
A communication architecture for UAV swarms

*A thesis submitted in fulfilment of the requirements
for the degree of Master of Technology*

by

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May 2019

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...

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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 [11], traffic management [24], remote sensing [27], precision agriculture and farming [10], disaster management [12], 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 [28]. As given by [31], 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, [31] and [13] 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 [30], much of the research community considers enabling UAV communications in infrastructure less environments, more significant. These so called

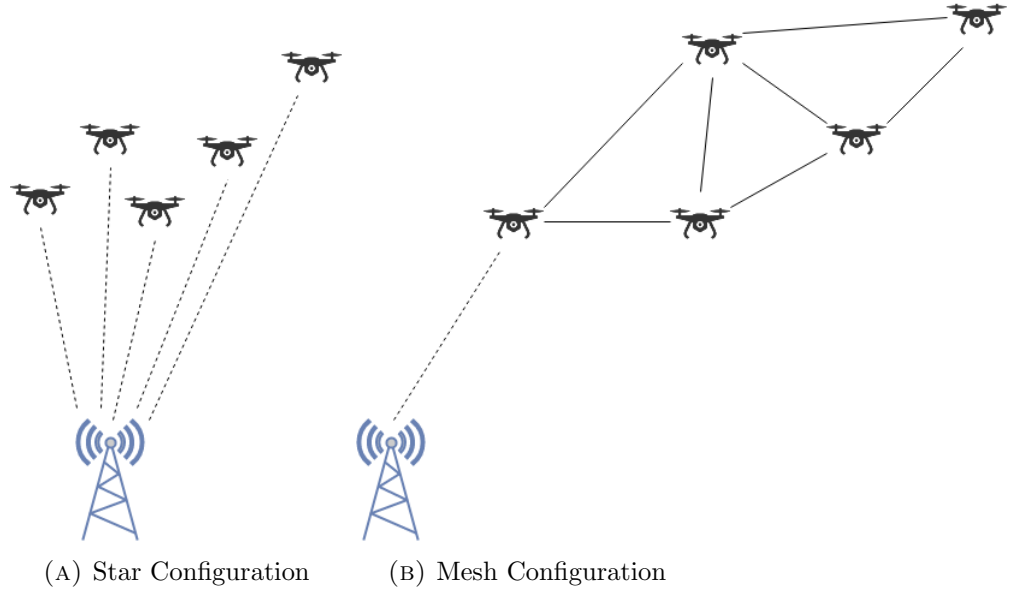


FIGURE 1.1: Possible network configurations for communications in UAVs

ad-hoc 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 [13] 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 ad-hoc network, they themselves form. Typically, the ground station is also a part of the ad-hoc 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 interest in FANETs, the Flying Adhoc Networks. There is much literature in the field and [31] 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 [9], Thread [4, 26] and Zwave [29], where the last two protocols are based on the IEEE standard 802.15 [3]. 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 [6] and UAVNET [20], 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 happens 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 architecture. 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 centralized 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 [15] 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.

