Data Ferrying to the Tactical Edge: A Field Experiment in Exchanging Mission Plans and Intelligence in Austere Environments

Kyle Usbeck, Matthew Gillen
Joseph Loyall, Andrew Gronosky
Raytheon BBN Technologies
Cambridge, MA
kusbeck@bbn.com, mgillen@bbn.com
jloyall@bbn.com, agronosk@bbn.com

Joshua Sterling
NVESD
Fort Belvoir, VA
joshua.d.sterling.civ@mail.mil

Ralph Kohler, Richard Newkirk
David Canestrare
Air Force Research Labs
Rome, NY
ralph.kohler@us.af.mil
richard.newkirk.2@us.af.mil
david.canestrare.1@us.af.mil

***Abstract*—The effectiveness of ground-based, wireless tactical data networks is often constrained by limitations such as communication range and line-of-sight. SATCOM is not always available because it is relatively expensive and highly contended. Data ferrying is an alternative method of data transfer in which data is uploaded from one network to a manned or unmanned vehicle, then the vehicle is driven or flown to within range of a second network where the data can be downloaded. Data ferrying via Unmanned Aerial Vehicle (UAV) can transport data over very rugged terrain without risking the safety of a human courier.**

This paper describes an implementation of data ferrying to provide low-cost, effective data communications between remote ground units and Forward Operating Bases (FOBs) in austere environments. It describes a field experiment in which a ground vehicle was used to wirelessly ferry data in a realistic scenario, and points out the lessons learned from that experiment.

I. Introduction

As data communications become increasingly central to tactical operations, the need to transmit data reliably over long distances and over rugged terrain becomes increasingly important. Tactical operations offer additional challenges to maintaining communications, including the following:

- Rapidly deployed command centers such as Forward Operating Bases (FOBs) without secure, high-capacity network access.
- The need to communicate with mobile tactical personnel and patrols, which have limited communication and power resources, move in and out of range, and can be highly susceptible to obstructions and weather that affects communications.

Current wireless tactical networks are typically limited to line-of-sight communication ranges. One approach to long-range data communications is reachback to a global data network. This may not be possible in austere environments, such as those in which FOBs and mobile troops are rapidly deployed. A second option, Satellite Communications (SATCOM), is relatively expensive and its bandwidth is highly contended, so it can be impractical for transferring the gigabyte volumes of data required by emerging tactical information systems. A third method is to interconnect wireless tactical networks by a series of line-of-sight links to form a bridge, which can be difficult to maintain with mobile troops.

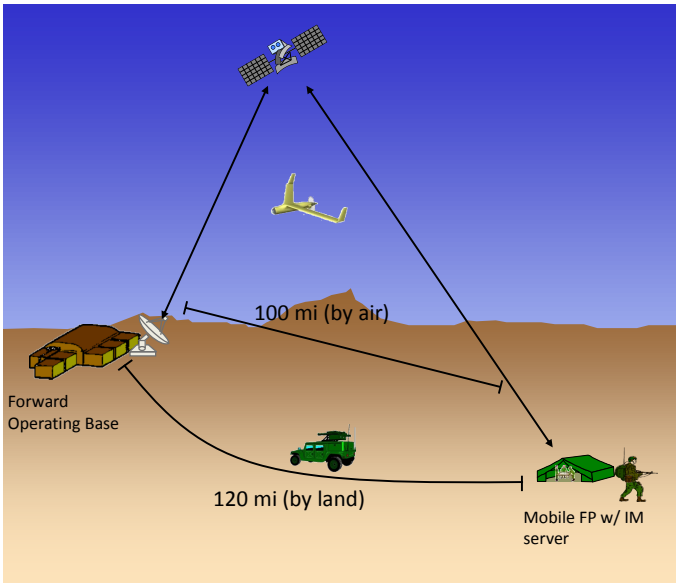

Fig. 1. Data Ferrying moves information over long distances more quickly and safely than SATCOM or using a human courier.

