Survey on Unmanned Aerial Vehicle Networks for Civil Applications: A Communications Viewpoint

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***Abstract*—The days where swarms of Unmanned Aerial Vehicles (UAVs) will occupy our skies are fast approaching due to the introduction of cost-efficient and reliable small aerial vehicles and the increasing demand for use of such vehicles in a plethora of civil applications. Governments and industry alike have been heavily investing in the development of UAVs. As such it is important to understand the characteristics of networks with UAVs to enable the incorporation of multiple, coordinated aerial vehicles into the air traffic in a reliable and safe manner. To this end, this survey reports the characteristics and requirements of UAV networks for envisioned civil applications over the period 2000-2015 from a communications and networking viewpoint. We survey and quantify quality-of-service (QoS) requirements, network-relevant mission parameters, data requirements and the minimum data to be transmitted over the network. Furthermore, we elaborate on general networking related requirements such as connectivity, adaptability, safety, privacy, security, and scalability. We also report experimental results from many projects and investigate the suitability of existing communication technologies for supporting reliable aerial networking.**

***Index Terms*—UAVs, swarms, aerial networks, communication, network infrastructure, quality of service, search and rescue, delivery of goods, cooperative UAVs.**

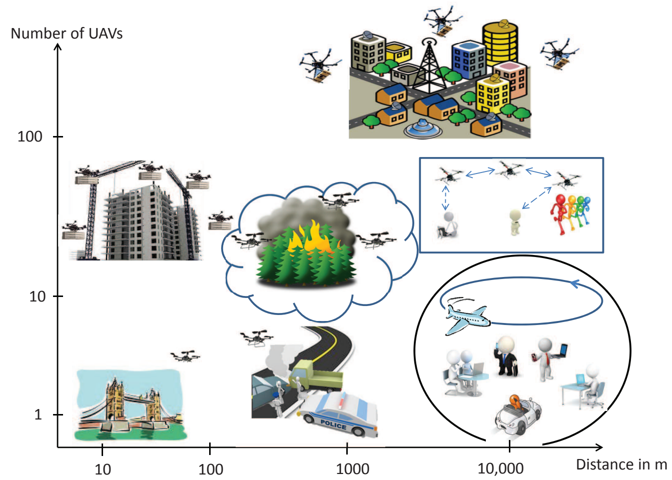


Fig. 1. Application areas over a range of distance vs. number of nodes.

I. Introduction

Small-scale UAVs are a practical choice for commercial applications due to their ease of deployment, low acquisition and maintenance costs, high-maneuverability and ability to hover. Such vehicles are being utilized in environmental and natural disaster monitoring, border surveillance, emergency assistance, search and rescue missions, delivery of goods, and construction [1]–[7]. Use of single or multiple UAVs as communication relays or aerial base stations for network provisioning in emergency situations and for public safety communications has been of particular interest due to their fast deployment and large coverage capabilities [8]–[11].

Multiple UAVs can be utilized for efficient and successful mission completion because of their sizes, capabilities, limited payload and flight time [12]. The number of UAVs and their travel distances vary over a wide range for different applications (see Fig. 1 for an illustration). Teams of UAVs can be deployed, for instance, as aerial base stations to provide service to disaster-affected areas or as an aerial sensor network, collecting data in large areas. Such teams can have the potential to perform tasks that go beyond the individual capabilities of the small UAVs. Communication and networking are essential to enable team behavior, coordinate multiple vehicles, and achieve *autonomous* aerial networks. It is very likely that high performance wireless links and connectivity in three-dimensional (3D) space will be required for several applications with data delivery meeting certain quality-of-service (QoS) demands [13]. Thus there is a need to establish which wireless technology should be employed for aerial networks. The technology of choice should be able to support air-ground and air-air links, taking into account the data needs to be delivered, regardless of significant height and orientation differences. Keeping in mind the QoS requirements, link diversity and high node mobility in aerial networks, it is yet not clear as to whether networking protocols developed for ground networks can be readily deployed in UAV networks. Several wireless technologies can be exploited for UAV networks such as IEEE 802.15.4, IEEE 802.11x, 3G/LTE, and infrared [14]–[20]. The question, however, remains unanswered as to whether the existing technologies fulfill the communication requirements for all UAV applications. To answer this we need to identify the requirements, constraints, and limitations in terms of networking and communication for different civil UAV applications.

This article surveys the characteristics and requirements of UAV networks for envisioned civil applications over the period 2000-2015 from a communications and networking viewpoint. To this end, we first give a background on the existing survey studies that highlight advantages of multi-UAV systems, their applications, communications and networking issues in a layered approach, and mobility models for different applications. We then specify the characteristics of a UAV network, i.e., an aerial network, based on its size and goal, the wireless channel, and the sensing capability and mobility of the vehicles. We identify the relation between the application the UAVs are deployed for and the role of communication and networking. We observe that diversity of the potential applications results in the need of a plethora of UAV network configurations (for instance, in terms of network size (i.e., low/high node density) and topology (single-hop (star), mesh/ad hoc (point-to-point))). We further observe that aerial networks differ significantly from traditional wireless networks, not only due to the characteristics of the links and devices used, but, because aerial networks are not *just* communication networks and as such they have varying yet very specific mission requirements depending on the application. The application specific requirements pose challenges over the network design and communication constraints varying in traffic type, volume, frequency, delay tolerance, communication range, mobility effects and frequency of topology change, control and coordination requirements among multiple nodes, network density, size and energy limitations. The UAV application versatility also pose other challenges on the communication layers that requires attention in the design of MAC, routing and transport protocols to achieve application requirements for reliability, scalability, adaptability and resilience. For instance, where applications like construction demand tight timing synchronization amongst devices in the system, other applications such as area coverage for crop monitoring may allow the UAVs in a system to work in a more time-independent manner with respect to each other. Applications such as aerial filming of events, for instance, for entertainment or journalism may demand high rate downlink transfers to multiple clients on the ground, whereas in applications where UAVs act as data mules for terrestrial wireless sensor networks, it may be safe to assume that traffic is uplink (low rate or bursty) from the ground nodes to the UAV. In short, different applications pose vastly varying demands on the design of the aerial network. Therefore, intuitively, *a study of such mission demands posed by applications may prove as the cornerstone for the design of the emerging aerial network communication technologies.*

Motivated by this, we classify the envisioned civil UAV applications into four categories: *Search and Rescue (SAR)*; *Coverage* (e.g., area coverage (monitoring, surveillance), network coverage (UAVs as relays/base stations/data mule)); *Delivery/transportation*; and *Construction*. These categories span aerial networks with different number of UAVs, mission distances, mission goals and requirements, and on-board sensors. The categorization, however, is not meant to cover all applications of multi-UAV systems but to broadly classify them such that the communication demands and requirements can be differentiated from one category to another. Given these application categories, we determine quantitative and qualitative communication demands for an aerial network. Specifically, we survey and quantify QoS requirements for each application category, network-relevant mission parameters, data type requirements (in terms of what to send, to whom, when, how), and the minimum data to be transmitted over the network for a successful mission. Furthermore, we also elaborate on general networking related requirements such as connectivity, adaptability, safety, privacy, security, and scalability. We then classify the existing projects pertaining to each application category in terms of their findings, constraints, assumptions, requirements, and report on experimental or simulation results. Based on the classification of these applications and their communication requirements, we evaluate the existing communication technologies and their feasibility for each application category along with the limitations and requirements for future developments.

The dependence of communication network design on mission requirements may pose constraints on the network design, but may also prove advantageous. Such a mission-dependent design as this survey reports may be difficult, since considering all possible applications and designing an aerial network that may satisfy the demands of each of these applications is not a trivial task. Hence, we aim to find common demands for most, if not all of the known aerial network applications. Advantages of such an application-based classification are manifold. Considering the qualitative and quantitative demands may enable the design of a communication technology that may be tuned to the specific demands of the aerial network applications. On the other hand, such a communication network design encompassing all application demands may be unfeasible or inefficient, which then opens new research areas. The article does not describe specific communication protocols, as has been done in other surveys, but paves a path for the design of such protocols by bringing to light the qualitative and quantitative requirements posed to the aerial networks by different applications.

We envision that such a survey on aerial networks will provide valuable insight for communication and networking needs of swarms of unmanned vehicles, that will occupy our skies in the near future. While the application domains for UAVs as well as data volume over the aerial links will keep on increasing beyond what has been investigated so far, we believe that the findings reported in this survey will serve as a significant building block to pave a path for the design of a reliable aerial communication network accommodating the requirements for multi-UAV applications.

The remainder of the article is structured as follows. Section II gives a background of the existing surveys on multi-UAV systems. Differentiating characteristics of aerial networks are provided in Section III. Section IV defines autonomy regarding UAV networks and illustrates the relationship between autonomy and communication. A classification of civil UAV applications is given in Section V, which is then used to introduce qualitative and quantitative communication demands from an application viewpoint in Sections VI and VII, respectively. Section VIII discusses whether the existing wireless technologies can meet the identified communication requirements. Section IX reports open issues and potential new research challenges and Section X concludes the survey.

II. Background

Small-scale UAVs, for instance multi-rotors [21], that have recently gained attention are envisioned to be part of our future societal life. The rotors of a multi-rotor UAV control its movement (yaw, pitch, roll and throttle). UAVs can be equipped with different sensors like IMU, range sensors (ultrasonic, infrared, laser), barometer, magnetometer, GPS, cameras and visual systems based on the application they are being used for [22]. Although UAVs can be used for various interesting applications, there exist many problems and open research issues that demand further study and research. In this section, we highlight these open issues identified in various survey studies on UAV systems and applications. One of the main problems, however, is of the approval from regulatory agencies for flying the UAVs in civil space [23].

The use of a multi-UAV system over a single UAV system for distributed processing is advocated in [12]. The authors report that the applications that employ cooperative teams of UAVs include but are not limited to *object detection*, where multiple UAVs search for a target and share the information with each other, *tracking* detected objects, e.g., a moving target, jointly, *surveillance*, *sensor data collection*, *navigation*, *collision avoidance*, *coordination*, *monitoring* (environmental, fire detection), *irrigation* and *water management*. Distributed processing is considered as a future research direction for applications involving multiple UAVs.

The multi-UAV system, classified as flying ad hoc network (FANET) in [24], is noted as a special form of mobile ad hoc network (MANET) and vehicular ad hoc network (VANET). The authors report that FANET bears different characteristics in terms of node mobility, node density, frequency of topology change, mobility pattern, radio propagation, power consumption, computation power, and localization compared to other forms of ad hoc networks. With such different characteristics, the communication challenges also differ in FANET from MANET and VANET. This calls for the need to propose, design and test new communication protocols in a layered approach suitable for FANETs. In addition, there is a need to develop a multi-UAV simulation platform that can be used to test the communication designs and protocols with different mobility models for different application domains and scenarios.

Open research issues on routing protocols, communication and networking in FANETs are identified in [25]. The existing MANET routing protocols, may it be static, proactive, reactive or hybrid are not sufficient for FANET since they are either not fault tolerant, scalable, or provide limited communication resources and are not designed for peer-to-peer mobile ad hoc networking between UAVs and the ground stations. It is identified that meshed communication architecture offers the best option in terms of flexibility, reliability, and performance compared to other possibilities [26]. Although mesh networking is promising for multi-UAV applications, the impact of mobility is the key issue with the challenge of nodes spreading out to leave them sparsely connected.

The heterogeneous unmanned aircraft system (HAUS) is developed to study multi-UAV communication networks and multi-vehicle cooperative control. Experiments conducted for ground-ground and air-ground communication demonstrate feasibility of mesh network on highly mobile nodes, however, it is discovered that the network could not distinguish if the packet loss is due to mobility or is due to the network congestion. This motivates the need for delay tolerant protocols (DTN). However, DTN protocols are required to be designed to cope with communication challenges in 3-dimensional space and account for times when the network becomes unavailable [26].

Mobility is a major concern in a multi-UAV system over the design of communication protocols. The network performance evaluation of developed protocols requires use of correct mobility models for particular applications, considering the fact that field tests are expensive and restricted to specifically designed settings [27]. The existing mobility models are classified as random, temporal dependent, spatial dependent, models with geographical constraints, and hybrid. These categorized models are evaluated based on their adaptability for multi-UAV systems, networking performance, and ability to realistically capture the attributes for multi-UAV systems.

Random models are unrealistic since randomly chosen points ignore the temporal and spatial correlation and does not mimic aerodynamic constraints of aerial nodes. The Gauss-Markov mobility models are more realistic since they take temporal correlation into account, however, they do not appropriately model the turn behavior of aerial nodes and do not consider safety requirements. The existing UAV mobility models include semi-random circular movement model that can typically be used for SAR applications and three-way random and pheromone repel mobility model possess spatial correlation properties and are suitable for coverage applications. Smooth turn mobility model captures spatiotemporal correlation of accelerations that are reflective of aerodynamics and captures frequent network topology changes and are more suitable for patrolling and reconnaissance applications. The flight plan mobility model depicts pre-defined flight plans and captures aerodynamics, high mobility and safety constraints. The flight plan mobility model is good for cargo and transportation scenarios where flight dimensions are known before hand. Although there exists a number of mobility models that are suitable for modeling mobility scenarios for different applications, none of them comprehensively consider safety requirements such as collision avoidance.

Besides the concerns about safety regulations, bandwidth and spectrum allocation is also an issue for multi-UAV systems and applications. The increase in the development and usage of new devices for wireless and cellular networks has developed the problem of spectrum scarcity. Cognitive radio technology (CRT) is a promising solution to address the problem of spectrum scarcity by harnessing the white spaces of licensed and unlicensed spectrum [28]. Many UAV applications including traffic surveillance, crop monitoring, border patrolling, disaster management, and wildfire monitoring have been identified that can use CRT for communication and networking, however, many integration issues and challenges need to be addressed to make use of CRT for UAV applications.

These surveys have identified several communication and networking specific open issues, which include: the need for a dedicated spectrum that could allow robust and sustainable communication; antenna design and radio propagation models fitting 3D communication; the development of physical layer protocols for movement aware rate adaptation to improve communication efficiency; the development of MAC layer protocols to cater for high link fluctuations and to minimize latency variations caused by high mobility and varying distances between nodes; the design of routing protocols that allow adaptability with the change in network density, topology and location of nodes and that consider node failures and admittance in a multi-UAV environment; development of transport layer protocols to address the reliability, congestion control, and flow control issues due to high bit error rates and link outages caused by frequent topology changes; and the design of protocols to support multimedia applications considering strict delay bounds, minimum packet loss, and high bandwidth demands and to support diverse traffic types including real-time, periodic and delay tolerant.

When we consider communication design issues for aerial networks in further detail, [24] addresses questions about any new demands that come into play because of the specific characteristics arising due to the agents in an aerial network that may pose demands for a new communications technology. Similarly, the authors pose open issues that arise from usage of current technologies when applied to aerial networks. [29] has looked into the implementation of pre-exisiting technologies to the design of aerial network, and discussed the pros and cons of using each of these technologies. However, it is hard to analyze the pre-existing technologies for their suitability of implementation to any and all of the application domains, and the authors in [29] mention technology implementation in relation to specific applications. Similarly, while considering the design requirements and challenges in 3D networks, [30] specify that mission objectives play an important role for such considerations. Some works, such as [31] and [23] focus on aerial networks for specific applications, such as disaster response and traffic surveillance, respectively. A survey for the unified solution to the problem of aerial network design considering application specific *qualitative* and *quantitative* demands is, however, missing. This work focuses on this aspect by considering aerial network applications. It is concluded from our study of the previous works that such a survey is necessary for a unified aerial network design, if possible.

More specifically, in this survey, we focus on identifying the minimum data and communication requirements of UAV systems, given their applications. In other words, we consider the multi-UAV system or the aerial network, as a mission-constrained network and analyze the requirements beyond that of a traditional communication network and give a detailed analysis of the communication demands posed by different application scenarios. We categorize the applications in four domains depending on their communication requirements. The categories cover most, if not all existing UAV applications, and differ from each other not only in terms of mission requirements but in terms of networking and communication demands, requirements, and communication priorities. We further present a comprehensive analysis of the existing communication technologies with their limitations and recommendations for different UAV applications. While we dedicate the qualitative and quantitative demand analysis to explaining how some of the reported issues are solved given our categorization, we also report the issues that are still open from joint communication, application, and mission planning viewpoint, which cannot be solved without considering all these dimensions our survey elaborates on. This work then will not only be useful in designing aerial communication protocols based on identified requirements but can also be helpful in selecting and improving appropriate communication technology for a given application.

III. Aerial networking – Network specific characteristics

Due to the nature of the devices used, some characteristics specific to aerial networks arise that differ from those of other wireless networks, such as MANETs, VANETs, and traditional wireless sensor networks (WSNs). The characteristics of aerial network from traditional communication and networking viewpoint including radio propagation model for aerial networks; power consumption and network lifetime; computational limitations due to size and weight constraints; adaptability with respect to mobility, node failure, effects caused by changing environmental conditions, and flight path updates; scalability with minimal performance degradation; and application dependent bandwidth and latency requirements are comprehensively addressed in [24]. However, each application where UAVs are deployed, comes with different demands in terms of number and type of vehicles, the size of the area the vehicles are deployed for, payload and flight time constraints, mobility requirements, and level of autonomy. For instance, observe from Fig. 1 that structural monitoring requires coverage over smaller areas, e.g., a bridge, a building, a power plant, and thus the number of expected vehicles employed is usually less than ten [32], [33]. In roadside surveillance, even though the areas to cover are larger, the number of nodes employed does not generally exceed ten [34], [35], [36]. Similarly, for network provisioning, where High Altitude, Long Endurance (HALE) UAVs are used due to their longer range of operation, a single UAV may be able to provide coverage over tens of kilometers [37]. On the other hand, tens of nodes may be required for construction, environmental monitoring and event coverage, even though each of these applications operate over different area sizes. For construction [38], more UAVs may be required to achieve task sharing and coordinated task execution. For example, several UAVs may be required to carry heavy loads or while some UAVs are picking up the structural loads, others may be responsible for fixing the structures at the destined positions. For wildfire monitoring, the detection areas over which the UAVs have to fly are expected to be in the range of kilometers [39]. In order to provide different vantage points [40], as well as to maintain continuous network connectivity to the ground personnel potentially using relay UAVs [15], a large number of UAVs is required. Similarly, for event coverage, such as sports event monitoring, tens of UAVs may be used to keep track of the participants of the event, as well as to form a potentially multi-hop communication link to the ground clients that are following the event [41]. In case of delivery of goods, such as medicine [42], post [43], etc., the areas over which the UAVs spans may range from kilometers to tens of kilometers.

The environment under consideration can be urban or rural [44]. To meet the clients' demands in such scenarios, hundreds of nodes are envisioned to be employed for delivering goods at several different locations requested by a number of customers, for example, delivery of packages using UAVs by Amazon [43]. In the following, we classify area sizes such that the term "small" stands for tens to hundreds of meters, "medium" sized areas range in kilometers, while "large" areas range over tens of kilometers and more.

