A communication architecture for UAV swarms

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by

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Certificate

It is certified that the work contained in this thesis entitled "A communication architecture for UAV swarms" by "Sai Aditya Chundi" has been carried out under my supervision and that it has not been submitted elsewhere for a degree.

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Abstract

UAVs have received considerable attention in the last decade, both in industry and academia. Potential applications are wide and varied, encompassing both military and domestic spaces. Search and rescue missions during disasters, environmental monitoring and surveillance, precision agriculture and farming are some of the domestic applications, while the scope of their usage in military space can be readily appreciated.

Communication is a critical component in realizing swarms of UAVs. There are two aspects of the communication architecture while considering UAV swarms. While there needs to be a reliable communication between the UAVs and a ground station, communication between individual UAVs is essential in enabling a distributed architecture for swarm applications. Wireless ad-hoc networks offer an appealing solution for inter UAV communication. While there have been works which used 802.11 based ad-hoc networks for the communication in multi UAV setups, these are short range links which are not suitable for the long range link between UAVs and the ground station. On the other hand, the commonly used 900 Mhz based radios for the communication between UAVs and the ground station in long range, are not well suited for inter UAV communication.

In this work, we present a novel communication architecture for UAV swarms, which combines both the long range and short range architectures. Moreover, our communication architecture is based on Robot Operating System(ROS), which ensures that any distributed application can be easily integrated into, and extended by the capabilities of ROS.

Acknowledgements

I would extend my sincerest gratitude...

Contents

List of Figures

For/Dedicated to/To my...

Chapter 1

Introduction

1.1 Rise of Unmanned Aerial Vehicles

Unmanned aerial vehicles or UAVs have become ubiquitous in the past decade, both in research and industry. A myriad of applications involving UAVs in diverse fields has made them quite popular. Potential domestic applications include Environmental monitoring and surveillance [10], traffic management [23], remote sensing [26], precision agriculture and farming [9], disaster management [11], to name a few. The use of UAVs for defence purposes is only poised to grow in the next decade. It is not hard to see the appeal of UAVs in the defence sector with applications ranging from simple surveillance and reconnaissance missions to offensives like *search and destroy* missions and targeted hits.

Much of the rise of this interest in UAVs can be attributed to associated advances in robotics, largely driven by the progress in robust and cheap sensors and communication technology. The emergence of scalable and extensible software architectures like the Robot Operating System(ROS), which enables easy integration of various subsystems further pushed the progress in these domains.

While early applications of UAVs were single UAV based, the focus is now shifting towards applications involving multiple UAVs, cooperatively completing tasks. There are

several advantages of multi-UAV systems over single UAV systems. In certain applications like search and rescue missions, for instance, the use of multiple UAVs for surveying an area can significantly reduce the time taken to complete the task [27]. As given by [30], other advantages of multi-UAV systems over single UAV systems include cost, scalability, survivability and speed.

Though UAV swarms have promising capabilities, they have quite a few challenges to overcome. Communication is one of the main hindrances to realize robust swarms of UAVs.

1.2 The Challenge of Communications in UAV swarms

While there is much literature regarding communication in UAV systems, [30] and [12] are two good survey articles regarding the current trends and issues in communication in UAV swarms. Besides pointing out the shifting interest towards multi UAV systems, due to their advantages over single UAV systems, they also identify the challenges in these systems, communication among the UAVs being the most notable one.

Since the first applications were single UAV based, communication architecture in these systems was simple and straightforward. Often, there only needed to be a communication link between the UAV and the ground station. In some cases where the UAV has to cover a larger area, there could be multiple ground stations, and the UAV would have to communicate with the ground station near it. Even then, the overall architecture was pretty basic. As we noted earlier, there is a rapidly growing interest in realizing swarms of cooperative and collaborative UAVs, accomplishing complex tasks. Robust and reliable communication among the UAVs is an essential and critical component in enabling cooperative and collaborative behaviour in these UAV swarms.

