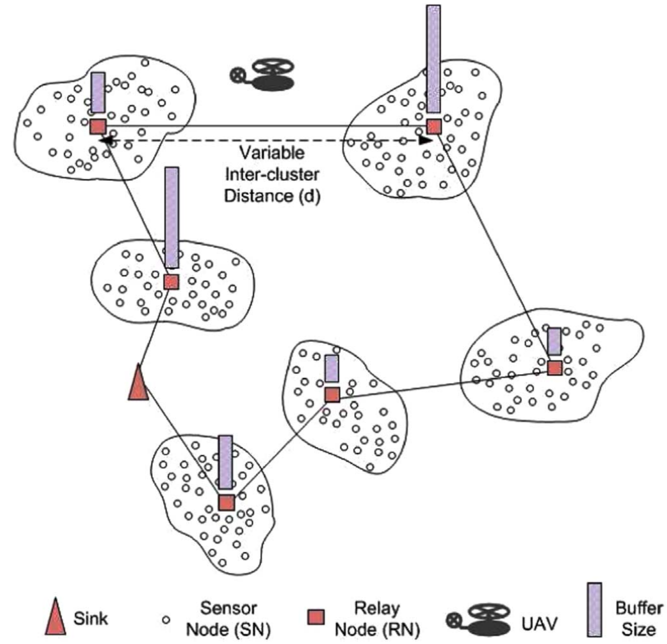


Fig. 9. UAV-based Data collection in clustered WSNs with randomly formed clusters in the 2-D area.

within its range and acts as a cluster head. Fig. 11 shows the exchange of data when the UAV is within the range of the RN node. The clusters formations are random in the 2-D area. The UAV moves in circular manner as it collects data from the RN in each WSN cluster and delivers it to the sink. In this model, in both cases, the distance between the clusters is variable. In most cases, random distribution of inter-cluster distance is exponential with a certain mean value, known as Poisson distribution. An optimized choice of the path that is followed by the UAV is similar to the NP-complete class of the travelling salesman problem (TSP). Some heuristic approaches have been proposed to choose a good approximation. Realistically, the movement of the UAV from one cluster to another can be though of as a logically linear movement in an LSN.

6.3. Geometric WSN

Fig. 10 shows an illustration of UAV-based Data Collection in a geometric-area WSN. In this model, the area is divided into squares that contain a randomly placed set of sensors. Each square is considered a cluster. A centrally located SN is designated as the cluster head which acts as a relay node (RN) responsible for collecting data from SNs in its cluster and transmitting the collected data to the UAV. Two sinks are located at opposite ends of the area. Two UAVs move from one end to the other to collect data from each cluster in the squares as indicated in the figure. Using this setup, the WSN constitutes an LSN from a logical point of view. In such cases, if multiple UAVs are used for data collection in a large WSN network, several research issues can arise. One such issue is related to load-balancing in sharing the data collection load between the UAVs. A dual-direction load balancing strategy, which has been used in Mohamed et al. (2013) for fast file downloads in a cloud architecture can be adopted. We are currently exploring this strategy for future research in this important area.

6.4. SN Node functions and services

The SN node has the responsibility of data collection according to the application for which the WSN is deployed. The SN node will then send the collected data to the RN node in its cluster, using one of two

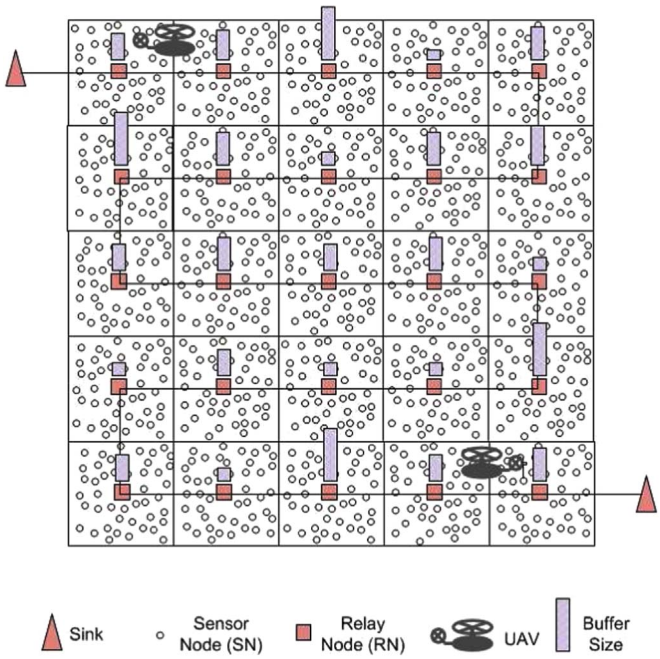


Fig. 10. UAV-based Data Collection in a geometric-area WSNs with two sinks and two UAVs collecting data from each RN (CH). UAV moves and collects data from the RN in each cluster.

