J Intell Robot Syst (2009) 54:21–37
DOI 10.1007/s10846-008-9253-2

Networking Issues for Small Unmanned Aircraft Systems

Eric W. Frew · Timothy X. Brown

Received: 15 March 2008 / Accepted: 30 June 2008 / Published online: 17 July 2008
© Springer Science + Business Media B.V. 2008

Abstract This paper explores networking issues that arise as a result of the operational requirements of future applications of small unmanned aircraft systems. Small unmanned aircraft systems have the potential to create new applications and markets in civil domains, enable many disruptive technologies, and put considerable stress on air traffic control systems. The operational requirements lead to networking requirements that are mapped to three different conceptual axes that include network connectivity, data delivery, and service discovery. The location of small UAS networking requirements and limitations along these axes has implications on the networking architectures that should be deployed. The delay-tolerant mobile ad-hoc network architecture offers the best option in terms of flexibility, reliability, robustness, and performance compared to other possibilities. This network architecture also provides the opportunity to exploit controlled mobility to improve performance when the network becomes stressed or fractured.

Keywords Unmanned aircraft system · UAS · Airborne communication networks · Controlled mobility · Heterogeneous unmanned aircraft system · Mobile ad-hoc networking · Delay tolerant networking

1 Introduction

The proliferation of small unmanned aircraft systems (UAS) for military applications has led to rapid technological advancement and a large UAS-savvy workforce poised

E. W. Frew (✉)
Aerospace Engineering Sciences Department, University of Colorado,
Boulder, CO 80309, USA
e-mail: eric.frew@colorado.edu

T. X. Brown
Interdisciplinary Telecommunications Program Electrical
and Computer Engineering Department, University of Colorado, Boulder, CO 80309, USA
e-mail: timxb@colorado.edu

to propel unmanned aircraft into new areas and markets in civil domains. Small unmanned aircraft systems have already been fielded for missions such as law enforcement [29], wildfire management [34], pollutant studies [10], polar weather monitoring [11], and hurricane observation [26]. Proposed UAS span numerous more future civilian, commercial, and scientific applications. A recent study concluded that in 2017 the civil UAS market in the USA could reach $560 M out of a total (civil plus military) UAS market of approximately $5.0 B [32]. That study projects 1,500 civil UAS will be in service in 2017 and that approximately 85% of those will be small UAS.

As the number of fielded small UAS grows, networked communication will become an increasingly vital issue for small UAS development. The largest current barrier to the use of unmanned aircraft in the National Airspace System (NAS) of the USA is satisfaction of Federal Aviation Administration (FAA) regulations regarding safe flight operations and Air Traffic Control (ATC). In particular, the FAA requires almost all aircraft operating in the NAS to have a detect, sense, and avoid (DSA) capability [3] that provides an equivalent level of safety compared to manned aircraft [1, 33]. While onboard sensors are expected to be a component of future DSA solutions, communication to ATC and operator intervention will also be required, either from a regulatory or practical perspective. Thus, one of the primary concerns of the FAA regarding the ability of UAS to meet safety regulations without conflicting with existing systems is the availability and allocation of bandwidth and spectrum for communication, command, and control [2]. Although the particular regulations just mentioned refer to operation in the USA, similar concerns apply to the operation of small UAS anywhere.

Small unmanned aircraft (UA) are defined here to encompass the Micro, Mini, and Close Range categories defined in [5]. This classification means small UA have maximum takeoff weight less than or equal to 150 kg, maximum range of 30 km, and maximum altitude of 4,000 m mean sea level (MSL). The weight limit effectively means small UA can not carry the equivalent weight of a human operator. The altitude limit taken here means small UA cannot fly into Class A airspace (the airspace from 18,000 to 60,000 ft MSL where commercial aircraft fly). Although it may be possible for vehicles in this category to fly at higher altitudes, the regulatory issues are significantly more challenging and it is reasonable to assume most small UA will not fly in that airspace. In fact, most small UA would probably fly substantially closer to the ground. Likewise, the maximum range of 30 km represents typical operational limits on this class of aircraft and there can be notable exceptions [11]. Finally, note that a small UAS can be comprised of multiple heterogeneous small UA with highly varying capabilities.

Unlike larger unmanned aircraft, small UAS are in a unique regime where the ability to carry mitigating technology onboard is limited yet the potential for damage is high. Given the size and payload constraints of small UAS, these unmanned aircraft have limited onboard power, sensing, communication, and computation. Although the payload capacity of a small UAS is limiting, the kinetic energy stored in a 150 kg aircraft can cause significant damage to other aircraft, buildings, and people on the ground. Furthermore, the limited sizes of small UAS make them accessible to a wider audience (e.g. a variety of universities already have small UAS programs [4, 9, 16, 21, 28]) than larger systems and the percentage of small UAS deployed in the future will likely be high relative to larger unmanned aircraft systems [32]. The limited capabilities of small UAS lead to unique operational requirements compared to larger UA that can more easily assimilate into the existing ATC framework (e.g. larger UA can carry the same transponder equipment as manned aircraft).

This paper explores networking issues that arise as a result of the operational requirements of future applications of small unmanned aircraft systems. These requirements are derived from a set of representative application scenarios. The operational requirements then lead to networking requirements (e.g. throughput, which is the rate at which data can be sent over a communication link, and latency or delay) that greatly exceed those of current manned aircraft. Further, the networking requirements are mapped to three different conceptual axes that include network connectivity, data delivery, and service discovery. The location of small UAS networking requirements and limitations along these axes has implications on the networking architectures that should be deployed.