Data Ferrying is an alternative method for providing a high-bandwidth, low cost, and safe way to transport information bi-directionally to and from remote areas, as shown in Figure 1. An Unmanned Aerial Vehicle (UAV) with a short-range/high-bandwidth radio can bring packages of mission planning and intelligence information (e.g., current satellite imagery) to a remote area, and reciprocally transport archives of data (such as photographs and raw sensor data) from the tactical edge back to a larger installation for processing and analysis. The general concept is that a ground or air vehicle (such as a UAV) is driven or flown between two networks, automatically uploading a pre-designated set of data from the source network and then automatically downloading it to the destination when it comes within range. Ferrying a gigabyte of data by a UAV such as a Scan Eagle from a FOB to a mobile deployment 100 miles away can be done in less than five hours,

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14. ABSTRACT
The effectiveness of ground-based, wireless tactical data networks is often constrained by limitations such as communication range and line-of-sight. SATCOM is not always available because it is relatively expensive and highly contended. Data ferrying is an alternative method of data transfer in which data is uploaded from one network to a manned or unmanned vehicle, then the vehicle is driven or flown to within range of a second network where the data can be downloaded. Data ferrying via Unmanned Aerial Vehicle (UAV) can transport data over very rugged terrain without risking the safety of a human courier. This paper describes an implementation of data ferrying to provide low-cost, effective data communications between remote ground units and Forward Operating Bases (FOBs) in austere environments. It describes a field experiment in which a ground vehicle was used to wirelessly ferry data in a realistic scenario and points out the lessons learned from that experiment.

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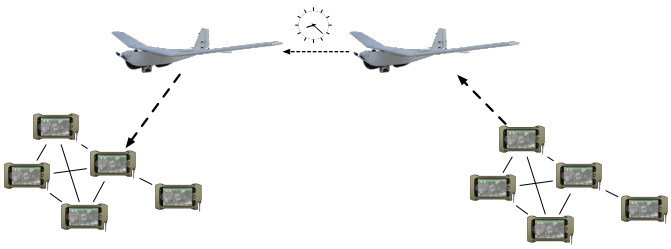

Fig. 2. Data Ferrying network scenario.

versus eight hours by HMMWV (with extra manpower and exposure to threats) and 87 hours via satellite communications.

Data ferrying differs from network bridging in that it eliminates the requirement for two networks to be interconnected by a chain of line-of-sight bridges. Instead, data is moved between networks using a single device that connects to one network to upload data first, then travels within range of the other network to download it.

The contributions of this paper include:

- A description of the requirements, design, and implementation of a functional data ferrying system suitable for deployment on a UAV.
- The results of a field experiment that evaluates the data ferry's performance in a realistic, ground-based scenario.

This paper is organized as follows. Section I motivates the need for data ferrying in tactical data networks and provides background into the technologies we utilize to implement a data ferrying capability. Section II describes our approach to design a data ferrying capability for providing low-cost, effective data communications between remote ground units and FOBs in austere environments. Section III describes a field experiment that we conducted using a ground vehicle to wirelessly ferry data in a realistic scenario. Section IV discusses some of the other related work that has been conducted in data ferrying. Finally, Section V provides some conclusions and discussion of future work.

A. Motivation

Consider a situation where a group of soldiers are communicating between themselves over their local network. At some point, the group leader needs to share a piece of information with personnel at the FOB. Unfortunately, the FOB is now tens of miles away, and there is no available network bridge.

However, with a data ferrying capability, the soldiers and FOB can exchange information with each other, by storing the information in an airborne ferry and automatically sending it to the FOB when it comes within range of the ferry, as shown in Figure 2.

B. Background

Our data ferrying design and implementation is based on two technologies: the *Marti* information broker and the Android Tactical Assault Kit (ATAK) situational awareness application. In this section, we describe these technologies and discuss the network environment in which data ferrying operates.