strategies: (1) One-hop mode; or (2) Multi-hop mode. The strategy that is used depends on the geographic size of the cluster with respect to the node transmission range. If the size of the cluster (or square) compared to the node transmission range is such that the RN node is within range of all of the SNs in the cluster, then the SN can transmit its data directly to the RN node using the one-hop mode. On the other hand, if the size of the cluster is much larger than the SN transmission range, then a lot of the RN nodes will not be within range of most SN nodes. This situation is expected to be present in very large WSNs. In such cases, SNs can send their collected data to the corresponding RN node in their cluster using one of the various WSN routing algorithms that are available in the literature. Such protocols include strategies such as gradient-based, energy-aware, directed diffusion, energy-aware, and rumor routing (Akkaya and Younis, 2005). In addition, depending on the application, other protocols that employ a hierarchical approach can also be used. Such protocols include APTEEN (AdaPtive Threshold sensitive Energy Efficient sensor Network protocol), PEGASIS (Power-Efficient GAthering in Sensor Information Systems), and LEACH (Low-energy adaptive clustering hierarchy). The authors Cordeiro and Agrawal (2011) provide a detailed summary of these and other WSN routing protocols.

6.5. RN Node functions and services

As mentioned earlier, each cluster has an RN node that acts as a cluster head. The RN node can be of the same type of the SNs or it can be a node with more resources, including additional energy, storage, and processing capabilities. The RN node is responsible for collecting data from the SN nodes in its cluster. Furthermore, each RN node can provide additional services including data compression, data fusion, as well as processing services. For example, it might take the average, minimum, or maximum value of a particular sensing parameter after examining the collected values from the various SNs in its cluster. It can also provide programming and configuration services for the SN. It can receive programming, and configuration data from the UAV and program the SN accordingly. In addition, the RN node might disseminate sleep schedules to the SN nodes in order to save energy in cases where the density of the SN nodes is high. A scheduling policy that turn ON only a subset of sensors periodically, can lead to considerable energy savings and significant increase in network lifetime.

6.6. Link-level communication from SNs to RNs

The connection between SN and RN nodes can be achieved using various communication protocols. Since, typically, the required data rate for this connection is low, the IEEE 802.15.4 protocol can be used. This protocols is short range, has low energy consumption, and a lower data rate. It covers the physical and data link layers. The upper layers including the application layer are covered using the Zigbee standard. If higher data rates are required, the IEEE 802.15.3 protocol can be used, which is also characterized by a short data range and lower energy consumption.

6.7. Link-level communication from RNs to UAV and from UAV to sink

For communication between the RNs and the UAV as well as the UAV and the sink, various medium to longer range wireless protocols that are presented in Table 1 can be used. If the height of the UAV is within one hundred to several hundred meters, the IEEE 802.11 protocol with its various versions can be used. If the height of the UAV is larger, then the IEEE 802.16/WiMAX protocol would be more appropriate since it has a longer range that can go up to 56 Km. Another possibility would be the use of the cellular or satellite communication protocols. However, these protocols might be more costly and would require support from the communication infrastructure that would have to be available in the corresponding geographic region.