Of the existing possible network architectures for small UAS, only delay-tolerant mobile ad-hoc networking architectures will provide the needed communication for the large number of small aircraft expected to be deployed in the future. Since small UA are relatively cheap, future UAS will likely deploy multiple vehicles coordinated together. Many small UAS applications will require quick response times in areas where permanent supporting communication infrastructures will not exist. Furthermore, current approaches using powerful long-range or satellite communications are too big and expensive for small aircraft while smaller radios fundamentally limit the small UAS operational envelope in terms of range, altitude, and payload. The delay-tolerant mobile ad-hoc network architecture offers the best option in terms of flexibility, reliability, robustness, and performance compared to other possibilities. This network architecture also provides the opportunity to exploit controlled mobility to improve performance when the network becomes stressed or fractured.

2 Communication Requirements

2.1 Operational Requirements

This work is motivated by the Heterogeneous Unmanned Aircraft System (HUAS) developed at the University of Colorado as a platform to study airborne communication networks and multivehicle cooperative control (Fig. 1 shows the various small UA included in HUAS). Specific applications studied to date include the impact of mobility on airborne wireless communication using off the shelf IEEE 802.11b (WiFi) radios [7]; net-centric communication, command, and control of small UAS [16]; sensor data collection [22]; delay tolerant networking [6]; and a framework for controlled mobility that integrates direct, relay, and ferrying communication concepts [13].

As an example application consider a UAS to track a toxic plume. In this scenario a toxic plume has been released in an accident and the goal is to locate the plume extent and source [17]. To characterize the plume, multiple small UA fly while sensing the plume with onboard chemical sensors. Different sensors may be in different UA because it may not be possible or desirable for every small UA to carry every sensor. UA with the same chemical sensors onboard need to find each other to form gradient seeking pairs. Chemical gradients can be defined by sharing sensor

Fig. 1 The HUAS vehicle fleet includes (*clockwise from top left*) the CU Ares, the CU MUA, the Velocity XL, the MLB Bat 3, the CU ground control station, and the Hobico NextGen

data and the UAS can cooperatively track boundaries or follow the gradients to the source. UA can potentially move far away from their launching ground stations and each other. In this example, the UAS consists of potentially many heterogeneous UA. They need to fly freely over a large area and be able to dynamically form associations autonomously without relying on a centralized controller.

As a second example consider a UAS deployed to act as a communication network over a disaster area. Here, normal communication infrastructure has been damaged but various entities on the ground such as first responders, relief agencies, and local inhabitants require communication in order to organize a coordinated response. An unmanned aircraft system flying overhead can provide a meshed communication architecture that connects local devices, e.g. laptops with wireless networking or cell phones, with each other or back to the larger communication grid. Since communication demand will vary as the severity of the disaster is assessed and relief efforts are mounted, the UAS must be able to reposition itself in response. Since the actions of the ground units are in direct response to the emergency situation, the actions of the UAS must be dependent on them and not limit their efforts. Also, the UAS will likely operate in the vicinity of buildings and other manned aircraft so obstacle and collision avoidance will be critical.

The two scenarios described above share properties with many other potential small UAS applications and lead to communication requirements for the UAS itself. In particular, these communication needs can be broadly classified into platform safety, remote piloting, and payload management (Fig. 2). In general, the UAS will communicate with multiple external parties that could include ATC, the pilot, and payload operators who may be in widely separate locations.

2.1.1 Platform Safety

From a regulatory perspective, platform safety is the most critical component of an unmanned aircraft system. Like a manned aircraft, the pilot of the UAS must communicate with ATC in most controlled airspace [33]. This communication may be mediated by the UAS whereby the UAS communicates via conventional radio

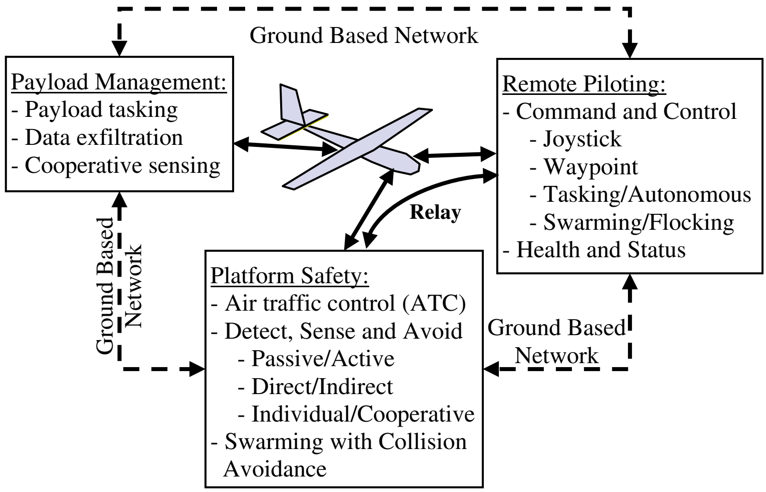


Fig. 2 Types of communication in an unmanned aircraft system

to the ATC and this communication is then backhauled to the pilot. This implies an inherent inefficiency. A single ATC radio channel is shared by all planes in an area. But, each UA requires a separate backhaul to its respective operator, and multiplies the communication requirements. Future non-voice approaches to managing aircraft are being contemplated [14]. In principle, ATC commands (e.g. to change altitude) could be acted upon directly by the UA without pilot intervention obviating the need for the inefficient backhaul. However, it is likely that a pilot will always be expected to be "on the loop" so that UAS operations are completely transparent to ATC. Future communication system analysis estimates the average ATC voice and data rates to be about 10 kbps per aircraft particularly in autonomous operations areas typical of UAS operations [14].