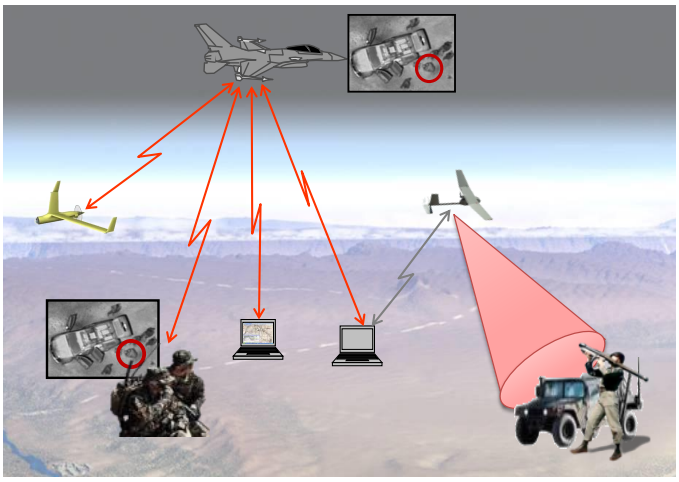

Fig. 3. Marti is a publish-subscribe information broker providing information dissemination through QoS-managed tactical radio links.

1) Marti: Marti is an advanced tactical information management system that can be deployed on a low-cost single-board computer. Marti uses a publish-subscribe model: information producers (publishers) are decoupled from information consumers (subscribers). Publishers submit information to Marti with metadata describing the time, location, and content of the information. Subscribers register a policy describing their information needs (their *subscription*) and Marti automatically delivers published information matching that subscription. Marti also supports archiving published information and allows consumers to query the archive for relevant information that was published in the past. Marti can communicate over any IP network, including tactical wireless IP networks. As shown in Figure 3, Marti can be deployed on a manned or unmanned aircraft to provide Beyond Line of Sight (BLOS) data communications. Marti provides Quality of Service (QoS) management to adjust and prioritize message traffic to the bandwidth available and to meet low-bandwidth requirements on tactical networks. More detail about the Marti system is available in [1] and in [2]. [3] explains how Marti is used to extend communications to BLOS in wireless network environments.

Marti supports communications in a variety of formats, including Cursor on Target (CoT) [4] and HTTP. CoT is an eXtensible Markup Language (XML)-based data interchange protocol that is required by the Department of Defense (DoD) to be used in many applications. Marti uses the Apache Tomcat web application server to handle all HTTP interactions including a user interface for tactical users.

2) ATAK: ATAK is a situational awareness application designed for mobile devices running the Android Operating System. It features a moving map with support for displaying offline map layers and sharing information over a network.

ATAK can share information in a variety of formats, including CoT and file transfers over HTTP. *Mission Packages* are specially formatted files that are shared by ATAK and the content of which can be displayed on the destination device(s). Mission package availability is advertised via CoT, transferred over HTTP, and acknowledged over CoT.

3) Network Assumptions: Both Marti and ATAK are network-agnostic in that they only rely on an underlying IP network. Thus, we assume that the network is capable of supplying IP connectivity and routing. Furthermore, both applications utilize well-known multicast groups to discover network services (such as the presence of other applications on the network). Thus, we also assume that the network can support (or at least emulate) standard IP multicast.

For the data ferrying capability, we require that the ferrying device is addressable at the IP layer by the device(s) that will contribute data to be ferried and consume the ferried data. Also, the data producers and consumers must be IP addressable by the data ferry. Since the data producers and data consumers are not addressable simultaneously (by definition of data ferrying), the data ferry must be able to join multicast groups and send data via multicast on each of the data producers' and data consumers' networks. We make no assumptions about the number of networks (i.e., there can be multiple network interfaces/radios) as long as the consumers can be addressed via IP by the data ferry.