The above discussion illustrates that each application area varies in its *system demands* that might also affect a number of network parameters. Due to its mission-oriented nature, a UAV network imposes additional constraints and needs from communication viewpoint compared to traditional wireless networks. These mission-oriented communication requirements vary from application to application. For instance, some UAV applications may require reliable real-time communication, while others function with delay tolerant traffic. It is thus important to highlight the characteristics of aerial networks and further identify the communication demands and constraints for mission oriented UAV networks. In the following, we briefly describe the characteristics of aerial networks focusing on the *types of vehicles, the payload, and flight time constraints*, that might affect the range of communication and network lifetime. We then brief upon the *3D nature of aerial links* and the *mobility of aerial devices* that result in frequent topology changes. The open issues arising from these characteristics and the existing solutions in literature are also mentioned. It is important to emphasize here that we focus on these characteristics (among the many detailed and analyzed in [24]), since each of these characteristics are affected by the mission demands of the aerial network applications and have a direct impact on the design of the communications network, which we survey in the latter sections.

A. Aerial vehicles and their constraints

The vehicles used for aerial networking come in various forms due to the requirements of the applications they are deployed for. A classification of aerial vehicles based on their range, endurance, weather and wind dependency, maneuverability, and payload capacity can be found in [45].

An aerial network can encompass one or many of these vehicles, depending on the requirements of the network. In a scenario, where there is a need to provide long-term connectivity to ground devices, such as network coverage provisioning, balloons may be the devices of choice due to their high endurance [11], [46]. If large areas need to be covered, as in monitoring and mapping applications, fixed-wing devices are more favorable due to their longer flight times [47]. However, in operations where the UAV is expected to hover close to objects with good command over flight maneuvers, for example for structural monitoring [32], rotary-wing systems may be the devices of choice [45]. The choice of the vehicles affects the range of operation and the number of required vehicles. Large unmanned devices usually offer longer range of connectivity over a single link since they can carry heavy dedicated transceivers, while small UAVs employing Wi-Fi compliant radios, the same range of connectivity can be expected using multiple devices with ad hoc networking.

Commercially available small UAVs that are used today, though cheap, are constrained in their payload and flight time capacities. There is an inverse relation between the payload and flight time capacity of the UAVs [48]. However, to counter the currently faced challenge of flight time constraint, one can employ different techniques. These techniques may highly depend on communication network formation, or may be completely independent, based on methodology of implementation to address the challenge. As an example, a visual mapping problem with real-time constraints is considered, where the area of interest is outside the communication range of the base station. A single UAV taking images of the area can perform multiple trips for complete coverage, renewing battery after each trip [49] (communication independence). Similarly, to avoid the back and forth flight, a relay chain of nodes can be placed between the sensing UAV and the ground station to transfer the images in a real-time manner [50] (communication dependence). These design choices determine the communication needs to be met.

B. 3D nature

The 3D nature of the network demands the support of various types of links. The links in an aerial network can be either air-air (A2A), air-ground (A2G) or ground-air (G2A). These links have been analyzed against each other as well as against ground-ground (G2G) links [15], [18]. It has been stated that these links have to be modeled differently due to their distinct channel characteristics, which affects the supportable network related QoS, and hence the sustainable traffic on each type of link. The wireless channel is also affected by elements in the 3D space, which corresponds to the terrain over which the UAV is flying, along with the number of obstacles in the space. The high mobility of the devices in 3D space is also important to consider, since antenna orientation, and hence link quality fluctuates widely with mobility [51]. Antenna structures supporting an omni-directional coverage in 3D space is a challenge and has been addressed in literature for rotary wing [16], and fixed wing devices [52].

C. Mobility

In many application scenarios, the aerial devices can facilitate time efficiency due to their high mobility [39], [40]. Due to this high mobility, however, the terrain over which the UAVs are flying is expected to change very frequently, for instance, from woodlands to lakes to buildings during a single flight. Not only do terrain-induced blind spots affect the wireless channel, but they may also introduce frequent topology changes amongst multiple devices that require connectivity (UAVs, ground clients, and base stations). High mobility is also a characteristic of VANET, however, VANET mobility models follow restricted routes in 2D, for example, highways and roads, whereas aerial devices are characterized by the demand for mobility in 3D space. Thus, not only may the terrain over which the UAVs are flying change frequently, but also the altitude of flight may have to be varied to avoid obstacles and collisions. Constraints posed on the altitude of flight of UAVs are emphasized in [39]. It is stated that even though high altitudes correspond to a larger field of view, the currently available sensors are constrained in their accuracy, and hence prevent the UAVs from flying beyond certain altitude levels. Thus, for higher detection probabilities, the UAVs may be constrained in their flight altitudes and speeds. Wind speed at higher altitude is also a limiting factor, as commercially available UAVs are currently unable to sustain stable operation during high winds and other adverse weather conditions.

Considering these characteristics, the communication protocols developed for an aerial network should allow robust networking of highly mobile devices. Link availability estimation in highly mobile aerial networks for reliable routing has been the focus of [53]. However, the speed of the devices under consideration in this work is between 700 km/h to 1000 km/h, which is much higher than those of commercially available small UAVs. Mobility in aerial networks also demands that the network protocols should be more flexible than VANET protocols in terms of mobility modeling. Some common mobility models for ad hoc networks include random waypoint mobility model [54], random direction model [55], Brownian like mobility model [56], etc. Readers are referred to [57] for an exhaustive survey on mobility models in wireless networks. However, with mission oriented scenarios such as in aerial networks, such mobility models are likely not suitable to satisfy all types of missions [27]. For instance, UAV mobility can be pre-defined as in [58], where paths are optimized based on computed picture points to maximize coverage in the given mission time, can be planned in advance as in [59] to avoid collisions while multiple UAVs participate in the construction process, or can be adapted online during the mission meeting coverage and communication constraints [60]. Furthermore, controlled mobility can also be used as in [61], where the UAVs are constrained in a soccer field to provide coverage of a sports event while the UAVs move with the movement of the soccer ball. Some other mobility approaches including flocking movement, potential field movement and virtual spring movement are discussed in [62] for collecting sensor data and images from a field. Trajectory design for network coverage and data collection from sensor nodes based on Hilbert Space Filling Curve considering node density and connectivity is proposed in [63]. The overall goal, however, is to maintain connectivity through controlled mobility and achieve specific mission objectives. Since in aerial networks, the mission objectives and network conditions vary, the mobility shall be controlled considering a lot of network parameters. This includes, the node density, terrain, connectivity range, communication technology and mission requirements e.g., traffic type, frequency, and traffic priority.

Furthermore, as in other networks, mobility can be used as an advantage in aerial networks, where the network may not be fully connected all the time. In this case, the highly mobile devices can be positioned at optimized locations in a time efficient manner such that some network QoS can be supported [64], [17]. Also, the controlled mobility in 3D space can be used to enhance range using directional antennas [65]. Thus, mobility can play a significant role when designing aerial networking protocols.

In the following sections, we survey the design needs of multi-UAV systems from a communications viewpoint. Specifically, we focus on autonomous mission-oriented aerial networks and we emphasize on the relationship between aerial network solutions for different application scenarios and communication, and discuss their dependence on methodology of implementation.

IV. Communication Demands of Autonomous Mission-Oriented Aerial Networks

Up to this point in the survey, we have considered the communication demands arising from the intrinsic characteristics of the aerial network and the devices used in the network. We now move on to analyze communication demands that arise from "Aerial System Design" viewpoint. For several of the envisioned UAV applications, it is expected that the system of UAVs has to work autonomously towards the desired goal. Autonomy in an aerial network can be classified as "Device" (individual) and "Mission" (system) autonomy, both of which have a great impact on the communication demands of the aerial network. The following subsections aim to address autonomous aerial network design and the resulting communication demands, capturing the mission-oriented nature of the UAV networks.

A. *Device Autonomy*

Device autonomy relates to the control of the UAVs and can be used to specify whether a UAV can fly autonomously or needs remote controlled (RC) navigation by a (human) pilot. It is important to note that to ensure safety, UAVs are obligated by law to stay in RC range for human intervention in case of an emergency. UAVs can fly autonomously following pre-computed or adaptive waypoints. These waypoints can be decided by a central processing entity, like a base station, and then sent over a communication link to the UAV. The UAV can also decide its path on-the-fly by using the information collected from the environment (terrain, obstacles, as well as presence of other UAVs) via on-board sensors. Communication demands vary based on the methodologies employed, but always increase as the level of autonomy is enhanced [66]. Different levels of autonomy have been specified and employed by [67] in their work. These are operator controlled (i.e., no autonomy), centralized processing for data association and tracking, and complete on-board decision autonomy. Intuitively, each level poses different requirements on the aerial network design. As a first step, we quantify these demands by classifying the exchanged traffic necessary to enable device autonomy.

Considering device autonomy, we classify transmitted traffic into *control* traffic (RC data exchange), *coordination* traffic (waypoint or mission plan exchange), and *sensed* traffic, in a similar fashion as in [13]. In the following, we describe the varying traffic exchange requirements considering different levels of device autonomy. For instance, when there is no device autonomy, and a human operator is responsible for the control and navigation of the UAV through an RC, the traffic that is required to be exchanged between the UAV and the RC unit is the control traffic. If we go a step further in the level of control autonomy, where a central entity can provide waypoints to the UAV to fly autonomously, the data exchange requirements change and also include support for coordination traffic. For fully autonomous devices, where the next waypoint to fly is decided on-board the UAV itself, the UAV is required to be equipped with some sensors to locate itself related to obstacles and other UAVs in its vicinity. In this case, the RC traffic exchange is accompanied by the demand for sensed data exchange as well. This sensed data is to be provided to the on-board processing unit, and may also be provided to a central entity (for decision making by ground personnel in case of, for example, a disaster situation, or for providing a higher level of redundancy to ensure safety). Additionally, some coordination traffic exchange may be required amongst the decision-making UAVs for acquiring knowledge of the individual path plans of the neighboring UAVs. Thus, for design of a functional flying device, the communication module has to be designed considering these traffic exchange requirements, which depend on the level of expected device autonomy.

For a fail safe communication system design, it is important to consider the basic control information exchange requirements that enable device autonomy. This can help us in estimating if currently available technologies are capable of supporting such information exchange. Currently, the autopilot control for UAVs includes tasks like pitch attitude hold, altitude hold, speed hold, automatic takeoff and landing, roll-angle hold, turn coordination and heading hold [68], [22]. This demands that system states be provided to the autopilot at a rate of 20Hz [18]. Current technology promises support for such rates [68]. As an example, with AR Drone, the control loop maintains a connection using watchdog command every 30 ms. The control commands are 20-60 Bytes. The device performs emergency landing if no command is received in a duration of 2 seconds [1].

B. Mission Autonomy

Mission autonomy relates to the coordination between the entities in the network, including UAVs, base stations and other devices forming part of the network. Having a central decision making entity (DME) offers a simpler solution than a distributed system of decision making devices, in terms of design and processing power required on-board each device. However, distributed decision making may offer superior solutions in situations where avoiding a single point of failure is desired. Also, as mentioned previously, in aerial networks, which suffer from payload and flight time constraints, parallel processing on-board multiple devices may be a desirable attribute to increase time efficiency.

For an aerial network, we define mission autonomy and corresponding traffic requirements depending on the DMEs and the decision making process, as shown in Table I, using a two dimensional decision matrix. We define the DMEs as either *centralized* or *distributed*, represented by the rows of the matrix. The columns stand for the decision making process,

[1]AR.Drone SDK 1.6 Developer Guide. Parrot USA, 2011

TABLE I
DECISION MATRIX TO CHOOSE THE LEVEL OF MISSION AUTONOMY AND INFORMATION EXCHANGE

<table>
<tr><th rowspan="2"></th><th rowspan="2">Offline</th><th colspan="2">Online</th></tr>
<tr><th>Min Info</th><th>Max Info</th></tr>
<tr><td>Distributed Individual</td><td>Telemetry</td><td>Telemetry</td><td>Telemetry
Sensed</td></tr>
<tr><td>Distributed Consensus</td><td rowspan="2">Telemetry</td><td rowspan="2">Telemetry
Coordination</td><td rowspan="2">Telemetry
Coordination
Sensed</td></tr>
<tr><td>Centralized</td></tr>
</table>

which according to our definition can be either *offline* or *online*. The elements of the matrix describe the methods that can be adapted for the mission completion. The level of autonomy in the network depends on a combination of entities and processes. An offline, centralized decision provides the least amount of mission autonomy, while an online decision, made in a distributed manner, ensures highest level of mission autonomy.

The table also summarizes the traffic to be exchanged between the devices given the DME and process. Observe that the communication demands do not depend entirely on the mission autonomy. These demands increase with the amount of information exchanged during online processing. They also depend on whether the distributed decision making is done on an individual basis or through consensus between the network entities (e.g., UAVs). Consensus-based decision making [69] is expected to pose higher demands on the design of the communication component than an individual based [70]. This is because distributed individual decision making does not require coordination information exchange between entities in the network. The data that is needed to be supported by the communication module considering such classification is shown in Table I. We divide the exchanged mission data into *telemetry*, *coordination*, and *sensed* data. The classification is based on the functionality each type of data provides, as their names indicate. To be more precise, *telemetry* includes the inertial measurement unit (IMU) and global positioning system (GPS) information [71]. *Coordination* data is any data that needs to be exchanged for coordinating the entities in the network. This may include synchronization information, flight path decisions, routing information, etc. Lastly, *sensed* data encompasses anything that is used to measure the physical environment. The information exchange before the mission starts (offline decision dissemination) and RC data exchange is not considered here.

According to the above classification, the minimum information that may need to be exchanged is the location information, which falls under telemetry. In case of centralized decision making, the minimum information exchanged from the central entity to the UAVs would also include coordination data [72]. For consensus based decision making, coordination information may also be required to be exchanged, as in [73]. In case of maximum information exchange, additionally, sensed data needs to be exchanged, so that each UAV can contain a complete belief map of the other UAVs based on their observations. For individual decision making in a distributed scenario, this can be seen in [74], while for consensus based case, [40] uses complete belief map exchange.

At first glance, Table I may seem to answer the question posed about the demands from the communication module of an aerial network, by relating the exchanged traffic to the decision making methodology employed. It may seem that if we are able to quantify the traffic for mission autonomy in a similar manner as that for device autonomy (see Sec. IV-A), we may be able to design an aerial network fulfilling the demands of all application areas employing UAVs. This, however, is not the case. Decision making methodologies represent possible solutions to the problem of an aerial network design for certain applications. However, they do not provide the complete picture in the design of the required communication system, since there is no one-to-one relationship between a methodology and an application scenario. For example, one may use centralized decision making to address SAR mission, arguing in favor of the simplicity of implementation of the solution. This is because no processing power is desired on-board the UAVs. Also, a centralized solution can easily address collision avoidance amongst UAVs. However, in this approach, a bulk of data needs to be transferred downlink to the central DME. A multiple-source, single-destination system may suffer from worse outage performance. This has been addressed in [75], where the authors propose use of as many receiving antennas at the destination as the source nodes to reduce the outage probability. Another solution to reduce bulky data transfers on the downlink is the use of distributed decision making. Thus, by transferring some of the processing power on-board, the same SAR scenario can be addressed in a distributed way. Therefore, specifying the communication demands in relation to methodologies does not answer the following question: *What are the basic communication demands from an autonomous aerial network posed by applications in aerial networks?* To answer this question, we need to look at the objectives and constraints posed by the aerial network application areas. These objectives and constraints will provide an understanding of the *minimum requirements* of these application areas and hence, will pave a path for the *design of a global, reliable aerial communication network*, if possible.

We observe that it might not be feasible to specify a set of objectives and constraints that address all applications falling under the vast field of UAV commercial usage. The next section addresses this issue by dividing the application areas into domains that share similar characteristics, objectives, and constraints. The methodologies implemented by real-world projects for these domains are summarized to emphasize how each application category can be treated using different methods. However, none of the projects take into account the minimum traffic requirement for their chosen implementation methodology. Thus, the purpose of stating the methodologies here is not to compare them amongst each other in terms of communication demands, but to emphasize that each application can have multiple implementable solutions. The aim of the following discussion is that the readers may be able to design their aerial communication network by keeping in mind the application under consideration (Sec. V), the qualitative (Sec. VI) and the minimum quantitative (Sec. VII) communication demands for the addressed application, and the methodology chosen for implementation (Table I). Alternatively, keeping in mind the limitations posed by the current standard communication technologies (Sec. VIII) in terms of parameters such as communication range, maximum physical layer rate and latency etc., the readers may be able to design the solution methodology of implementation accordingly.

V. Categorization of Aerial Network Applications from Communications Viewpoint

There is a plethora of UAV applications with varying demands and goals, which makes the classification of aerial networks into specific application domains a difficult task. In this survey, we attempt to classify the currently researched application areas from a communications and networking viewpoint (see Fig. 2). Namely, we identify mandatory (solid lines) and desirable (dashed lines) qualitative and quantitative communication needs and determine four general application categories with the identified needs. These application categories are: *SAR*; *Coverage* (e.g., area coverage (monitoring, surveillance), network coverage (UAVs as relays/base stations/data mule)); *Delivery/transportation*; and *Construction*. To the best of our knowledge, such classification of application domains taking into account communication requirements has not been done before. We discuss the qualitative requirements mentioned in Fig. 2 in more detail in Sec. VI. Note that while there are overlaps in qualitative demands amongst the classified domains (e.g., connectivity to a decision making entity is a mandatory requirement for all application domains), there are enough distinctions that may demand different communication architecture for handling each domain.

We expect that most if not all of the current civil UAV applications can be fit into one of the identified application categories, however, we do not claim to have included all existing and emerging applications in this survey. The purpose of this classification is to have distinct application domains that can effectively represent the communication demands for aerial network design. For instance, considering our classification of the applications, one can observe that while *SAR* and *coverage* can be viewed as communication networks (e.g., MANET or wireless sensor network), *delivery of goods* and *construction* can not be viewed as such, but may benefit from the presence of a reliable communication network. Both *SAR* and *coverage* domains require low to high network traffic to be transferred over short or long ranges based on the mission requirements. The difference between these two domains is the distinct mobility requirements in *SAR* domain due to specific mission characteristics (life threatening, time-limited situations), while all other aerial communication related missions fall under *coverage*. For *delivery of goods* and *construction* domains, the UAVs are not used to form an aerial network for data transfer. However, presence of a network can be desirable in these domains. For *delivery of goods*, we require that the network should be capable of long range connectivity and carry small amount of data traffic. Thus, long-range, low-capacity links and periodic data transfers characterize the communication network that can facilitate the delivery of goods application. On the other hand, for *construction* domain, the distances are much shorter, but the transmission frequency of network traffic is quite high. Such a network design will require consideration for high-frequency, short-range, reliable links. All this is elaborated in more detail in the following discussion, where we describe the characteristics of the application categories and summarize the existing works falling into each category. We survey the constraints, assumptions, mission requirements, and methodologies of implementation employed by the existing projects, to extract information which will be used later in Sections VI and VII, in order to report the identified qualitative and quantitative demands. These are illustrated with the help of Figures 2-7, and summarized in Table III in more detail.

