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Information Ubiquity in Austere Locations

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Abstract

In today's world, connectivity is increasingly taken for granted. Wireless networks, cell towers, and satellites provide ubiquitous connectivity through a number of devices. However, in austere locations constant connectivity cannot be assumed, e.g., due to the remoteness of the area, due to a disaster or combat situation, or due to insecurity or lack of access to available communications. This paper describes a system, Marti, which the authors have been developing and demonstrating that can provide inter-connectivity and access to information in austere locations. Marti is rapidly deployable and interoperates with a large number of existing devices and client applications.

Keywords: Publish-subscribe; information discovery; information brokering

1. Introduction

Ubiquitous and constant connectivity is becoming increasingly prevalent and, in many cases, assumed. The increasing availability of wireless infrastructure in many locations, including mobile hotspots, cell towers, and satellite communications has made constant connectivity assumed through an increasing number of devices, including handhelds (e.g., mobile phones), tablets, and even the radios utilized by emergency and military personnel.

However, there are, and always will be, *austere* locations in which ubiquitous and constant connectivity cannot be assumed and, in fact, is unlikely to be available. The austerity and lack of connectivity can be due to the following:

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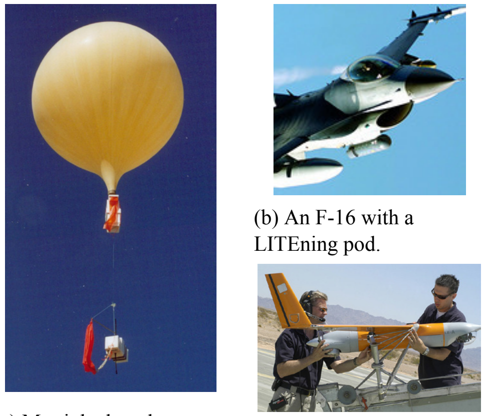
- The remoteness of the location, in which there are no cell towers or access points, or they are too distant to be reached reliably.
- Natural disasters or human activity (such as war) that can destroy or overload the existing communication infrastructure.
- Natural phenomenon, such as weather or terrain, which can interfere with the availability or reliability of communications.

Even in situations in which communication infrastructure exists, constant connectivity can be missing. For example, there might be cell towers, but they aren't accessible (e.g., different service provider), are incompatible (e.g., GSM vs. CDMA), or are insecure for one's purposes. There might be satellite communications, but its access might be restricted, it might need to be reserved well in advance, or it might be highly contended. In other situations, such as emergency response or tactical operations, radios might be commonplace, but they might not interoperate.

We have been researching and prototyping *Marti*, an information management system (IMS) that can be used to provide or augment connectivity in austere locations. Marti provides a publish-subscribe information broker that can be hosted and rapidly deployed on manned or unmanned aircraft or on high altitude balloons, as shown in Figure 1. At high altitudes, Marti provides beyond line-of-sight information brokering for tactical users, through standardized information formats and interfaces, utilizing existing applications and devices, including Android-based devices and a variety of tactical radios. Because it is based on a publish-subscribe model, users can connect dynamically and register subscriptions for future information that might become available or query for archived information. Information discovery and client connection is simple and dynamic. Marti utilizes standards-based information formats, a Web Services interface, and adapters to work with existing application interfaces.



(a) Marti deployed on a balloon at 65K-100K feet.

(b) An F-16 with a LITEning pod.

(c) The Scan Eagle UAV.

Figure 1. Marti has been deployed on a high altitude balloon, a pod attached to a manned aircraft, and unmanned aircraft, including the Scan Eagle.

The rest of this paper describes the Marti IMS, how it provides connectivity in austere locations, the experiments and demonstrations we have conducted with Marti, and related work.

