Enhancing Wireless Communications with Software Defined Networking

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Abstract—**In defence and emergency operations, integration between multiple wireless networks offers the choice of selecting the connection best suited to the type of information transferred, while at the same time expanding the coverage area in regions where only certain networks are available. Without effective command and control systems, response units at the operational edge, where critical real time information is generated and consumed, become "information islands". Controlling network traffic at higher echelons, in order to make better use of the limited network bandwidth available, improves the situational picture at the control centre and competence of emergency response units on the field. Traffic prioritization, remote network control, and multiple radio integration are three important criteria we are considering in the design of a two-level hierarchical software defined networking architecture for wireless networks, which expand on other SDN properties such as network agility, scalability, and programmability. We have built a prototype with multiple radio interfaces that can provide backhaul for response units by selecting the interface with the highest available throughput, where both policies and configuration can be programmed remotely. Even if our primary use case is geared towards emergency services, military communications challenges share many of the characteristics of emergency operations.**

Keywords-software defined networking, radio integration, wireless networks, network programability

I. INTRODUCTION

Communications are a vital component in defence and emergency operations. In the past, military and government networks were the most advanced in terms of capability and technology. Today, wireless commercial communication systems are being developed and improved upon constantly, and in general provide far better performance than existing military or government emergency systems. For this reason, commercial networks are being used increasingly in emergency operations (police, fire, and ambulance services), with government networks holding the advantage of superior coverage area in remote areas.

One of the important issues in communication networks, and wireless networks in particular, is scalability [1] [2]. There are three meaningful dimensions to scalability. First, with respect to the amount of data being transferred, the network must be able to handle ever-increasing amounts of traffic, and new services such as video communication and streaming push existing capabilities to the limit. Second, with respect to networking equipment, the network must be able to integrate new devices, which may use different standards and protocols. Third, with respect to communication infrastructure and protocols, the system must be able to integrate multiple types of networks. Cellular networks, wireless data networks, mobile broadband networks, VHF/UHF voice and data networks, and satellite communications are all used frequently in defence and emergency operations, depending on operational constrains and environment.

In this paper, we consider the use of the software defined networking (SDN) architecture for wireless communication networks to enhance scalability with respect to traffic forwarded, integrating network equipment, and integrating communication protocols. Software defined networking [3] is an approach to managing network services that is based on abstracting functionality by decoupling the system that forwards network packets (the data plane) from the system that decides where traffic is forwarded (the control plane). Current research on SDN aims to improve on the limitations of current networks and to enable:

- *network programmability*, such that network control is decoupled from forwarding functions and directly programmable;
- *configuration programmability*, such that network managers can configure network resources programmatically; *agility*, such that network traffic flow can be adjusted dynamically to meet different needs;
- *central management*, such that optimisations and network policies can be dynamically implemented and applied to a single logical network switch;
- *vendor neutrality*, such that no dedicated vendor-specific devices are used.

SDN is used successfully in wired networks in large environments, such as data centres [4] [5], university and campus networks [6], to remove manual provisioning of network services. However, in the case of large wireless networks, the lack of a standard programmable wireless network data plane is preventing SDN to achieve its goal of abstracting lower-level functionality from network control. One of the ways in which this issue can be tackled is by using software-defined radios [7] (SDR). Special-purpose radio components that previously were implemented in hardware may now run as software on embedded systems with general-purpose processors, powerful enough to handle the necessary signal processing required. However, using SDR provides new challenges, both technical, from integrating SDN with SDR [8], and operational, as it requires replacing all existing equipment. Instead, we propose the use of a two-level hierarchical SDN architecture for wireless networks. The first-tier central SDN controller acts as a manager for second-tier controllers, providing them with the necessary SDN applications while maintaining a global view of the network. Each wireless device in the network can also be a second-tier programmable SDN controller, running SDN applications and having their global view of the network updated by the first-tier controller. We argue that this approach allows for a better use of the existing infrastructure, as second-tier controllers can be added to current networks and programmed to work with existing controllers, while at the same time providing the benefits of software defined networking and allowing for scalability, agility and programmability.