Other platform safety communication is related to detect, sense, and avoid requirements which generally require the UAS to have equivalent ability to avoid collisions as manned aircraft [1, 33]. This may require onboard radar (active sensing), backhaul of image data (passive sensing), transponders, or cooperative sharing of information between UA. The communication requirements here can depend significantly on the approach. The least communication demands are required when the aircraft uses active sensing, only reports potential collisions to the operator, and autonomously performs evasive maneuvers when collisions are imminent. The communication requirements here are negligible. More demanding systems send full visual situational awareness to the operator which can require 1 Mbps or more (e.g. Fig. 3).

The communication requirements for small UAS are simplified in many instances. Small UAS often fly in uncontrolled airspace. No transponders are required, nor is communication with ATC. Small UAS can operate directly in uncontrolled airspace without the need of an airport. They are often catapult or hand launched and can have parachute, net, or snag recovery systems. Small UAS generally fly over smaller regions than larger UAS. Small UAS are still subject to DSA requirements, however, for very short ranges, the pilot or spotters on the ground can provide the see and

Fig. 3 Situational awareness provide by imagery from onboard a small UA

avoid. For larger ranges active or passive techniques are required. The smaller platform size limits the ability to carry onboard autonomous DSA systems.

Small UAS participating in the example scenarios described in Section 2.1 will clearly be operating in environments with significant other air traffic so platform safety will be important. Manned aircraft for emergency response and from news agencies will surely operate in the environment where the UAS will be deployed. The UAS pilot will require significant communication with ATC to coordinate operation with these other aircraft. From the perspective of network or radio bandwidth and throughput, the requirements for this communication traffic are low since messages are limited in size (or length) and are sent sporadically. However, the safety critical nature of this traffic will require high reliability with low latency.

2.1.2 Remote Piloting

Remote piloting of the vehicle has requirements that vary with the type of flight control. On one extreme is direct joystick control of the aircraft. This requires low delay and high availability. At the other extreme, tasking commands are sent to the aircraft which are autonomously translated to flight paths (Fig. 4 shows the user interface for the Piccolo autopilot that allows for point and click commands [31]). Here delays can be longer and gaps in availability can be tolerated. The UA to

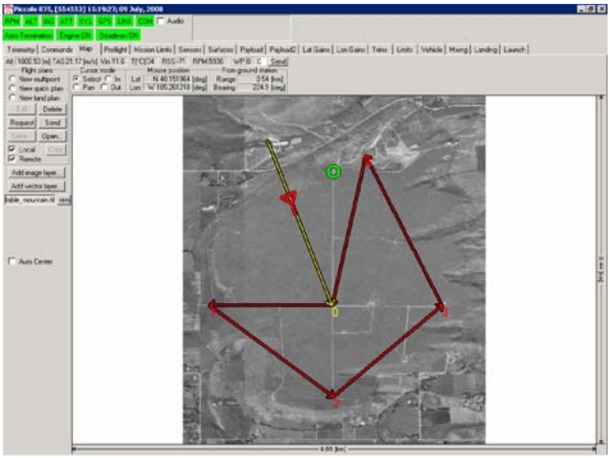


Fig. 4 Cloud cap technologies piccolo autopilot command center [31]

pilot link contains not only commands from the pilot to the UA but also essential health and status information from the aircraft back to the pilot. As examples, on the joystick end of the spectrum commercial digital radio control (R/C) links have data rates below 10 kbps and one-way delays below 100 ms are preferred. On the autonomous end of the spectrum, an Iridium satellite link is sufficient for waypoint flying of the Predator UAS. Iridium has 2.1 kbps throughput, delays of 1–7 s, and has gaps in connectivity with 96% average availability [25].

Small UAS are lower cost and are more likely to operate in cooperative groups. There is a strong push to enable one-to-many pilot-aircraft interactions for UAS [27]. This mode of operation would require increased amounts of UA autonomy with the pilot in charge of higher level mission planning and tasking. As such, UA must be capable of autonomous collision avoidance and therefore plane-to-plane communication becomes another significant communication component. Collision avoidance between two UA will also have low data rate and low latency requirements. However, the presence of multiple vehicles all performing plane-to-plane communication complicates the networking and introduces the need for bandwidth and congestion control. The possibility of varied capabilities and aircraft attrition also necessitates dynamic service discovery routines whereby system capabilities can be updated internally.

2.1.3 Payload Management

Communication with the payload can range from a few bits per second for simple sensor readings to megabits per second for high-quality images (Fig. 5). For instance, the Predator uses a 4.5 Mbps microwave link to communicate payload imagery when in line-of-site of the ground station [23]. The types of payload communication needed by small UAS can be highly varied. For example, depending on the type of chemical plume being tracked, real-time data assimilation may not be needed. In that case large amounts of data can be stored at intermediate nodes and transmitted opportunistically back to the end user. In contrast, if a toxic substance is released in an urban setting, source localization could take priority over all other requirements including DSA. Using multiple UA to provide information to multiple dispersed users also necessitates dynamic service discovery routines.

In summary, the communication requirements for UAS are modest for ATC communication and remote piloting while UAS can potentially require data rates in the megabits per second for payload management and DSA. It is this requirement for multiple connections, some of which are at high data rates, that distinguishes UAS from manned aircraft communications. There are also other considerations

Fig. 5 High quality payload imagery from the MLB Bat small UAS [24]

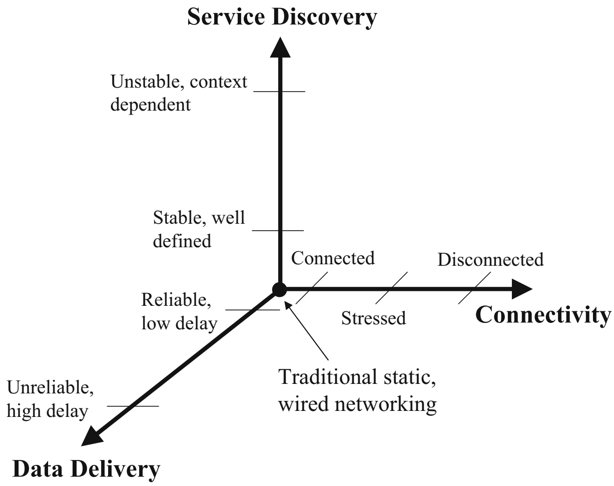
than data rates, latency, and availability. ATC, remote piloting, and other flight safety communication will likely be required to operate in protected spectrum that is not shared with payload and non-essential communication [14, 20].