6.8. UAV data collection algorithms

Several UAV movement algorithms can be considered as the UAV moves between the RN nodes or clusters in order to collect data and deliver it to the sink. They are as follows:

- *Constant Speed UAV (CSU)* : With this algorithm, the UAV moves with a constant speed and collects the data from the RNs when it comes within range.
- *Variable Speed UAV (VSU)*: With this algorithm, the UAV moves using two different speeds. It uses a slower speed when collecting data from the RNs and a faster speed when moving between the RNs or clusters in order to minimize the end-to-end data collection delay.
- *Adaptable Speed UAV (ASU)*: With this algorithm, similar to the VSU algorithm, the UAV moves using two different speeds. However, the speed used for data collection is determined to allow time for downloading the data from the RN node while it is in communication range, and another speed is used when moving between the RNs or clusters.
- *Hover with Unlimited Service Time (HUS)*: In this case, the UAV is capable of hovering above the RN node when it is collecting data, which allows it to collect all of the RN node's data. It then moves at a faster speed between the RNs or clusters.
- *Hover with Maximum Service Time (HMS)*: Here, the UAV movement is similar to the HUS case. However, the UAV can only hover for a maximum amount of time above a given RN or cluster. This prevents an unacceptably large end-to-end data collection delay and prevents starvation of the remaining RNs in the path of the UAV.

The selection of the appropriate UAV movement strategy would depend on the application involved, various desired network parameters, capabilities of the UAV, and the size of the geographic area that is being monitored. More research can be done in this area in order to determine an optimal strategy for various system characteristics and WSN topologies.

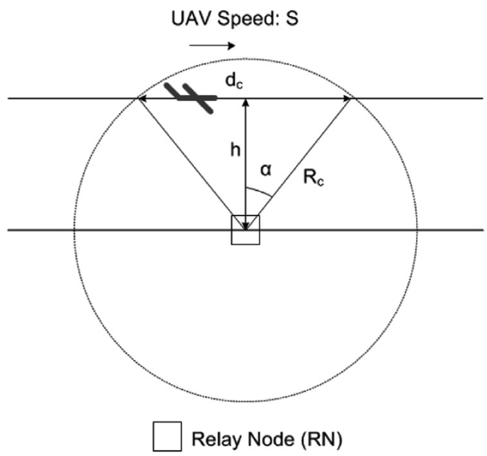


Fig. 11. Exchange of data when UAV is within the range of RN.

7. Performance evaluation

In this section, we evaluate several UAV data collection algorithms for a clustered WSN where the clusters are formed in a linear fashion (e.g., Fig. 7). We intend to use the evaluation results on this representative scenario to show the effectiveness and efficiency of the proposed architectures and algorithms.

7.1. Evaluation setup

General Setup. We generate the linear clustered WSN based on the model mentioned in this paper. Based on the observations from realistic applications, the default parameters are set as follows. We assume that the number of relay nodes (i.e., cluster heads), denoted by n, is 50. The distance between two consecutive relay nodes, denoted by d, is 10,000 m. The communication range of every relay node, denoted by R_c is 2000 m. The height of UAV, denoted by h is 1000 m. These parameters could be found in Fig. 11. The data transmission rate between relay nodes and UAVs, denoted by R is 1 Mbps. The buffer size of each relay node, denoted by B is 8000 bytes. When a relay node receives more than B bytes data from the other sensor nodes, then it would need to drop some data using some policy.

The best effort and priority traffic are generated based on exponential distributions with an average arrival rate that is uniformly generated from an interval. In our experiments, the average best effort traffic in bytes per second is uniformly generated between 1 and 3, the average priority traffic per second in bytes is uniformly generated between 8 and 16. The lambda in our evaluations is always set to 0.6. In the following experiments, we ran experiments with one varying parameters while keeping the others to their default values. Each running lasts for a sufficiently long time, so as to better reflect the performance of the proposed algorithms.

Data Collection Algorithms. We are interested in evaluating how the data collection algorithms mentioned in Section 6.8 perform under various settings. Here, we briefly present how these algorithms work.

Constant Speed UAV (CSU). As its name indicates, CSU employs a UAV that moves in a constant speed along the linear WSN back and forth. CSU is simple, however, choosing a proper speed is not trivial. On one hand, the speed should not be too small, since, otherwise, the message delay would be large. On the other hand, the speed should not be too large. This is because, if the UAV moves fast, the time for it to collect data from each relay node would be too short to drain the buffer of each relay node. In our evaluations, we set the UAV speed in CSU, denoted by s, to 100 m/s.

Variable Speed UAV (VSU). Difference from CSU, VSU allows the UAV to move in two different speeds: a small speed, denoted by s_c, which is used by the UAV when it is within the communication range of a relay node, and a large speed, denoted by s_{nc}, which is used by the UAV when it is not in communication with any relay nodes. By default, s_c is set to 100 m/s, and s_{nc} is set to 200 m/s.