A. Search and Rescue (SAR)

One of the main application categories that has attracted considerable attention is SAR. For instance, SINUS [72] aims to develop a reliable network of UAVs keeping in mind the needs of first responders such as fire fighters. The system design considers the dependencies between communication, coordination and sensing components. CLOSE-SEARCH [76] aims to address the problem of unknown terrain, as a disaster may change the known map completely. SMASH's [77] objective is to incorporate feedback from the ground personnel into distributed decision making and collaboration amongst UAVs. The project keeps in mind the limitations in bandwidth when multiple devices require the use of the wireless channel. SUAAVE [40] considers time critical disaster situations and aims to rapidly acquire aerial imagery in dangerous terrains from different vantage points. RESCUECELL [78] focuses on developing a cost-effective, robust and lightweight technology that is easily portable to disaster struck zones. The aim is to provide a complete coverage of disaster area in minutes and robustly locate the victims. SHERPA [79] focuses on SAR in alpine regions in particular to the targeted application areas. The project aims to develop a system of ground and aerial robots that is capable to collaborate with the rescue personnel. There are many other projects that design their systems keeping in mind some of the many aspects of SAR. However, the mission objectives for SAR remain the same and need to be specified here in order to understand the characteristics and requirements of the SAR category.

In a search and rescue/track scenario, the UAV(s) are required to search for and detect single or multiple targets (stationary or mobile), and keep track of the state of the target(s) to facilitate rescue personnel in reaching the target(s) in a time efficient manner [12]. For example, in SAR operations for avalanche victims, where the survival time of the victims under snow is estimated to be less than 20 minutes [80], the ground personnel has very limited time to track the victims. Due to the time critical nature of SAR operations, *mission response time* has been considered the most important metric to optimize, to ensure support for victims' lives [81]. Observe that mission response time determines the type and number of vehicles to be used in the desired search region and hence affects the communication architecture.

1) Constraints: For the SAR operation, the testbeds and simulation works take into account certain specific constraints. In SAR operations where the size of the disaster struck area is on the order of kilometers [82], limited communication range of the commercially available small UAVs may act as a constraining parameter. Multi-hop communication may be required to satisfy communication in SAR operations covering large areas [83]. SMASH project [77] also takes into account the scalability vs. available bandwidth in disaster scenarios. Limited bandwidth becomes a more critical constraint when considering a disaster scenario such as an earthquake, where victims stuck under rubble are trying to connect to first responders via their mobile devices. This constraint on the bandwidth increases with the number of victims trying to establish connectivity. Intuitively, however, the most important constraint in SAR applications are temporal and spatial constraints [84]. The temporal constraint corresponds to the constraint on mission response times imposed due to the life threatening nature of most SAR scenarios. On the other hand, some level of spatial decorrelation is also required to avoid collisions and enable more effective coverage of large search areas during flight. In terms of network design, the temporal constraint translates into low communication latency, while the spatial constraint demands large communication ranges.

2) Assumptions: The projects under development presume communication between devices to be available, either using infrastructure (i.e., star topology) [39], [67] or ad hoc mode (point-to-point) [40], [84], [77]. There are also arguments that support the use of Delay Tolerant Networks (DTN) for SAR operations [17]. Bandwidth is generally assumed to be limited [77]. Most projects assume that there is at least some a priori knowledge of the terrain before the commencement of the mission [39], [85]. For the design of a robust network, the a priori knowledge of the terrain helps in choice of the suitable propagation model. It is also expected that the devices used in the mission have knowledge of their current GPS coordinates [72].

3) Mission requirements: There are many facets to the development of an aerial system of commercial UAVs that can help first responders in successful and timely completion of SAR operations. The projects mentioned here focus on different aspects that may help achieve timeliness in SAR missions, and hence, the problem statement varies accordingly. The system needs to be designed keeping in mind that the target may be mobile [39]. Thus the aerial network is required to consider search area expansion as the search time proceeds. Longer ranges of communication or multi-hop ad hoc connectivity may be a requirement in such scenarios. As bandwidth is a limiting constraint, it is important to efficiently utilize bandwidth during multi-client, multi-device SAR operations using UAVs. Thus, QoS-based preferential bandwidth allocation may provide a solution to the bandwidth limitation problem [77]. Lastly, there is a need to understand the dependencies of different modules of an aerial network design to facilitate integration of these modules. Therefore, a robust and reliable aerial network is a unified system incorporating communication, coordination and sensing [72].

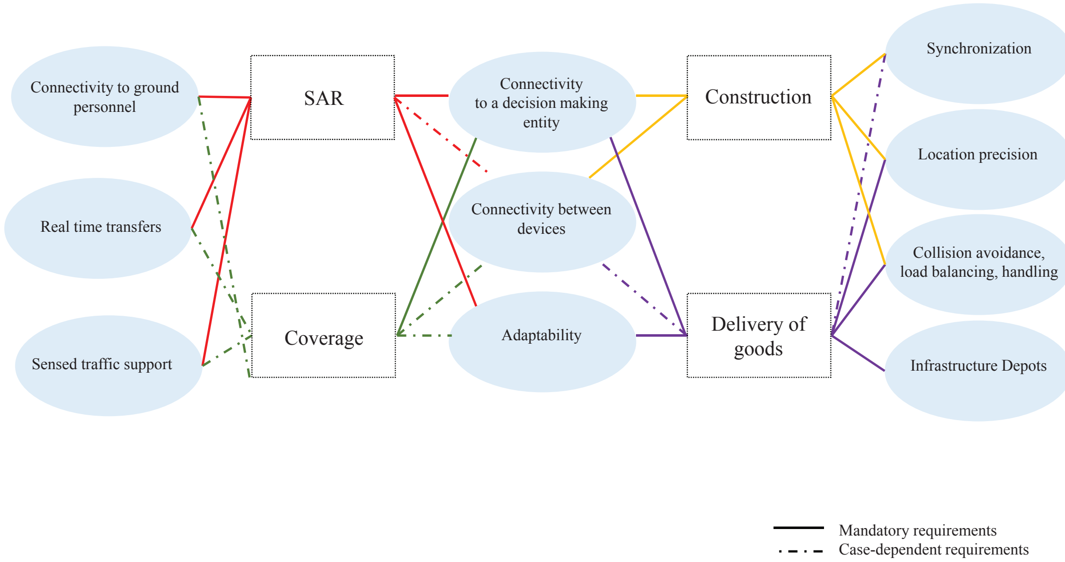


Fig. 2. UAV application domains are classified as Search and rescue (SAR), Coverage, Construction and Delivery of goods. Each application domain constitutes of multiple applications. The mandatory and case-dependent qualitative requirements are identified with respect to the application categories.

4) Methodologies: In [86] the authors consider the possibility of locating multiple targets/victims and propose the use of decentralized decision making for successful mission completion. Other projects also use distributed processing when using multiple UAVs in SAR operations [87], [77]. Distributed approach is more useful also in scenarios where the area is inaccessible and the terrain has changed drastically after a disaster. However, centralized approach has been applied in various projects where some a priori knowledge of the terrain is assumed, as it is simpler and less costly in terms of processing requirements on-board the UAVs [39], [84], [72], [76]. As mentioned previously, the choice of methodology of implementation has a direct impact on the network design (see Sec. IV).

5) Categories: Lastly, SAR can be further subdivided into two categories in terms of communication demands: SAR operations in disaster situations and for searching and tracking of lost persons or animals. In disaster situations, the critical constraint on response time is likely higher than in search and track of lost persons and animals. In Section VII, where we specify the quantitative requirements of missions in various application domains, the differentiation of these categories is clarified further.

B. Coverage

We denote the next UAV application domain as coverage. This domain encompasses the most applications, as many aerial network applications require covering an area considering specific mission demands. We subdivide this category into *area* coverage applications such as monitoring, surveillance, and mapping, and *network* coverage where UAVs are used as communication relays or data mules. A list of several real-world application areas and the corresponding projects (or proposals) is given in Table II. The applications are categorized for area sizes of small, medium and large (refer to Section III for definitions of area sizes).

For potentially large area coverage scenarios such as monitoring and mapping, UAVs can offer a more cost-effective and time-efficient solution. For example, time efficiency, processing efficiency, and manpower are used as the metrics to illustrate the potential advantages of using UAV systems over the conventional techniques in [88]. The role of UAVs is crucial also in network coverage provisioning, as in disaster situations where the terrestrial network infrastructure is lost, aerial devices may be the only means to enable and maintain communication to facilitate first responders [82].

The functionality provided by a UAV system for this domain can vary from acquiring images from a bird's eye view to sensing chemical plume (both classified as *area* coverage), to providing connectivity to ground clients or collecting data from ground WSN nodes and carrying it to a sink node (both requiring *network* coverage). This means that the traffic requirements of this domain of application areas may vary significantly. We can still classify such scenarios as belonging to the same domain, as the main goal is to provide coverage related to a certain entity.

1) Constraints: The constraints in the coverage scenario depend vastly on the environment where coverage is being performed and the operational area sizes. For instance, for large area coverage [82], [107], and in obstacle-ridden environments [50], communication range is a limiting factor. Multi-hop communication may be required to enable continuous connectivity [15] or delay tolerant network may need to be considered [17]. The constraints also vary according to the mission requirements, such as traffic and connectivity. *Area* coverage missions can have different traffic requirements.

TABLE II
CURRENT APPLICATIONS IN AREA AND NETWORK COVERAGE DOMAINS WITH RESPECT TO AREA SIZES

	Small-sized area	Medium-sized area	Large-sized area
Area coverage	structure and surface monitoring [32] [89] [90], construction site monitoring (cDrones [72]), mapping of archaeological sites [91] [92], bridge inspection [93]	vegetation monitoring [47] [94], aerial photography [95], event coverage and journalism [61] [96], mapping of disasters such as hurricanes [97], measuring contamination such as chemical plume [98] [99], earthquakes [100], landslides [101], surveying of disasters such as volcanic ash cloud analysis [102] etc	wildfire monitoring [67], highway surveillance [35] [103], Maritime surveillance [104], pipeline monitoring [105], border surveillance [106], Large area disaster mapping such as floods [107]
Network coverage	Network coverage in obstacle-ridden mapping or disaster scenario [50], Communications relay for autonomous underwater vehicles [108]	Temporary network coverage for mobile users or sports events [109], ground WSN coverage [110] [111]	Emergency network coverage in disaster scenario [82], [112]

Traffic can be *real-time*, *periodic*, or *delay-tolerant* as shown in Fig. 7. For instance, where mapping [113] and aerial photography [95] applications may be categorized as delay-tolerant (continuous connectivity is not a necessity), highway [103] and border surveillance [106] require real-time traffic support (connectivity to a base station is a requirement). On the other hand, *network* coverage of ground WSNs using a sink or relay UAV [110], [111] may require periodic data transfers (intermittent connectivity). Another important constraint while considering *network* coverage is on network bandwidth, where it may be expected that a large number of clients are trying to connect to each other [109], or to a UAV that is following players on a sports field [61]. Thus, bandwidth limitations need to be taken into account. It is important to state here that it is difficult to come up with global constraints for coverage, due to the diversity of applications in this domain.

2) Assumptions: Even though, as mentioned previously, bandwidth is a constraint for the system design in any application scenario, in coverage domain, where there is a large number of devices in the network, it is assumed that communication is available in cases, where real-time transfers are a necessity. This can be seen, for instance, in most scenarios of *network* coverage [82], and for surveillance applications [50], [107], [99]. However, additionally, some applications in the coverage domain also assume the presence of some reception infrastructure, for example a base station. This is commonly seen in *area* coverage applications such as border and highway surveillance [35], [103]. It is also assumed for most *area* coverage applications that some a priori information is available about the environment that makes the initial deployment of the system easy, for example, a map of the coverage area, presence of obstacles, location of roads, etc. [34], [103], thus allowing assumptions on the propagation model.

3) Mission requirements: Coverage is the domain that encompasses the most number of application areas, and hence the mission requirements and problem statements for the projects under development vary in nature. However, surveillance and *network* coverage share the aim of providing communication security and reliability [104], [82]. It is expected that the data will be asymmetric in *area* coverage. In *area* coverage, most information collected by sensors on-board the UAVs needs to be sent downlink to a base station [61], [72], [89], [90]. For *network* coverage scenarios where a UAV acts as a sink or relay to collect sensor readings over an area that needs to be monitored, while sensor motes on the ground are responsible for capturing the environmental measurements [114], the traffic transfer is mostly uplink [110], [111]. However, UAVs employed for *network* coverage in disaster scenarios might be expected to handle the same amount of uplink and downlink traffic. That is why projects focusing on communication in aerial networks analyze both uplink and downlink traffic patterns [18]. For *network* coverage, altitude of the devices in relation to the radius of provided coverage is the focus of research in [115].

In real-time and dynamic coverage scenarios like surveillance and network provisioning, the network should be able to reconfigure itself. For example, in surveillance, UAVs are expected to perform a seamless handoff between the base stations in an infrastructure network while tracking a vehicle [35]. Surveillance projects also propose vision based tracking along with GPS based localization [116], arguing that GPS connectivity may be lost in areas like tunnels [103]. Real-time monitoring and mapping application of forest fire detection is the focus of [67], where a system of heterogeneous (in tasks and capabilities) UAVs is developed for the purpose of cooperatively detecting, confirming, localizing and monitoring wildfire. For *network* coverage provisioning, network dynamics may involve clients entering and leaving the network, or topology change due to mobility [62].

4) Methodologies: Due to the diversity of the applications in this domain, it is intuitive that some demands may be mandatory for coverage, while others are case-dependent, according to the application under consideration (see Fig. 2). This also implies that many different algorithms and methodologies can be used to address the mission requirements, and this can be witnessed in the approaches adopted by the surveyed projects.

In [70], the authors use a decentralized decision making approach to provide *area* coverage employed for target detection and tracking. The work further aims to explore the minimum number of nodes required for coverage in a certain scenario. Similarly, in [117], the authors consider decentralized and cooperative decision making for task allocation in aerial coverage to harbor surveillance. On the other hand, in [118], where geo-referencing of real-time video is used for accurate localization in monitoring and mapping operations, a centralized decision making approach is utilized. Some works take communication system design under consideration while trying to achieve the system goals. In [119], the devices are expected to collaborate by employing distributed decision making to locate targets. This work assumes some periodic but imperfect "suspected target location information" communication from a satellite to the devices, which is used by the devices to decide which target to follow.

Communication system implementation of a network of UAVs for traffic surveillance and monitoring is the focus of [34]. A cellular network is used to collect downlink traffic from the UAV and provide to the ground users, and as such, the decision making is done in a centralized manner. In [120], the authors specially focus on the design of the aerial network communication system by considering beyond line-of-sight (LOS). Algorithms developed in the work enable relay chains calculation and relay tree optimization. Decision making is still implemented as centralized.

In [121], authors explore the situations where *area* coverage may either require or might be facilitated by swarms of UAVs. Even though autonomy is a focus of the work, the decision making is still done centrally via a base station. The different A2A, A2G and G2A channels needed for aerial swarm networking are described. In [67], where different levels of control and mission autonomy are explored, both distributed and centralized approaches are considered. Decentralized decision making is deemed advantageous in scenarios where multiple UAVs are acting as communications backbone for a group of ground clients [122]. The proposed approach is based on game theory, where coverage optimality is based on non-cooperative game. Lastly, a very important case study is [82] that provides the traffic requirements in an emergency *network* coverage scenario after disasters. The study argues in favor of using UAVs for forming an emergency aerial network in disaster scenario by stating that the population of victims in a large disaster struck area is generally confined in smaller places. It is, thus, more useful to form an overview of the disaster area using UAVs to locate such populated areas, so that rescue resources and time are not wasted. The study provides valuable information regarding communication requirements based on real-world data collected during hurricane Katrina. A decentralized decision making approach is considered.

5) Categories: Even though all the application areas included in this domain share the common mission requirement of providing spatial coverage (*area* coverage through sensors or *network* coverage of an area), there are some differentiating characteristics on the basis of which we can subdivide this domain into further classes. For the purpose of this survey, we classify this domain such that monitoring and mapping focus on acquiring some information from the environment, surveillance focuses more on event detection and tracking (and hence is real-time), while network provisioning mainly provides coverage to enable communication between disconnected clients. The differentiating characteristics can be clarified through Fig. 2, where sensed traffic support is a necessity for monitoring and mapping, and surveillance, whereas for network coverage provisioning, sensed traffic support is not required. Similarly, connectivity between devices and to the ground personnel may stand out as a necessity for network coverage provisioning and surveillance, but not for monitoring and mapping. Similar arguments exist for real-time transfers and adaptability. The differences amongst the classes in coverage domain will be clarified further in the next sections.

C. Construction

Construction using aerial robots is another unique and new application domain that features small aerial robots that lift building elements and position them at their precise locations. It is envisioned that construction using aerial robots can be less expensive and more efficient since they can fly in 3D space and place building blocks at locations that are hard to access with usual construction machinery [38]. Depending upon the payload capacity of the robot and the weight of the building block, the number of the required robots can be estimated for construction. Possibly more than one UAV is required to lift the structures, such as beams or building blocks to be placed precisely according to the digital blue print.

1) Constraints: For construction domain, constraint on the timing and synchronization among multiple UAVs, while the UAVs are constructing a structure, is of utmost importance. The timing constraint must be adhered such that when one UAV is lifting a building block from a pool, the other must be placing it at its destined location, and a third may be on the way to pick up the next block from the pool. Thus, the movement and task execution of an individual UAV should not conflict with another UAV participating in the construction process. Synchronization can also be a constraint when multiple UAVs are participating in building a structure as in [38], [123], [124], while it is a requirement when multiple UAVs are jointly lifting a load/building block [38]. In the latter case, synchronization is required between the UAVs for load balancing and maintaining the load's center of gravity while in the former synchronization is required among the UAVs to adhere to the timing constraints to avoid collisions. From communications viewpoint, there should be minimum delay and jitter for such tight synchronization.

2) Assumptions: For construction domain, the ground station instructs the UAVs with the location of the building blocks to be placed according to the digital blue print [6], [38]. Thus the ground station continuously monitors the location of the UAVs and instructs for trajectory changes in real-time [59]. From communications viewpoint, scalability affects the amount of data traffic (for synchronization and for localization) to and from the UAVs and the ground station, since multiple attempts may be required to grasp a building block requiring synchronization in real-time, when multiple carrier UAVs participate [6], [123]. Similarly, information on sequencing the building blocks also needs to maintained by the ground station and communicated to all participating vehicles if multiple UAVs serve in construction assembly simultaneously [123].