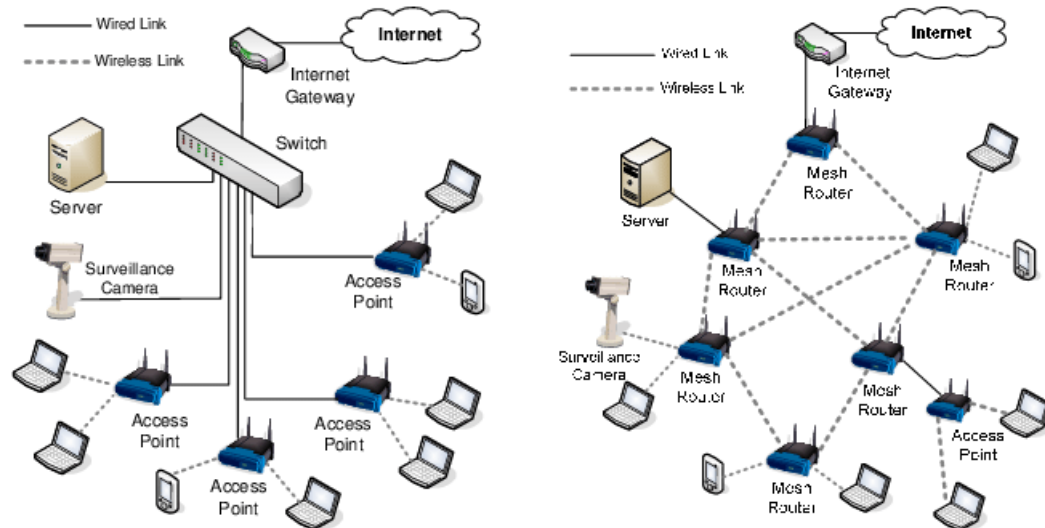


FIGURE 2.1: A comparison of 802.11 wlan and 802.11s mesh networks

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 system. 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) [8], *Destination Sequenced Distance Vector*

(DSDV) [22], *Better Approach To Mobile Adhoc Networking* (BATMAN) [16], 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) [17], *Adhoc On Demand Distance Vector* (AODV) [7].

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) [14] and *Temporarily Ordered Routing Algorithm* (TORA) [21], 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* [5, 18, 19] 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 proactive and reactive aspects 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.