Adaptive Speed UAV (ASU). Neither CSU or VSU pays attention to the message delay. ASU moves in different speeds within the communication ranges of different relay nodes: if a relay node has more messages to transfer, the UAV may move slowly; otherwise, the UAV may move fast. In ASU, we allocate different delay quotas to relay nodes based on their relative locations to the sink. Therefore, as the UAV moves in the forward direction, it collects less data from the early relay nodes (which have lower delay quota allocation), and more data from the relay nodes that are closer to the destination sink (which have higher delay quota allocation). The opposite process is used in the backward direction. In our evaluations, by default, the delay quota, denoted by Tq is set to 0.2 s, and the time out value, denote by T is set to 5000 s.

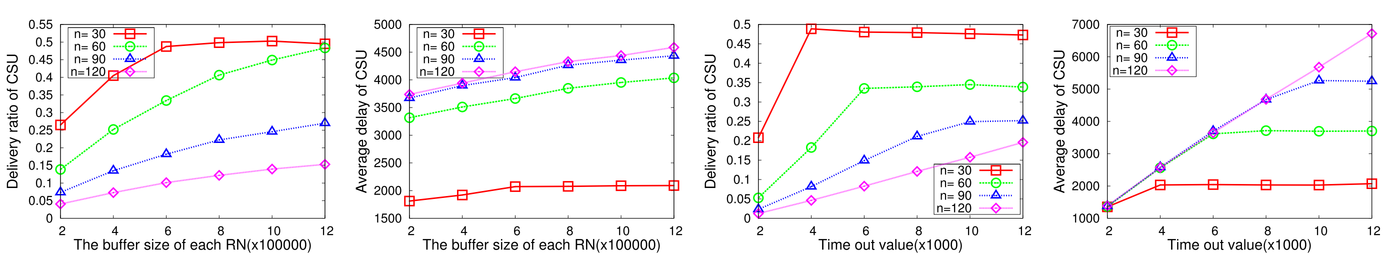
Hover with Unlimited Service Time (HUS) and Hover with Maximum Service Time (HMS). In these two algorithms, UAV may have to hover above a relay node when it collects data from the relay node. In HUS, the time for hovering is unlimited, while there is an upperbound on the service time in HMS.

Performance Comparison Metrics. The performance metrics used in our evaluations are the delivery ratio and the average delay. The delivery ratio is the ratio of the successful packets received by two sinks to the overall packets generated by all sensor nodes. The average delay is the average delay experienced by the successful packets.

7.2. Evaluation of results

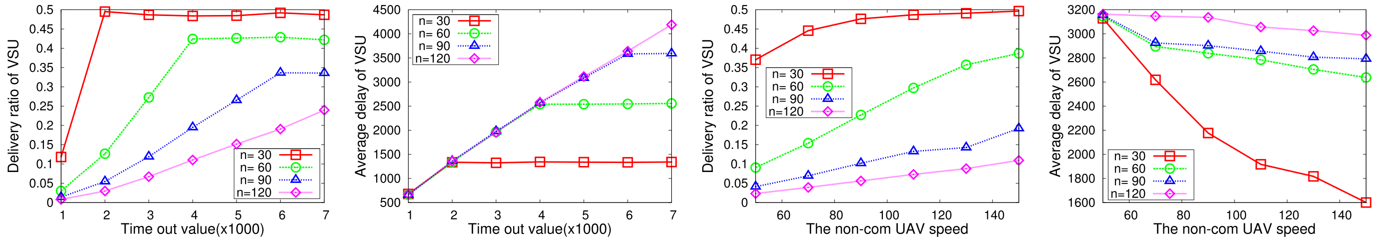
7.2.1. CSU

Fig. 12 shows the delivery ratio and average delay of CSU under varying buffer sizes and UAV speeds. Generally speaking, CSU produces higher delivery ratio and lower average delay when the number of relay nodes is small. In Fig. 12(a), the delivery ratio of CSU increases when the buffer size of each relay node increases. The main reason behind this is, when the buffer size of each relay node increases, less packets would be dropped due to buffer overflow. We also see that, the buffer size has a larger impact when the number of relay nodes is small. In Fig. 12(b), the average delay of CSU increases slightly when the buffer size increases. The main reason is that, the packets are kept in a sorted queue in each relay node, when the buffer size increases, the



(a) Buffer size vs. delivery ratio (b) Buffer size vs. average delay (c) Time out value vs. delivery ratio (d) Time out value vs. average delay

Fig. 12. CSU performance results.