Our first contribution is designing an abstraction layer for a two-tier hierarchical software-defined networking controllers, that exposes a modular, application-centric interface to program wireless networks. The key idea aligns to the SDN concept of separating forwarding and control into different components, with a network manager being able to program the control module, which in turn will configure the network hardware.

Our second contribution is a framework for integrating different network technologies that allows for interoperability between wireless technologies. Interoperability is an important issue in military and emergency operations, where different parties might be using different networks and protocols. For example, the lack of interoperability between communications networks was found to have seriously impacted on the emergency response in the 2013 Tasmanian bushfire. At this stage, we have a prototype implementation for a radio integration unit capable of switching between multiple wireless technologies based on the existing radio conditions that can be used as a programmable backhaul device. We use Wi-Fi and mobile broadband to establish proof-of-concept, but plan to add the Australian government radio network (GRN) and satellite network connectivity in the coming months.

The remainder of this paper is organized as follows. In Section 2, we outline a specific use case for software defined networking and inter-operability between different networks in emergency operations. Section 3 presents our design, while its feasibility is discussed in Section 4. Section 5 contains the related work and we present our conclusions in Section 6.

II. USE CASE

Communications in emergency operations

In January 2013, Tasmania experienced a record heat wave across the state that contributed to catastrophic bushfire conditions. The bushfires and emergency response operations that followed were severely hindered by the lack of seamless communications between different emergency organizations [9]. Even though computer modelling could be used to predict fire conditions, the underlying assumptions used for modelling may be inaccurate without updated information from the field, and fire-fighters are reliant on the information accessed through radio communications to update their situational awareness. Moreover, in emergency operations, the information flow can be severely hindered as soon as operators start moving - technical restrictions limit the integration of mobile systems and they tend to form “islands of information”. Without effective command and control systems, response units have to be operated based on slow and unreliable voice communication, vulnerable relay stations, hand drawn maps and visual signals. These “information islands” were most common at the operational edge, where critical real time information is generated and consumed. A dangerous “information fog” results when real-time data is not fed quickly enough through the command system, to update the “situational picture” at higher echelons. There are proprietary devices that can switch communications traffic between radio networks, but they still require manual interventions and are often slow and difficult to configure [10]. The requirement for at least near real-time response for many of the supported systems thus presents substantial challenges for network designers.

The New South Wales Rural Fire Service (RFS) networks present another example of the set of challenges in maintaining seamless emergency communications [11]. New South Wales RFS uses several network systems for its communication devices, operating on three levels: strategic, tactical and task. The strategic network (STRATNET) consists of 25 Personal Mobile Radio (PMR) sites, connected to the Government Radio Network (GRN) where available. PMR delivers point to point communications across NSW, between regional offices, district fire control centres, satellite district fire offices and RFS headquarters. The RFS operates some 370 PMR sites as backbone infrastructure for a fire control centre to work with local brigades within a district. At the tactical level, communications are typically between centres and fire appliances, tankers and aircraft. The task level covers communications between brigade members operating within one local area. These are local communications, typically between ground appliances and tankers to fire-fighters, and fire-fighter to fire-fighter. In this scenario the distances are short and communication is carried out directly from handset to handset. Brigade members are called to duty predominantly through a state-wide network of over 10,000 pagers, activated by a network of communications towers. The towers form the backbone of the RFS communications system and could be threatened by adverse conditions including the fire itself. Maintaining these multiple networks in an emergency operation provides an integration challenge.