2. The Marti Information Management System

The goal of the Marti IMS is to increase the situation awareness (SA) of tactical users by supplying ubiquitous access to information. When the fixed infrastructure that we take for granted is not present, fails, or is inaccessible (due to security or ownership concerns), information access by tactical users requires that they can establish line-of-sight (LOS) connectivity (through their tactical radios) to something that can provide beyond line-of-sight (BLOS) reachback to remote information sources and networks. By providing a rapidly deployable, scalable, and interoperable IMS platform, Marti provides users in austere locations with access to real-time and on-demand information. The remainder of this section explains how Marti is designed to support ambient information access through its modular architecture, service discovery mechanisms, intent to maintain interoperability, and bandwidth management utilities.

2.1. The Marti Architecture

The Marti IMS is designed as a modular, service-based publish-subscribe-query (PSQ) system. PSQ is a design paradigm that decouples information producers (publishers) from information consumers (subscribers and querying clients). Consumers request information that is of use to them and might become available in the future by registering interest in (i.e., subscribing to) information based on its type and indexable characteristics (i.e., *metadata*), regardless of when it becomes available and its source. Information that has been collected in the past is available through a query interface. PSQ provides access to *real-time* information, i.e., subscribers receive the information they desire as soon as it is collected[a], and to *archived* information.

Maintaining modularity in the Marti architecture enables extensibility as new features and services become available [5]. Marti's core services (shown in Figure 2) include the Submission Service, the Information Brokering Service, Query Service, Web Service, and Dissemination Service, which provide the following functionality:

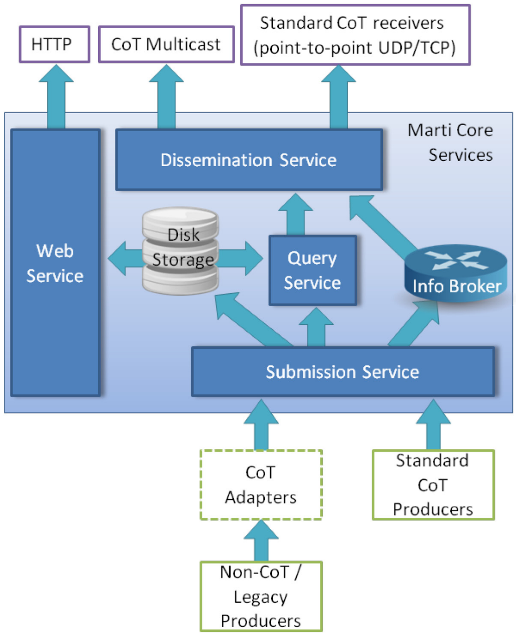


Figure 2. Data-flow through the high-level components of the Marti architecture.

- The *Submission Service* accepts published messages, archives them, and forwards them to the Query or Information Brokering Service. The submission service also performs traffic shaping when applicable.
- The *Query Service* provides users with *on-demand* access to past information by extracting and filtering information from the archive (Disk Storage).
- The *Information Brokering Service* (Info Broker) manages the subscriptions (i.e., which subscribers are subscribed to what information types) and guides information dissemination (i.e., to which subscribers should each information object be sent).
- The *Web Service* provides an HTTP request/response interface for viewing archived information and manipulating the behavior of the system (e.g., system configuration).
- The *Dissemination Service* controls the information that is transmitted to each subscriber. Furthermore, the dissemination service implements a variety of Quality of Service (QoS) management techniques to effectively utilize limited communication channels.

2.2. Network Formation, Scalability, and Discovery

For Marti to be an ambient system, it must provide readily accessible connectivity and transparent access to information. Marti provides these by being quickly deployable, handling dynamic numbers of users that come and go, supporting discovery of new platforms and users, and reaching back through connections to other, more fixed infrastructure.

Marti is designed to be quickly deployed in austere locations, either onboard airborne platforms or in a centralized location on the ground. Once deployed, Marti utilizes pub-sub and service discovery as ways of reducing the configuration burden on clients. The pub-sub paradigm allows subscribers to register their

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[a] In reality, there is some latency between the time of collection and the time of subscriber receipt, however the authors go to great lengths to minimize that latency.

interest in certain information without the knowledge of which publishers have that information.