II. Approach

Our main approach to providing a data ferrying capability is to augment Marti with support for advertising mission packages to be ferried, and for receiving, storing, and forwarding mission packages to designated recipients when they are automatically discovered. This includes augmenting Marti with the following capabilities:

1) Receiving mission package advertisements and downloading mission packages;
2) Maintaining a list of ATAK contacts, their open network IP/port, their names, and the last time we received an advertisement from them; and
3) Sending mission package advertisements upon connecting to a specified mission package receiver.

We added a Data Ferry component to Marti that can be enabled/disabled at runtime. The Data Ferry component is configured with a list of mission package receiver names and the amount of time (in seconds) that an ATAK contact is considered disconnected.

Basically, the ferrying process works as follows. An ATAK instance on a device, which can be a soldier's handheld device or in a FOB, puts together a *mission package* that it wants to ferry and advertises it. When a Marti instance on the ferry comes within range, it receives the Mission Package advertisement and uploads the mission package. When Marti discovers an ATAK instance (which could be on a soldier's handheld device or in a FOB) that matches the recipient list for the mission package, Marti downloads the mission package to that ATAK instance.

The data flow for the Data Ferry component, illustrated in Figure 4, is event-driven. There are two separate events that trigger processes in the Data Ferry component: *(1)* the receipt of an ATAK advertisement meaning that an ATAK instance is in range of the ferry, and *(2)* the receipt of a Mission Package advertisement, which means that a node has information to upload to the ferry.

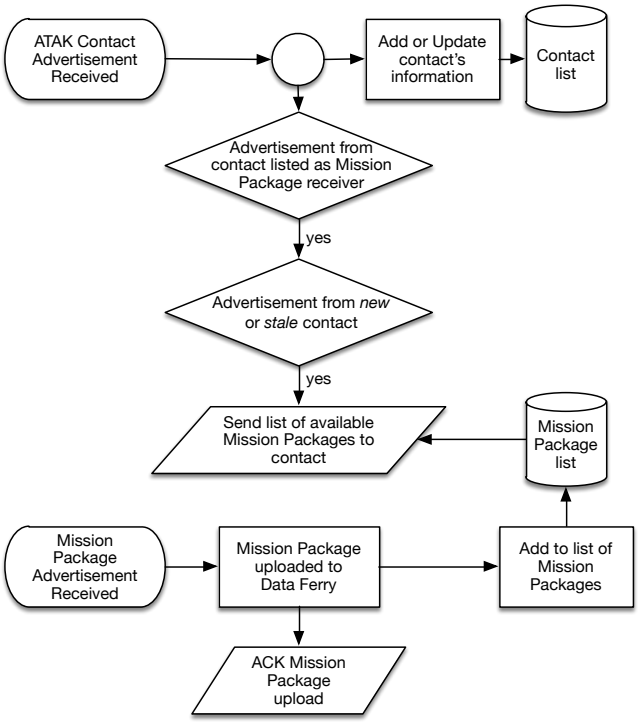

Fig. 4. Data flow diagram for Marti's data ferry component.

Upon receipt of a Mission Package advertisement, Marti uploads and persists the mission package to disk, which adds it to its current list of Mission Packages. Simultaneously, Marti sends an acknowledgement that it successfully uploaded the Mission Package to the ATAK instance from which it was uploaded.

Marti's Data Ferry component is also listening for advertisements from ATAK instances—maintaining a list of contact names, last advertisement received time, and the IP address/port/protocol upon which the application is listening. When it receives an advertisement, Marti adds or updates the contact's information in its contact list. If the contact is listed as a *mission package receiver* in the configuration, we check to see if this is a new (i.e., it did not previously appear in the contact list) or "stale" (i.e., the last advertisement receive time exceeds the configured stale time) contact. If it is a new or stale contact, then we send the contact a list of mission packages. The contact can then decide which mission packages to download from Marti's HTTP server.

