A Reliable Sensor Data Collection Network Using Unmanned Aircraft

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ABSTRACT

This paper presents a method for reliably collecting data events from sensors and forwarding the data via a MANET to sensor monitoring stations located on an external network. At the core is a MANET concept that consists of ground and unmanned aircraft nodes. Unmanned aircraft enable a model whereby widely-spaced sensors are intermittently connected to the network and data is sent in stages as connections become available along each stage. The paper describes the sensor data collection model, the reliable multicast data delivery mechanism, and our experiences on a network test bed including the control of an unmanned aircraft through a MANET.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Architecture and Design—*network communications, wireless communications*

General Terms

Algorithms, Design, Experimentation

Keywords

Ad hoc networks, unmanned aircraft, sensor data collection

1. INTRODUCTION

This paper considers the role of a mobile ad hoc network (MANET) to support sensor data collection. In this model an area has intelligence, surveillance, and reconnaissance (ISR), envrionmental monitoring, or other sensors that can range from small and simple thermometers to large and highly functional RF scanners. These sensors need to report occasional short event messages in near realtime to one or more sensor monitoring stations (SMS) located at remote locations. The sensor interfaces with a MANET node (MN) which in turn delivers the event message to a gateway node (GW) which connects to an external backhaul network to the SMS. The MANET can have stationary ground nodes to support this communication. A ground node typically has short range and can not support sensors over a wide area. Therefore, in order to provide a node capable of long-range communication and also having wide-ranging coverage, unmanned aircraft (UA) are outfitted with radio interfaces. The concept diagram is shown in Fig. 1.

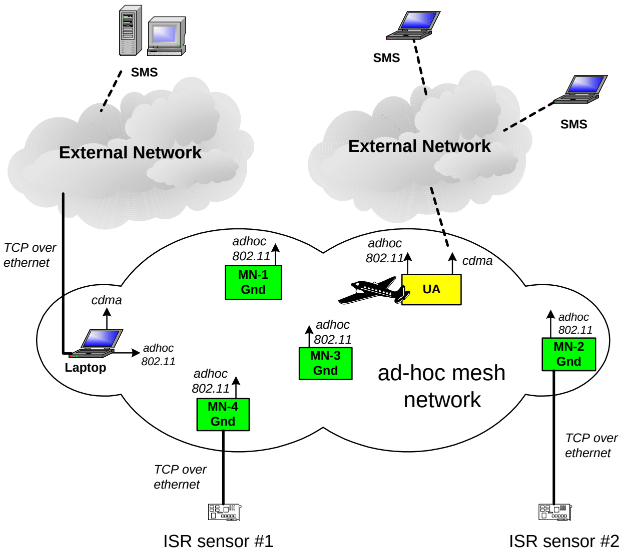

Figure 1: Sensor Data Collection System Components

The first goal of the MANET is to provide reliable backhaul of sensor data through the sparsely connected network to the multiple SMS. The second goal is to provide extended connectivity to the UA for command and control.

The sensor is assumed to be simple and should be isolated from network specifics such as the number and network location of the SMS. The addresses of the sensors, MN, and external network nodes must be managed not only to enable the multicast delivery of sensor data to each SMS, but also to enable an individual SMS to make queries to specific sensors. The MN, in turn, should be isolated from the specifics of the GW to SMS backhaul network.

The UA can move so that it collects the sensor data according to waypoint plans. The MANET also provides the primary command and control link when the UA is in autonomous flight. The link allows an operator to monitor UA activity and to command the UA autopilot to fly different flight plans. The correct flight plan depends on the communication demands, distribution of sensors, realities of radio propagation, and flight dynamics.

A UA data retrieval system similar to our project uses small plane-deployed sensors [4]. However it collects data through a point-to-point wireless backhaul with high availability. The networking in this project extends availability

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through ad hoc protocols and uses delay tolerant network concepts when unavailabile [3, 6]. Further it implements a full-scale test bed to expose the significant interactions between network protocols, radio propagation, and vehicle mobility constraints. The UA sensor data collection test bed is based on an earlier test bed developed for the ad hoc UA ground network (AUGNet) concept [2]. This concept integrated and tested MN mounted in UA to provide better real-time connectivity between ground nodes. This paper describes the significant additions to this concept in order for AUGNet to be suitable for sensor data collection.

2. COMMUNICATION ARCHITECTURE

Three types of communication are supported: event communication from one ISR to all active SMS, Command communication between a single SMS and ISR, and ordinary MANET communication between nodes in the MANET.