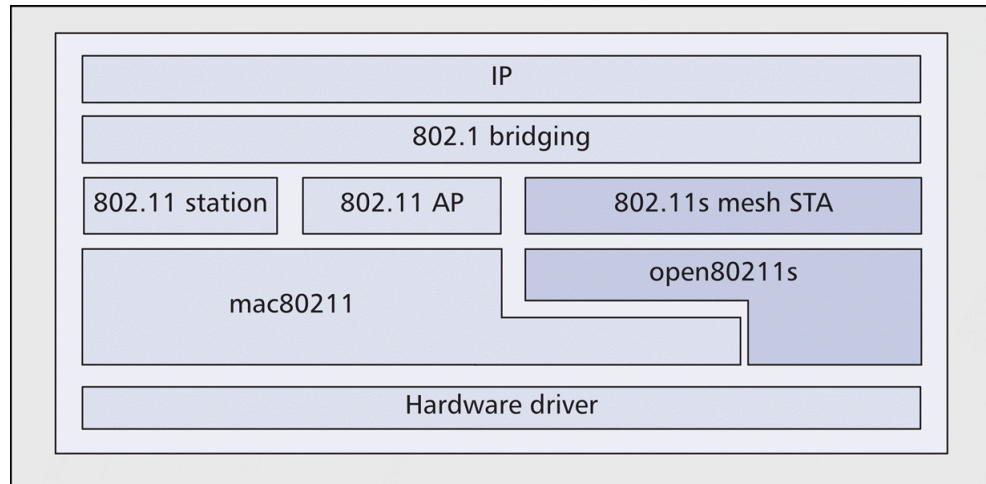


FIGURE 2.2: open80211s stack on Linux kernel

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

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 Implementation



FIGURE 2.3: logo of OpenWrt

source: <https://openwrt.org/>

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

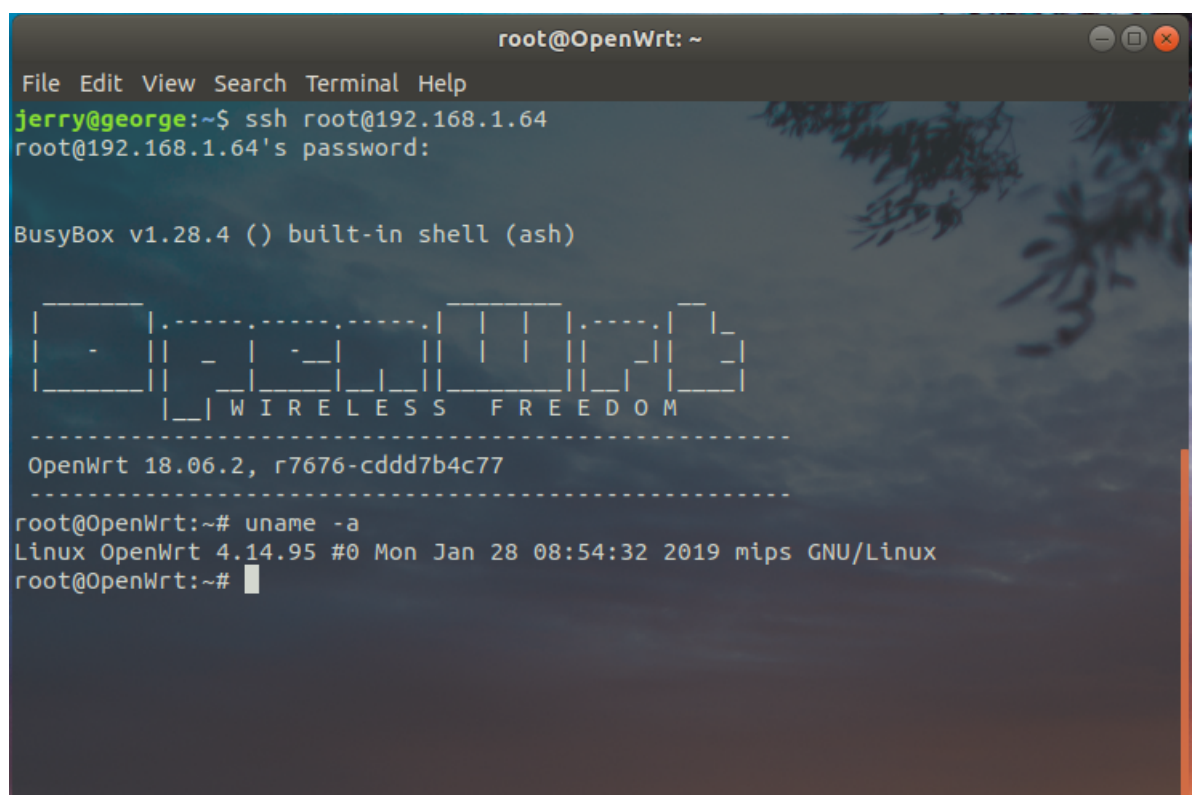


FIGURE 2.4: An ssh shell on an openwrt flashed router

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 in via `ssh`, from an host pc connected to it by ethernet.

2.2.2 Hardware

Let us now look at the actual routers we have used to realize the mesh networks. We have tested the entire setup with two wireless routers. Both the routers are compatible with openwrt and were decided upon going through the list of supported hardware on the webpage <https://openwrt.org/toh/start>.

2.2.2.1 Tp-Link WR902AC



FIGURE 2.5: Tp-Link WR902AC

The first router is Tp-Link TL-WR902AC v3. Its device page on openwrt can be found at https://openwrt.org/toh/hwdata/tp-link/tp-link_tl-wr902ac_v3. The router has a 10/100 Mbps ethernet port, a 2.0 USB port and micro usb port. It needs external power

supply of 5V/2A via the micro USB port. The default firmware the device comes with supports the standards IEEE 802.11ac/n/a @ 5GHz and IEEE 802.11b/g/n @ 2.4 GHz, making it a dual band router. It can support wireless speeds up to 300 Mbps @ 2.4GHz and 433 Mbps @ 5GHz. The transmit power is <20dBm @ 2.4GHz and <23dBm @ 5GHz. The openwrt port for the device doesn't support the device operating at 5GHz.