2.2 Operational Networking Requirements

The communication needs can be explored along three axis (Fig. 6). The first is connectivity. In traditional networks, node connectivity is well defined; a physical wire connects two nodes. These links are designed to be reliable with rare transmission errors. Further, the links and nodes are stable with only rare failures. This yields a well defined network topology with clear notions of graph connectivity that is consistent across network nodes. In a small UAS, the links are less reliable wireless links with connectivity that ranges from good when nodes are close to poor for nodes that are further away. Even when connectivity is good packet error rates are high relative to wired standards. The transmission is broadcast and can reach multiple receivers so that connections are not simple graph edges. Further, broadcast transmissions interfere with each other so that the ability of two nodes to communicate depends on the other transmissions at the same time. As we add UA mobility, connectivity becomes dynamic and as UA speeds increase relative to the nominal communication range different UA may have inconsistent notions of connectivity.

The second axis is data delivery. In traditional networks, connectivity is well defined and stable so that data delivery is based on an end-to-end model. For instance, with TCP protocols the source and destination end points manage data delivery over a presumed reliable and low latency network. As these connectivity assumptions break down this model of delivery is not possible. As already noted, small UAS connectivity is unreliable and dynamic. Furthermore, small UAS may become spread out over a mission so that end-to-end connectivity simply does not exist for data delivery.

Fig. 6 Communication requirements can be characterized along three axes



The third axis is service discovery. In traditional networks, resources are stable and can be found through well defined procedures. To find a webpage, we use a URL (e.g. http://www.springer.com), this is translated by the DNS service into a network address, and we request the webpage from the server at that address. In contrast, with small UAS nodes, services, and users can come and go over the life of a mission and the resources sought may be ephemeral or context dependent. Each UA may have different capabilities (e.g. the chemical sensors in the plume tracking example) and onboard capabilities may be available for use by other UA (e.g. coordinating cameras for stereo imaging). As small UAS spread out these resources, even when they exist, may be difficult to discover. This concept of service discovery can be pushed down from aircraft to the subsystems aboard the aircraft. By connecting onboard subsystems via local subnets to the external meshed network, dispersed operators as well as other aircraft in the UAS can discover and communicate directly to different components of the aircraft avionics system.

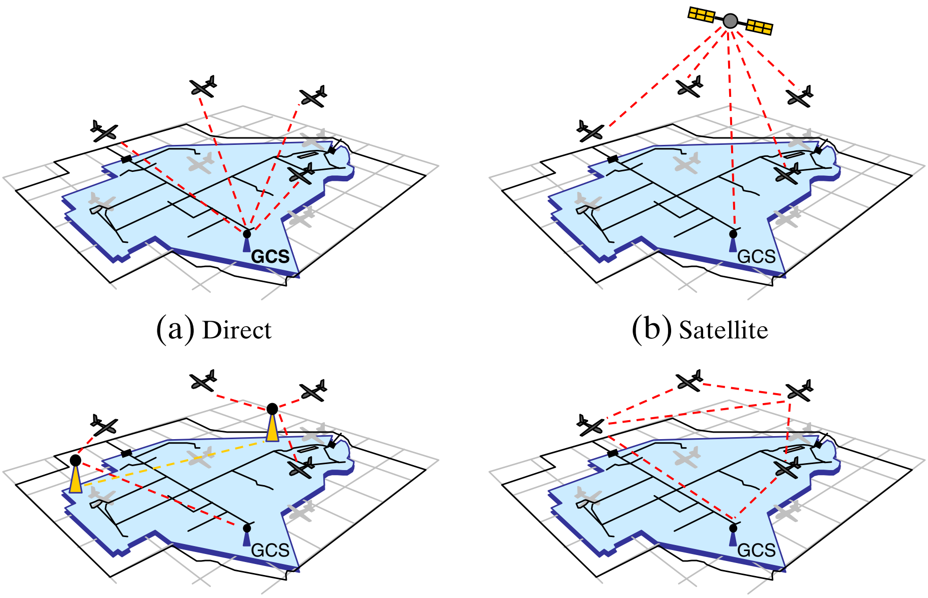
3 Networking for Small UAS

The goal of small UAS networking is to address the communication needs given that small UAS differ from traditional networks along the connectivity, data delivery, and service discovery axes. To this end, this section describes the merits of different communication architectures and introduces the delay tolerant networking delivery mechanism. It also discusses how the mobility of the small UAS can be exploited to improve networking.

3.1 Communication Architectures

There are four basic communication architectures which can be used for small UAS applications: direct link, satellite, cellular, or mesh networking (Fig. 7). Each has advantages and disadvantages which we outline here. A direct link between the ground control station and each UA is the simplest architecture. It assumes connectivity is maintained over dedicated links to each UA and therefore data delivery is reliable with low latency. Since the ground station communicates to each UA, service discovery is easily managed by a centralized agent at the ground station. Unfortunately the direct architecture is not suited for dynamic environments and non-line-of-sight (NLOS) communication. Obstructions can block the signal, and at longer ranges the UA requires a high-power transmitter, a steerable antenna, or significant bandwidth in order to support high data rate downlinks. The amount of bandwidth scales with the number of UA so that many UAS may not operate simultaneously in the same area. Finally, plane-to-plane communication will be inefficiently routed through the ground control station in a star topology and not exploit direct communication between cooperative UA operating in the same area.

