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Using OpenFlow to control redundant paths in wireless networks

Elias Molina, Eduardo Jacob and Armando Astarloa

Department of Communications Engineering,

University of the Basque Country UPV/EHU, Spain

Tel: (+34) 946 014 214   E-mail: elias.molina@ehu.eus

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Abstract

The deployment of wireless networks in critical industrial environments must ensure the availability of monitoring and control applications, for which it is essential to exploit redundancy techniques. In order to reduce to zero the failover time, in this paper, the Parallel Redundancy Protocol (PRP) is used in Wireless Local Area Networks (WLAN) which are implemented under the Software-Defined Networking (SDN) paradigm. It is discussed how the OpenFlow protocol allows an external controller to configure redundant paths between dual-homed devices. As a result, critical services can be protected in interference and mobility situations. The improvement in availability has been obtained by using both emulation and simulation.

Keywords: OpenFlow, Parallel Redundancy Protocol, Software-Defined Networking, Wireless automation.

1 Introduction

Despite the fact that wireless technologies have been proposed for automation systems from 1988 [1], existing infrared technologies posed significant problems to be overcome in these environments. Therefore, industrial networks have traditionally used wired communications for transmission of critical information. However, as identified in [2], it emerges the need for wireless monitoring and control systems, which reduce installation and maintenance costs compared to wired ones. Moreover, these scenarios more frequently require the interconnection of mobile nodes, as well as rapid network deployment and configuration. Consequently, wireless networks are an appropriate solution. In particular, IEEE 802.11-based Wireless Local Area Networks (WLAN) are analyzed in this paper.

Although wireless links suffer from unreliable data transmission due to non-deterministic factors, these networks have to ensure continuity of operations, so that availability and performance are not affected. Wireless automation requirements are specified in IEC 62657-1, differentiating them according to the applications critically. Numerous time-sensitive environments, such as Smart Grid or transportation systems, require minimal latency and loss of information. For example, communications in power delivery systems are defined in the IEC 61850 standard, which also specifies network requirements for substation automation. In particular, the maximum allowed recovery time is defined in the IEC 61850-5 specification [3], requiring no interruption of critical services, such as, for example, to provide teleprotection commands, or implement inter-tripping between circuit breakers.

To achieve these objectives, networks must have redundant components and be able to restore communications in the event of a network failure. Unlike the case of standby redundancy, in which traffic is switched to backup resources when necessary, the spatial redundancy can be exploited by using n-casting. That is, to simultaneously duplicate a flow through different paths. In this way, PRP (IEC 62439-3 [4]) nodes transmit multiple copies of data along two different routes, avoiding retransmissions and improving reliability. Taking into account that PRP does not specify how to compute routes, in this paper, the use of OpenFlow for configuring redundant flows in WLAN is proposed. According to the SDN paradigm, OpenFlow separates the control and data planes. Thus, the proposed solution benefits takes advantage of using an external agent having a global view of the network status to flexibly assign resources to different services.

This work is an extended version of [5], including a thorough review of wireless technologies used for industrial automation. The remainder of the paper is structured as follows: characteristics of PRP are outlined in Section 2; Section 3 explores the opportunities of wireless networks in critical systems. The OpenFlow specification is described in Section 4, whereas Section 5 details the proposal. The technical implementation and results are presented in Section 6. Finally, Section 7 contains conclusions and future work.

2 Parallel Redundancy Protocol

PRP is implemented in the end hosts themselves, which are called Double Attached Nodes (DAN, see Fig. 1). A DAN is connected to two independent LAN through interfaces with the same MAC address. According to the specification, these networks must be identical in protocol at the MAC-LLC level, but may have different topologies and performance. Moreover, they are PRP agnostic and can connect PRP incompatible nodes (Single Attached Nodes, SAN). Besides, these off-the-shelf devices can be attached to PRP proxies (RedBox), which do redundantly connect to both networks.

A DAN includes a Link Redundancy Entity (LRE), which generates multicast supervision frames and manages the duplication of Layer 2 traffic, as shown in Algorithms 1 and 2. Each frame is extended by a so-called Redundancy Control Trailer (RCT) that is used to discard duplicates. It includes:

1. a sequence number,
2. a label that identifies the LAN to which send the frame, and
3. the size of the Link Service Data Unit (LSDU) [4].

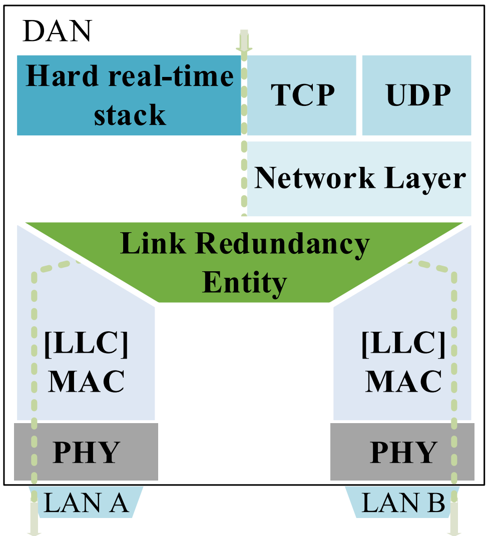

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Figure 1: Scheme of a PRP device [4].

while *true* **do**
  send a multicast supervision frame;
  for *every datagram received from upper layers* **do**
    create two frames by adding an RCT with the same sequence number and size field;
    calculate a new checksum per frame;
    send out the frames through its both ports at the same time;
  end
end

Algorithm 1: PRP sender node operation

while *true* **do**
  receive multicast supervision frames;
  for *every frame received on one of the two ports* **do**
    check if the frame is a duplicate or not (MAC source address and sequence number);
  end
  if *yes* **then**
    discard the duplicate;
  else
    remove the RCT;
    transparently forward the received frame to its upper layers;
  end
end

Algorithm 2: PRP receiver node operation

Although PRP was initially targeted to be used in wired Ethernet deployments, this paper studies the combination of PRP in IEEE 802.11 networks in order to use monitoring and control devices with redundant wireless interfaces.