III. Experimental Setup and Results

The purpose of the Data Ferrying exercise is to evaluate our ability to move, with a single transport, many types of information between disconnected groups of users that are separated by distances that far exceed current network bridging capabilities.

A. Experimental Setup

The experiment was conducted as part of an integration activity meant to test many different technologies. As such, it occurred over the course of one day with extremely limited

Fig. 5. Raspberry Pi, battery, radio, and case for the data ferry.

range-time, thus limiting the number of experiments and repetitions that we could perform.

1) Hardware: The data ferry ran on a Raspberry Pi (Rev B) single-board computer with a 15000mAh external battery and connected to Persistent System's Wave Relay MPU4 tactical radio. The external battery is capable of powering the Raspberry Pi for approximately 21 hours and the MPU4 is capable of running for 14 hours. The components were placed in a cloth case as shown in Figure 5 and transported by a Polaris RZR XP four-wheel ground vehicle.

The ATAK system consists of Samsung Galaxy Nexus and first-generation Nexus 7 Android devices connected to an 802.11 WiFi network with a bridge to the tactical Wave Relay network through Persistent System's Quad Radio Router.

2) Experiment Scenario: An ATAK user (designated as Remote ATAK) is sent to a remote location out of network range of the FOB. This device represents a deployed asset in an austere location. An ATAK user at the FOB (designated as FOB ATAK) utilizes ATAK to produce a mission package. Mission packages can contain various data types including, but not limited, to the following:

- A photograph (e.g., JPG),
- An ATAK Map package,
- A geo-referenced map file (e.g., GeoTiff),
- Elevation data (e.g., DTED),
- A gridded reference graphic (GRG),
- A configuration file (e.g., XML),
- A security certificate (e.g., PKCS 12),
- A video (e.g., mp4),
- A geo-referenced annotation file (e.g., KML),
- A geo-spatial route,
- An audio clip, (e.g., mp3), and
- CoT (spatio-temporal) data.

The FOB ATAK user waits until ATAK discovers the periodic heartbeat messages from Marti on the airborne data ferry. Then, the FOB ATAK user sends the Mission Package to the Data Ferry. When the Data Ferry has successfully received the file, the FOB ATAK displays a notification.

Marti is configured with a list of users such that, when each user becomes reachable by radio, Marti informs that user about Data Ferry file(s) that it can download.

During the experiment, the FOB ATAK user tasks the data ferry transport to move to the area where the Remote ATAK user was sent. When the Data Ferry nears the Remote ATAK, Marti sees the Remote ATAK's position updates and sends the Remote ATAK the file(s) that were uploaded by the FOB ATAK. ATAK automatically downloads the files that Marti advertises and displays a notification to the Remote ATAK user when the download is successfully completed.

3) Data Collection: During the experiment, we collected a significant amount of data that enabled us to evaluate the efficacy and performance of the data ferrying capability. We were particularly interested in measures of latency, because latency is typically a primary concern for users awaiting data in the field. Additionally, measurements of application-level latency intrinsically incorporate the time requirements for lower-layer (e.g., network) failures and recovery mechanisms for handling those failures (e.g., timeouts, retries, back-offs).

To acquire latency measurements, Marti's data ferry service was instrumented at the completion of each stage with time-stamped log messages. All the logging was collected on the data ferry to eliminate the need for time synchronization between devices. The times that were logged include:

- Times at which ATAK users are discovered
- Time when mission package uploads begin
- Time when mission package uploads end
- Times at which ATAK users are notified of new files to download
- Time when a file download begins for each user
- Time when a file download ends for each user

B. Experimental Results

Table I shows the quantitative experimental results for two experiments. Both experiments used the same hardware and software, and transferred the same 14MB (compressed) mission package, but the experiments differed in the networking situation. For both experiments, the FOB was situated between two lakes and surrounded by a densely wooded area as shown in Figure 6.