3) Mission requirements: The main objective of the construction application is to build structures based on the input from a digital blue print [124]. When using multiple UAVs, collision avoidance is one of the main concerns. [59] suggests a trajectory planning algorithm to avoid collisions and conflicts during assembly and structure construction proposed by the ARCAS project [125]. The trajectory algorithm takes the waypoints and expected arrival time of the aerial vehicles as input to identify conflicts. Once conflicts are identified, the trajectories are recomputed adjusting the velocities and acceleration to avoid collisions.

The ARC project [38] demonstrates a prototype called Flight Assembled Architecture to construct a 6 meter tall tower using a fleet of aerial robots with similar requirements of coordination, synchronization, localization, sequencing, and scalability. Special focus on the design of the building blocks is given such that the building blocks have some defined connection methodology and are able to construct a wide variety of structures. Thus scalability is added in terms of the area and style of the constructed structures.

Maintaining the correct sequence of the building blocks is also important for construction while multiple aerial vehicles are participating. Robots keep track of the number of blocks available in the pool; i.e., ones that have already been placed and where to place the next one.

For the construction application using aerial robots, aerial grasping capability, trajectory planning, collision avoidance, localization, coordination, synchronization and sequencing are the general requirements to be considered. The impact of these requirements on the communication and networking design is still to be investigated.

4) Methodologies: The existing works [38], [59], [123], [124], [126] that employ UAVs for construction using building blocks or tensile structures use a centralized architecture where the movement or location information of each UAV is fed to the central processing unit that computes the trajectories and velocities and sends commands to the UAVs to adjust their maneuverability.

5) Categories: In general, based on the existing projects, the construction application using UAVs can be categorized as a single UAV carrying low load, multiple UAVs carrying high load and multiple UAVs coordinating for building tensile structures or scaffolds as shown in Fig. 5.

D. Delivery of goods

The commercial availability of UAVs has not only attracted the attention of big package delivery companies like Amazon [43] with an idea to deliver goods even faster, but also startups like Matternet [42] to deliver medicines and small packages urgently in a disaster situation. Other companies like Zookal [127] is using UAVs for delivery of books in Sydney, and Tacocopter [128] aims to deliver Mexican delicacies with this new means of transportation. The aim however, is to deliver goods and products in a fast and efficient manner. This efficiency may be related to time, energy, or cost.

1) Constraints: Unlike other application classes, this class requires an infrastructure for the storage of goods and replenishing of energy for the UAVs, like in any transport scenario. This is because the travel distances for package bearing UAVs to cover are expected to be much larger than what can be supported by a single battery's energy (in current standards). The distance the goods need to be carried and distance the UAVs can travel identifies the required number of intermediate charging stations. As an example, the goal of the flying donkey challenge [44] is to deliver and collect 20 kg of payload safely within 24 hours, traveling a total distance of 200 km with only 6 ground stations along the way. Such an infrastructure may also be used as communication base stations to track the mobility of the UAVs [129], [130].

2) Assumptions: An important assumption for delivery domain is on available communication means and information exchange during the flight, irrespective of the distance from the base station. The connectivity with the base station may only be required for GPS tracking of the devices, or to send control information to and receive status updates from the devices. Thus, some form of communication is required for which connectivity is assumed [129]. This however depends upon the technology being used for communication, and the frequency and the amount of information being exchanged along with the distance between the base station and the UAVs.

3) Mission requirements: An ideal concept of operations for transportation such as cargo delivery is suggested by Aerial Cargo/Utility System AACUS [129]. It encompasses the VTOL based autonomous obstacle detection and collision avoidance and precision landing capabilities using autonomous path generation from take-off to landing points, that is modifiable in real-time by a human operator on the ground, thus requiring real-time data transfers.

For heavier loads that exceed the payload capacity of a single UAV, multiple UAVs are required to transport jointly. However, this involves cooperation in terms of physical coupling and information exchange between the UAVs, as suggested in [131].

Another consideration is the distance from the pick-up and delivery point. Since this application can scale from small to large distances, beyond LoS connectivity with the ground station is required to control and intervene for any changes during the mission to avoid collisions and to get status updates, GPS positioning, etc. [129]. If the UAVs do not have autonomous obstacle detection capability, a safe path for the vehicles is required to avoid collisions with other objects in the flight path [132]. At minimum, connectivity to keep track of the UAVs to identify any unusual behavior is a requirement [133], [131].

Safe and efficient transportation of load is another concern to be addressed while using UAVs for delivery of goods. Position and orientation information is fed to the designed controller in [134] at the base station to adaptively and cooperatively adjust trajectory and velocity of the quadrotors, to maintain the center of gravity of the load and swing-free maneuvering for safe carriage.

Considering the existing studies and commercial applications relating to delivery of goods, coordination and cooperation among UAVs for load handling [131], safety, security and stability [135], [136], [134], [137], obstacle detection [132], trajectory planning [131], [136], localization [42], [43], [127],

[128], and connectivity with the ground station to send control signals and get status updates [129], are some of the general requirements.

4) Methodologies: For delivery of goods, both centralized and decentralized approaches are used. A decentralized approach can be used if multiple UAVs need to coordinate for joint load transportation and direct communication with the ground station is not possible. In [131], the UAVs plan for trajectories, synchronize themselves for joint load transportation and resolve conflicts to avoid collisions. However, the mission and other control tasks are specified by the user through a human-machine interface (HMI) to these UAVs at the start of the mission. The HMI also displays status updates of the mission. The latter can be avoided in case connectivity is not possible and is independent of cooperation for joint load transportation. In [136] a centralized approach is used to demonstrate stability of the load being carried by multiple UAVs with slings. For experimentation purposes, the motion information is captured by VICON motion tracking system and is fed to a central station that computes the trajectories, orientation, acceleration, and velocity of the UAVs and sends control commands to the UAVs. Another slung load transportation system using single and multiple small size helicopters is studied in [138], that uses a centralized approach with focus on the control and movement of the rope connecting the load and helicopters to achieve stability.

5) Categories: Keeping in mind the communications requirements, the applications for delivery of goods can be categorized as a single UAV carrier for low loads and small distances (1 km) like Google project wing [139] or Amazon Prime Air [43], for medium distances as for Matternet [42], or for large distances with a network of base stations a few kilometers (approx. 10 km) apart. Another category is multiple UAV carrier for high loads and small distances as in [138]. Readers are referred to Fig. 2, Fig. 6 and Fig. 7 and related description for further details.

VI. Application-based Qualitative Communication Demands of Aerial Networks

The main goal of this survey is to establish demands imposed on the communication module of an aerial network design. Understanding the *quantitative* demands is very important to specify the technologies that may be able to satisfy such demands. However, there is also a need to elaborate on *qualitative* communication-related requirements in aerial networks, which depend on the application categories identified in the previous section. Fig. 2 illustrates the relation between the applications and the envisioned qualitative requirements from our viewpoint. Observe that the relation might be mandatory (solid lines) or optional (dashed lines) depending on the application. In Fig. 3-6, we break down these qualitative demands for each application category, illustrating only the methodology-independent mandatory demands for each domain. We relate these mandatory demands to communication by specifying the traffic that needs to be exchanged as a result of these qualitative demands. Taking into account the constraints, assumptions, and requirements, we have identified from existing works in the previous section, we report on how the defined qualitative demands are met for each application. For each application, there are different possible solutions. We report all these solutions from application viewpoint, whereas the references to relevant projects and solutions have been provided for each mandatory demand in Figs. 3-6. We aim to use this information to develop the minimum quantitative demands posed by each application from communication viewpoint in the next section.

A. Connectivity

Intuitively, the first qualitative demand that needs to be explored is related to connectivity in networks of UAVs. For the application domains considered, we classify the connectivity demand into three categories. Firstly, demand for connectivity to a DME is a necessity in any network of UAVs, as the paths of the UAVs need to be tracked at all times for safety and security. Secondly, the UAVs may be required to connect to some ground clients, for instance ground personnel in case of disaster situations. Observe that it may not be necessary that such ground clients are also acting as DMEs. Lastly, we describe the requirement of connectivity amongst the devices.

1) Connectivity to decision making entity: Connectivity to a DME can be seen as a general requirement in any application scenario, especially when multiple UAVs need to coordinate for a mission. A DME is defined as a device that can track the flight path of the UAVs in the system and can intervene in case of emergency by sending out some control or coordination commands. Thus, the UAVs are required to be connected to DMEs via single or multiple hops at all times. Usually a node (mostly a ground node) that has a higher processing power is used for this purpose. However, the DME may be an RC, single or multiple ground base stations, or single or multiple UAVs. As a minimum functionality, these DMEs help to track the flight of UAVs and interfere in normal mission operation (for instance, for emergency landing using RC in case of low battery power). Further, these DMEs may also act as coordinating entities, deciding the mission plan for all devices in the network. In the centralized scenario, one or a few DMEs, that coordinate amongst themselves, are responsible for design of such mission plan, while in a distributed system, all the network devices act as DMEs.

For SAR, coverage scenarios and delivery of goods, there may be a hierarchical task allocation structure. This means that one or more entities in the network may be responsible for decision making while others may have the responsibility to complete mission tasks assigned to them by the DMEs, such as sensing [34], [39], [84], [72], [76], [118], [120] etc. In each of these projects, the UAVs maintain connectivity to a DME, which is responsible to coordinate the devices. Control and coordination commands are sent from the DME suggesting changes in the planned trajectory for collision avoidance, aborting the mission, moving to pickup points for delivery domain and so on. All the UAVs send on downlink their telemetry information to the DME for allowing control and tracking by the DME. Thus, for instance, in delivery of goods, where it is important that the UAVs deliver packages

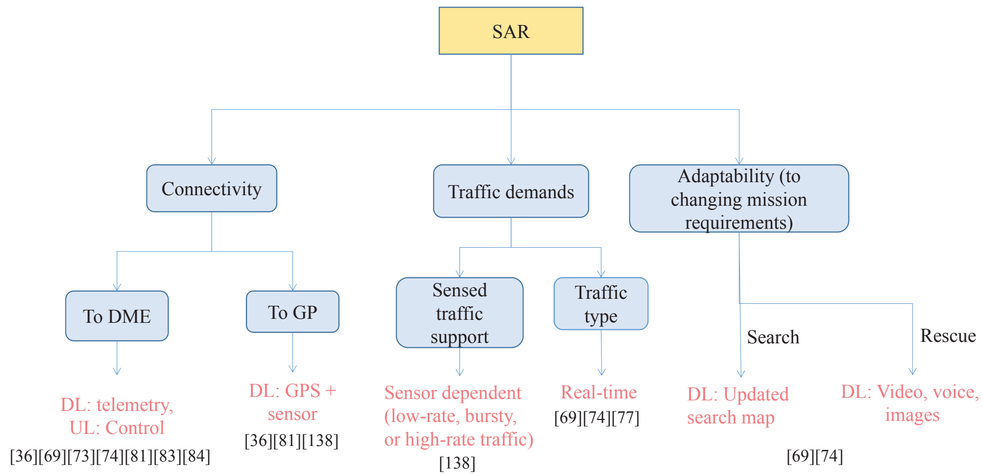


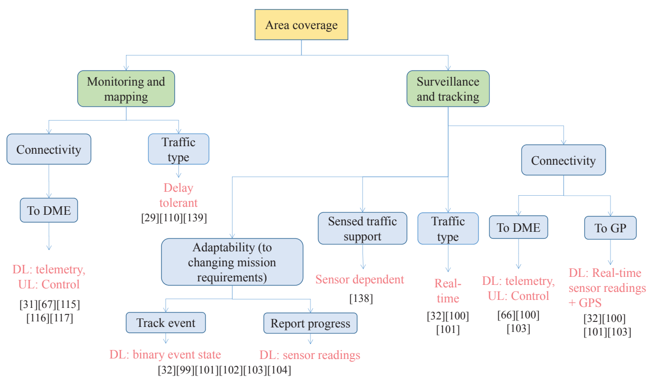
Fig. 3. Qualitative communications demands of SAR domain. Connectivity to DME demands uplink (UL) control data transfer as well as downlink (DL) telemetry transfer. GPS coordinates as well as sensor readings need to be transferred to the ground personnel (GP) on the downlink. During the search part of the mission, downlink data may constitute of updated search map, while during the rescue part of the operation, video, voice or images may need to be sent downlink to the GP.

at accurate locations, the connectivity to DME ensures that the UAVs are following the planned trajectories [131], [136], [134]. All the UAVs may be connected to the DME in a star topology, or maintain connectivity via relay nodes for continuous uplink coordination and downlink telemetry in case of online centralized decision making [140]. However, as mentioned in Section IV, in case of fully mission autonomous networks with distributed decision making capability, the entities in the network might not need to rely on coordination information exchange with a DME [87], [70], [77], [86], [119]. For distributed as well as offline decision scenario, continuous telemetry downlink would still be a requirement. In [83], where flight path and picture point decisions are made offline, continuous telemetry downlink is ensured via the long range x-bee interface.

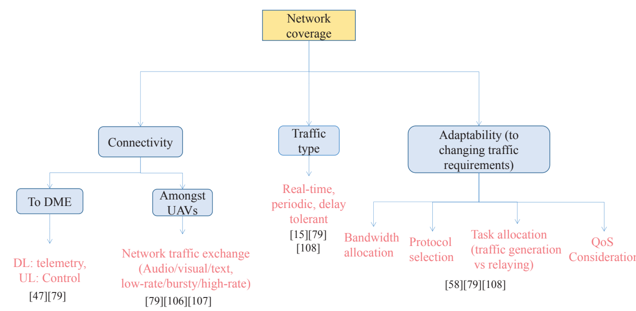
For delivery of goods, it is envisioned that customer demands arrive at some infrastructure storage depots. As the customer demands affect the trajectory planning, UAVs need to coordinate with such infrastructure depots even if a level of decision autonomy is employed on-board the devices. Such depots can act as energy replenishing centers for the UAVs too [42]. For construction domain, connectivity to the DME is a more critical requirement to ensure that structures are built according to the digital blue print [38], [59], [123], [126]. Sequencing and tracking information of the building blocks can be maintained centrally and the UAVs can send feedback to the DME accordingly. Also, motion of the UAVs can be tracked and heading, speed, velocity, and trajectory information can be reinforced to avoid collisions. The connectivity to a DME is translated into the requirement for exchange of telemetry information on downlink, as well as control traffic on uplink. This is true for all application domains and is illustrated in Fig. 3-6.

2) Connectivity to ground personnel: For applications such as disaster management, there is an added demand for maintaining connectivity to the ground personnel or clients, as without the intervention of ground personnel such as first responders, the mission can not be completed. This is especially true in case of SAR domain as shown in Fig. 3.

In SAR projects, the UAVs facilitate rescue operations by providing a quick overview of the area to locate victims in a timely manner [39], [84], [141]. After the search operation by UAVs is complete, the ground personnel is responsible to carry out the rescue operation. This requires that the UAV's have the capability to communicate their GPS coordinates as well as any sensor information (for instance thermal images, videos) to the ground personnel on downlink. For coverage domain, the demand for continuous connectivity to ground personnel varies depending on the nature of the application area. For example, *area* coverage in case of agricultural [142], or structural monitoring [32] demands an overview image of the area to be monitored. The only requirement in such applications is that the UAV is capable of delivering the high resolution images to the client. There is little timing constraints in such scenarios. However, *area* coverage in surveillance applications may demand continuous connectivity to ground personnel [35], [103], [104], [106]. This can be seen in (Fig. 4(a). In case of *network* coverage, this requirement is case-dependent. Aerial *network* coverage for source-to-sink connectivity of ground WSN does not require connectivity to ground personnel [110]. This holds true for *network* coverage during sports events [109]. In case of disaster scenarios, however, the connectivity requirement to ground personnel may be intrinsic [82]. Being a case-dependent demand, connectivity to ground personnel is not depicted in Fig. 4(b). For construction and delivery scenarios, connectivity to ground personnel does not stand out as a network design requirement.



(a) Area coverage



(b) Network coverage

Fig. 4. Qualitative communications demands of Coverage domain. Connectivity to DME demands uplink (UL) control data transfer and downlink (DL) telemetry transfer in all cases. For surveillance and tracking, there is an added demand for transfer of real-time sensor readings and GPS data to ground personnel (GP), where binary event states may be sent downlink while tracking the event, whereas sensor data is transferred to report event progress.

To maintain such continuous connectivity in case of large areas, relaying devices may be required, depending on the size of the area, the number of obstacles in the environment [120], [50] and the probability of finding victims in certain limited locations inside the large area [82].

3) Connectivity between UAVs: The connectivity between the vehicles in aerial network is a design parameter and is implementation methodology dependent (see Table I). Thus, in situations where the terrain has changed a lot after a disaster and SAR operations are required to be performed in a decentralized manner [77], connectivity amongst UAVs may become a requirement. However, many projects developed for SAR employ centralized offline decision making, as described in Section V-A4. In such cases, connectivity amongst the UAVs participating in the SAR operation is not required. That is why, we do not mention this as part of the mandatory qualitative requirements in Fig. 3. Considering applications falling under coverage domain, it is not required for UAVs in *area* coverage scenarios to be connected amongst themselves. The connectivity between UAVs is a necessity when these UAVs are employed for providing *network* coverage, in order to provide connectivity between clients and external networks in disaster scenarios [82]. On the other hand, if *network* coverage is being used to facilitate connectivity to a ground WSN, there is also a requirement for the devices to be connected amongst themselves, as in many situations, the source and sink are not in communication range of each other [110]. In such cases data may need to be communicated over single or multiple hops from source to sink. This follows that for *network* coverage, the traffic demands are vastly varying (voice/videos/images for disaster scenarios, low-rate, bursty, high-rate for ground WSN support). This has been illustrated in Fig. 4(b), which elaborates that the design of a network for *network* coverage requires consideration of all types of network traffic exchange. In construction, precise localization for pickup and placement of building blocks and synchronization amongst the UAVs is vital [38]. An added level of connectivity in construction, thus, is between the devices sharing the loads [59]. Referring to Fig. 5, this requires exchange of flight dynamics information. This may hold true for delivery of goods in situations where multiple UAVs coordinate for joint transportation of heavy loads [131]. However, coordination among UAVs is required only in situations where a single UAV's payload carrying capability is not enough to transport the package and multiple UAVs are required for joint load transportation. Connectivity between UAVs for delivery is thus methodology dependent and hence is not mentioned as mandatory requirement in Fig. 6.

B. Traffic demands

After connectivity, understanding the traffic demands in a network plays an important role in the design of the communication system and protocols. In the following, we describe these traffic demands in relation to sensors on-board the UAVs, the type of traffic that needs to be exchanged in the network, and the frequency of such traffic. We specify only the qualitative part of the traffic demand here. This paves the way for quantitative data exchange demands, which will be the focus of the next section.