Satellite provides better coverage than a direct link to the ground control station. As a result, the UAS network can remain well connected, however this connectivity would still be provided by routing data through a centralized system. Data delivery is relatively poor using satellite. Lack of satellite bandwidth already limits existing UAS operations and will not scale with the increasing demand of 1,000s of small UAS operations in a region. For high data rate applications, a bulky steerable dish antenna mechanism unsuitable in size, weight and cost for small UAS is necessary.



(a) Direct (b) Satellite

(c) Cellular (d) Mesh

Fig. 7 Four basic communication architectures for small UAS. The ground control station (GCS) represents the operator or end user

Further, the ground control station requires a connection to the satellite downlink network. The ground control station may have obstructed satellite views because of terrain or clutter. Finally, multiple UA operating in an area will suffer high delays if their communication is mediated by satellite.

Cellular refers to an infrastructure of downlink towers similar to the ubiquitous mobile telephone infrastructure. The cellular architecture has several advantages that can provide good levels of network connectivity and reliable data delivery. First, coverage can be extended over large areas via multiple base stations. UAS would hand-off between different base stations as needed during flight. Second, the multiple base stations provide a natural redundancy so that if one link is poor another link may perform better. Third, a limited bandwidth can be reused many times over a region and capacity increased as needed to meet demand. The reuse can grow by adding more base stations as the number of users grows. Fourth, the infrastructure can be shared by different UAS. Once installed, many UAS can each pay for the fraction of the infrastructure that they use. These advantages must be weighed against the cost. A typical mobile telephone base station is expensive for the tower, tower site, radio equipment, and associated networking infrastructure. Such a solution applies where the infrastructure investment can be amortized across frequent and regular UAS flights. Examples might include agricultural monitoring or border surveillance. Such architecture is not suited for applications like wildfire management or polar climatology where demand is transient. The existing mobile telephone infrastructure is not designed for air to ground communication. A single UA transmitter can blanket a large area with its signal degrading system performance. Therefore, small UAS operations may require a dedicated cellular infrastructure.

Meshing refers to a networking architecture where each node (i.e. a radio on a UA or ground node) can act as a relay to forward data. Communication between a UA and a ground control station can take place over several ŞhopsŤ through intermediate nodes. The shorter range simplifies the link requirements and bandwidth can be reused more frequently and thus more efficiently. Plane-to-plane communication can be direct and also benefit from the mesh routing protocols that employ additional relays as needed to maintain communication. However, such meshing requires intermediate nodes to be present for such relaying to take place. Furthermore, nodes may be required to move specifically in order to support communication.

Mobile ad-hoc networking (MANET) is a particular example of a mesh architecture comprised of a self-configuring network of mobile routers which are free to move randomly throughout the environment. The MANET topology changes rapidly due to the motion and the nodes in the network rapidly self-organize in response. The MANET approach is promising for UAS applications where infrastructure is not available and multiple UA are operating cooperatively. Data relaying in MANETs reduces the connectivity requirements since source and destination nodes only need to be connected through the intermediate nodes. Due to the decrease of radio transmission power, and hence communication capacity, with separation distance [30], the presence of the intermediate relay nodes can actually improve data delivery performance over direct communication [18]. Further, since MANETs are design to self-heal, they can respond well to the dynamic network topologies that result from UA motion. Service discovery in MANETs is more important and more complex than the other architectures since the network tends to become fractured for periods of time and there is no centralized node to coordinate network activities.

Meshing can also leverage the other technologies described above. A direct, satellite, or cellular link to any node in a connected mesh enables communication with all the nodes providing additional redundancy in the communication. Meshing combined with mobility can extend range. For instance, as a group of UA move beyond the range of a direct link, some of the UA can be assigned to stay behind forming a chain of links back to the direct link. In an extreme form of this UA can fly back and forth to ferry data between nodes that have become widely separated. It is this flexibility, robustness, and added range that makes meshing an integral part of any small UAS operations.

3.2 Delay Tolerant Networking

Real-time communication is challenging for mobile ad-hoc networks on small UAS because of inherent variability in wireless connections combined with the fact that nodes may become spread out and sparsely connected. Connections that exist can be dynamic and intermittent, antenna patterns shift with aircraft maneuvering, sources of interference come and go, and low flying UAS can be separated by intervening terrain. In the extreme case of sparsely connected, moving nodes, some nodes might not be able to connect with any other node for a long time. In such environments, traditional end-to-end network protocols such as the ubiquitous TCP perform poorly and only delay-tolerant communication is feasible. So-called delay tolerant networks (DTN) are designed for these challenged environments [8, 15]. DTN provide a smooth spectrum of communication ability. Data is delivered quickly when end-to-end connections exist and as quickly as opportunities appear when intermittently connected. The DTN also supports data ferrying where, for instance, a ground sensor can deliver data to an overflying UA that then physically carries the data back to a network gateway to an observer.

The data flowing through the MANETs deployed on small UAS will have large variety of data types and quality of service requirements. For example, Voice over IP (VOIP) between first responders, UA control data, or critical process monitoring will require prioritized real-time flow. For a wireless ad-hoc network to be able to carry real-time data there needs to be a contemporaneous, reliable connection from sender to receiver. The more nodes that participate in the network in a given area, the more likely a path can be established. Other data types, such as email, non-critical messaging, or sensor data from long-term experiments, will not carry the same sense of urgency and consist of delay-tolerant traffic where only eventual, reliable reception is important. Continuous multi-hop links from the sender to receiver do not need to be maintained as long as a data packet is carried or forwarded to its destination in some reasonable amount of time. The DTN architecture provides seamless mechanisms for integrating these various requirements into a single network.