The first two types depend on reliable forwarding composed of two mechanisms. The first uses a staged delivery from the ISR to the first MN (denoted the terminus), the terminus to each GW, and from each GW to the SMSs. The second mechanism is a reliable forwarding mechanism similar to the R-UDP protocol [1] but stripped of unneeded functional overhead. The staged delivery shields nodes in different stages from needing to know the addressing schemes of nodes in other stages. The terminus and GW nodes take custody of packets they receive and coordinate IP address usage via Network Address Port Translation (NAPT) [8].

In order for the staged delivery to be successful, the terminus must discover the GW and the GW must discover the SMS. This problem is complicated since GW and SMS may come and go over time as UA take off and land, and SMS choose to join the network and leave. A GW centric approach is taken to solve the problem. Heartbeat packets are used by GW to keep track of which SMS are active. A heartbeat packet is sent to potential SMS, and active SMS respond to these packets. This model is chosen since the SMS are relatively stable and have routable IP addresses. On the MANET side GW that have active SMS responding to their heartbeat packets are considered active. Active GW advertise their presence via a periodic flood in the MANET. Each terminus stores a list of GW sending these advertisements in an active GW list.

Event communication consists of isolated packets sent via the modified UDP protocol. An ISR initiates an Event communication by sending a UDP packet to a special address and port number. The MANET forwards this packet to a Terminus. It is necessary to give the sensor one dedicated point of contact, i.e., the Terminus, since with the sensor's limited networking capabilities it can not know the number and addresses of all possible GW in the ad hoc network.

Each UDP packet received by the Terminus is stored, copied, and reliably forwarded to a fixed port on each active GW. Each UDP packet received by the GW is stored by the GW, copied, and reliably forwarded to a fixed port on each active SMS. This approach manages the multicasting to multiple SMS, increases reliability of communication as it is forwarded in stages, and enables packet transmission in intermittently connected networks without contemporaneous end-to-end connections between ISR and SMS.

An SMS may communicate directly with one ISR by sending command or query messages via the modified UDP protocol. At each stage of the event communication, the packet source uses an ephemeral port number as a "call back number" that allows NAPT to direct command packets back to individual ISR. These command packets use an ephemeral source port to provide a unicast return path for command responses from the ISR to the commanding SMS.

3. IMPLEMENTATION DETAILS

All ad hoc network nodes are running on Soekris net4511 single board computers with an AMD Elan i486-based processor, 100MHz clock, 64MB RAM, 512MB CompactFlash memory cards, and two Ethernet ports. An Atheros-chipset-based Engenius NL-5354-MP miniPCI card provides 802.11b wireless connectivity. An RF power amplifier increases the output power to 1W for enhanced coverage. An external GPS receiver provides location and altitude information to the node, which are used for situational awareness and displayed on the user interface.

The nodes run a custom-built embedded Gentoo Linux distribution with a 2.6 kernel. The WiFi card is driven by a Madwifi driver variant called SoftMac[1]. This driver allows switching of MAC layers as well as raw packet transmission and reception with RadioTap header information.

All ad hoc routing and data collection logic was implemented using the Click Modular Router [7] framework. The internal network routing is based on our DSR implementation [5] with monitoring function. Gateway advertising, SMS discovery, reliable UDP forwarding, heartbeat protocols, and NAPT are written as modular elements that can be added as needed.

Testing takes place in the lab, at a local 7km^2 test range, and is leading to a full-scale demonstration in Alaska that will incorporate several sensors, as well as CDMA and Inmarsat backhaul networks.

4. DATA FORWARDING EXPERIMENTS

The network setup utilizes a ground based wired network of ISR sensor, terminus, gateway, and SMS for baseline network measurements. All nodes are Soekris single board computers. This experiment was performed in the lab. One event message was generated every second at the ISR sensor, its timestamp and sequence number recorded, sent through the network to the SMS, and from there reflected back to the ISR. Round trip time and network stability were observed when various intermediate links were disconnected.

The network test results show a robust forwarding of event messages through the network, with an average round trip time with fully connected network of 41ms from ISR to SMS and back. As expected, disconnections of intermediate links only temporarily disrupt the message flow, but do not lead to message loss. Upon reconnection of links the network forwards stored packets in bursts and normal operation is restored within seconds. The maximum RTT for each packet depends on disconnection time as well as timing of link outages of different links in the network. In a worst-case scenario the links go down and up in a cascading fashion, and the worst-case RTT can reach the packet retransmission timeout multiplied by number of hosts in the packet's path plus each link's disconnection time.