1) On-board sensors: All UAVs come with various on-board sensors for control, coordination, and mission purposes. For all the application categories, it is expected that the position of the UAVs is available to a control entity (for example, an RC or a base station), for instance, to track the movement of the UAVs and update the mission status in case of emergency. For this purpose, the related sensing data, i.e., telemetry data as described in Section IV needs to be delivered continuously. Sensing data also refers to the data collected from the physical environment (deployment area and neighboring vehicles). In the following, sensed traffic refers to the latter.

In many applications of coverage domain (see Table II), spatial coverage of an area is required. Each application area in this domain requires different physical quantities to be measured, and hence different types of sensors, depending on the mission requirements. As shown in Fig. 4(a) sensed traffic support is a necessity for surveillance and tracking. The communication design has to take into account the data rate requirements of the employed sensors (low-rate, bursty, or high-rate). A list of required sensors, alongside the missions where they are employed, is provided in [141]. It is also important to note that for *network* coverage, the requirement for environmental sensing may not always exist. In SAR, sensors are required to detect the targets and hence the sensors on-board the UAVs vary depending on the detection technique employed (see Fig. 3). Similar to coverage domain, in SAR, the sensed traffic is sensor dependent and can be low-rate, bursty, or high-rate. This consequently has an effect on the network design. The demands on sensing in construction and delivery are more specific, and relate to load handling, balancing, and stability. Sensing is also required at the grasping assembly to grasp and release the load accurately as in [38], [123], [124]. Sensing can be used in any application domain for ensuring device safety, for example for collision avoidance [77]. It can also be used for swarming [143]. This, however, is not a necessary requirement, as communication can facilitate these functions as well. For example, if UAVs can communicate their GPS locations to their neighbors, the need for visual sensors can be avoided [144]. Similarly, where recording the Received Signal Strength (RSS) of the neighbors is possible, visual sensing may not be required [70].

2) Data delivery and data types: As mentioned in Section IV, each domain can be implemented using different methodologies, and hence, the demands on the amount and type of delivered traffic vary. However, some particular qualitative demands of each application domain define the data type that is required to be transferred for each domain, and the frequency of such transfers. To this end, we will classify data types according to their functionality, and their timing demands and delay tolerance. According to functionality, the data can be classified as control, telemetry and sensed traffic, as specified in Section IV. On the other hand, based on timing, the data types are real-time, periodic, or delay tolerant (as seen in Fig. 7). For categories like mapping in *area* coverage [32], [113], [142] and *network* coverage provisioning [15], the UAVs may be required to only provide spatial network coverage and connectivity amongst clients in a delay-tolerant manner, and no online sensed data transfer may need to be supported. Therefore, decision making can be offline-centralized, offline-decentralized, online-centralized, or online-decentralized. On the other hand, coverage for surveillance requires continuous sensing of the environment for up-to-date situation analysis [35], and hence real-time traffic support. Such scenarios demand support for real-time control, telemetry as well as sensed traffic. Decision making in dynamic situations, for instance following a car with a certain license plate, can be performed either in an online-centralized or online-decentralized way. This is also true for disaster situations, which pose more strict timing demands on sensed traffic delivery [80], [141]. Hence, for SAR [72], [77] and coverage operations in disaster situations [82], the network is required to carry control, telemetry as well as sensed data traffic simultaneously in a real-time manner. In domains which may require multiple devices sharing load or performing tightly synchronized tasks, for instance construction, the synchronization information exchange has to be real-time as well, to avoid collision and maintain motion synchrony [59], [136], [132]. However, the data that needs to be exchanged in such a situation comprises only of control and telemetry traffic [59], [123], [124], [126], as the support for sensed traffic is required only based on the methodology of implementation. Delivery of goods also demands support for control and telemetry data transfers [131], [136], [134], [138], though periodically.

It is important to specify this qualitative demand, as it helps establish the quantitative demands each domain poses on the minimum throughput and frequency of traffic, which the network needs to support for successful mission completion. Such quantitative demands are explained in detail in the following section.

C. Infrastructure Depots

Infrastructure in terms of aerial networks may mean communication enabling base stations on the ground, such as those employed in [35], [67]. These base stations can be part of the already existing cellular network infrastructure.The demand for having a communication infrastructure for most applications is methodology-dependent. Considering real-world implementations, application areas addressing disaster situations (including SAR and coverage in disaster scenarios) mostly assume an absence of both supplies as well as of communications infrastructure [77], [82]. In such situations, UAVs are used to provide an emergency aerial infrastructure for communication network provisioning [82]. However, for surveillance applications in *area* coverage, in many projects, a terrestrial communication infrastructure is employed [35], [103]. We have described such network infrastructure as DMEs in Sec. VI-A1. In this section, we describe only the demand for storage infrastructure.

For delivery of goods, infrastructure depots refer to storage depots where the packages and energy replenishing instruments are stored. For delivery of goods, an infrastructure of such storage depots may be a necessity for delivery to far off areas where the UAVs cannot reach without recharging or refueling. Such an infrastructure can also provide network connectivity for tracking the goods carrying UAVs or sending control commands to the UAVs, if base stations are installed as part of the infrastructure [44], [128], [129], [130]. Hence, the infrastructure can act as both a storage and communication facility. As can be seen in Fig. 6, it is necessary for the UAVs to transmit their telemetry data to, and receive control and coordination information from such infrastructure depots. This is required in order for the UAVs to keep the depots up-to-date about their current flight and energy status, and stay updated about the customer demands and online up-to-date flight plans. For construction, storage depots may refer to the bins where construction parts and elements are stored. As the area over which the construction domain spans is expected to be small, there is no need for an infrastructure of such storage depots.

D. Adaptability

Robustness in any network demands adaptability of the network. For aerial networks, this adaptability includes network adaptability as well as adaptability to varying mission demands, as explained below.

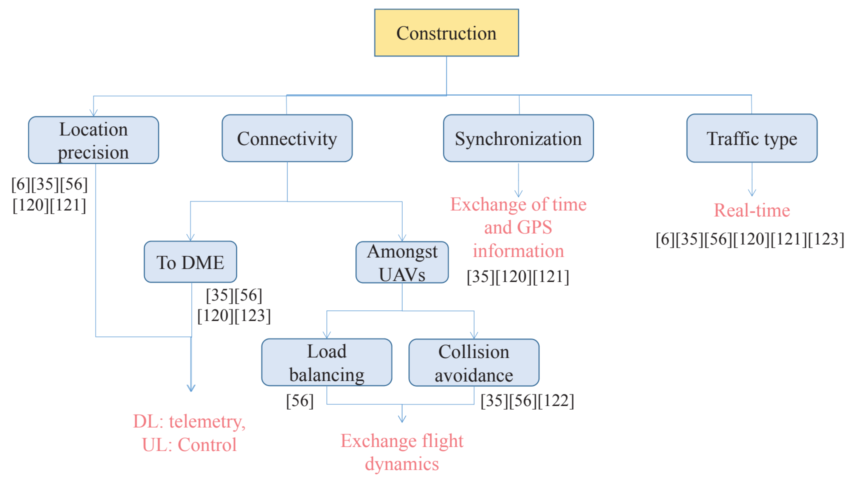


Fig. 5. Qualitative communications demands of Construction domain. The qualitative demand for connectivity to DME and location precision translates into communication demands for telemetry transfer on downlink (DL) and control data on uplink (UL). For synchronization, time stamps and GPS data may need to be exchanged amongst all entities in the network.

A robust network should always be adaptable to nodes joining and leaving the network, and hence, topology changes. As mentioned earlier, the topology changes are more pronounced in networks with high device mobility. In large-area applications, such as coverage and delivery, adaptability to topology changes may be a basic requirement as high mobility of the devices may cause highly variant terrain and wireless channel conditions.

The dynamism in aerial network is not just caused by the high mobility, terrain changes, channel conditions or node failure, but also due to the dynamic mission demands. In other words, for the successful completion of a mission, the objectives of the mission may change and so may the tasks assigned to the UAVs. For example, in SAR, after having successfully located the target, the UAVs may have to establish communication between the rescue personnel and the victim [77]. Thus, the mission objectives may change from searching for a victim to, for instance, voice/video transfer between the victim and rescue personnel, as can be seen in Fig. 3.

Adaptability in terms of varying mission demands also holds true in some cases of coverage domain. For example, in surveillance missions (*area* coverage), the mission may initially require detection of a target event, for instance pipeline leaks for pipeline surveillance [105], illegal border crossings in border surveillance [106], and accidents in highway surveillance [35]. After the event has been detected, the UAVs may be required to monitor the events continuously. Thus an aerial network for surveillance is required to be adaptable to changing mission demands. Considering coverage domain for monitoring and mapping [32], [47], [91], [142], the mission task may be formation of a 3D model or overview image of the area, or sensing of certain physical quantities. This may be the only task required from the UAV system and may not change over time. Thus, mission adaptability may not be required. On the other hand, for *network* coverage, the mission plan may not change in terms of movement but the traffic carried may change and hence the network protocols need to adapt [82]. This translates into the requirement for adaptable bandwidth allocation, protocol selection, QoS consideration and network tasks allocation (traffic generation vs relaying) from communications point of view, as is illustrated in Fig. 4(b). For construction, adaptability to change in network size may be a requirement. UAVs need to synchronize themselves if more nodes are added in the network or if one node fails [123], [126]. We speculate that for delivery application, adaptability is also required against varying demands (i.e., number of clients requesting packages over time) in the network. In terms of traffic transfer, the trajectory information may need to be exchanged between the UAVs and ground depots and updated periodically (see Fig. 6). It is important to state that the network adaptability against failing nodes remains a requirement for all applications falling under coverage domain.

E. Synchronization

In the following, we assume that all application domains require a level of network time synchronization, and proper time-stamping for the network traffic. This is important not only to make sure how up-to-date the received data is, but also to have time synchronization in a network with multiple devices. For instance, in a network where multiple UAVs are sensing the environment from different vantage points [40] or using different sensors [84], the readings are required to be synchronized in time and space. The term “synchronization”, from here on out, refers to synchronous movement of the devices performing a coordinated task.

Synchronization amongst UAVs is especially an important requirement for construction application, when multiple UAVs are used to coordinate for building structures. These coordinating UAVs synchronize themselves so that no two UAVs perform the same task at the same time and location. As can be seen in Fig. 5, this demand for synchronized mobility translates into communication demand for the continuous exchange of time and GPS information. Synchronization is a methodology dependent requirement for delivery of goods when multiple UAVs are involved in the joint load transportation. The participating UAVs are required to coordinate and synchronize on heading, acceleration, velocity, speed, pitch, roll and yaw for safe and stable transportation of the load [131]. However, synchronization being methodology dependent in delivery of goods, is not mentioned as a mandatory requirement in Fig. 6. For SAR and coverage applications, we envision that such tight motion coupling amongst multiple UAVs may be methodology dependent and may not be a stringent demand.

F. Location accuracy

Location accuracy with respect to the surrounding environment is important when we consider multiple devices operating in a certain area, or an area presenting many obstacles. Most of the real-world projects implemented for SAR and coverage domains use GPS localization (SAR [67], [72], coverage [82], [110], [145]) to achieve location precision. On the basis of this information, it is speculated that the required location accuracy for these domains can be in the order of meters [144]. Precise location information is important for construction since the building blocks are to be placed with accuracy. Thus accuracy in the order of millimeters is required while the building blocks are being placed at the destined locations [59], [123], [124], [146]. Similarly, for delivery of goods [43], accuracy higher than that offered by current GPS localization technology is envisioned. Location accuracy higher than that provided by GPS localization (for instance for construction (Fig. 5) and delivery of goods (Fig. 6)) may demand exchange of high frequency telemetry information on the downlink and high frequency control and coordination information on the uplink.

In terms of network design, the wireless links over which location information is being exchanged should be reliable and robust in order to ensure collision avoidance and safety of devices and personnel involved in the mission utilizing the aerial network. This translates into the quantitative QoS requirements for the employed localization modules, such as frequency of data transfer over wireless links. Dedicated fail-safe or redundant links for such control information exchange may be desirable for use in aerial networks.

G. Safety, security, and privacy

The issues of safety, security, and privacy can be addressed more generally for application domains in aerial network and applies in a similar manner to each domain. Safety, security, and privacy affect the design of the aerial network in different ways as compared to all the qualitative demands mentioned previously, and hence are not illustrated in Fig. 3-6.

In terms of safety, device and human safety is important to consider in all application domains. To ensure such safety, there should be a way for human pilot intervention in case of emergency, for example, for collision avoidance. Currently, autonomous flight of UAVs is enforced by law to be accompanied by a pilot in RC range of the UAV, for intervention using the RC whenever needed. In projects like SINUS [72], to ensure safety of the devices and persons involved, interference with the RC traffic channels in 2.4 GHz is avoided by using the 5 GHz 802.11a radios for sensed traffic transfer. In the design of the RC module, foremost importance is given to the support of real-time, reliable traffic where packet sizes are small [147].

For a network of UAVs to be able to perform the specified tasks, it is also important that the UAV system is secure against malicious factors. For example, in application scenarios where UAVs have to deliver packages, it is important to ensure that the UAV carrying the package is not intercepted on the way to the client. Similarly, for privacy and safety concerns such as in *network* coverage [109], UAVs responsible for transferring traffic reliably from one point to another also need to ensure data security against malicious attacks as well as interference. In terms of communication, allowing the system to operate on secure channels by allocating aerial network specific bandwidth can counter frequency jamming and hence interception of the UAVs [148]. To ensure safety, it is expected that the RC link to the UAV also be made secure. It can thus be stated that for a UAV system to perform in a safe and secure manner, there may be a need for licensed frequency bands for commercial UAV systems [145]. A useful platform to analyze the cyber security issues in a UAV system is the simulation testbed called UAVSim [149], which has been used to evaluate the effect of the number and transmission range of jamming attack hosts.

Another important issue regarding aerial networks is the privacy concerns raised due to the use of camera-equipped UAVs. Government regulations are being enforced in most parts of the world (for example by FAA [150] in USA) where UAV related research is being carried out to address these concerns.

H. Scalability

As a first step, we define what scalability means in terms of aerial network design. As with other types of networks, network scalability may correspond to the increase in number of devices/nodes employed in the network. Such scalability may be limited by the choice of communication technology employed and the traffic requirements in the network, as increasing the number of hops between the traffic source and destination pair inversely affects the throughput and may increase data delay between the pair. The results of such an analysis for 802.11 technology are provided in [151]. Network scalability also poses the question about decision making in the network. It is suggested in [152] that a decentralized approach is capable of offering easier scalability of networks as compared to centralized approaches. Another important factor to consider for scalability is area and terrain. To keep the density of nodes constant, for larger area coverage and SAR, a larger number of UAVs may be required in the network. Similarly, due to different channel conditions, time constrained mission completion (coverage or SAR) performed in urban

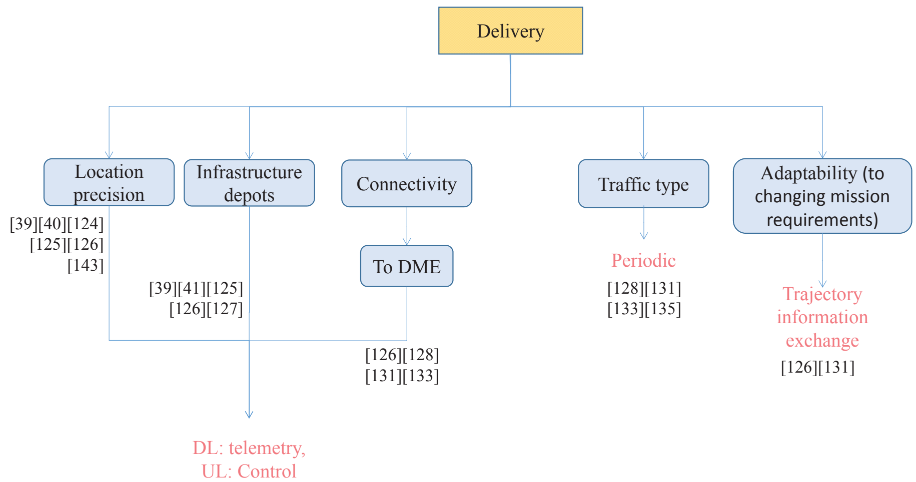


Fig. 6. Qualitative communications demands of Delivery/Transportation domain. The qualitative demand for infrastructure depot, connectivity to DME and location precision translates into communication demand for telemetry transfer on downlink (DL) and control data on uplink (UL).

environment may require larger number of nodes than in rural environments [153].

Apart from general issues addressed relating to network scalability, considering each specific application domain, scalability may also incorporate some mission variables. For instance, in SAR operations, the network design should work as efficiently for search of multiple victims, as it does for a single victim [154]. Similarly, for delivery of goods, scalability in terms of number of nodes in the network depends also on the size (multiple UAVs carrying heavier payloads [138]) and demand of packages to be delivered (higher demand in urban than in rural environments [43]). Scalability for construction may also be important in terms of the variety and range of the structures to be built and on the number of UAVs that can participate in building the desired structure(s). The requirement for scalability in any domain poses the question of efficient bandwidth allocation. Network scalability, though affecting the network design immensely, has not been mentioned in Fig. 3-6. This is because we speculate that in most if not all UAV applications, a single large vehicle, with higher payload, longer flight times, and larger communication range, may be able to replace multiple smaller ones. For instance, as depicted in Fig. 1, and described in Section III, a single large UAV may be used for *network* coverage provisioning [109], as opposed to using multiple small UAVs as in [82]. Thus, demand for network scalability is treated as methodology dependent.

VII. Application-based Quantitative Communication Demands of Aerial Networks

In this section, we present communication-related quantitative requirements for the specified application categories. We envision that these requirements, together with the mandatory qualitative requirements extracted in Sec.VI, can help in establishing metrics for optimization as well as estimating bounds on these metrics for a robust network formation for the application at hand. We classify the requirements into *mission, system*, and *network* requirements. We summarize the *mission* and *system* requirements in Fig. 7 and the *network* requirements in Table III. In Fig. 7, we specify area and terrain/environment as parameters to elaborate on the mission requirements. Similarly, for system requirements, the parameters analyzed are network mode and number of nodes. An account of existing projects and real-world implementations considering these parameters is provided to establish the relation between them. As the survey is about communications demands of aerial networks, we start by classifying the traffic based on the periodicity of transfer into *real-time, periodic*, and *delay tolerant*. Application domains that fall into each category are mentioned. These are further classified based on the area size into *small, medium* and *large*. Further, terrain is added as *urban* and *rural*. For system parameters, we classify the network into *infrastructure* and *ad hoc*. The number of nodes provide an account of the number of UAVs and base stations used in each project, based on the area, terrain, and network classification. The specified projects are mentioned at the end of each branch. Table III completes the picture by providing values for *network* requirements such as *frequency of data transfer, throughput, traffic type*, and *delay* for both co-ordination and sensed traffic. Mission specific requirements, if any, are also mentioned. A thorough description of parameters mentioned in Fig. 7 and Table III is provided in the following.