DTN are a current topic of research. An example DTN was implemented on the University of Colorado's HUAS for delivering sensor data to one or more external observers outside the UAS [22]. Sensors on UA or on the ground generate data and a DTN procedure delivers the data in stages through gateways to the observers. Each stage takes custody of the data and stores it in the network until a connection opportunity to the next stage arises. End nodes can operate with no knowledge of the DTN through proxy interfaces.

In addition to extending the capability of MANET architectures to sparse or fractured networks, the DTN concept is also important for maintaining system responsibility and accountability in the face of UAS failure. In traditional MANET architectures, data is not transmitted if an end-to-end connection is not present and therefore data will be lost if a link goes down due to failure. In contrast, the DTN protocols store data at intermediate nodes until it is safely transmitted to the source. Thus telemetry, health and status, and other data collected during periods when a node is disconnected from the network can still be collected. This includes information from moments before a failure which may be stored and can be collected for post analysis.

3.3 Exploiting Controlled Mobility

Unlike terrestrial networks which tend to be static and satellite communication systems which are in fixed orbits, meshed networks of small UA offer a unique opportunity to exploit controlled mobility. Even when a continuous link is established, environmental factors such as multipath, interference, or adversarial jamming, can degrade real-time performance relative to expected models. In these cases the mobility of the nodes themselves can be exploited to improve the network performance. In sparse networks, node mobility enables data ferrying, i.e. physically carrying data packets through the environment, between otherwise disconnected nodes. In the case of a connected network, node mobility enables adjustment of local network behavior in response to unmodeled disturbances.

Given the presence of node mobility in an ad-hoc network, transmission of data between a source and destination can take three forms (Fig. 8). *Direct*

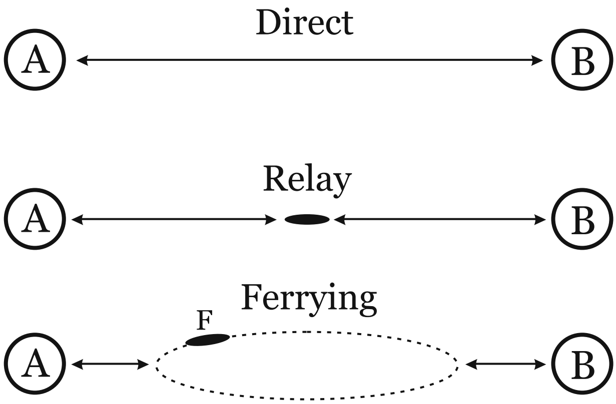


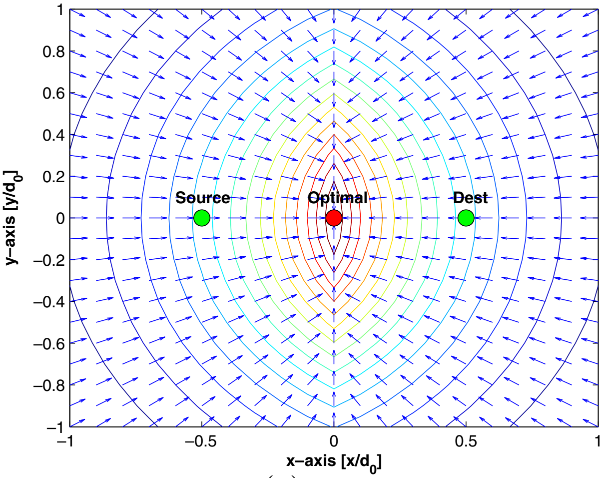
Fig. 8 Three modes of maintaining a communication link between two static nodes A and B

communication occurs when two nodes transmit data directly to one another. *Relaying* occurs when additional nodes are used to receive a transmission from a source and retransmit it to a destination. Finally, *data ferrying* occurs when a mobile node physically stores and carries data from one location to another. Each of these modes has a place in communication. For instance, at 5 km a low-power wireless direct link might support only a few 10's of kbps, while a ferry with a 50 megabyte buffer and velocity of 30 m/s can deliver data at a rate of over 1 Mbps. However, the direct link can deliver a packet in under a second while the ferry will require minutes. Thus, using mobility requires understanding the tradeoffs in delay and data rate. These ideas have been explored in [6] which defines the different operational regions and the tradeoffs in each.

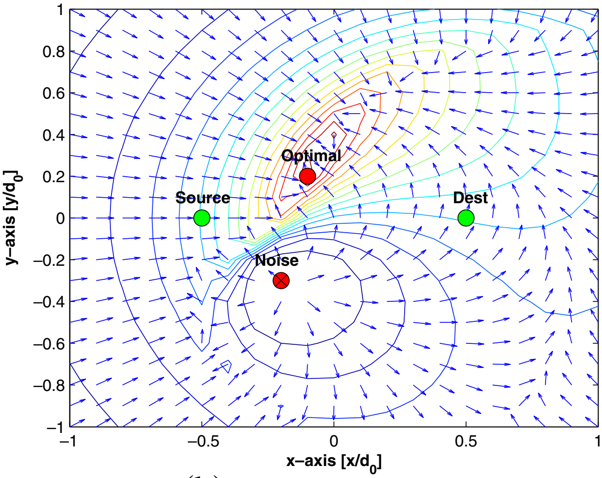
To further illustrate the role of mobility in determining network performance, consider an example with two task nodes that wish to communicate with one another and additional mobile helper nodes in the environment that can act as relays between the task nodes. The two task nodes could represent a time-critical sensing system and a human-operated ground station or two relay nodes electronically leashed to convoys of ground vehicles. As the distance between the task nodes increases, one or more helper nodes are needed to relay data between them. While networking protocols controlling the flow of data between nodes have been extensively studied, the issue of how to best deploy or position these helper nodes is still open. Position-based solutions break down in the presence of noise sources and terrain that distort the radio propagation and power models from simple cases [12]. For example, Fig. 9 shows how a single noise source distorts the contours of end-to-end chain capacity as a function of relay node position for a simple 3-node network. For a multiple UA chain providing multi-hop communication, decentralized control laws can optimize chain capacity based only on measures of the local 3-node network perceived by each UA [12].