Platform and information discovery greatly simplify the client configuration – allowing clients to gather connection criteria about the IMS at runtime. Information discovery is automatic; a client registers a subscription and if and when information matching the subscription is published, it is disseminated to the client. However, if multiple subscribers match a published message, then multiple copies of the message will be sent. In a severely bandwidth-limited broadcast environment – in which Marti is commonly deployed – this wastes bandwidth. Furthermore, it provides no support for clients to discover the types of information that are available for them to request.

To facilitate publish-subscribe over the broadcast medium, Marti utilizes IP multicast and an existing capability for service discovery. As shown in Figure 3, each client joins a well-known *registry* multicast group. The Marti information broker periodically *beacons* (i.e., sends to the multicast group) a list of information types and multicast groups. Each client receives the beacon (because it belongs to the *registry* group), chooses which types of messages it wants to receive, and joins the multicast groups for those information types. When a message is published, the Marti dissemination service sends it to the multicast group associated with the message type which delivers it to all the subscribers in the group.

There are several limitations to this approach. First, subscriptions registered in the IMS and multicast groups are redundant. That is, to "subscribe" to messages, the subscribing client can examine the beacon and join the proper multicast group or the subscriber can register a subscription that matches the published information (which then disseminates the message directly to the subscriber). The former is more appropriate in a broadcast environment (the dominant environment for Marti) in which there are many subscribers to each message. The latter is more appropriate in a point-to-point environment or an environment in which there is one subscriber to each message.

Another limitation is that the Marti broker has no visibility into which clients (if any at all) have joined the multicast group for a message. Thus bandwidth can be wasted by (1) sending messages to empty multicast groups; (2) sending multiple copies of messages to individual subscribers; and (3) continuous beaconing. This lack of visibility into whether (and how many) clients are in a multicast group also limits the ability to prioritize messages when bandwidth is limited (and bandwidth is *always* limited) because the Marti broker cannot determine which messages are needed by important clients and operations.

Point-to-point subscriptions have issues as well. A particular problem manifests itself in intermittent environments: the protocol that Marti uses to send events to subscribers connects to subscribers when there is an event to send (we have no control over the particulars of this protocol). From a subscriber's point of view, it is not possible (without out-of-band monitoring) to tell the difference between a situation in which it is disconnected from Marti and one in which there just are not any matches to the subscription. Worse, if a client is disconnected for a long time and Marti fails to send an event a certain number of times, Marti needs to disable the subscription. Once the client comes back on line, there is currently no way to know (again, without using out-of-band monitoring) that the server has disabled the subscription. These problems are certainly not insurmountable, but solving them in the existing architecture would add complexity.

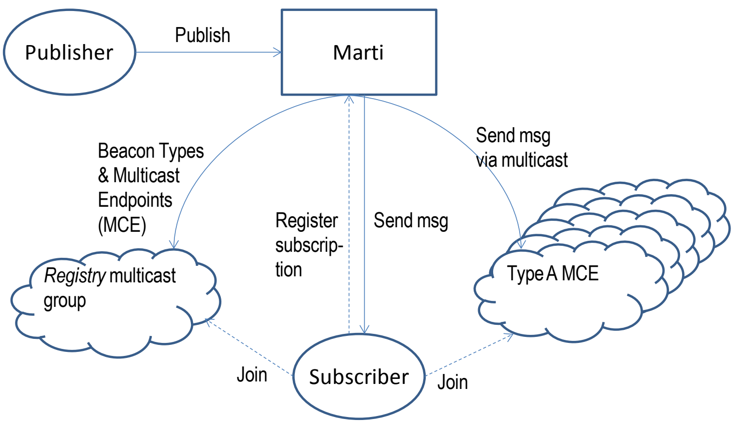

Figure 3. Marti's support for information discovery.