A. Mission requirements

Mission requirements correspond to quantitative requirements that arise specifically for each application category. As mentioned previously and illustrated in Fig. 7, parameters such as area and environment/terrain are mission dependent and hence change from one application domain to another. Mission requirements also include information about *what data* needs to be exchanged for each application category, what are the

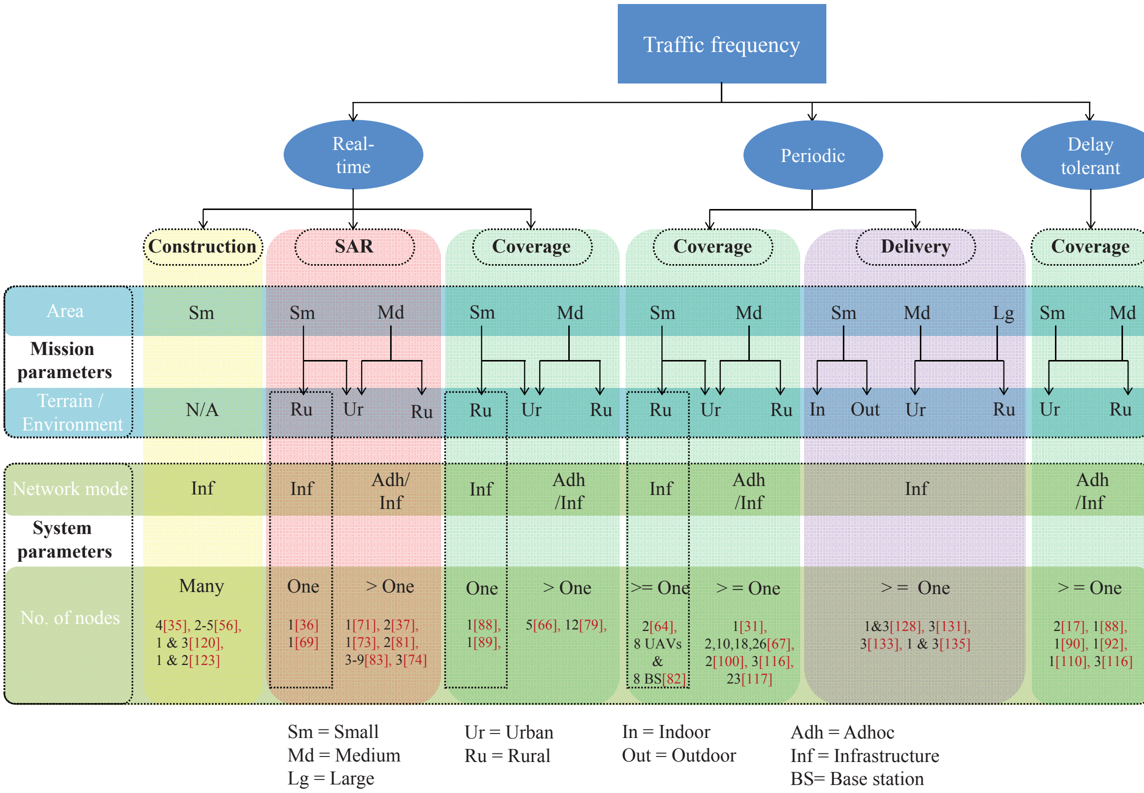


Fig. 7. Mission and system parameters for different application domains based on traffic classification. Number of UAVs employed by real-world projects (referenced) in red.

types of links that need to be supported in each category, and *how often* we need to exchange information amongst devices. Quantifying these demands provides a basis for the design of an application-tailored aerial network. For the sake of simplicity, we address each of these requirements/parameters individually in the following.

1) Exchanged data: We start by elaborating on the data that needs to be exchanged for each application category. We classify data types based on the description provided in [13] into control, coordination, and sensed data. Control data includes telemetry downlink from the devices to, and control commands uplink from a control entity. As mentioned in Sec. VI-A1, this is the information that needs to be exchanged between the UAVs and the DMEs in the network, and is mandatory for all application domains. The minimum information to be exchanged in an aerial network is expected to include RC data on the uplink and telemetry traffic including GPS location on the downlink.

To this point in the survey, we have considered only the mandatory aerial network demands. In the following, however, we focus our attention on the data types that, as explained in Sec. VI, have been established to vary from one application domain to another. These are coordination and sensed traffic. Our goal is to identify the minimum communications-related demands posed by each application domain. The established demands, related to both coordination and sensed traffic for all application domains mentioned in this survey are then quantified in Table III. According to [13], coordination traffic may include telemetry, some sensed traffic, and decision making and task-assignment commands. Sensed data includes any traffic generated by the sensors on-board the UAVs.

The coordination data exchanged amongst the UAVs (A2A) or between a ground station and a UAV (G2A) for SAR depends on methodology of implementation. In case of centralized decision-making, this information may include only location and heading information for flight path specification [39], [72] exchanged from the central DME to the UAVs. In case of online decision making, the DME may require some sensed traffic on the downlink to coordinate the UAVs to meet dynamic mission demands [85]. If UAVs are required to plan and coordinate using consensus in a decentralized manner, exchange of timestamped belief map [40] may be required. On the other hand, decentralized decisions made individually by each device may not require the exchange of such belief maps [70].

Similarly, in coverage domain, due to the diverse nature of the application areas encompassing this domain, the exchanged coordination traffic varies based on the implemented methodology. Most projects focusing on applications in coverage domain utilize a single UAV controlled manually [47], [91],

[93], or via a ground base station utilizing offline path planning for UAV's autonomous flight [88], [94], [100]. For instance, for *area* coverage, [72] uses offline, centralized decision making when performing construction site monitoring. Waypoints in longitude and latitude and direction to fly, etc. are provided to the UAVs in an offline manner. On the other hand, when multiple UAVs are utilized for coverage, demands on coordination traffic exchange may increase if *online* decision making is implemented. For instance, no coordination information exchange is required in [155] as the paths have been assigned to the UAVs offline by a centralized planning entity. On the other hand, coordination traffic exchange becomes a necessity for distributed *online* decision making. For instance, authors state in [140] that the central decision node is responsible for incorporating feedback obtained via interactions with system clients (e.g. first responders) and part of mission plan that has been executed, into the new plan. This new plan (flight paths) is then required to be updated on the UAVs, while the central decision node monitors the returned tasks and the plan execution status via the downlink information received from the UAVs (such as telemetry information). It is important to note here that using centralized decision making, the communication demands from the central entity increase with increasing number of devices that need to be coordinated. This can be countered by an approach similar to [119], that uses online individual path planning for surveillance and event detection. This is done by using some a priori information in the form of a belief map, provided by satellites to UAVs, which gives a rough estimate of target locations. The UAVs coordinate their future flight path based on this belief map information, constituting the GPS location and certain probability of target detection. Individual belief maps are not fused in this approach. Belief map fusion is used for multi-UAV coordination in a distributed manner using consensus amongst the UAVs for monitoring the environment in [156] in an online manner.

Construction is intrinsically expected to be a multi-UAV application domain, where the UAVs may be in close proximity of each other. Thus, motion tracking information is of high importance [38], [59], [123], [124], [126], since precise localization is required to pick up and place the building blocks. Motion tracking also provides information on state estimations (waiting on bin, picking up, waiting for assembly, assembly, finish) and information on the orientation and heading of the UAVs. This information is then fed at the ground station for trajectory planning [157] and reinforcing it to the UAVs to avoid collisions and achieve synchronization among the devices [59]. Control commands are sent on regular intervals from the ground station to the UAVs, which generally include trajectory information and commands for acceleration, speed, heading, altitude, etc. [123], [124], [126], [158], [159]. If multiple UAVs are jointly carrying the construction blocks, information exchange e.g., trajectory and motion information between them is also required for load balancing and collision avoidance.

Though both construction and delivery of goods applications involve transportation, delivery of goods likely requires much larger areas to cover and different demand parameters to cater for on the A2A, G2A, and A2G links. The information required can just be limited to GPS coordinates through a mobile phone application, where the GPS position of the package delivery location is specified and UAV position is tracked on the way [127] or can be extended to coordination, localization, visual [132] and safety information [129]. At minimum, task information [131] and control commands [136] are sent to the UAVs from ground nodes and position information [136], [134] and execution state [131] is monitored. In case of multiple UAVs jointly transporting the load and when it is assumed that the UAVs may go beyond the communication range, spatial trajectory information and status updates are exchanged between the aerial devices to avoid any collisions [131], [132]. Multi-hop communication can also be used if communication with ground station is required to relay status updates to the ground station and control commands to the UAVs.

For SAR and many applications in coverage domain (apart from applications falling under *network* coverage), as mentioned in Section VI-B1, sensing the environment is an integral component of the mission. The data to be exchanged between the UAVs and the base station includes, apart from the coordination traffic mentioned above, some sensor data as well, which may vary depending on the physical quantity to be sensed. For example, for SAR operations, searching the environment may employ some kind of visual [39], [72], [160], or thermal sensors [76], [161], [162]. Similarly, for *area* coverage, depending on the mission requirements, some sensors may be employed on-board the UAVs. For instance, the sensors on board are responsible to gather images and temperature readings in case of fire [67], for a disaster involving toxic plume, chemical analyzers are required as sensors [98], whereas for monitoring of volcanoes for future eruptions, ultraviolet and infrared spectrometers and electrochemical sensors are used for analyzing the gas fluxes [102]. Each type of sensor has its own traffic pattern and traffic exchange requirement. For instance, temperature sensors usually read the environment at a very low rate [163], as compared to vibration sensors, that require sampling of the sensor readings at a higher frequency [164]. The next subsection deals with this, by emphasizing on the demands of traffic exchange frequencies for each type of traffic.

2) Information exchange frequency: It is important to keep in mind the frequency of information exchange to establish the bandwidth requirements in the network. As mentioned previously, telemetry and RC data exchange is a requirement shared amongst all application domains and the demands on these types of information do not change with application domain. Thus, the standard frequency of telemetry data exchange for all application domains is 4-5 Hz or less [165], [166]. Similarly, RC traffic also needs to be supported in all application domains due to safety issues, requiring the UAV to be in the RC range at all times. Control data is expected to be more frequent (20-50 Hz), to enable real-time system response to RC commands [68].

We now focus on the data that varies from one application domain to another, that is, coordination and sensed data. For design of a reliable communication module that supports both coordination and sensed traffic, it is very important to consider the demands of both types of traffic. In cases where some form of sensed traffic is being sent over the network, for example video downlink (sports events [61], video downlink to enable rescue operations [81], etc.), coordination data acts as background traffic. Such background traffic has a high impact on the quality of streamed video [167], and thus, has to be considered when choosing the video coding scheme for streaming high quality videos.

The frequency of coordination traffic exchange varies not only with the algorithm for decision making, but also depends on what constitutes the coordination traffic and how often the "successful mission completion" requires the exchange of this coordination traffic. For *offline* decision making, intuitively, no coordination traffic needs to be exchanged, similar to the case where decisions are made on an individual basis, as can be seen in Table I. Coordination is required in case of *online* decision making, either centralized, or if the devices use consensus to decide about their future plan of action for mission completion. For instance, in [168], the authors claim that 1 Hz is enough to perform centralized or decentralized coordination amongst UAVs if coordination constitutes only of differential GPS correction. In other situations, where belief map exchange is required for coordination amongst devices in an online manner, this exchange is periodic and is performed after certain number of time steps (after every 10 sec in [70]), after each sweep of the area (after every sortie in [85]), or whenever the devices are in communication range of each other [69].

The frequency of sensed data for coverage domain varies depending on the objectives of the mission and the type of physical quantity that is being measured. An example of the former case for coverage domain is [113], which requires a local map formation at an update frequency of 1 Hz using the sensed data. On the other hand, depending on whether the transferred visual content is images or video, the frequency of data transfer may vary. For example, considering a surveillance scenario in an urban environment (with a lot of background noise), an update frequency of greater than 10 Hz is required for the ground personnel to efficiently track a mobile target [169]. On the other hand, in most situations where video streaming is required, the exchange frequency is expected to be greater than 30 Hz [82], [170]. For voice traffic in *network* coverage scenarios, [82] specifies the transfer frequency of 50 Hz as the basic demand, based on the requirement study performed during Hurricane Katrina. The above holds true for SAR missions as well, and depends on the sensors used for the operations. In [74], where a laser sensor is used for search in urban environments, the sensor data exchange frequency is set to 10 Hz. If visual sensors are used, images need to be streamed at a rate greater than 20 fps [167].

For construction, motion tracking information and control information are of importance for coordination of the devices. Thus coordination traffic constitutes of such motion tracking and control traffic. In [123] motion information is sent at a fixed rate of 150 Hz (6.6 ms). i.e., approximately four times higher frequency than in [171] where motion information of ground robots is captured every 25 ms. The frequency interval for sending control commands in construction application ranges between 50 Hz and 100 Hz. As for delivery of goods, in [136] the motion information is sent at a fixed frequency interval of 100 Hz whereas the frequency of control information varies between 20 Hz [136] and 100 Hz [134]. In Table III, "Frequency" column under "Mission Requirements" is used to summarize the above discussion.

3) Mission specific requirements: For coverage domain, the main mission specific requirement is to complete coverage of an area in a timely fashion and any network specific quantitative requirement arising in this application category can be related to this. If coverage of a large area is required (whether it is *area* or *network* coverage), it may be necessary to use multiple devices [82]. Thus, the network should be able to support traffic from many devices, possibly in a multi-hop fashion, and should be scalable. The specific quantitative requirements for each coverage mission, however, depend on the size of area, the number of UAVs forming the network, and the specific mission's timing constraints. This is because for applications falling under *monitoring and mapping* (such as agricultural monitoring [142], structural monitoring [32], archaeological site monitoring [91] and mapping [95]), mission completion time is not a strict constraint, whereas for *surveillance* applications (such as border and highway surveillance [35], [104], and disaster monitoring [67], [98], [102]), mission completion time is a more critical parameter to consider. Also, network coverage provisioning in disaster situations faces timing constraints. For example, as mentioned in [141], in case of loss of communication in disaster situations, the network reestablishment via UAVs may also be time constrained to less than 2 hours.

The timing limitations on mission completion in SAR missions are also highly stringent due to the disastrous nature of the application in this domain. In SAR, the response time of rescue personnel and the mission completion duration is of immense importance. Response time has been specified as the metric to optimize in SAR operations in [81], a study of SAR missions that took place in Oregon over a length of 7-year period. It states that for search and track of missing persons, the probability of finding the missing target alive drops to $\sim$1% after a duration of 51 hours. Similarly, in SAR operations initiated after a disaster, the cut-off time for mission completion is usually less than 2 hours [141].

In case of construction there may not be a stringent timing requirement, but synchronization and precise localization [38], [126] are the mission requirements that may affect the network design. In order to ensure this synchronization, all the UAVs should receive their next tasks with equal delay, which requires minimum jitter in the network.

In case of delivery of goods, a common mission specific demand is to monitor the execution state [128], [131] of the UAVs in flight and send control commands for any changes e.g. to avoid collisions or change in the mission plan. Although the trajectories are generally pre-computed/planned [129], [136], changes during the mission may be required to reinforce new trajectories. If, however, multiple devices are sharing the load, synchronization in terms of exchange of trajectories/way points and coordination commands among the

UAVs for joint load transportation is required [131]. Similarly, exchange of data and commands for joint load transportation is required for load balancing handling [136] and safe and efficient transportation [134].

4) Area size: The area size varies from one domain to another and needs to be specified, due to its impact on the number of UAVs employed, network implemented, and topology used. We refer the readers to Fig. 7 for classification of specified application domains based on area size, and to Section III for classification of area sizes. Fig. 7 illustrates that for construction, the area over which the UAVs have to operate can usually be classified as small [59], [123], [126]. For other domains, however, the area over which the UAV network is deployed vary vastly. Coverage applications may span over acres for agricultural monitoring [142], network coverage provisioning in disaster scenarios [82] or highway surveillance [35]. The area to cover may be medium sized for ground WSN network coverage [70], or aerial photography and mapping [95], while for applications like structural or surface monitoring [32], [89] or bridge inspection [93], the areas to cover may be small. Similarly, for SAR operations, coverage area can be classified as small for indoor search [74], which can be medium for outdoor SAR such as in case of forest fire [67] and missing person search [39]. For delivery operations, the area to cover by the UAVs may be classified as small [172], medium [173] or large [42]. When the size of the area is known along with the throughput requirements for reliable data transfers (refer to Table III), it is also easier to estimate whether using multiple hops to achieve full connectivity over the area satisfies the throughput requirements, or it is more desirable to use DTN [17]. Another important issue to mention is that for the same network, if we employ multi-hop instead of single-hop, the links that are to be supported in the network include not only A2G and G2A, but also A2A. Moving from single-hop to multi-hop, the throughput supported in the network will also reduce [83]. That is why all the requirement values specified in Table III specify minimum requirements with respect to end-to-end connection.

5) Terrain/Environment: The terrain over which the UAVs are flying plays a very important role in the design of the network. It is shown in [115] that the UAV-UAV communication is affected in terms of modulation scheme employed and attenuation in different terrains such as obstacle-ridden Manhattan scenario vs. free space scenario. Having a Manhattan like urban scenario may also require the use of multi-hop networks to ensure continuous connectivity between two devices separated by obstacles. Also, the multi-path effects would be more prominent and have to be taken into account.

As shown in Fig. 7, for construction domain [123], [124], intuitively, the terrain is obstacle ridden and does not change quickly over time. As described in [174], delivery applications are envisioned to be implemented in indoor (office, factory [172]), outdoor (postage [173], pizza [175], beer [176]) as well as urban (Package delivery services like Amazon [177]) and rural (Matternet [42]) environments. Indoor and outdoor SAR operations have been the focus of projects too [74]. There are works specifically focusing on urban SAR [72], [76], [77], while others that consider rural SAR environments [39], [67]. Similarly for coverage domain, urban [32], [61], [50], [89], [93], [96], [107] as well as rural [47], [92], [105], [106], [102], [178] environments have been the focus of research. Classifying the terrain into urban and rural environments is just one of the many ways in which the terrain can vary. Based on whether, for instance, the rural environment corresponds to desert, forest, water mass or mountains, the network requirements would differ, as each environment introduces varying channel conditions [179]. Also, the weather conditions for each terrain may vary and affect not only the channel conditions [180] but also the device hardware [181].

B. System Requirements

After classifying the applications based on traffic types and branching them out based on the mission requirements, we further add the system requirements to make the analysis complete. We take into account the type of network implemented (infrastructure or ad hoc) and the number of nodes to describe the system implementation adapted by real-world projects employing UAVs.