While there is some interest in infrastructure based communication in UAVs, like using cellular infrastructure for UAVs [29], much of the research community considers enabling UAV communications in infrastructure less environments, more significant. These so called
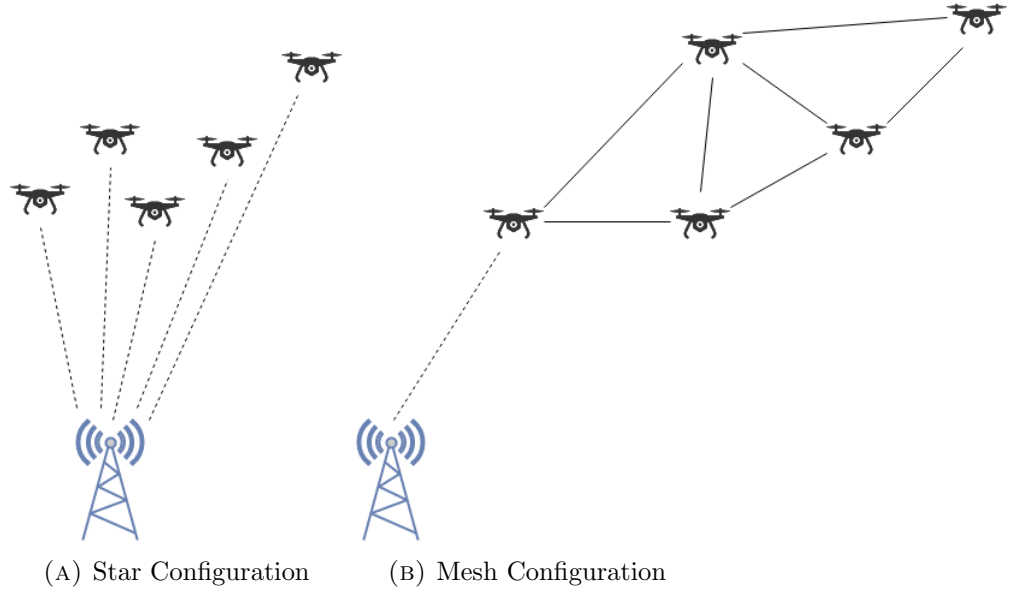
(A) Star Configuration   (B) Mesh Configuration

FIGURE 1.1: Possible network configurations for communications in UAVs

adhoc networks are important, for instance in disaster management scenarios where the existing infrastructure is damaged, or in military applications where there is no pre-existing infrastructure. The authors in [12] try to identify several possible communication architectures for multi UAV networks.

Figure 1.1a shows the star topology, where all the UAVs are connected to the ground station. In this configuration, the necessary communication among UAVs also needs to be routed through the ground station. Figure 1.1b shows the mesh topology, where the UAVs communicate among themselves using an adhoc network, they themselves form. Typically, the ground station is also a part of the adhoc network. In the star configuration, since all the data has to be routed through the ground station, there would be higher latency and congestion in the network.

On top of that, if the UAVs are considerably far from the ground station, the network in star configuration may not provide reasonably high bandwidth for the communication among the UAVs. Moreover, if any of the UAVs loses its link to the ground, it cannot be accessible by any other UAVs, even if they are close. It is clear to see that the mesh configuration has a considerable advantage over the star configuration. Indeed, there

is a consensus in the literature that realizing adhoc networks is the best solution for communication in multi UAV systems. There is a growing intereset in FANETs, the Flying Adhoc Networks. There is much literature in the filed and [30] introduces and outlines the current and future trends in FANETs.

1.3 Motivation and the Current Work

With the advent of Internet of Things(IOT), there are now several communication standards which enable mesh networks like Bluetooth mesh networks [8], Thread [3, 25] and Zwave [28], where the last two protocols are based on the IEEE standard 802.15 [2]. Despite these, mesh networks which are based on the wifi, as standardized in IEEE 802.11s, better suit the needs of UAVs because of their high data rate and range.

While there are previous works which have used wifi based adhoc networks in UAVs like AUGNET [5] and UAVNET [19], they have several issues, not least of which is the range of the networks. Though the mesh networks enable reliable communication among the UAVs at an acceptable range, the link between the UAVs and the ground station is much more vulnerable. While the distance between the neighbouring UAVs can be kept relatively small, one cannot restrict the distance between the ground station and a UAV. A typical scenario would be that of a group of UAVs flying as a swarm far from the ground station. Even though the UAVs are in range and allow communication among themselves via the wifi mesh, the ground station at a larger distance can no longer be a part of the mesh. This is certainly a limiting factor in mesh networks for UAVs. This is one of the motivations for this work, in which we address this issue by using two different radio modules, a long range and a short range one(the wifi mesh). We propose a new architecture which blends short range and long range aspects of the communication. Note that the long range radios typically provide low bandwidth and are not suited for robust inter communication among the UAVs, demanded by many emerging distributed applications. This is not a concern in the case of the link between the UAVs and the ground station as long as, much data is not needed at the ground station, which is the case in autonomous applications, where much

of the decision making happeds on board the UAV and ground station is merely used for monitoring.

Another aspect of motivation for this work is its integration with the Robot Operating System or ROS. ROS is a widely accepted software platform for research in robotics, which became popular as *Linux for Robotics.* ROS, with its distributed and modular architecture, active development, collaborative environment and vibrant community has seen widespread adoption by individuals and organizations, across the board in robotics research. Thus the goal was to integrate our communication architecture into ROS, enabling development of distributed applications among UAVs without the need to worry about the underlying communication architecture.