(a) Time out value vs. delivery ratio (b) Time out value vs. average delay (c) Non-communication UAV speed vs. delivery ratio (d) Non-communication UAV speed vs. average delay

Fig. 13. VSU performance results.

UAV would collect more packets that are generated a long time ago.

In Figs. 12(c) and (d), the delivery ratio and the average delay of CSU increase when the time out value increases, respectively. We also note an interesting observation that, in these two figures, each curve first goes up, then stays almost unchanged after a critical time out value. Specifically, the critical time out values in four curves are about 4000, 6000,8000, and 10000 s in two figures. The main reason is that, for example, it takes the UAV about 2000 s to travel from the primary sink to the second sink.

7.2.2. VSU

Fig. 13 shows the effect of the timeout value and UAV speed of each relay node. In Figs. 13(a) and (b), we note that there may be some critical values of the time out value: when the time out value is larger than the critical value, the delivery ratio and the average delay of VSU changes a little.

Figs. 13(c) and (d) show that, when the UAV speed during the non-communication period increases, the delivery ratio in Fig. 13(c) goes up, and the average delay in Fig. 13(d) goes down. As shown in Section 4.2, the main reason is that, when the non-com UAV speed increases, the time for a UAV to travel from one sink to the other sink becomes shorter, thus more packets would be delivered to the sink more quickly, and the UAV can collect more packets in a fixed length of time period.

In Fig. 13(c), the delivery ratio of VSU first goes up and then goes down slightly, when the UAV speed increases. The main reason behind this phenomena is that, when the UAV speed increases, more packets can be delivered to the sinks more quickly; however, when the UAV speed is too large that there is not sufficient time for the UAV to collect packets from the sensor nodes, the delivery ratio then goes down. In Fig. 13(d), the average delay of VSU goes down with increasing UAV speed, because that the packets in the UAV buffer can be more quickly delivered to the sinks.

7.2.3. ASU

The performance results of ASU with different parameters are shown in Fig. 14. In Figs. 14(a) and (b), both of the delivery ratio and the average delay of ASU increases slightly when the buffer size goes up, however, we observe that the effect of buffer size on the delivery ratio is less great.

Figs. 14(c) and (d) show the delivery ratio and the average delay, respectively, of ASU, when the delay quota Tq goes up. Fig. 14(c) shows an interesting phenomena: the delivery ratio of ASU in the $n = 30$ setting achieves its maximum when Tq is about 0.2 s. The main reason is that, when Tq is larger than 0.2, the respective quota for each sensor node is sufficient for them to transfer their packets the UAV; therefore, the overall delivery ratio begins to goes down. Based on this, different network scale may have different critical values of Tq. However, our simulation is limited, and thus can not reflect this in the other three curves. Fig. 14(f) demonstrates that, when Tq goes up, the average delay also goes up, which is in accordance with our intuition.

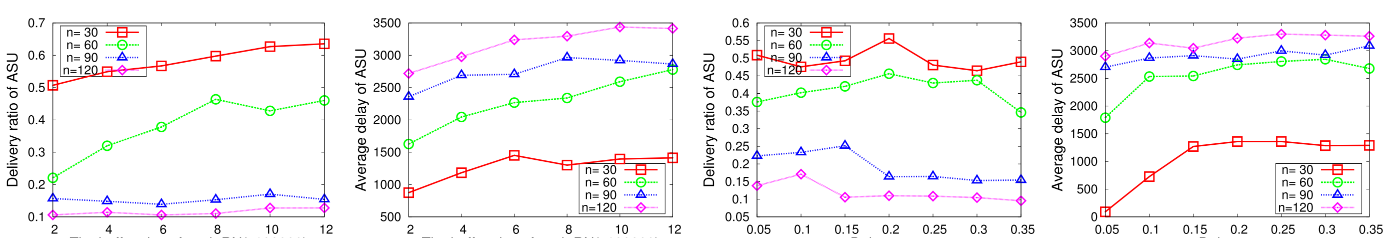
7.2.4. HUS and HMS

We also generate simulation results of HUS and HMS in Fig. 15. Fig. 15(a) and Fig. 15(b) show how HUS performs with varying UAV speeds. We see that, when the UAV speed increases, the delivery ratio also increases. This is reasonable, since a fast speed means less time on travelling between relay nodes. When the UAV speed increases, the average delay decreases. This is also reasonable, since a fast UAV speed delivers messages more quickly.