As the separation distance between the task nodes grows relative to the communication range of the helper nodes (i.e. the density scale decreases) positioning of the helper nodes becomes more difficult. Given relatively static node placement and knowledge of their position, deployment of the helper nodes becomes a resource allocation problem [18]. As the density scale decreases and the separation between nodes grows, it becomes difficult for helper nodes to build consensus on deployment.

Fig. 9 Contours of end-to-end chain capacity for a three-node network and the vector field showing the gradient of capacity. Interference distorts radio propagation from standard models and makes position-based solutions for relay placement suboptimal. **a** Contours and vector field with no noise; **b** Contours and vector field with a localized noise source



(a) No noise



(b) Localized noise source

Centralized strategies in which the helpers converge to build consensus trade advantages with distributed approaches that enable helper nodes to make decisions based only on local information. The best approach is not apparent. Furthermore, as the separation distance between nodes grows beyond a certain point it becomes impossible to establish a connected chain between them and the helper nodes must exploit their own mobility to ferry data back and forth [19]. While this seems to be a basic process, the fact that the nodes are not in a fully connected network at this point hinders consensus building among the helpers and the implementation of globally optimal behavior.

Although deployment of helper nodes is challenging in relatively static scenarios, the problem is further complicated when nodes (task nodes and helper nodes) are capable of moving quickly relative to their communication range (i.e. the dynamic scale increases). If we allow the task nodes the freedom to perform their primary task, the helper nodes must cooperatively distribute themselves through the environment to provide multi-hop communication. Motion of the helper nodes has a greater effect on the performance of the communication network and the problem shifts from resource allocation to continuous coordinated control.

This simple example scenario illustrates the effects of mobility on communication in delay tolerant networks. It is clear that the establishment and maintenance of networks of mobile nodes, especially given a subset of nodes dedicated to primary missions such as sensing, requires some form of distributed cooperative control. Furthermore, in order to exploit node mobility in a distributed control architecture, communication metrics such as quality of service requirements must be incorporated explicitly as objectives in the mobility control scheme.

4 Conclusion

This paper explored requirements for networking of small unmanned aircraft systems. The networked communication demands of unmanned aircraft systems in general, and small unmanned aircraft system in particular, are large compared to manned aircraft since telemetry, command and control, health and safety, and payload data must be sent from multiple aircraft to multiple dispersed users such as the unmanned aircraft system operator, air traffic control, and other aircraft in the vicinity.

The communication environment for small UAS was shown to deviate significantly form traditional networking assumptions. Connectivity is lower quality, less well defined, and dynamic. Data delivery can not depend on reliable, low-latency, and end-to-end connections. Network service discovery must operate in isolated networks to discover dynamically available resources.

In this environment, we described how mesh networking, supported by delay tolerant networking, and robust service discovery can operate. Mesh networking is designed to work in mobile environments and allows two UA to communicate by dynamically piecing together links to form a communication path. Delay tolerant networking is designed to work in sparse connectivity environments and inserts intermediate custody points so that communication can make progress in smaller stages over time as connections become available. Service discovery allows aircraft to advertise their capabilities and so others can find and use them.

The small UAS networking environment is challenging but provides some opportunities. A small UAS will likely have multiple aircraft. When needed some of these can be devoted to support communications, moving to locations to relay between disconnected groups or in extreme cases the aircraft can ferry data by physically carrying the data back and forth.

Small UAS provide unique challenges to networking. What is reported here is based on our experience implementing and testing networks on small UAS. Our research continues to address these challenges. These include methods for seamlessly and safely integrating flight critical command and control data with less critical payload date on a single communication network.

Acknowledgements The authors would like to thank the members of the University of Colorado AUGNet Research Group. This work was supported by the US Air Force under Grant FA9550-06-1-0205, by the Federal Aviation Administration under Grant 07-G-014, and by L-3 Communications.