We are developing an alternative discovery technique that combines the active subscription matching with multicast groups, enables better management of limited bandwidth, is robust in intermittent networks, and supports scaling to multiple Marti servers. As shown in Figure 4, in this alternative technique, instead of the Marti server beaconing its information types, each subscribing client periodically beacons its subscription predicate to the special (registry) multicast group. The Marti broker is a member of that multicast group and constructs a filter consisting of "or"s of the full set of predicates. Subscription matches are sent to a second multicast group that all the subscribing clients have joined. The Marti broker filters published messages and disseminates them to the subscriber multicast group only if they pass the filter, i.e., they match at least one subscription.

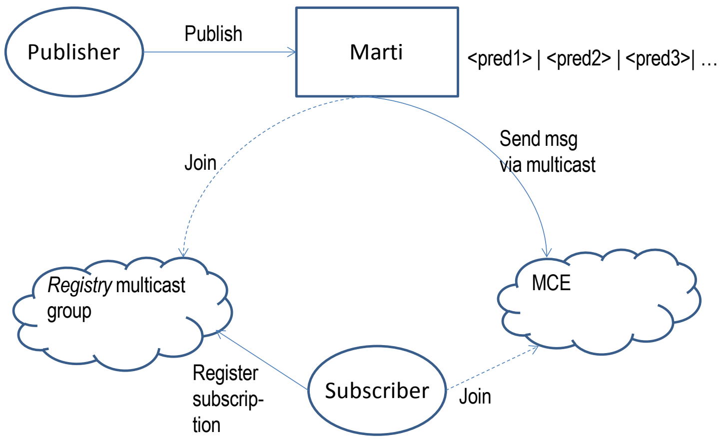

Figure 4. An alternative discovery technique supporting bandwidth constrained ambient environments.

This technique has advantages in severely bandwidth limited environments, including the following:

Automatic discovery of newly available information types	A client does not need to monitor the service beacons and explicitly join the multicast group for a new information type.
Potentially significant savings in bandwidth	Messages are only sent if there is some subscriber that wants them and each is sent once no matter how many subscribers want the message.
Message prioritization	Prioritization of messages across publishers, types, and subscribers.
Facilitate support for multiple Marti servers	A new server receives the beacon of subscriptions and filters messages published to it using the subscriptions. Subscribing clients automatically receive matching messages from the new server without having to explicitly register with it.

The main drawback of this technique is that subscribers can receive messages in which they have no interest. This is analogous to the current state of existing broadcast media, in which everyone in broadcast range can receive transmissions. Client side filtering of messages can remedy this situation.

2.3. Interoperability

Another challenge Marti faces in providing ambient functionality in austere locations is interoperability. For the information system to be truly invisible to its human users, it should support the users' current tools and workflows. It is important that Marti not require additional or different equipment than that already carried by tactical users. Marti accomplishes interoperability by supporting information types commonly used by existing tactical systems, including the XML-based Cursor on Target (CoT) type used by many military users [14] and multiple video formats, including H.264 and Key-Length-Value (KLV). CoT is an extensible XML-based specification that can be transmitted by nearly any IP-interface-enabled client over TCP or UDP (including multicast). CoT's low barrier to entry creates a large user-base for new clients. Marti already integrates with several existing client applications that run on military grade equipment, Android tablets, and handhelds. Thin wrappers trivially translate messages from legacy applications into CoT (and vice versa). Also, Marti's web services allow any HTTP-enabled client to view archived information. By supporting users' current tools and workflows and fostering a large user-base for client applications, the Marti IMS is an interoperable communication substrate that remains invisible to its human users.