Fig. 15(c) and Fig. 15(d) show how HMS performs under different maximum service times. When the maximum service time threshold increases, the delivery ratio also increases. Because the UAV has more time for hovering above each relay node to collect data. However, the amount of data in each relay node is not unlimited, therefore, when the maximum service time exceeds some value, the delivery ratio would not increase too much. Fig. 15(d) shows HMS performance with varying maximum service times. We see that, when the maximum service time increases, the average delay also increases. This is because, data in the UAV has to wait a longer time than before to reach the sink.

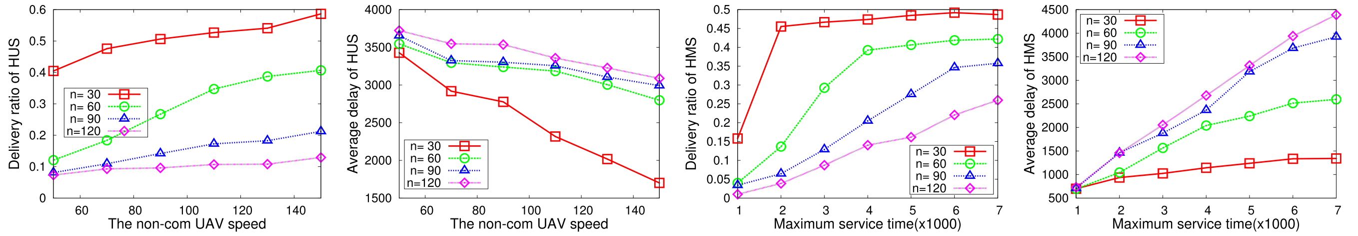
7.3. Summary

When the buffer size of each relay node increases, all of the propose algorithms can deliver more packets to sinks. However, as the generated packets in each sensor node is stored in a sorted queue based on their generation time and the UAV gives high priority to packets with small generation time in our implementation, the average delay of the proposed algorithm goes up when the buffer size increase.



(a) Buffer size vs. delivery ratio (b) Buffer size vs. average delay (c) Delay quota vs. delivery ratio (d) Delay quota vs. average delay

Fig. 14. ASU performance results.



(a) UAV speed vs. HUS delivery ratio (b) UAV speed vs. HUS average delay (c) Maximum service time vs. HMS delivery ratio (d) Maximum service time vs. HMS average delay

Fig. 15. HUS and HMS performance results.

When the time out value increase, all of the proposed algorithms perform better in terms of delivery ratio and average delay. Moreover, there may exist some critical time out values, which correspond to the length of the time period for a UAV to travel from one sink to other sink.

While preliminary, our results indicate that the propose algorithms perform well in a wide variety of environments. We wish our simulation will provide some potential guidelines for future data collecting systems.

8. Conclusion

Considerable advancements in UAV technology are 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 outlined different functions and requirements that are important and need to be addressed by researchers in order to provide robust, efficient, and energy-aware communication in UAV-based systems. We presented an overview of various U2U and U2I networking architectures and the different communication protocols that can be used at the layers of the OSI networking model. We described classification of the various types of data traffic that can be present in U2U and U2I communication. We also discussed various communication protocols and technologies that can be used in different links and layers in a UAV-based networking architecture. In addition, we offered a case study where UAVs are used for efficient data collection from a WSN. More specifically, we discussed the use of UAVs for data collection in different WSN topologies including LSNs, and cluster and geometric WSNs. We also evaluated some of the strategies that can be used for the data collection process. As UAVs continue to quickly evolve, they are expected to be used in an increasing number of applications, involving every aspect our lives, including government, industry, environment, and society. Efficient and seamless communication in UAV-based networks is essential in order to make the use of UAVs and their safe deployment and operation reach the desired and expected levels of effectiveness and success.

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