III. DESIGN

In this section we look in depth at the design of our proposed two-tier hierarchical SDN framework. Similarly to the traditional SDN architecture, shown in Fig. 1, we propose to abstract the control plane from the data plane. However, traditional SDN assumes that the controller is always available to produce a forwarding decision [3]. In a dynamic wireless

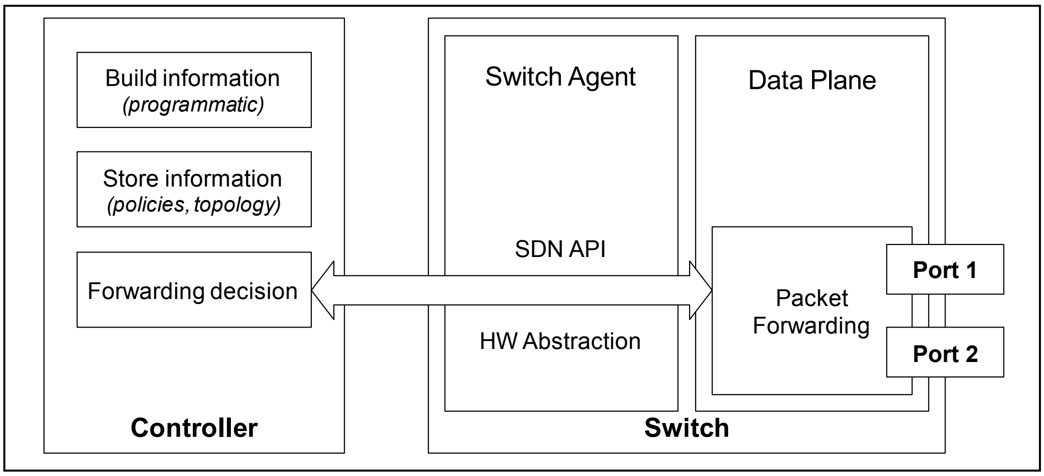

Figure 1. Traditional SDN architecture

environment, with changing radio conditions, this assumption is no longer valid. Network connectivity might be lost, even if a different radio interface might be used to establish another connection. As capabilities and speeds may vary between different interfaces and radios, the decision taken in forwarding traffic should reflect situational awareness. Accordingly, determining traffic flows with a traditional external SDN controller may lead to disasters when connectivity is lost. For example, streaming video from the field to a control centre in the case of a fire situation might be possible at the same time with broadcasting fire-fighters GPS location data when using a 3G mobile broadband connection, but location data should always be prioritized. As the radio environment is inherently shared between users (in this case, fire-fighters), it would be useful for the control centre to be able to control traffic such that only video from regions of interest is being forwarded by the network, making better use of the limited bandwidth available. When a mobile broadband is not available, a satellite connection makes possible forwarding critical location data to a control centre, while forwarding video packets should be disabled due to poor transfer speeds over satellite networks. This example highlights three important criteria we are considering in our design: *traffic prioritization*, *remote network control*, and *multiple radio integration*.

A. Traffic Prioritization

At its core, SDN specifies a packet processing state machine, called a switch. Fig. 1 shows the components of a traditional SDN switch. Each network packet is processed based on the packet contents and the configuration state (policies, topology) managed by an SDN controller. The data plane is the component of the switch that performs packet forwarding and manipulation, and is defined by ports, flow tables, classifiers, and actions. Network packets arrive and leave the switch on ports; packets are matched to flows in the flow table based on classifiers; flows contain instructions and actions that are applied to each packet it matches. The switch agent translates the control decisions from the controller (received via the standard SDN API) into the necessary instructions for the data plane. The instructions and actions are used to modify the packet state or forward the packet to a particular port. The OpenFlow protocol [12], a widely used set of SDN specifications, allows actions against port identifiers and up to four protocols. Fig. 2 shows the action types available in OpenFlow, which are used programmatically via the controller to create complex flows that prioritizes traffic accordingly.