2.2.2.2 Alfa Tube 2H

The second router we tested is Alfa Tube 2H. The corresponding device page on openwrt can be found at https://openwrt.org/toh/hwdata/alfa_network/alfa_network_tube2h. This router too has a 10/100 Mbps ethernet port. It also has an N-type male antenna port to connect external antennas. It supports passive *Power Over Ethernet*(POE) and is powered using ethernet port itself. Unlike the Tp-Link device, it is a single band router, which supports IEEE 802.11b/g/n, operating at 2.4GHz. It can support wireless speeds up to 150Mbps. Its transmit power can go upto 500mW or 27dBm. The Alfa Tube 2H offers two main advantages as compared to WR902AC. First, its transmit can go upto 27dBm whereas the WR902AC can only support a transmit power upto 20dBm. This translates to higher range for communication. Second, unlike the WR902AC, the Tube 2H supports external antennas which can further increase the range of the device.



FIGURE 2.6: Alfa Tube 2H

2.2.3 Network Configuration

Since Openwrt is a full fledged operating system based on the linux kernel, it offers tremendous flexibility in configuring the wireless devices for the network. The directory structure of the system is quite similar to normal linux distributions except a few minor changes. For instance, all the configuration files for different subsystems can be found in the folder */etc/config*. Changing these files and restarting the respective services, or the entire system would change the configuration of the system.

To connect the router to a wifi access point, we would first have create a device interface in *client* mode in */etc/config/wireless*. We would also have to specify the *ssid* of the *AP* and provide authentication, if any. Then, we would have to create a network interface for the above created device, assign an IP address to it in case of static address or specify DHCP etc., in */etc/config/network*. Restarting the system or the network services, then , would connect the router to the specified *AP*.

2.2.3.1 LUCI

Openwrt also provides an easy gui interface to do the network configuration. The interface is called LUCI, which can be accessed by typing in *https://<IP address of the router>*, in a web browser, of the host pc, connected to the router, via ethernet. The interface can be used to connect the router to an access point, or make the router an access point and share its network. However, luci has limited functionality and cannot be used to configure 802.11s mesh networks. We would have to do that by manually changing the configuration files. Figure 2.7 shows the luci interface opened in a web browser.

2.2.3.2 802.11s mesh configuration

After the routers are flashed with an image of openwrt and booted up, they do not have the capability of supporting 802.11s mesh by default. Some setup and configuration is needed to implement 802.11s on these devices. First, we connect the router to the internet