1) Network implementation: We classify the network implementation into infrastructure and ad hoc modes. There has been some work done comparing the performance of infrastructure networks to ad hoc networks [83], describing the network characteristics such as throughput, delay and jitter for each type of network. Whereas infrastructure mode offers a central access point for connectivity amongst the devices, ad hoc mode promises peer-to-peer connectivity. Thus, intuitively, infrastructure networks may be more feasible if centralized decision making is implemented, and each device gets its tasks from and provides information back to a central entity. On the other hand, distributed decision making may require the devices to form peer-to-peer connections, with each device contributing to the decision making process either on individual or consensus basis. There are some characteristics of the application domains under consideration that may prioritize use of one type of network over the other. For instance, the projects focusing on construction domain [123], [124] use a central entity for decision making and all devices are connected to this central entity for receiving their synchronization and task assignment information. Thus construction domain has been implemented using infrastructure mode, as shown in Fig. 7. The figure also shows for SAR projects like [85] focusing on small sized rural areas, infrastructure mode has been the choice for network implementation. However, for SAR operations performed in medium sized urban and rural environments, the choice of network implementation is methodology dependent, with some projects favoring infrastructure implementation [39], while others implementing ad hoc mode [40], [73], [74]. In addition, both infrastructure and ad hoc modes of communication are used in [121], by maintaining links to a central access point, and opening co-op channels amongst UAVs whenever required.

Similar trend can be noticed for projects focusing on coverage. We can find examples of implementation of infrastructure and ad hoc networks for any combination of area size, terrain and traffic type. In [11], infrastructure networking for establishing an airborne base station for providing network coverage in emergency scenarios for suburban or rural large sized areas is implemented. Ad hoc networking is used in [82] for providing emergency network coverage in urban large areas. For both scenarios, the traffic constitutes of real-time, periodic and delay tolerant data. For real-time traffic, ad hoc networking has been used for forming relay-chains in an urban environment considering medium sized areas in [50]. On the other hand, infrastructure network has been employed for the same traffic, area size and terrain considered in [34]. Most area coverage applications like vegetation monitoring [47], agricultural monitoring [142], archaeological site monitoring [91] and photographic mapping of large areas [88] do not require real-time data transfers, and thus use infrastructure mode with offline data transfers after mission completion. However, in other cases where, for example, coverage of large crowds for target detection, large groups of animals, or multiple wildfire spots is required [182], distributed swarms of UAVs may be more useful than single UAVs that are able to cover dynamic targets over large areas in an efficient manner [12]. In such cases, peer-to-peer connectivity may be required for cooperative coverage ensuring collision avoidance [183]. For coverage in small sized areas, where a single UAV is employed for mission completion, infrastructure network formation has been the preferred choice in [32], [93].

Delivery of goods is a domain where the requirement for infrastructure may seem as a necessity in terms of storage, fuel replenishing, and also task assignment and decision making. For delivery scenarios, delivery tasks may pop up in an online manner. Such tasks may be stored at a central base station and scheduled in a manner such that delivery of goods is ensured in accordance to some optimality criteria. For this reason, [123], [129], [131] all propose the use of infrastructure network for delivery operations.

2) Number of nodes: The number of nodes employed in a network depends on the size of the mission area under consideration, the transceiver characteristics, as well as the types of nodes employed in the network. Certain transceivers offer longer range of communication and may enable the use of fewer devices than other low range transceivers. Such transceivers are usually specially designed, expensive, and heavy, and it may be more beneficial to use cheaper, off-the-shelf counterparts with the commercially available, payload constrained UAVs. One such example of specially designed transceiver system for UAVs that act as base stations for fast moving trains is given in [184]. Similarly, a specialized transceiver design is also developed in [185] for aviation transport supervision, telemetry data link and remote control traffic management. However, such systems' weight is outside the payload capacity of commercially available mini and micro UAVs. That is why, most research works focusing on communications design for UAV systems use commercial off-the-shelf available transceivers, for example in [16], [17], [18], [83]. The type of UAVs employed for a certain mission also affects the number of nodes required in the network for a certain mission completion in a timely manner. For example, in an SAR scenario, on one hand, a large UAV may be capable of carrying both visual and thermal cameras for rescuing victims [76], [186], but may be an expensive solution for most SAR organizations. The cheaper, smaller, commercial UAVs can be used instead, but their payload constraint may demand that the visual and thermal cameras be carried by separate UAVs, thus increasing the deployed number of nodes in the network [187].

In Fig. 7, we provide the number of nodes employed by each project alongside the project reference. As mentioned previously, infrastructure network is employed for UAV system design for construction domain, with the varying number of UAVs: 2-5 in [59], 1-2 in [126], 3 in [123] and 4 in [38]. For SAR operations in small sized urban areas, infrastructure network is employed by both [85] using 8 UAVs and 8 base stations, and in cDrones project [16] employing a single UAV. For all other terrain and area size combinations, projects developed have implemented both ad hoc and infrastructure networks with varying numbers of UAVs. For instance, ad hoc networking is used in [74] using a single UAV, in [40] using 2 UAVs, in [69] using 5 UAVs, and in [77] using 3 UAVs. On the other hand, infrastructure networking is used in [39] with a single UAV, similar to [76].

In case of coverage domain, most applications considering small areas allow delay tolerant networking, for instance, monitoring and mapping applications [91], [93], [95], [113]. In such cases, data transfer is usually offline, where only a single UAV is used to perform the tasks. However, 2 UAVs are used in [33]. If real-time transfers are required, for instance, for surveillance, already established infrastructures, such as cellular base stations are employed. A single UAV for real-time video downlink for highway surveillance is used in [35], while [103] employs 2 UAVs. A single UAV with infrastructure networking is also employed in [34] for real-time surveillance. In case of periodic transfers, 1, 10, 18 and 16 UAVs have been employed by [70] in a rural medium sized area setting, while [119] uses 3 UAVs. For a small sized urban environment, 23 UAVs are employed by [120], while [188] use 10-50 UAVs to compare mobility models for coverage. For periodic network coverage provisioning [15] use up to 2 UAVs in their experimental setup in a medium sized urban environment. One UAV for forest management is used by [189], considering a small sized rural area.

Fig. 7 mentions the mission and system parameters and the projects implemented for each combination of the considered parameters. The task to describe the network parameters, and the expected network requirements that enable a UAV network implementation satisfying mission requirements for each domain still remains, and is addressed in the following subsection.

C. Network requirements

Network requirements specify constraints on network specific parameters such as expected throughput or data rate, QoS demands such as tolerable delay in the network, and reliability. With these requirements, one can easily analyze the currently available technologies for their feasibility for each application category. We investigate the real-world projects in each application category to extract these requirements.

1) Throughput requirements: Telemetry and RC data are exchanged in all application domains. Regarding throughput, telemetry expects approximately 24 kbps. For RC data, as the packet size is very small (8 channel RC packet = 11 Bytes), the throughput expected is very low ($\sim$ 5 kbps).

A list of quantitative requirements in SAR and coverage provisioning in disaster scenarios are given in [141], keeping in mind the type of sensed traffic that needs to be supported for each type of disaster scenario (video, images, audio or textual sensory data). The values, according to our classification of application domains, are also provided in Table III. WiMAX has been tested for emergency response using UAVs [115], and it is established that the symbol rates expected in [141] for disaster management are satisfied for the distances considered in the tested scenarios. According to [141], the uplink coordination traffic requirements are 4.8 kbaud for SAR and coverage. No further data about the throughput requirements for coordination information exchange was found in other project descriptions. For the sensed traffic, [141] states the minimum requirement for the downlink traffic to the base station as greater than 64 kbaud for disaster scenarios involving SAR, tracking and monitoring, while the downlink traffic requirement for network coverage provisioning is 9.6 kbaud. Other sources, which analyze the sensed traffic, specify the throughput requirement to be 2 Mbps for video streaming [170] and 1 Mbps for image downlink [167]. The demands for network throughput of 12.2 kbps in case of audio transfers and 384 kbps for video transfers for network coverage provisioning have been specified in [82].

The minimum A2G information required for construction application is to track the motion of the UAVs. The throughput requirements regarding motion tracking information is not specified in the literature related to the applications with UAVs, however, performance analysis is done with ground robots. According to the experimentation performed in [171], the visual tracking precession consumes 9.3 Mbps of bandwidth and 104 kbps is required for position, velocity and force signals when periodically transmitted every 25 ms. The expected required throughput is low for construction with UAVs. Similarly, the throughput demand is low for G2A communication for sending control signals and trajectory information. ZigBee is used for sending the control commands in various experimentation works under consideration [123], [190]. The maximum bit rate for ZigBee according to specifications is 250 kbps. The other factors that affect the communication performance in terms of the required bandwidth is the number of UAVs simultaneously communicating with the ground station and their relative distance. In [59] and [126], the area considered for construction is 10 m $\times$ 10 m, hence, a relatively small communication range is required. The number of UAVs used in experiments for demonstration range between 1 - 5 and ZigBee is usually used for communication.

The throughput requirement for delivery of goods application is also not high, since only control and telemetry information needs to be transmitted to the UAVs and status updates and images (optionally) are required at the base station. However, the range can be a concern since the distance to transport the packages may vary from a few meters [131] [136], [134] to several kilometers [42], [43], [44]. If the distance is large, licensed cellular technologies can be used but they require an existing infrastructure. In disaster situations or where such an infrastructure is not available, long distance wireless communication may not be possible with existing available technologies. For shorter distances ZigBee [136], [134] or Wi-Fi [132] is used.

If multiple UAVs are coordinating to transport a mass jointly, an A2A communication link might be necessary for coordination and to avoid any collisions. A good communication link is also required to deliver status information (GPS coordinates, roll, pitch, yaw, acceleration, speed, heading) and control information e.g., any change in mission (mission abort, parameters to avoid collisions, trajectory, etc.). However, these are methodology dependent and the expected throughput varies accordingly.

2) Traffic type: The design of a communication network requires understanding of the type of traffic that needs to be supported in the network. That is why we classify the application domains according to different types of traffic in Fig. 7, i.e., real-time, periodic, and delay tolerant. For a stable network, the QoS related to such traffic exchange also needs to be considered. Thus it may be important to specify whether the transfers have to be reliable or best-effort [196].

As coordinating the movement of the UAVs is integral for the safety of the devices as well as humans around the UAVs, coordination traffic always needs to be reliable. That is why for all application domains, the coordination traffic is classified as reliable. Sensed traffic can be reliable or best-effort, depending on the type of traffic. For instance, for voice and video traffic, reliability needs to be ensured [197], [198]. This is because voice is sensitive to data loss and video is sensitive to jitter in the network and both traffic types need prioritization. On the other hand, if the sensed quantity is measuring some physical quantity from the environment, for instance temperature [199], or pressure [102], the transfer can be classified as best-effort.

As concerns the traffic type, due to timing constraints for mission completion, applications such as those relating to SAR domain, or surveillance require both coordination and sensed traffic to be real-time. On the other hand, traffic in monitoring and mapping does not require to be transferred real-time and hence can be delay-tolerant, or periodic, depending on whether the decision making process is offline [32], [142], or online [70]. Sensed data traffic is mostly delay-tolerant in monitoring and mapping scenarios [88]. In case of network coverage provisioning, as traffic may include all types of data, the network needs to be able to support any traffic. Coordination amongst the entities can be periodic, similar to any WSN. For example, in [188], different mobility models are compared for coverage, and the coordination information is updated every 30 sec. The data sent over an aerial network for both construction and delivery scenarios is for coordination purposes. In construction, the traffic has to be real-time in order to enable the synchronization amongst the devices for load balancing and parallelism in task completion. In delivery scenario, coordination is performed periodically to exchange information about the number of requests in the network, current location of the nodes, battery levels and availability

TABLE III
QUANTITATIVE COMMUNICATION REQUIREMENTS FOR UAV APPLICATIONS. *VALUE DERIVED FROM SYMBOL RATES PROVIDED IN [141].

Application domain	data type	Mission Requirements		Network Requirements		
		Frequency	Mission Specific Requirements	Throughput	Traffic type	QoS (Delay)
SAR	coordination	depends on plan-ahead timesteps [39], >1.7 Hz with 2 nodes for required network throughput of 1 Mbps [191]	disaster response time: usually 1-2 hrs, missing person or animal: 51 hr	4.8 kbaud [141]	real-time	reliable (50-100 ms) [192]
	Sensed	image sensor dependent: >20 fps [167], 30 fps [170], laser sensor: 10 Hz [74]		2 Mbps [170] in case of video streaming, >=64 kbaud [141]	real-time	reliable (50-100 ms) [192]
Monitoring and Mapping	coordination	0.1 Hz [70], 1 Hz [113], 4-5 Hz [118]		4.8 kbaud [141]	Periodic or DTN	reliable (–)
	Sensed	1 Hz [193], 12 Hz [194]		9.6 - 64 kbaud [141]	DTN	can be best-effort or offline
Visual Tracking and Surveillance	coordination	Similar to SAR		4.8 kbaud [141]	real-time	reliable (<3 sec) [119]
	Sensed	>10 Hz to incorporate mobility and noise in urban area [169], >15 Hz [34], 300 Hz [195]		1 Mbps [167] for images, 2 Mbps [170] for video streaming, >=64 kbaud [141]	real-time	reliable (50-100 ms)
Network coverage provisioning	coordination	depends on plan-ahead timesteps		–	periodic	reliable (–)
	Sensed	50 Hz for voice traffic and 30 Hz for video (H.264) [82]		12.2 kbps for voice, 384 kbps for video [82], 9.6 kbaud [141]	real-time	reliable (50-100 ms)
Construction	coordination	Control Command: 100 Hz - 50 Hz, Motion Tracking: 150 Hz	Motion tracking, Trajectory planning, Localization, Collision avoidance, Synchronization, Coordination	<250 kbps	real-time	reliable (–)
Delivery of goods	coordination	Control Command: 100 Hz - 20 Hz, Motion Tracking: 100 Hz	Trajectory planning, Monitor execution state (Position, State), Load handling (Balancing, Safety), Collision avoidance, Demand scheduling	<250 kbps	periodic	reliable (–)

of goods in storage. However, for systems like Amazon or DHL, heavy delivery requests can be anticipated where real-time traffic may become necessary catering for a dynamic demand scenario.

3) Delay: An important QoS metric that affects the performance of a network is the tolerable delay in the network.

For sensed traffic that requires real-time visual or audio data transfers, the delay should be not more than 50-100 ms [192], [198]. This is particularly true for SAR and surveillance, where the ground personnel needs immediate information about the tracked victim/object [72], [80], [103], etc. This can also apply to network coverage provisioning in disaster scenarios where real-time video and audio transfers are required for rescue purposes [82]. On the other hand, for monitoring and mapping, the sensed data transfer to a ground client can be performed offline after the mission completion [32], [88], [142].

For SAR, online coordination traffic has to be real-time as well, and hence, due to the dynamism of the domain, the real-time constraint on delay applies here as well (50-100 ms). For surveillance, such as border or highway surveillance, [119] states that this delay can be up to 3 sec. For the cases of monitoring and mapping, and network coverage provisioning, these values could not be found. This is because for monitoring and mapping, most of the times, coordination is performed offline. Similarly, delay values for construction and transportation are not mentioned in the literature. On the other hand, for coverage, the value for the tolerable delay depends on the speed of flight, number of UAVs and number of clients to connect [200].

VIII. Communication Technologies: Suggestions and Evaluation

In the previous sections, we have established that to identify the appropriate and alternative communication technologies for each application domain, we have to consider the qualitative and quantitative requirements, as well as the design methodology. In this section, we use all the information extracted in the previous sections to answer such fundamental questions as: Whether a global aerial communication network, catering to the needs of all types of applications is possible? If so, whether the existing communication technologies can support all the specified qualitative and quantitative demands? If not, do we look for newer solutions? Or do we design application specific aerial communication networks? For this, we survey the existing wireless technologies in relation to aerial networks, which can help determine potential communication technologies for the so far analyzed application domains, considering the mission requirements and network requirements from Table III. We further present proposed improvements to current protocols in order to facilitate aerial networks. We conclude the section with throughput measurements from real-world experiments over UAV testbeds.

A. Wireless technologies and their feasibility for aerial networks

In Table IV, we have categorized the wireless technologies firstly based on spectrum type (licensed/unlicensed). Using unlicensed spectrum offers a multitude of off-the-shelf, cheap and lightweight communication interface devices. However, the unlicensed spectrum is prone to interference and potential security risks. Table IV then shows the technologies with support for mobility, which is a critical aspect of aerial networks. Maximum number of devices allowed in each technology is an important consideration in terms of device scalability, while network topology provides information about requirement for a network infrastructure, network scalability, and network control (centralized vs distributed). However, the most important factors to consider include maximum communication range, the theoretical maximum physical data rate, and latency. In the following, these factors are described in more detail in relation to traffic demands established in the previous sections for each of the considered application domains.

The demand for control traffic is rather low and can be supported by all wireless technologies, however, the range and reliability for such traffic is important. Hence, a dedicated RC channel is used for such communication although its range is also limited to a few hundred meters. If higher range for control traffic is desired, based on the comparison performed in Table IV, switching to licensed technology (EDGE, UMTS or LTE) may need to be considered.

In the following, we address the demands posed by the four main application domains categorized in this survey, to analyze whether the current standard wireless technologies can cater to these demands from our viewpoint.

For *SAR*, the coordination data includes task assignment commands, exchange of location and heading information and belief maps, requiring 4.8 kbaud, whereas, the sensed traffic can be either images or video stream that requires 1 Mbps and 2 Mbps, respectively. However, the SAR domain requires real-time traffic with strict delay bounds between 50 - 100 ms and cover small and medium size areas. Considering these parameters, Wi-Fi, WAVE, WiMAX, UMTS and LTE technologies can be considered depending on the area size and density of UAV nodes.

For *coverage* domain, the traffic exchange requirements vary significantly from one application to another, and the methodology of real-world implementation of each application (see Sec. V-B). As specified in Fig. 7, from study of real-world projects, it can be seen that most current real-world coverage applications span over small/medium sized areas. However, these applications differ in their traffic demands from real-time to periodic to delay-tolerant. This has also been emphasized in Table III. Generally, coordination traffic includes the offline/online decision making of flight paths and monitoring the execution status of the mission, requiring 4.8 kbaud in *sensor* and *area* coverage applications (monitoring and mapping, visual tracking and surveillance) [2]. In case of sensed traffic, the data can be visual in the form of images and videos or sensor readings like temperature and humidity or voice traffic. In case of visual coverage, streaming images requires 1 Mbps, while 2 Mbps is required for video streaming. Much lower throughput may be required for sensors such as temperature, pressure and humidity sensors (see Sec. VII-C). Thus, the required throughput for sensed traffic varies between 9.6 - 64 kbaud. Concerning the communication requirements for aerial network coverage provisioning, a comprehensive study has been performed by the authors in [82] and [201]. In [201], the authors analyzed the performance of aerial LTE base stations for deployment as communication backbone in emergency scenarios. The work illustrates that such aerial LTE eNodeBs can satisfy the communication requirements stated in [82]. These requirements for aerial network coverage provisioning have been summarized in Table III. However, [202] also contests that aerial network coverage with UAVs may benefit more from 802.11s mesh network than cellular networks in terms of TCP goodput and delay for small sized networks. Most real-world coverage applications employ a single UAV (see Sec. V-B), where offline decision making and offline sensed data transfer have been implemented. Therefore, 802.11 standard has been the preferred wireless technology for real-world implementations.