B. Remote Network Control

In the traditional SDN architecture, a message bus between the controller and the switch is assumed to be present, such that packets not matching any existing flows can be forwarded to the controller for a forwarding decision. While this may not be an issue in a wired environment, with a reliable network

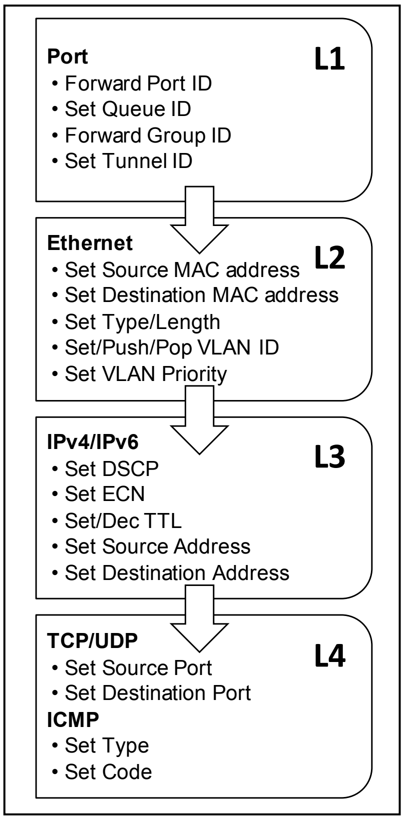

Figure 2. Available OpenFlow SDN action types

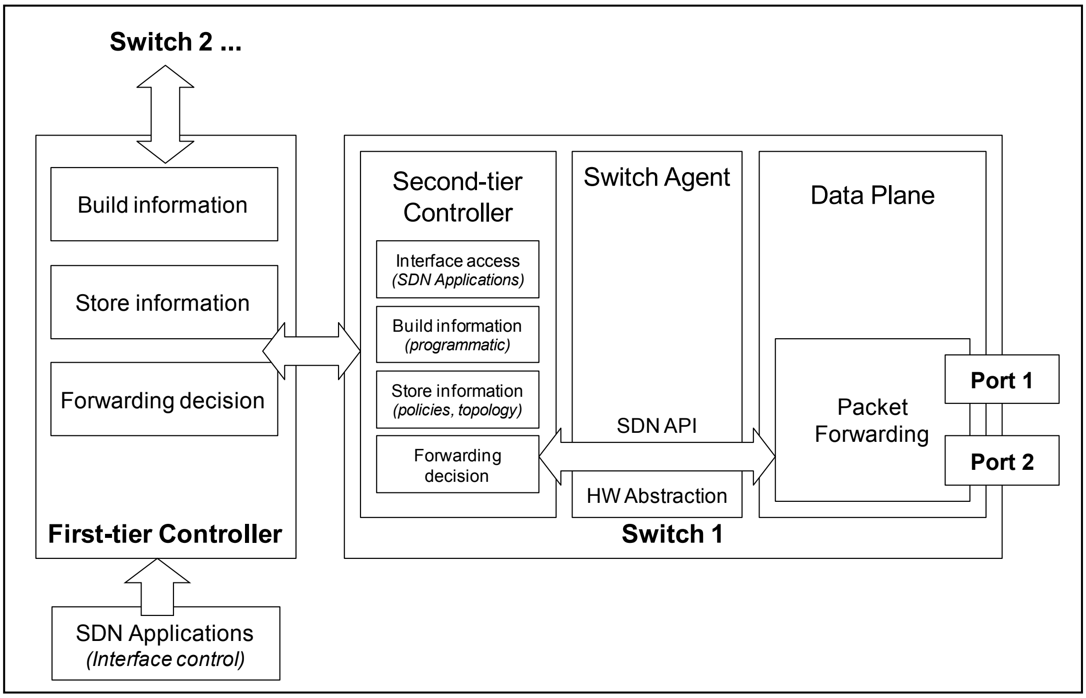

Figure 3. Proposed hierarchical SDN architecture

connection where a static route to the controller can be programmed, wireless environments pose connectivity challenges especially in military and emergency operations. Fig. 3 presents our hierarchical SDN architecture, where the local (second-tier) controller is responsible for determining a configuration state based on information available to the device. When backhaul connectivity is available, the second-tier controller is synchronizing its configuration state with the first-tier controller at the control centre. With information gathered from all local controllers, the first-tier controller is able to determine the entire network topology even in highly dynamic environments, and update each second-tier controller of changes and policy updates programmed by network managers from control centre.

