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A simulation study of ad hoc networking of UAVs with opportunistic resource utilization networks

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ABSTRACT

Specialized ad hoc networks of unmanned aerial vehicles (UAVs) have been playing increasingly important roles in applications for homeland defense and security. Common resource virtualization techniques are mainly designed for stable networks; they fall short in providing optimal performance in more dynamic networks—such as mobile ad hoc networks (MANETs)—due to their highly dynamic and unstable nature. We propose application of Opportunistic Resource Utilization Networks (Oppnets), a novel type of MANETs, for UAV ad hoc networking. Oppnets provide middleware to facilitate building flexible and adaptive distributed systems that provide all kinds of resources or services to the requesting application via a helper mechanism. We simulated a homeland defense use case for Oppnets that involves detecting a suspicious watercraft. Our simulation compares performance of an Oppnet with a baseline case in which no Oppnet is used. The simulation results show that Oppnets are a promising framework for high-performance ad hoc UAV networking. They provide excellent performance even under imperfect (and realistic) conditions, such as a less invasive use of helpers, denial of help by some of the candidate helpers, and imperfect detection capabilities of Oppnet components.

1. Introduction

Mobile Ad hoc NETworks (MANETs) of Unmanned Aerial Vehicles (UAVs) are specialized ad hoc networks with increasingly widespread use. Their popularity is due to the cost-effective wireless communication and surveillance capabilities they provide. UAVs have had increasingly prominent roles in a variety of fields—including homeland defense and security, natural disaster recovery, real-time surveillance and reconnaissance among others. All these applications involve demanding applications in terms of rapid response to events.

Today's homeland defense operations rely heavily on MANETs of UAVs, as these offer actions free from possible human losses and have the advantage of being autonomous. UAVs have been great assets for homeland defense in the past few decades. Recently, the United States Congress has expressed a great interest in using UAVs for homeland security as well. In particular, they can improve surveillance coverage along remote sections of the U.S. borders (Haddal and Gertler, 2010; Homeland Security Unmanned Aerial Vehicles (UAVs), 2013). UAVs are becoming indispensable tools for many other homeland security missions including emergency preparedness and response, intelligence activities, infrastructure and perimeter surveillance, detection of dangerous materials, etc. (cf. Homeland security, 2013).

Effective resource virtualization is the key to the success of MANETs, as it facilitates communication between network nodes and speeds up operations in the whole network involved in the target mission. Traditional resource virtualization techniques have been developed mainly for fixed and stable network infrastructures. These techniques cannot adequately function over MANETs of UAVs, because MANETs are highly variable, highly dynamic, unstable, lacking in infrastructure and pose additional challenges for resource virtualization. These challenges include frequent link breakage, inconsistencies in data rates, incompatibility of resources, and temporary unavailability of needed resources and communication links.

In this paper we propose *Opportunistic Resource Utilization Networks*—in short, *Oppnets*—for UAV ad hoc networking. Oppnet is a paradigm for virtualizing resources and acquiring necessary resources (e.g., sensors, computers, lightweight clients, and other

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networks) and capabilities via a network (Lilien et al., 2006, 2010). The Oppnet technology provides middleware to facilitate building flexible and adaptive distributed systems that provide all kinds of resources or services to the requesting application via a helper mechanism.

In order to test the effectiveness of Oppnets in ad hoc networking, we developed a use case scenario and simulated the developed scenario for the cases where Oppnets are *not* used for achieving the target mission vs. cases where Oppnets are used for the mission. Results of the simulation experiments show that the use of Oppnet capabilities results in a significantly higher mission success rate and takes significantly shorter time to complete, which is promising for the use of the proposed approach in real-life operations.

The rest of this paper is organized as follows: Section 2 provides a brief overview of related work; Section 3 describes the general characteristics and operation of Oppnets; Section 4 describes our use case scenario involving UAVs and Oppnets; Section 5 provides the details of the simulation setup; Section 6 provides the results of the simulation experiments; and Section 7 concludes the paper, and provides future work directions.

2. Related work

MANET-based communication systems have been studied by many researchers for various emergency response applications. Jang et al. (2009) proposed a rescue information system for earthquakes based on MANETs of notebook PCs. Fujiwara and Watanabe (2005) proposed a hybrid wireless network, combining ad hoc networks and a cellular network, for maintaining connectivity between a base station and nodes in a disaster. Berioli et al. (2007) introduced Wireless Infrastructure over Satellite for Emergency Communication (WISECOM), which aims to develop a complete telecommunication solution that can be rapidly deployed after a disaster, replacing the traditional use of satellite phones or heavy devices. Oh et al. (2010) proposed content-centric networking as a communication architecture providing retrieval of content by name in emergency MANETs.