It is worth noting here that, due to the diversity of applications in the coverage domain, it can only be stated that an appropriate technology from the licensed and unlicensed bands can be considered for coverage applications based on

[2]No real-world projects providing information about coordination traffic throughput requirement are found

parameters such as area size, terrain, number of nodes and traffic type (real-time, periodic traffic, or delay tolerant).

The *construction* application requires small communication ranges and low throughput. This is because the coordination traffic constitutes of motion tracking of UAVs and trajectory planning for collision avoidance and coordination. The expected required throughput based on study of real-world projects is <250 kbps. In such projects, Zigbee is employed as the technology of choice to fulfill the communication requirements in construction domain. However, considering device scalability (refer to Fig. 7 where currently implemented number of UAVs varies from 1 to 5), the throughput requirement for sending control commands and receiving motion information may increase. In such a case, Wi-Fi may be more suitable to satisfy the communication demands.

Similar to construction, the *delivery of goods* application requires low throughput for trajectory planning and execution state monitoring but for transportation the considered area size lies in all the three considered ranges i.e., small, medium and large. Since the communication range for unlicensed spectrum technologies is limited, they cannot provide high capacity communication support over single hop links for large area sizes. Therefore, an appropriate licensed technology may need to be selected. However, considering the energy constraints of micro-UAVs, intermediate charging stations are envisioned for transportation which can also include base station infrastructure, in which case a multi-hop, access point based 802.11 network may also work.

The above discussion leads to the conclusion that depending on range and throughput requirements, Zigbee or a multi-hop 802.11 network may be considered for small and medium range aerial network applications. If high payload vehicles are used, the choices of technologies increase significantly including specialized radio transceivers. Similarly, network interfaces with data security support may need to be developed for certain applications. It is important to note that if the coverage area is large and multi-hop 802.11 is unable to support the required throughput demands, licensed spectrum technologies like WiMAX, GPRS, EDGE, UMTS and LTE may be more suitable. However, these technologies require an existing infrastructure. Areas where such infrastructure based licensed technologies are not available or in disaster struck areas, communication coverage for medium and large areas sizes may not be possible until alternate technologies for such situations are devised.

B. Adaptations of current protocols for aerial networks

There may be a need to alter the currently existing technologies, algorithms and protocols to cater to the needs of newly emerging UAV applications. A promising technology that can help satisfy the spectrum demands of the emerging UAV applications is cognitive radio (CR) technology. However, currently available CR routing protocols can not satisfy the mobility demands of aerial networks. Thus, there might be a need for a bottom-up CR protocol design keeping in mind the specific characteristics of aerial networks [28]. Policy-based radios, which is a class of CR has been proposed for use by [222], with appropriate UAV-related changes. Authors claim that the use of policy-based radios can help predict the unavailability of spectrum in certain conditions to avoid safety failures. In [223], the authors propose a new MAC protocol to counter the delay introduced by CSMA/CA in high density sensor networks where a UAV is used to collect data from source nodes as a relay sink. The communication delay in such a network is more severe due to the high speed of the UAVs. Similarly, another variant of CSMA/CA to cater for QoS in WSN using UAVs as relay sink has been proposed in [224], which employs contention-window adjustment for handling transmission priorities. Another such example of using pre-existent protocols for the design of a robust aerial communication system can be witnessed in [112]. This work uses analytical and simulation results to illustrate that high diversity gain in aerial network can be achieved by using network coding. As mentioned in Sec. III, having knowledge of the intrinsic characteristics of a network helps tune the existing technology effectively. This has been the focus of [225], which develops a variant of Optimized Link State Routing (OLSR) protocol to predict link quality based on GPS information for high speed aerial networks. Considering the dynamics of missions in UAV applications and high mobility in a network of UAVs, it may also be more advantageous to consider geographical routing protocols for aerial network design. In [51], authors propose a mobility prediction based routing protocol, and illustrate the improvements as compared to Ad hoc On-demand Distance Vector (AoDV) routing in terms of end to end delay and packet delivery ratio with the help of simulation results. Another interesting example of use of existing algorithms is the use of Consensus Based Bundle Algorithm (CBBA) for task allocation in an aerial network, proposed in [226]. The work uses CBBA to assign the relaying task to under-utilized UAVs in order to increase network connectivity and improve communications in a multi-UAV system.

C. Results from real-world tests

Some experimental work has been performed using standard wireless technology for throughput measurements for single and multi-hop cases, as shown in Table V. As of now, since there are no formal spectrum re-allocations specifically for aerial networks [227], for experimental purposes, license exempt technologies have been the popular choices. From the experimental work performed, it can be seen that the focus of these tests have generally been on sensed data delivery, which likely demands more capacity than coordination and telemetry data.

Throughput and range analysis for aerial nodes, and connectivity analysis for ground clients, with an ad hoc network of UAVs, has been the focus of [14], employing 802.11b radios. Similarly, 802.11g radios have been installed on board the UAVs to form a mesh network, using the standard 802.11s mesh implementation [15]. This work compares aerial relaying versus ground relaying between two disconnected ground clients. The throughput performance of 802.11n has been analyzed in [228], where employing fixed physical layer data

TABLE IV
COMPARISON OF WIRELESS TECHNOLOGIES

Technology	Standard	Spectrum Type	Device Mobility	Comm. Range	Maximum PHY Rate	Latency	Maximum # of Cell Nodes	Network Topology	References
Bluetooth v4	802.15.1	Unlicensed	Yes	150 m	1 Mbps (gross air data rate), up to 3Mbps (with Enhanced Data Rate)	3 ms	Not defined; implementation dependent	Ad hoc piconets	[203], [204]
Zigbee	802.15.4	Unlicensed	Yes	10 - 100 m	250 kbps	Channel access: 15 ms	<65000	Ad hoc, star, mesh hybrid	
Wi-Fi	802.11a	Unlicensed	Yes	35 - 120 m	54 Mbps	Slot time: 9 μs SFIS: 16 μs DIFS: 34 μs Propagation Delay: 1 μs	-	-	[205], [206] [207], [208] [209]
	802.1b	Unlicensed	Yes	38 - 140 m	11 Mbps	Slot time: 20 μs SFIS: 10 μs DIFS: 50 μs Propagation Delay: 1 μs	-	-	
	802.11n	Unlicensed	Yes	70 - 250 m	600 Mbps	Slot time: 9 μs SFIS: 16 μs DIFS: 34 μs Propagation Delay: 1 μs	-	-	
	802.11ac	Unlicensed	Yes	-	6933 Mbps	-	-	-	
WAVE	802.11p	Licensed	Yes	1000 m	27 Mbps	≈100 ms	-	Ad hoc	[210]
WiMAX	802.16	Unlicensed	No (Line of Sight)	48 km	32 - 134 Mbps	-	-	Single last hop access, wide-area wireless back-haul network deployed in Mesh mode	[211]
	802.16a	Licensed	No	48 km	75 Mbps	-	-		
	802.16e	Licensed	Yes (Limited)	1 - 5 km	15 Mbps	-	-		
GPRS	GPRS	Licensed	Yes	-	115 kbps	≈500 ms	-	-	[212], [213] [214], [215] [216], [217] [218], [219] [220], [221]
EDGE	EDGE	Licensed	Yes	-	384 kbps	≈300 ms	-	-	
UMTS/ WCDMA	UTRA	Licensed	Yes	-	2 Mbps	≈280 ms	-	-	
UMTS/ HSPA	HSUPA, HSDPA	Licensed	Yes	-	14.4 Mbps	≈38 ms	-	-	
LTE	LTE	Licensed	Yes	-	DL: 300 Mbps	User Plane: 5 ms	-	-	
LTE Advanced	LTE Advanced	Licensed	Yes	-	DL: 1 Gbps	User Plane: 10 ms	-	-	

rates is compared to adaptive rate control. The experimental work shows that the performance of 802.11n radios was much lower than expected using adaptive rate control of commercially available off-the-shelf network interface modules. The authors employ internal planar, and external circular antennas with fixed-wing as well as quadcopter UAVs. They conclude that the degraded performance may be caused by chassis of the quadcopters blocking the communication link and causing packet loss. On the other hand, [16] illustrates the impact of antenna orientation on the networking performance of UAVs and proposes a three-antenna structure to provide omnidirectional coverage. The performance of the proposed setup is tested with 802.11a, 802.11n, and 802.11ac compliant radios [16], [20]. It is shown in [20] that higher throughput over longer distances can be achieved using commercially available 802.11n modules employing the three-antenna structure on the quadcopter platforms. The performance difference for 802.11n compared to [228] shows that, while deploying a communication system on-board the UAVs, care must be given to the 3D nature of the network, especially, the on-board antennas need to be tuned for the application at hand to optimize performance. A newer technology 802.11ac has also been tested in [20]. While the laboratory measurements show significant improvement over 802.11n, the outdoor tests result in similar throughput for 802.11n and 802.11ac. Furthermore, the performance of a two-hop UAV network has been analyzed in [83], where performance of different network architectures, i.e., infrastructure vs mesh mode using standard 802.11s implementation over 802.11a radios, have been compared. In addition, [229] also analyzes a multi-hop network of fixed-wing small-scale UAVs equipped with IEEE 802.11n wireless interface in ad hoc mode with an implementation of Optimized Link-State Routing (OLSR). Throughput measurements for aerial Wi-Fi networks for several IEEE 802.11 technology standards are summarized in Table V. Multi-hop network tests measure TCP throughput, single-hop tests measure UDP throughput, and the maximum transmit power (P_{tx}) is used if not stated otherwise.

For experiments performed using 802.15.4 Xbee PRO, [17] states that long range (approximately 1.5 km) can be achieved with low data rates of up to 256 kbps and [18] uses fixed Physical layer rate of 56 kbps, employing five UAVs that fly up to a distance of 500 m from the base station, for A2A, A2G, and ground-ground (G2G) link analysis.

TABLE V
THROUGHPUT MEASUREMENTS OF AERIAL WI-FI NETWORKS FOR LINE-OF-SIGHT LINKS INCLUDING A2A, A2G, G2A AND, FOR COMPARISON, G2G.

Technology	Link	Topology	Throughput
802.11b	A2G	single-hop	1.4 Mbps (2 km) [14]
802.11a (three-antenna)	A2G, G2A, A2A	single-hop single-hop	UDP: 14 Mbps (350 m), 29 Mbps (50 m) [16] TCP: 10 Mbps (500 m), 17 Mbps (100 m) [83]
802.11n (three-antenna, P_{tx} = 12dBm)	A2G, G2A,	single-hop	TCP: 10 Mbps (500 m), 100 Mbps (100 m) [20]
802.11ac (three-antenna, P_{tx} = 10dBm)	A2G, G2A,	single-hop	TCP: 5 Mbps (300 m), 220 Mbps (50 m) [20]
802.11n (internal antenna)	A2A	single-hop single-hop	plane: 1-2 Mbps (300 m), 22 Mbps (20 m) [230] copter: 20 Mbps (80 m), 60 Mbps (20 m) [17]
802.11g + 802.11s [15]	G2G G2A–A2G	multi-hop	no UAV: 0,064 Mbps (75 m) 2-hop: 8 Mbps (75m)
802.11n + OLSR [229] (fixed rate: 13 Mbps)	A2G A2A–A2G	multi-hop multi-hop	1-hop: 1 Mbps (600 m) 2-hop: 2 Mbps (600 m)
802.11a + 802.11s (P_{tx} = 12dBm) [83] (fixed PHY rate: 36 Mbps)	A2G A2A–A2G	multi-hop multi-hop	1-hop: 5 Mbps (300 m) 2-hop: 8 Mbps (300 m, Access point mode) 2-hop: 5 Mbps (300 m, mesh mode)
802.15.4 Xbee-PRO	A2G, A2A	single-hop	up to 250kbps (500 m) [18], (1.5 km) [17]

IX. OPEN RESEARCH ISSUES AND CHALLENGES

Surveys addressing communication demands of aerial networks have pointed out many open issues that may be of interest to the research community interested in aerial network design [13], [24], [29], which are summarized in Section II. In the following, we further elaborate on some of these issues, present the impact of application-driven design on them, and provide a list of new challenges identified by the current survey.

Real-world experimental findings suggest that pre-existing technologies like IEEE 802.11 may act as a feasible solution to the needs of many application domains. It is not clear, however, if the findings would scale to larger networks of UAVs and whether the existing ad hoc networking protocol implementations need to be adapted for multi-hop aerial networks. Furthermore, as has been the practice with VANETs, it is yet not clear if a new IEEE 802.11 standard needs to be developed for aerial networks. A deployable aerial communications architecture is nevertheless under discussion. Due to the need to support communications over A2A, A2G, and G2A links in line-of-sight and obstacle-ridden environments regardless of height or orientation differences, antenna structures tailored for small-scale UAVs are necessary. The impact of antenna structures has been illustrated in literature and some solutions are proposed, however, these antenna-enhanced aerial Wi-Fi networks are not tested for different application scenarios, e.g., that require real-time traffic support or reliable networking. Especially, the coordination traffic among UAVs needs to be reliable to ensure safety and avoid collisions. While some UAV swarms have been deployed, it is still not clear whether existing wireless technologies are suitable for distributed coordination of the vehicles, when strict latency deadlines must be adhered to. Therefore, while the reported results so far are encouraging, there is still a need for more efficient routing and medium-access control protocol solutions for multi-hop communications beyond two-hops. With the growth in the number and scope of commercial applications for UAVs, security and privacy issues may also arise. Thus, considering the networking demands and legal aspects, it may be safe to suggest that for a continuous growth, UAV networks may benefit from operation in licensed spectrum.

Such licensed spectrum may also be needed to increase the customer trustworthyness for aerial networks, for instance, in situations where the UAVs are carrying packages/data, to increase reliability of such delivery. The network interface devices for the technologies developed for aerial networks must also be such that they are easily deployable on the commercially available UAVs, as payload and space can be seen as important limitations for commercial UAVs.

The application specific network design has a strong impact on the design of communication protocols for aerial networks. The most important consideration is that of traffic type. Based on the applications, the transferred data may have varying deadlines and QoS demands, as illustrated in Section VII. Based on such varying demands, it is intuitive to ask if the new technologies developed for aerial networks need to be able to satisfy any and all QoS, or whether it would be more feasible and efficient to have multiple technologies, tuned to application domains under consideration. Another issue arising from the diversity of aerial network applications is the varying timing requirements, which in turn affects the employed mobility models. Specification of new application-based mobility models for aerial networks offers an interesting future research topic.

On the protocol design level, as mentioned above, there are also open issues arising from application diversity of aerial networks. For instance, experimental work has shown that while technologies like 802.11n may satisfy the demands of certain applications, they may lack in fulfilling the demands of others [20]. The device mobility and aerial dynamics cause the rate adaptation to fluctuate greatly in its choice of employed rate. For applications demanding low jitter, new physical layer design has to be considered. The physical layer has to be designed keeping in mind the node density requirements of the application domain under consideration, the distance between the UAVs and the changes in the environment of deployment. The deployment environment also introduces open issues for MAC layer design, as certain environments may introduce higher link outages than others. As reliability of data transfer is very important for control and coordination traffic (Section III), MAC layer design has to consider the constraints on packet latency in aerial network applications. Also, the access technology employed needs to satisfy the application traffic demands. A hybrid approach, employing reservation-based access for time critical data, while contention-based access for delay-tolerant traffic may offer a desirable solution. Network layer is also affected by application driven design of aerial networks. Thus, the answer to questions such as relaying-vs-ferrying of data depend on the traffic requirements of application at hand. Other considerations include geo-routing, routing for dynamic bandwidth allocation and multipath delivery. Similarly, transport layer design is also greatly affected by the link outage (which in turn may depend on deployment terrain of the application). A high degree of reliability is desirable in all cases for control and coordination data transfer, as mentioned previously. At the cross-layer protocol design level, the design of mobility aware rate adaptation protocols may offer an interesting future research direction. The designed protocols have to be highly scalable, as many commercial UAV applications envision swarms of UAVs.

The applications like delivery of goods and coverage require long range communication where intermediate infrastructure depots could be a possibility to maintain connectivity. In such scenarios handover techniques similar to licensed technologies would be required that remains an open research direction.

In case of an autonomous multi-UAV system, high priority communication intercepts shall be designed to cater the needs of safety and security. Unprecedented events like obstructions caused by a flock of birds or similar may occur during the course of a mission that require immediate action either autonomously or through a control center. Possibly an application layer intercept to communicate such an event allowing the mission to be adaptable in such situations needs investigation.

X. Conclusions and Outlook

Teams of small-scale UAVs are envisioned to be part of future air space traffic. Reliable communication and networking is essential in enabling successful coordination of aerial vehicles. Therefore, in this survey, we have reported the characteristics and requirements of UAV networks for envisioned civil applications from a communications and networking viewpoint. We have highlighted that UAV networks cannot be treated as only wireless communication networks due to their mission-oriented nature and hence their network characteristics and communication requirements should be analyzed taking into account the constraints of the applications at hand. Number of existing applications have motivated us to categorize them into four groups that have distinct qualitative and quantitative communication needs, e.g., short vs long range, high vs low capacity, delay tolerant vs real-time, etc. To the best of our knowledge, such analysis has not been done before. Using both network and mission characteristics of the proposed application domains, we have surveyed the communication needs, discussed whether existing technologies can facilitate the given applications, and have reported on real-world measurements, aiming to address all the necessary ingredients for the design of an aerial network that can fulfill the mission demands of the application at hand.

We have observed that IEEE 802.11 technologies are commonly used on-board the commercial small-scale UAVs to enable connectivity due to their wide availability in current networking devices, high performance links, and their suitability for small-scale UAVs. However, the communication demands, in terms of QoS, depend on the application the UAVs are deployed for and further research is necessary to determine whether Wi-Fi is the right communication technology for the application at hand. Without paying special attention to an application, several real-world measurements are conducted using UAVs equipped with different IEEE 802.11 standards for line-of-sight scenarios. Reported results show that in terms of required average throughput and delay, Wi-Fi technology can support many applications that require a few number of hops between the communication nodes. However, as reported, there are still many open issues to the design of an aerial network, that can efficiently address commercial UAV applications, which makes it an interesting, emerging communication and networking research field.

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