2.4. Effective Bandwidth Usage

Effective bandwidth usage is critical to providing ambient information access to austere areas with a highly-constrained communication medium. Marti employs several QoS techniques for managing bandwidth. First, dissemination bandwidth is rate-controlled per-client to prevent the system from overloading the bandwidth to any individual client. Maintaining queues of outgoing information messages also allows for other latency-decreasing operations. For example, stale information in a dissemination queue can be replaced by newer information of the same type[b]. Also, maintaining dissemination queues allows prioritization for differentiated services (DiffServ) [8]. Further research [2] shows promise for passively monitoring and automatically configuring the bandwidth to subscribers with highly-dynamic network connections. Second, traffic shaping is employed in Marti, for example, to reduce the size and resolution of an extraneously large image. Finally, in situations where the network is naturally a broadcast medium, multicast is used to prevent multiple copies of the same message from being transmitted point-to-point to different subscribers. Effectively managing the utilization of bandwidth in Marti increases the number of users that can participate in using the ambient system.

2.5. The Marti Prototype

The Marti IMS is built using a lightweight tactical version of Phoenix, a pub-sub service-based system developed by the US Air Force [6]. Marti has been hosted on a variety of platforms, including high-altitude (up to 85,000 feet) unmanned balloons, sensor pods (e.g., LITEning Pod [10]) attached to manned and unmanned aircraft, and on unmanned aerial systems including the Scan Eagle.

3. Experiments and Evaluations

Marti has been used in a variety of field demonstrations, often involving several airborne assets. These demonstrations provided a wide range of scenarios, with varying numbers and types of clients and information and including scenarios that are very bandwidth-limited and others that are CPU-bound.

The first set of field demonstrations hosted Marti on PC/104 boards on a high-altitude balloon to provide information management for beyond-line-of-sight communication between multiple ground users. These balloons flew at near-space altitudes (with no tether), and used a low-throughput IP radio that provided on the order of tens of kB/s of bandwidth. The very low bandwidth and lack of positive control over the airborne platform made for difficult experimentation. In particular, intermittent connectivity was a constant problem. Another problem unrelated to software and connectivity was overheating. The computer on which Marti ran needed to be in a sealed container to protect against moisture, and once at altitude the ambient temperature was cold enough to keep the board cool via convection. However, during ascent we observed overheating problems.

Marti has been flown on the payload board on Group 2 unmanned vehicles (UAVs) (low altitude, long endurance) [12]. These tests used radios with much shorter range than those we used on the high-altitude

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[b] Because some types of information should not be replaced, a per-information-object-type replacement policy controls whether or not a type of information should be replaced.

balloon, but much higher bandwidth. Marti ingested imagery being produced by the sensors onboard the UAV, archived it, and distributed it in response to subscribers.

As a way to improve throughput to bandwidth-constrained subscribers, we added multicast capabilities to Marti as we expanded to demonstrations involving larger UAVs and targeting pods [10]. Multicast added some useful capability, such as being able to more efficiently deliver identical data to multiple receivers. However, multicast introduces a host of other issues, the most important being inconsistent support by radios. Multicast also presents a challenge for managing QoS in publish/subscribe systems, because multicast group membership is not exposed by the IP layer. As a consequence, not only is it difficult to prioritize based on current users, but when using radios that support sparse-mode multicast it is difficult to know how much bandwidth is actually being used (data may never be transmitted if there are no other members of the multicast group).

Within multicast groups, however, we implement prioritization schemes based on properties of the publishers and information with the option of replace-per-publisher policy to enforce QoS [5]. This allows us to control the delivery of important information in preference to less important information and to manage latency and queue growth in the face of overloaded or constrained networks. Figure 5 shows the performance of Marti in terms of cumulative number of information objects lost while delivering imagery to a multicast group over a 220 kbps network. One of the imagery streams is being collected from an area of interest (AOI) and, hence, is higher importance than the other streams. With only three image streams (from AOI UAV, UAV1, and UAV2) the network is not overloaded and no information is lost. However at time *S* (indicated by the vertical line in the figures), a fourth UAV (UAV3) also starts publishing imagery. The additional data from the fourth UAV causes the publishers to overload the network, and because the producers are using a best-effort protocol (UDP) the overload is manifested as loss of information. In the baseline case, shown in Figure 5(a), with no QoS management, the loss due to the congestion in the network is uncontrolled, and the AOI UAV feed (the most important one) is unlucky enough to suffer significant loss. Figure 5(b) shows that with Marti, the most important image stream (from AOI UAV) suffers no loss, and the other streams suffer more controlled loss.