C. *Multiple Radio Integration*

In addition to the traditional SDN roles, the second-tier controller manages a set of SDN applications that control the network interfaces available on the device (*Interface access applications* in Fig. 3). This allows a large degree of flexibility in terms of network connectivity. New radio interfaces can be added, and may be configured remotely from control centre by uploading the corresponding SDN control application. The second-tier controller periodically verifies the radio conditions and switches to the radio interface with the best connectivity. This change is transparent to applications and services running in the network.

IV. FEASIBILITY

To study the feasibility of using software defined networking for wireless communications, we have built a prototype designed to be used as a programmable backhaul access device in emergency situations, while at the same time providing user GPS location data to a control centre. We use Wi-Fi and 3G mobile broadband for backhaul as proof-of-concept, but we plan adding satellite network connectivity, and South Australia's government radio network, after the completion of its current upgrade that adds data services.

Our prototype is based on a low-cost ARM micro-controller that integrates a system-on-a-chip with one Ethernet controller and three USB expansion ports that are used for connecting radio interfaces. Currently, our prototype uses one Wi-Fi USB adapter (802.11n 150Mbit/s), one 3G USB adapter (UMTS 7.2Mbit/s) and one DigiMesh [13] radio receiver. The Ethernet port is used for connecting to a local network, the Wi-Fi and broadband are for backhaul, and the DigiMesh receiver receives location information from multiple GPS-enabled transmitters that are carried by users in the field. The prototype's primary role is to forward traffic between its different network interfaces, and provide an SDN-compatible abstract layer to allow programmability. This is achieved by running Open vSwitch [14] (OVS), an SDN-capable virtual multi-layer software switch with programmatic extensions. The OpenFlow SDN interface in OVS is accessed through RYU [15], an open-source SDN framework. A diagram containing the software components in our prototype is shown in Fig. 4. In addition to being an OpenFlow controller, RYU provides an API that can be used to create SDN applications. We have implemented a policy-based interface switching algorithm as an SDN application (simple_switch app), which works by selecting for backhaul the interface that is estimated to provide the highest available data throughput.

Estimating throughput is a difficult problem, as it usually requires measuring the time it takes to transfer a large amount