References

1. Federal Aviation Administration: order 7610.4k. Special military operations (2004)
2. Federal Aviation Administration: meeting the challenge: unmanned aircraft systems. In: Federal Aviation Administration R&D Review, vol. 4 (2006)
3. Federal Aviation Administration: title 14 code of federal regulations (14 cfr) part 91 (2008)
4. Beard, R., McLain, T., Nelson, D., Kingston, D., Johanson, D.: Decentralized cooperative aerial surveillance using fixed-wing miniature UAVs. Proc. I.E.E.E. **94**(7), 1306–24 (2006)
5. van Blyenburgh, P.: Unmanned Aircraft Systems: The Global Perspective. UVS International, Paris, France (2007)
6. Brown, T.X., Henkel, D.: On controlled node mobility in delay-tolerant networks of unmanned aerial vehicles. In: Proc. of Intl Symposium on Advanced Radio Technologies, Boulder, CO (2006)
7. Brown, T.X., Argrow, B.M., Frew, E.W., Dixon, C., Henkel, D., Elston, J., Gates, H.: Experiments using small unmanned aircraft to augment a mobile ad hoc network. In: Bing, B. (ed.) Emerging Technologies in Wireless LANs: Theory, Design, and Deployment, chap. 28, pp. 123–145. Cambridge University Press (2007)
8. Cerf, V.G., Burleigh, S.C., Durst, R.C., Fall, K., Hooke, A.J., Scott, K.L., Torgerson, L., Weiss, H.S.: Delay-Tolerant Network Architecture. Internet Draft, IETF (2006)
9. Claus Christmann, H., Johnson, E.N.: Design and implementation of a self-configuring ad-hoc network for unmanned aerial systems. In: Collection of Technical Papers - 2007 AIAA InfoTech at Aerospace Conference, vol. 1, pp. 698–704. Rohnert Park, CA (2007)
10. Corrigan, C.E., Roberts, G., Ramana, M., Kim, D., Ramanathan, V.: Capturing vertical profiles of aerosols and black carbon over the Indian Ocean using autonomous unmanned aerial vehicles. Atmos. Chem. Phys. Discuss **7**, 11,429–11,463 (2007)
11. Curry, J.A., Maslanik, J., Holland, G., Pinto, J.: Applications of aerosondes in the arctic. Bull. Am. Meteorol. Soc. **85**(12), 1855–1861 (2004)
12. Dixon, C., Frew, E.W.: Decentralized extremum-seeking control of nonholonomi vehicles to form a communication chain. Lecture Notes in Computer Science, vol. 369. Springer-Verlag (2007)
13. Dixon, C., Henkel, D., Frew, E.W., Brown, T.X.: Phase transitions for controlled mobility in wireless ad hoc networks. In: AIAA Guidance, Navigation, and Control Conference, Keystone, CO (2006)
14. EUROCONTROL/FAA: Future Communications Study Operational Concepts and Requirements Team: communications operating concept and requirements (COCR) for the future radio system. Tech. Rep. 1.0 (2006)
15. Fall, K.: A delay-tolerant network architecture for challenged internets. In: SIGCOMM '01, pp. 27–34 (2003)
16. Frew, E.W., Dixon, C., Elston, J., Argrow, B., Brown, T.X.: Networked communication, command, and control of an unmanned aircraft system. AIAA Journal of Aerospace Computing, Information, and Communication **5**(4), 84–107 (2008)
17. Harvey, D.J., Lu, T.F., Keller, M.A.: Comparing insect-inspired chemical plume tracking algorithms using a mobile robot. IEEE Trans. Robot. **24**(2), 307–317 (2008)
18. Henkel, D., Brown, T.X.: Optimizing the use of relays for link establishment in wireless networks. In: Proc. IEEE Wireless Communications and Networking Conference (WCNC), Hong Kong (2008a)
19. Henkel, D., Brown, T.X.: Towards autonomous data ferry route design through reinforcement learningi. In: Autonomic and Opportunistic Communications Workshop (2008b)
20. Henriksen, S.J.: Estimation of future communications bandwidth requirements for unmanned aircraft systems operating in the national airspace system. In: AIAA InfoTech@Aerospace, vol. 3, pp. 2746–2754. Rohnert Park, CA (2007)
21. How, J., King, E., Kuwata, Y.: Flight demonstrations of cooperative control for uav teams. In: AIAA 3rd "Unmanned-Unlimited" Technical Conference, Workshop, and Exhibit, vol. 1, pp. 505–513. Chicago, IL (2004)
22. Jenkins, A., Henkel, D., Brown, T.X.: Sensor data collection through gateways in a highly mobile mesh network. In: IEEE Wireless Communications and Networking Conference, pp. 2786–2791. Hong Kong, China (2007)
23. Lamb, G.S., Stone, T.G.: Air combat command concept of operations for endurance unmanned aerial vehicles. Web page, http://www.fas.org/irp/doddir/usaf/conops_uav/ (1996)

24. MLB Company: MLB Company—The Bat. http://www.spyplanes.com/bat3.html (2008)
25. Mohammad, A.J., Frost, V., Zaghloul, S., Prescott, G., Braaten, D.: Multi-channel Iridium communication system for polar field experiments. In: International Geoscience and Remote Sensing Symposium (IGARSS), vol. 1, pp. 121–124. Anchorage, AK (2004)
26. NOAA: NOAA News Online: NOAA and partners conduct first successful unmanned aircraft hurricane observation by flying through Ophelia. http://www.noaanews.noaa.gov/stories2005/s2508.htm (2005)
27. Office of the Secratary of Defense: Unmanned Aircraft Systems Roadmap: 2005–2030 (2005)
28. Ryan, A., Xiao, X., Rathinam, S., Tisdale, J., Zennaro, M., Caveney, D., Sengupta, R., Hedrick, J.K.: A modular software infrastructure for distributed control of collaborating UAVs. In: AIAA Guidance, Navigation, and Control Conference, Keystone, CO (2006)
29. Sofge, E.: Houston cops test drone now in Iraq, operator says. Web page, http://www.popularmechanics.com/science/air_space/4234272.html (2008)
30. Taub, B., Schilling, D.L.: Principles of Communication Systems. McGraw-Hill, New York (1986)
31. Vaglienti, B., Hoag, R., Niculescu, M.: Piccolo systrem user's guide: software v2.0.4 with piccolo command center (pcc). http://www.cloudcaptech.com/resources_autopilots.shtm#downloads (2008)
32. Wagner, B.: Civilian market for unmanned aircraft struggles to take flight. In: National Defense Magazine (2007)
33. Weibel, R., Hansman, R.J.: Safety considerations for operation of unmanned aerial vehicles in the national airspace system. Tech. Rep. ICAT 2005-01 (2006)
34. Zajkowski, T., Dunagan, S., Eilers, J.: Small UAS communications mission. In: Eleventh Biennial USDA Forest Service Remote Sensing Applications Conference, Salt Lake City, UT (2006)