Likewise, Figure 6 shows the average latency and standard deviation of images from each publisher before and after the network is loaded with Marti providing QoS management. In the overloaded situation, the prioritized stream (*AOI UAV*) maintains low latency and low jitter delivery of imagery, while the other image streams are degraded consistently to make room for the high priority stream.

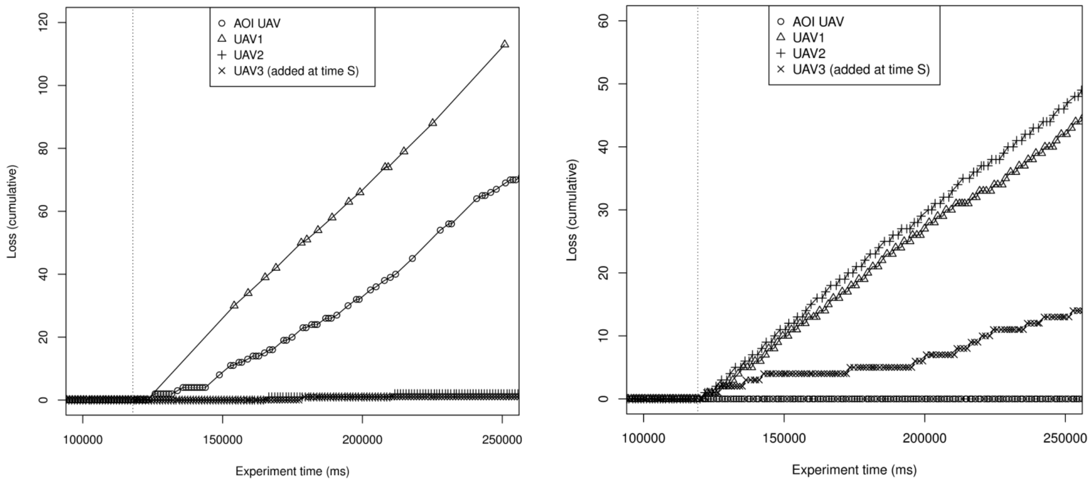

Figure 5. Information loss in (a) a baseline overload situation with no QoS management and (b) with Marti QoS management in which the stream of AOI imagery suffers no loss.

With the UAV and pod exercises, the focus of Marti shifted from providing a smart-relay (as in the balloon scenarios) to providing services related to on-board sensor arrays. This shift played into Marti's advantages and focus. For instance, for a variety of technical and non-technical reasons it is difficult to put QoS management into every sensor that is producing data. Having Marti on a LAN with the sensor (i.e., co-located on-board a UAV or pod) obviates the need for QoS management for that part of the data path. The part of the data path that remains (i.e., from the IMS to clients) is fully under Marti's control (since Marti is the sender), and QoS can be implemented and enforced across the full set of clients without burdening every client with QoS logic or Marti-specific protocols.

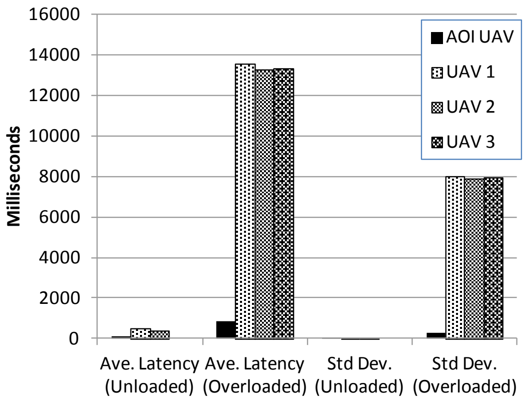

Figure 6. Average latency and standard deviation in milliseconds of the image streams prior to, and following, network overload with Marti providing QoS management.