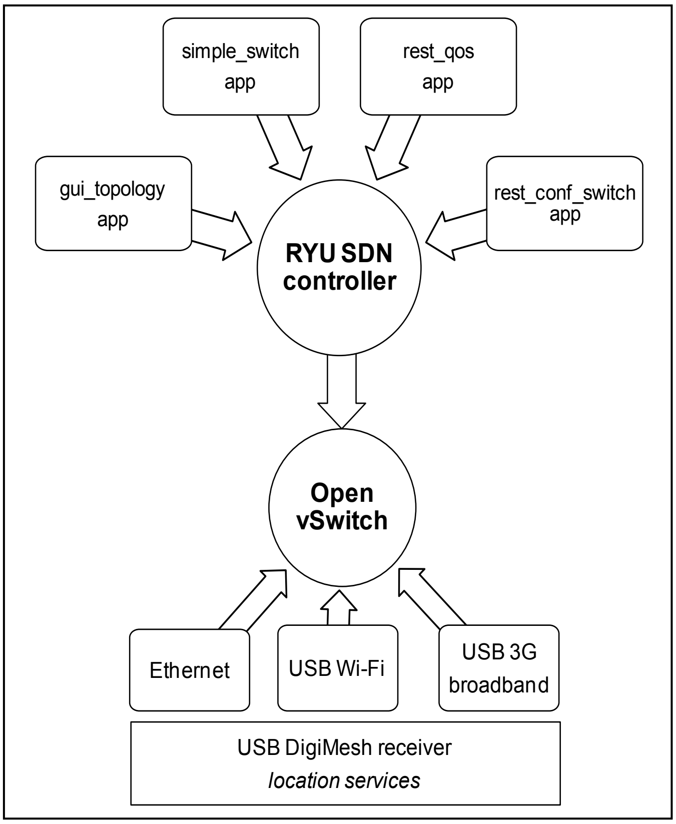

Figure 4. Prototype radio integration unit software components

of data, and averaging by the amount of data transferred. However, this method is not efficient in out use case, for two main reasons. Firstly, for emergency situations in remote areas network coverage is problematic and data speeds are low. Thus, transferring large amounts of traffic can be both expensive and take a large amount of time. Secondly, radio conditions and therefore data throughput are highly dynamic, and throughput estimation needs to accurately reflect this environment. To mediate the above constraints, we are using an algorithm that measures the highest theoretical throughput achievable by each interface, which is sufficient for a comparison that determines the best radio adapter for backhaul. The algorithm runs every ten seconds for each interface, and is based on the average instantaneous round-trip-time (RTT) for three data packets. If the interface is connected, the algorithm looks if the signal strength is above a certain threshold. The signal strength SS is determined by the RSSI (Received Signal Strength Indication for 3G broadband) and by the Link Quality LQ, Signal Level SL and Noise Level NL (for Wi-Fi), using the formula:

$$SS = LQ * SL/100 - NL$$

Next, three control packets are sent to the control centre server, and the RTT averaged. The interface maximum throughput is determined by the mobile adapter class level, for 3G broadband, and by the reported connection bit-rate, for Wi-Fi. Lastly, the throughput is determined using the formula:

$$Througput \leq \frac{RWIN}{RTT}$$

where RWIN is the TCP Receive Window (we are using the maximum size for the Linux operating system, 65,535 bytes) and RTT is the average round-trip-time calculated above.

In addition to the required SDN functionality, our RYU application is used to monitor connection status for all network interfaces (gui_topology app), modify routing behaviour (rest_conf_switch app), and implement specific quality-of-service requirements (rest_qos app), according to the policies specified by a network manager. Policies and configuration changes can be defined directly on the prototype, through a web-interface that is implemented as another SDN application, or remotely from the control centre, through the SDN API that exposed as a REST web service.

V. RELATED WORK

Most of the current SDN architectures rely on a centralized control mechanism that is ill-suited to the level of decentralisation, disruption and delay that is present in the wireless environments for emergency operations. Previous works have explored the use of SDN in wireless networks, for example OpenRoads [16] has been deployed in the campus of Standford Univesity to integrate WiMax and Wi-Fi access points, and Odin [17] has been used to simplify client management in WLAN. Our recent work has investigated the application of SDN in optimizing wireless ad-hoc networks [18]. There are also other SDN wireless applications that do not use Wi-Fi, such as the PhoneNet [19] infrastructure, which supports group communications among phones, and OpenRadio [20], a design for programmable wireless network data plane to automate software update. Thus far, no one has explored the challenges and benefits offered by SDN in heterogeneous environments with multiple radio network technologies and policies, as highlighted [21] in recent reviews.

VI. CONCLUSIONS

Achieving scalability in emergency operations communications poses multiple challenges that can be mitigated by traffic prioritization, remote network control and multiple radio integration. We have proposed a two-tier hierarchical framework that uses software defined networking to create a scalable communication network. We have shown this approach is feasible using a prototype backhaul access device that can be programmed over the network and can switch between multiple connections based on the estimated highest available throughput.

Military communications challenges share many of the characteristics of emergency operations. Environmental and operational requirements are generally dynamic, demanding the use of multiple means of communication. Perhaps one of the most significant challenges facing military communications is the need for enhanced agility between bearers, waveforms and networks where the processing burden has been shifted from human operators to software. Combining the advantages of SDR with SDN to achieve this desired level of agility holds great promise for meeting the often-stated requirement for seamless interoperability across diverse technologies.

ACKNOWLEDGMENTS

This work was supported by the Australian Research Council through grant LP140100489. We would like to thank Matthew Britton, from the Centre for Defence Communications and Information Networking, The University of Adelaide, and Sanjeev Naguleswaran, from QSPectral Systems Pty Ltd., for the help and support offered in this work.

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