MANETs specifically involving UAVs have also been studied mainly in the context of military operations. Reidt and Wolthusen (2008) proposed an authentication and negotiation protocol for MANETs to request services from UAVs in order to optimize the use of available network resources. They also investigated the effects of moving patterns of UAVs on network connectivity. Han et al. (2009) proposed an optimization model for the locations and movements of UAVs to improve MANET connectivity.

Most of the previous approaches for emergency response assumed a homogeneous network of resources, which limits the functionality and the performance of the systems proposed. The approach for UAV ad hoc networking proposed in this paper differs from previous work; it provides a framework capable of integrating heterogeneous resources into the MANET, thereby, maximizing performance with lowered response time.

3. Oppnets—Opportunistic Resource Utilization Networks

This section provides an overview of Opportunistic Resource Utilization Networks. Other publications provide implementation details of Oppnets (Lilien et al., 2007, 2010) and discuss their security and privacy challenges (Lilien et al., 2006).

The basic working principle of Oppnets is as follows (Lilien et al., 2010). To gain needed resources or services, an initially deployed Oppnet—known as the *Seed Oppnet*—starts discovering foreign nodes or application networks that are in the vicinity of the Oppnet. These foreign nodes and networks are not originally components of the Oppnet that discovers them. The Oppnet invites or orders some of them to join its efforts as *helpers*. The Oppnet grows into an *Extended Oppnet* by taking control over helpers that join it (without compromising their privacy), and incorporates their resources/capabilities.

This ad hoc mode of Oppnet operation contrasts with traditional networks (including application networks, or distributed systems) where all nodes are deployed together, and resource or service discovery is limited to nodes only within the infrastructure serving the networks. In addition, Oppnets—being Specialized Ad Hoc Networks and Systems (SAHNS) (Lilien, 2007) for well-matching applications—might provide more application support than other ad hoc networks.

Behavior of Oppnets is analogous to the operation of an emergency response team arriving at a scene of a natural disaster. As the emergency response team grows opportunistically by taking control over local resources provided by numerous helpers, helpers in the Oppnet significantly expand communication, computing, storage, sensing, actuating, and other capabilities of the Extended Oppnet. This gives Oppnets an unparalleled potential for leveraging resources recruited from their environments. An avalanche of capabilities can thus be acquired at a minimal cost or even for free when nodes join an Oppnet.

The set of potential helpers for Oppnets is very broad, including communication, computing and sensor systems, wired and wireless, free-standing and embedded. Before a Seed Oppnet can grow, it must discover its own set of potential helpers available to it. This is not limited to a lookup of previously prepared information (e.g., a directory), which is often referred to as “discovery”, but also includes the more challenging true discovery. True discovery could involve an Oppnet node scanning the spectrum for signals or beacons, and collecting enough information to contact their senders.

Ordering candidate helpers to join an Oppnet may be controversial. To ensure expansion, there is a category of systems always available on an order of an emergency or other critical-application Oppnet. Each such system is called an *Oppnet reservist* (Lilien et al., 2010). (To complicate things, some reservists could be listed in the directory, while others have to be discovered; the latter will reveal their reservist status only upon being contacted by an appropriate Oppnet category.)

Oppnets as discussed in this paper are different from the opportunistic networks proposed by other researchers including Pelusi et al. (2006) and Sistla et al. (2005), which basically provide specialized facilities for opportunistic data forwarding and dissemination. They are also different from Oppnets that have limited opportunism such as those restricted to opportunistic communication when devices are within each other's range (Chau, 2011).

4. Use case for ad hoc networking of UAVs

In this section we describe the use case scenario we simulated to demonstrate the efficacy of Oppnets in UAV ad hoc networking for defense operations. A visualization of the scenario can be seen in Fig. 1. The basic setting of the scenario is as follows. A Carrier Strike Group (CSG)—with one carrier and four Littoral Combat Ships (LCSs)—is deployed on Maritime Interdiction Operations (MIO) and mine clearing missions in a dangerous area. The LCS/CSG force conducts surveillance of likely transit routes, using surface and aerial assets, as well as off board surveillance systems (such as acoustic arrays).

A Northrop Grumman X-47B (2012), an Unmanned Combat Air System (UCAS), is deployed from the carrier for a maritime intelligence, surveillance and reconnaissance mission over the