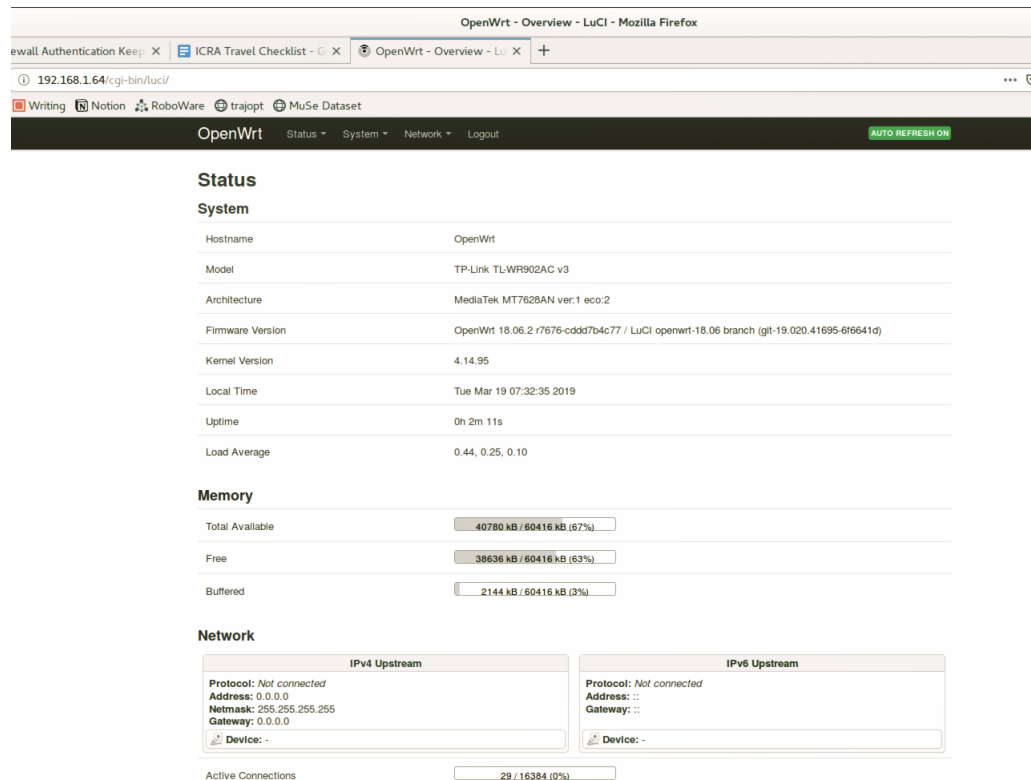


FIGURE 2.7: LUCI web interface for configuring openwrt routers

by connecting it to any wifi access point, via luci. Next, the package *wpad-mini* which is installed by default should be removed and the package *wpad-mesh* needs to be installed. This can be done by using the default package manager of openwrt, *opkg*.

Now, we could implement 802.11s on these routers. We create a device interface in mesh mode, specify the name of the mesh network in wireless configuration file. Then, we create a network interface for the mesh interface in network configuration file. In our case, we decided to use static ip addresses for the routers with the network address 192.168.1.0 and a subnet mask of 24. So, the ip addresses assigned to different routers are of the form 192.168.1.xxx.

After the setup, if two or more routers with the same configuration, but different ip addresses are powered on, they should be forming a mesh network among themselves. This can be verified by connecting one of the routers to a host pc, *ssh*ing into the router and pinging the other routers. The ping would be getting responses from the other routers.

2.2.3.3 Routing protocols

As we have noted in an earlier section, the standard 802.11s allows different routing protocols to be used on top of the 802.11 MAC layer, even though it defines a default routing protocol, HWMP. While it is theoretically possible to implement a custom protocol, there are a few routing protocols with open source implementations one can readily use. Among them the protocols BATMAN and OLSR are popular and have implementations for linux as well. Openwrt supports both the protocols and documents how to configure the 802.11s mesh to use these protocols. In our case, we have used BATMAN as the routing protocol as it is shown that BATMAN outperforms OLSR in real world scenarios [2].

2.2.3.4 Mesh networks among the host machines

In the last chapter, we saw how we implemented 802.11s mesh networks on commercially available wireless routers. In the end after everything is configured, we would just power on the routers and a mesh network would be established among them. But, we would not just like to create a mesh network among the routers themselves, but would like to create mesh networks among the machines to which these routers are connected.

The routers mainly have two interfaces within them, the ethernet interface and the wireless interface. The ethernet interface may be connected to a host machine, while the mesh network is formed on the wireless interface. In case we want to create a mesh network among the host machines themselves, we would need to have a way to share the mesh network on the wireless interface with the ethernet interface. For this, we bridge both the wireless and the ethernet interface. Bridging both the interfaces creates a single logical network interface. Though there are two device interfaces, there would only be one logical network interface after bridging, to which we would assign the IP address. Thus, bridging enables mesh networks among host machines themselves as long as they are connected to the so configured mesh routers. Figure 2.8 illustrates the bridging of the wireless and

ethernet interfaces in routers, where they established a mesh network among themselves and each of them is connected to a host machine via the ethernet port.