1.4   Organizaiton of the thesis

We have introduced and motivated the problem of communication in UAV swarms in chapter 1. In chapter 1, we shall look at the development of the mesh architecutre. We shall look at the long range communication architecture in chapter 1. We shall look at some future work and finally conclude this thesis with chapter 1.

Chapter 2

The Mesh Architecture

In this chapter, we will look at the short range communication architecture for inter communication among the UAVs which entails realizing a wifi mesh network based on the IEEE standard 802.11s. We shall also look at how it is integrated into ROS.

2.1   IEEE 802.11s

The IEEE WLAN 802.11 standard is quite a popular solution for high bandwidth networking services at reasonable distances. But, it is based on a centrailized architecture, where every networking node is a *Station*, STA. In the simplest architecture, one of the STAs acts as an *Access point*, AP, a centralized node which provides integration services to other STAs. It is a single hop architecture where *STAs* directly communicate with *APs*, and all the communication between *STAs* is routed through the *AP* to which they are connected. Essentially, it is a network in star configuration, at MAC layer.

With growing demand for more diverse wireless infrastructure and multihop networks, 802.11s [14] emerged as an ammendment to the original standard to accommodate mesh networking architecture. The 802.11s standard extends the 802.11 MAC layer, allowing a MAC based multihop architecture.
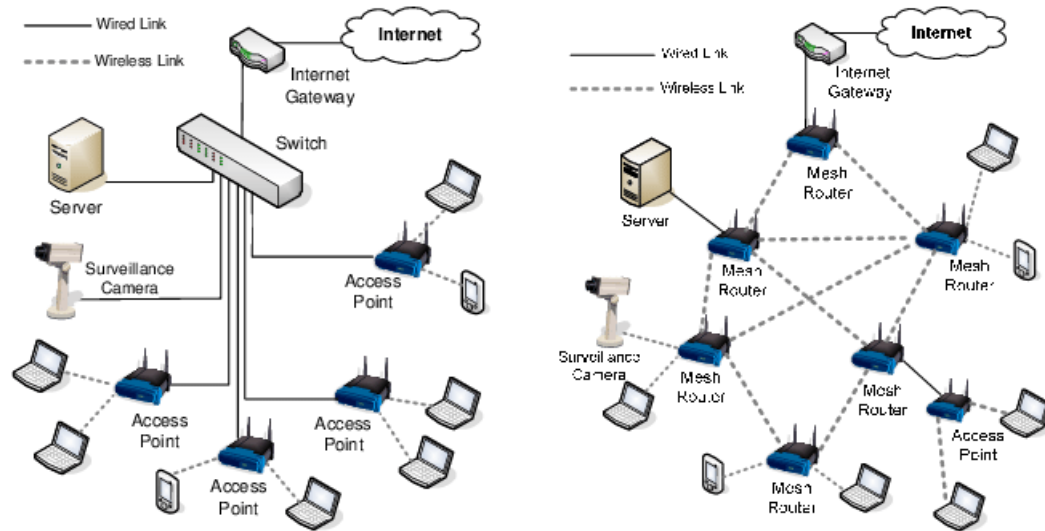
FIGURE 2.1: A comparison of 802.11 wlan and 802.11s mesh networks

source: Portmann, Marius. (2006). Wireless Mesh Networks for Public Safety and Disaster Recovery Applications. 10.1201/9781420013542.ch16.

2.1.1 Routing in 802.11s

Though there are a lot of routing protocols proposed in wireless mesh networks, the field is still active in research. What routing protocol to use closely depends on the application, and choice of the routing protocol may significantly impact the performance of the system. Different routing protocols can be mainly categorized into two types.

- *Proactive Routing Protocols:* Proactive routing protocols are those protocols where the nodes keep track of the routes of all the accessible nodes. This is typically done by storing tables of all the routes based on the topology of the network. The tables are updated as the topology changes. While transmitting data, the node can instantly find the next hop from the routing table, which allows little or no latency in the sytem. On the other hand, to keep the tables updated with the topology , a lot of messages have to be sent between the nodes, which decreases the effective bandwidth for data. Moreover, these protocols tend to be slow to adapt to fast changes in topology. Some of the popular proactive routing protocols include *Optimized Link State Routing* (OLSR) [7], *Destination Sequenced Distance Vector*

(DSDV) [21], *Better Approach To Mobile Adhoc Networking* (BATMAN) [15], to name a few.

- **Reactive Routing Protocols:** Where proactive routing protocols keep track of the routes based on topology, reactive routing protocols are on-demand routing protocols where a route between two nodes is found only when there needs to be communication between them. These protocols are defined to address the bandwidth issues of the proactive protocols. As they don't need to keep track of the routes, periodic flooding the network with messages to find the current topology, is not needed, which saves the bandwidth. On the other hand, these protocols tend to introduce more latency into the system as a route to a node has to be found before transmission of data. Some of the reactive routing protocols include *Dynamic Source Routing* (DSR) [16], *Adhoc On Demand Distance Vector* (AODV) [6].