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[1] https://systems.cs.colorado.edu/projects/softmac

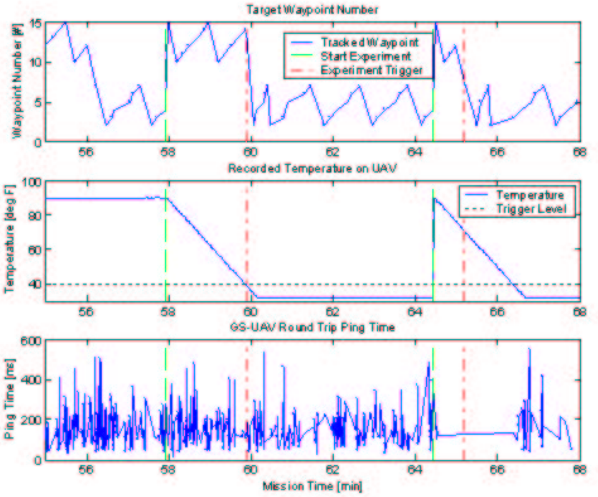

Figure 2: Results: a. Destination waypoint number b. Recorded onboard temperature c. Recorded ping times from the plane to the monitoring station

5. UA EXPERIMENTS

A concept system has been fully verified utilizing ground and UA nodes at an outdoor test range. The experimental setup involves a UA, ground station, and supporting network devices, and it verifies the plane operations on our outdoor test range. The UA is a small (10kg) vehicle built at the University of Colorado and composed of an MN, autonomous navigation a flight computer, a scientific payload, and interface boards to tie the systems together. The UA is controlled during the experiment through the MANET using a remote monitoring station. Terrestrial nodes are placed around the range to maintain connectivity between the UA and remote monitoring station.

The goal of the experiment is to demonstrate both control of the UA through the ad-hoc network, and the UA's ability to make mission level decisions based upon network status and sensor measurements. If UA to monitor station communication is down for more than a time out or the ambiant temperature crosses a wing-icing threshold, the plane autonomously switches from its mission flight plan to a "return to base" flight plan. These parameters are simulated as it is not desirable to lose complete communications with the monitoring station for experimental purposes and the ambiant temperature can not be changed. Communications is defined as the reception of a ping packet through the ad-hoc network which can be stopped at will and thus induce simulated network failures. Temperature is recorded from a sensor onboard the UA, but when the experiment is started, the hardware onboard the UA subtracts a degree from the reading for each second passed before transmitting the value over the network to simulate a temperature drop.

Fig. 2 shows the primary results of the experiment. All of the graphs shown depict a value vs. time in minutes since the plane began communicating with the network monitoring station before takeoff. The top graph shows the destination waypoint for the UA. The waypoint plans consist of waypoints 2-7 for flight plan 1 and waypoints 10-15 for flight plan 2. The second graph depicts the simulated temperature. Interesting points include the linear transition from the current temperature to 32 degrees Fahrenheit as the UA hardware subtracts from the actual temperature following a start of experiment command, and the transition back to actual temperature following a second start of experiment command. The bottom graph shows ping times in milliseconds for the round trip transmission of a packet from the monitoring station to the plane and back.

By analyzing this graph, it can be shown that the plane was able to autonomously make decisions based upon parameters set by the operator over the 802.11b ad-hoc link. The temperature limit was set to 40 degrees, as marked by the horizontal dashed line in the second graph. The intersection of the reported temperature and the limit is identified by the left-most dashed red line which is carried through the other two graphs. In the second experiment, a communications timeout between the plane and the monitoring station was set to 40 seconds. The point in the second experiment when this time out is reached is marked by the right most vertical dashed line which is carried through the other two graphs. At both places where an experiment is being performed (the plane is tracking waypoints from the second pattern) and a limit is reached, an automatic transition to waypoint pattern 1 can be seen.

6. CONCLUSION

This paper describes the design and implementation of a reliable sensor data collection network for sparsely deployed sensors. A meshed ad hoc network of ground nodes and small unmanned aircraft gathers sensor information and delivers them to sensor monitoring stations. The unique contributions of the conducted research are the control of the unmanned aircraft solely through a meshed ad hoc network and the reliable forwarding of single event packets from sensors to multiple monitoring stations through the intermittently connected network.

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