4. Related Work

Marti shares many similarities with Extensible Message and Presence Protocol (XMPP) servers (e.g., OpenFire, ejabberd) [7][13][15] in that they both have the capability of passing XML-formatted messages between de-coupled clients using the Pub-Sub paradigm. However, they differ in that XMPP servers require clients to establish and maintain a persistent connection to the server. This requirement is driven by the need for XMPP servers to send information to otherwise-unreachable downstream clients (i.e., that are potentially behind firewalls). Unfortunately, this restriction causes XMPP to suffer in networks with intermittent connectivity because each separate client shoulders the burden of maintaining a persistent connection to the server. Marti, on the other hand, excels in austere locations because it does not require its clients to establish or maintain persistent connections to the server.

Several prominent pub-sub systems have been developed in recent years as a means of distributing information in resource challenged environments. Perhaps most similar to the presented work on Marti is the Advanced Information Management Systems (AIMS) [3]. AIMS, like Marti, was designed with the goal of utilizing airborne platforms to extend network range beyond line of sight and provide publish, subscribe and query capabilities to users. While the Marti architecture supports integration with a wide range of clients through the use of adapters to and from the CoT specification, AIMS limited its legacy client to that of the two technologies from which it was derived, the Advanced Information Architecture (AIA) and the Joint Battlespace Infosphere (JBI).

The OMG Data-Distribution Service (DDS) [11] is a pub-sub middleware which has seen widespread use in recent years. DDS provides real-time information dissemination based on topic matching only and a rich set of QoS parameters, but does not support archival (beyond a limited *history* function). DDS's discovery feature is performed through subscription to *built-in* topics (such as *DCPSTopic* to get all topics that have been registered). QoS management across multiple client connections that share bandwidth requires application-level support (similar to what we are doing in Marti) outside of DDS.

Beyond line of sight communication is necessary for ambient computing in austere locations. Satellite links [1][4] are commonly used in such settings but have several shortcomings compared to airborne platforms such as those utilized by Marti. The greatest of these issues is dynamism and ease of deployment. Launching a satellite into orbit, or even maneuvering a satellite in orbit, requires a large amount of resources and significant planning. Such actions may not be feasible on the time scale necessary to deliver additional communication infrastructure to areas struck by disaster or facing a temporary rapid increase in population (such as a gathering of people). SATCOM is frequently highly contended, expensive, and in some cases must be reserved well in advance. The airborne platform approach taken by Marti requires significantly fewer resources. It has been shown that the equipment necessary to field a Marti instance can be rapidly attached to a wide range of platforms including piloted aircraft, UAVs, and weather balloons.

Mobile ad-hoc networks (MANETs) [16] and Disruption Tolerant Networking (DTN) [9] try to address some aspects of intermittent connectivity. However, these technologies deal with layer 3 (IP routing) issues, not application-level concerns. The dynamic nature of such networks enables them to be rapidly deployed in austere locations but also introduces potential usability problems. With nodes continuously entering and leaving a remote network a user may not be sure they are accessing all relevant information. Through a combination of service discovery and PSQ mechanisms, Marti is in a position to provide MANET endpoints with the information they require.

5. Conclusions

We have been developing Marti, an information management system that can provide ambient connectivity and access to information for tactical users in austere locations where other connectivity is scarce. Marti contains a number of advantages including that it is rapidly deployable, works with existing tactical devices and pervasive handhelds alike, is scalable, and provides the QoS management needed by critical users such as first responders, law enforcement, or the military. Marti has been evaluated in flight demonstrations and experiments, with multiple tactical users and client platforms, and in multiple realistic scenarios. Marti shows promise for providing needed connectivity in locations and situations in which fixed, accessible, and assumed connectivity infrastructure is not available.

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