Due to significant research in routing protocols for mobile adhoc networks, there have been other classes of protocols as well, apart from the two main categories above. There are *Hybrid Routing protocols* like *Zone Routing Protocol* (ZRP) [13] and *Temporarily Ordered Routing Algorithm* (TORA) [20], which try to blend both low latency and bandwidth efficiency of proactive and reactive protocols together. There are also a class of *Geographic Routing protocols* [4, 17, 18] which are based on the geographic positions of the nodes, like GPS data for instance.

The 802.11s standard defines a mandatory default routing scheme called *Hybrid Wireless Mesh Protocol* (HWMP), which is a hybrid protocol combining procative and reactive ascpects of routing protocols. However, it is not mandatory that one has to use the default HWMP and can implement any routing protocol while using 802.11s PHY and MAC layers.
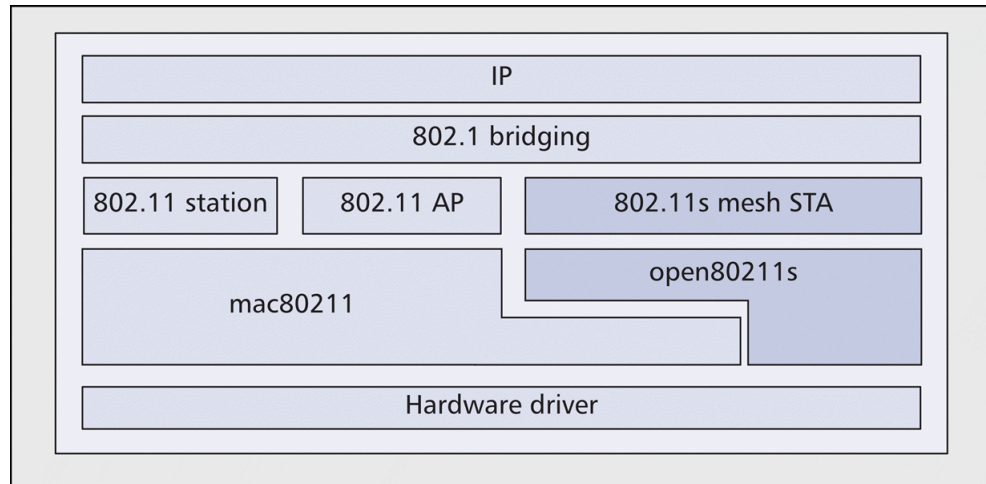
FIGURE 2.2: open80211s stack on Linux kernel

source: G. R. Hiertz et al., "IEEE 802.11s: The WLAN Mesh Standard," in IEEE Wireless Communications, February 2010.

FIGURE 2.3: logo of OpenWrt

source: https://openwrt.org/

2.1.2 open80211s

open80211s stack is an open source implementation of the 802.11s standard on the Linux kernel. It is based on mac80211 wireless stack, which implements the standard 802.11 on Linux kernel. Since it is based on mac80211 and makes minimal changes to the 802.11 MAC layer, it is supported on all legacy hardware that supports mac80211.

2.2 Hardware

In this section, we shall look at the hardware used for realizing an 802.11s mesh network. As we mentioned in the last section, the open80211s stack can be implemented

FIGURE 2.4: An ssh shell on an openwrt flashed router

on most linux machines with legacy wireless cards which are compatible with the standard mac80211 wireless stack. There is a lack of embedded wireless hardware for building 802.11s mesh networks. We wanted to build 802.11s mesh networks with easily available commercial 802.11 legacy hardware and we found a solution with OpenWrt.

2.2.1 OpenWrt

Openwrt [ope] is an embedded operating system based on linux kernel, meant for wireless routers. Basically, it is an open source project in which the community releases ports of the operating system for specific wireless routers, whose wireless hardware is compatible and whose memory and firmware allow reflashing the default firmware, these devices come with. Since, not all wireless routers can be flashed with openwrt, we would have to choose from a list of openwrt compatible hardware.

Once we obtain an openwrt compatible wireless router, we would have to flash the router with an image of the openwrt operating system. Typically, different routers have different instructions for flashing the image and are generally listed along with other details on the device page, specific to the router. Once the router is flashed with openwrt, the device will be running a full-fledged operating system based on linux kernel, albeit one with limited capabilities. When we power on the router, it boots up into openwrt with a default ip address of 192.168.1.1/24. If we connect the router to a host machine via ethernet and *ssh* into the said ip address, we would log into the openwrt with a secure shell. Figure 2.4 shows a terminal on a wireless router, flashed with openwrt and logged into it via ssh, from an host pc connected via ethernet.

2.2.2 Wireless routers

We have tested two different routers with openwrt. Both are routers are supported by the operating system, as listed on their website.

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