In the *Stationary Ferry Experiment*, the data ferry was placed within range of both the FOB ATAK and Remote ATAK and remained there stationary for the duration of the experiment. The Remote ATAK was turned off (i.e., not running ATAK) until the remote user wanted the mission package.

In the *Mobile Ferry Experiment*, the data ferry was loaded with mission packages from the FOB ATAK and driven via a

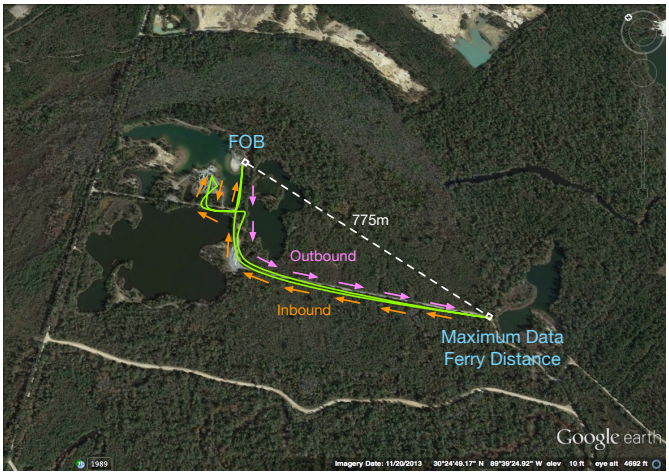

Fig. 6. Area covered by the mobile data ferry experiment.

TABLE I. EXPERIMENTAL RESULTS

Category	Stationary Ferry Experiment	Mobile Ferry Experiment
Upload Start → Complete	< 2s	78s
Number of upload failures	0	1
Notification → Download Start	< 1s	88s
Number of notification failures	0	2
Download Start → Complete	< 2s	103s
Number of download failures	0	6

ground vehicle to an austere location. The Remote ATAK was turned off (i.e., not running ATAK) until the data ferry was out of range (at a distance of approximately 775m) as shown in Figure 6. After starting the Remote ATAK, the data ferry was driven back towards the FOB and left within range of the FOB for several minutes.

The "failures" that are counted in Table I are all application-level networking failures—i.e., errors that are propagated to the application-layer rather than errors that are handled transparently (e.g., TCP re-transmits).

C. Analysis

The results from Table I show that each stage of the data ferrying component of Marti completed in under two seconds when networking conditions were near ideal (as in the stationary ferry experiment). With no application-visible networking failures, the mission package was automatically transferred from Marti to ATAK in less than three seconds after ATAK was discovered.

However, the effect of mobilizing the data ferry on the network was substantial. Operating at the borders of the network's range caused a considerable number of application-level networking failures. These failures, as well as lower-level errors (e.g., TCP re-transmits) caused the relative latencies to be significantly higher in the mobile ferry experiment than the stationary ferry experiment. The network conditions that caused these failures are difficult to reproduce in simulation or laboratory testing due to the complexities in emulating the physical and data-link layers of the situation. Thick foliage and RF interference could have played important roles in causing the networking errors in the mobile ferry experiment.

A qualitative result from this experiment was the re-enforced need for robust network error handling. During any of the phases of the upload/download process, application-layer network errors can occur over lossy data links. In the case of our mobile ferry experiment, errors occurred in each step of the process, i.e., during upload, notification, and download. Different forms of error handling were created for each stage, however. For example, the upload and download failures were limited to ten attempts (each) separated by a short, but constant waiting period before they would quit and report an error to the user through ATAK. The notification failures were handled differently in that they would retry indefinitely, but backoff exponentially between retries (up to a maximum interval of one minute). To ensure that the data ferry successfully transfers its mission packages in all situations, robust forms of error handling are critical.