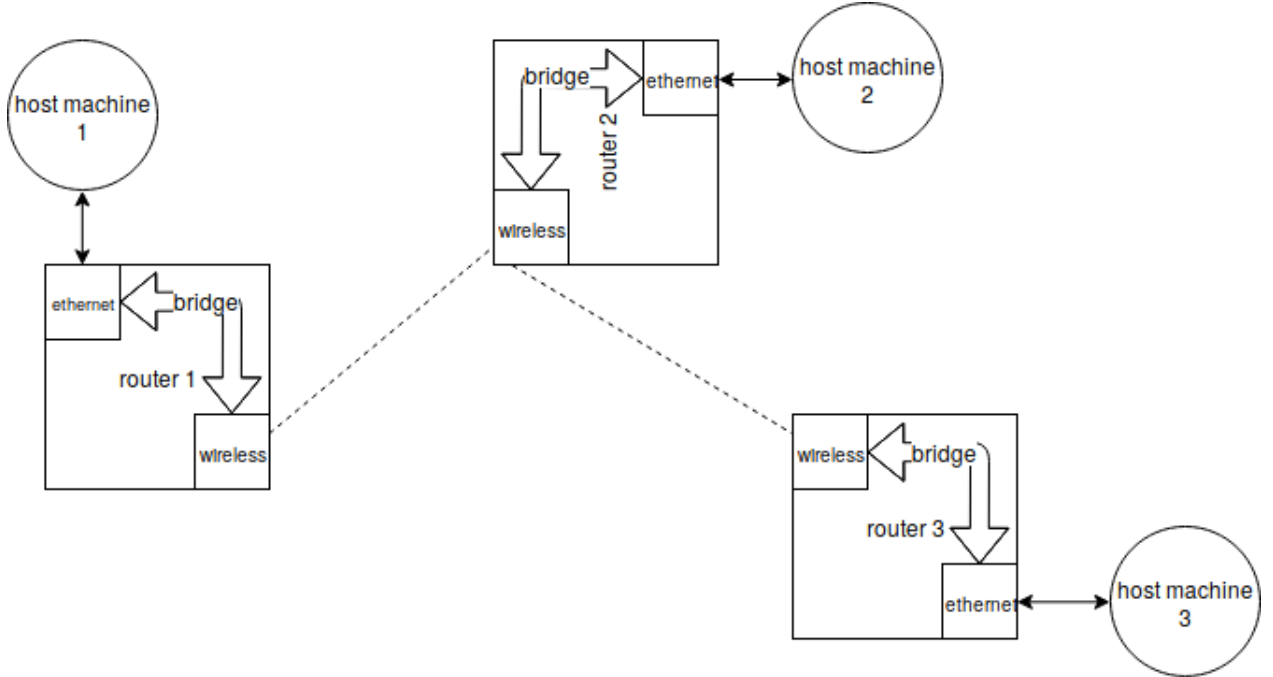


FIGURE 2.8: Mesh architecture with bridging of wireless and ethernet interfaces in routers

2.3 Integration with ROS

One of the motivations of this work is to integrate the communication architecture into ROS. ROS is quite a flexible framework allowing to run it on multiple machines pretty easily. ROS fits well in the application layer in the traditional OSI layers and uses TCP/IP for sending and receiving messages on ROS topics and services. Thus, as long as a TCP/IP stack is installed on the machines and network between them is established, it is trivial to setup ROS on these machines.

The standard way to do it is to specify one of the machines as a ROS master. This is specified by setting the environmental variable `ROS_MASTER_URI` to the IP address of the designated master on all the other machines. But, this setup establishes a star configuration in application layer, which is ROS. When ROS is run on multiple machines the

standard way, designating one of the machines as the ROS master, all the communication between nodes happen through the ROS master. So, when a node on one machine publishes a topic and another node subscribes to it, the data is actually being routed through the ROS master. This is very inefficient both bandwidth wise and latency wise. Thus, we implemented a multimaster version of ROS, where all the host machines will be running as a ROS master and still be able to access ros topics and services of the other masters.

2.3.1 `multimaster_fkie`

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