IV. RELATED WORK

Prior work in data ferrying has been dominated by research in the routing and control of ferries. This is different from our emphasis in this paper; we assume that the ferry is under the control of an operator or flying routes determined by other missions it is supporting. However, the work is directly related to the results that we report in this paper. The Switch-and-Navigate (SAN) approach is a hierarchical approach that uses a global policy (Switch) that moves a ferry between disconnected networks and a local (Navigate) policy that searches for nodes within a network for upload or download of information [5]–[8]. The SAN algorithms for searching for a node within a network would be a useful extension to our data ferrying implementation in cases where the ferry cannot sense the full range of nodes within a network, e.g., if some nodes are beyond the range of the ferry's radios.

Another approach to routing of ferries treats the ferries as intelligent agents and applies Markov Decision Processes (MDP) to learn an optimal route for the ferry [9]. A variation on this approach *chains* multiple ferries together to move information long distances [10]. Both of these are overkill for the purposes of the experiments that we are conducting and the users that we are targeting, although they are opportunities for extending the capabilities that we have prototyped. Medium size UAVs, like the Scan Eagle, have significant range and duration — 1500 km and 28 hours for the Scan Eagle — meaning that each can ferry for a large area and time period. Smaller UAVs, like the Puma, which have lower range and duration (3.5 hours) would be in more need of chaining and intelligent routing capabilities. In these situations, deploying multiple ferries at a time could require algorithms for routing and controlling multiple, cooperating ferries, such as those provided by Zhao et al [11].

Related to the movement of ferries is managing the transfer of information from a node on the ground to the ferry (upload) and from the ferry to a node on the ground (download). The ferry must stay within line of sight of the node for the duration of the transfer. Pearre describes an algorithm to compute a path through airspace within line of sight of a node that wishes to upload information to the UAV, where the path is the shortest possible, but enables transfer of the full set of data [12].

An issue that we don't address in this paper, but could be important to particular deployments of data ferries is power management. Jun et al describe an approach to computing the time until a ferry is in range, so that a node can sleep when a ferry is away, and wake up when the ferry is in range, conserving power [13]. Yang et al provide algorithms for handling failures in ferries, i.e., by using multiple ferries to provide fault tolerance for one another [14].

V. Conclusions

Data ferrying is a powerful method for connecting disconnected networks and is especially useful for tactical military operations to link soldiers with command centers or to bridge participants in remote operations in which communication infrastructure is not available, inaccessible, or unreliable. We have built a data ferrying capability, building upon two existing technology bases that are successfully used in current military scenarios. The Marti pub-sub information broker provides rapidly deployed tactical communications, while ATAK (one of the large sets of client applications that Marti supports) provides a rich set of situational awareness functions in a small Android platform. We created the data ferrying capability by developing new functions for Marti and ATAK for creating mission packages; advertising them; and uploading, storing, and downloading them; along with new capabilities to auto-discover ATAK instances, identify them as recipients of mission packages, offer a list of mission packages to ATAK users, and enable selection for downloading.

This new data ferrying capability is integrated as part of the existing Marti and ATAK software, which means that it is available for use by the growing set of current users and evaluators of Marti and ATAK, which includes military personnel. The experiments that we have conducted and described in this paper provide us with data and metrics that we plan to use to optimize and improve the baseline data ferrying capabilities.

The baseline data ferrying capability that we have designed and implemented has built upon the prior work conducted by others, although we have not (yet) emphasized areas in which much prior research has concentrated, such as ferry routing, control, and fault tolerance. On the other hand, we have addressed important issues that have been under-represented in the current literature, including QoS management, upload and download management, and client user interfaces. In the future, we expect to introduce and address additional functionality, such as information lifecycle management (e.g., how long to retain mission packages), fault tolerance, and power management. Also, we hope to repeat these experiments with an airborne data ferry transport.

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Acronym List

FOB Forward Operating Base
UAV Unmanned Aerial Vehicle
ATAK Android Tactical Assault Kit
CoT Cursor on Target
BLOS Beyond Line of Sight
XML eXtensible Markup Language
DoD Department of Defense
QoS Quality of Service
SATCOM Satellite Communications

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