3 Related work: wireless technologies in industrial automation systems

Willing et al. [6] analyzed how mature wireless technologies, including IEEE 802.11, 802.15.1 or 802.15.4 standards, can be applied in industrial applications through robust network designs in error-prone channels. In the case of the aforementioned Smart Grid applications, the opportunities posed by wireless sensor networks are assessed in [2], which describes technical challenges, such as ensuring a certain latency or Quality of Service (QoS). These challenges are associated with changes in the topology and connectivity due to the conditions of the physical layer. The propagation loss in power substations is also obtained in [2].

There are emerging wireless standards focused on providing industrial-grade reliability, such as WirelessHART (IEC 62591), ISA100.11a (IEC 62734) or WIA-PA (IEC 62601). They are based on the IEEE 802.15.4e Media Access Control (MAC) layer, which uses Time slotted Channel Hopping (TSCH) to provide reliable communication and deterministic latency. TSCH combines multi-channel TDMA (Time Division Multiple Access) with a very low cycle time, and frequency hopping. In addition, WirelessHART provides a reliable, connectionless transport service, whereas ISA100.11a supports unacknowledged and acknowledged services, and retry mechanisms to assure end-to-end delivery of messages based on UDP/IPv6. ISA100.11a is also capable of running TCP for non-real-time communications.

Furthermore, with the aim of increasing redundancy, diversity and, hence, reliability they are mainly used in inherently redundant mesh networks. Moreover, the ISA100.11a standard includes the *duocast* feature, which allows a device to send packets to multiple access points and receive acknowledgements in the same time slot. In [7], the advantages of *duocast* are applied to industrial plants.

These technologies are used at the sensor/actuator level for monitoring and automation applications. Therefore, all of them are aimed at short-distance (about 10 m) Wireless Sensor and Personal Area Networks. They can only achieve a low-data rate and, besides, they are not directly interoperable with Ethernet. As stated in [8], these issues can be overcome by using IEEE 802.11. On the one hand, regarding the interoperability of Ethernet and Wi-Fi networks in industrial environments, Reference [8] studies hybrid designs where link-layer frames are transmitted from wired backbones to the wireless channels and vice versa. On the other hand, unlike the carrier sense multiple access with collision avoidance (CSMA/CA) technique, the polling-based mechanism of IEEE 802.11, offers predictable communications and achieves shorter packet delay. This Controlled Channel Access (CCA) is based on the original Point Coordination Function (PCF) and “matches the requirements for automating various smart grid applications” [9]. In particular, the authors of [10] evaluated the latency of messages defined by the IEC 61850 standard in IEEE 802.11g networks, under interference levels previously characterized at different substations and scenarios. They “demonstrate suitability of an industrial WLAN for some innovative smart-distribution substation applications” [10].

There have also been proposals to integrate Real-Time Ethernet protocols into IEEE 802.11 networks by means of a scheduling function carried out by a managing node. For example, Ethernet Powerlink is used in [11] and a proprietary extension to PCF based on PROFINET IO (“Industrial PCF” developed by Siemens) is studied in [12].

3.1 Redundant paths in Industrial WLAN

Although IEEE 802.11 is not used in [13–15], they show the benefits of adopting redundancy in industrial wireless plants. Reference [13] decreases the failure probability by performing retransmissions that use different independent antenna and channels. Authors assume that the receivers may be responsible for processing multiple copies of the same packet. Re-

InForM [14] establishes multiple redundant paths, for which nodes have to be aware of the network topology and status. Diverse information (eg, desired reliability, channel quality and number of hops needed to reach destination) is added to the data packets, and it is needed to determine the transmission paths. Due to low-latency constraints, this approach is hardly applicable to industrial control systems. Moreover, despite reducing throughput, one of the benefits of sending redundant packets along multiple paths is not only avoiding retransmission, but also providing lower delay, which has been demonstrated in [15].

In order to improve the availability of services in IEC 61850-based substations, Reference [12] proposes the use of devices with wired and wireless interfaces, so that, although the wireless connection provides lower performance, it is valid as a backup mechanism. Also, recent researches have proposed the use of PRP in WLAN with the aim of increasing network resilience. Rentschler et al. propose in [16] to communicate two PRP nodes via two different channels, which operate as point-to-point links. As a result, lower error rate, latency and jitter are obtained. With the same approach, in paper [17] sending redundant frames is optimized with the addition of control messages, which prevent the transmission over lossy and erroneous channels.

These studies demonstrate the advantages of combining PRP and WLAN in applications with demanding availability requirements. However, point-to-multipoint connections and mobility scenarios have not been analyzed. Moreover, none of the above proposals is focused on the network management; while in this study OpenFlow is proposed as control mechanism.

4 OpenFlow as a wireless control protocol

This section provides an overview of the OpenFlow protocol [18], which allows a controller to control the forwarding paths in a network. Thus, the controller add rules to the forwarding tables of switches. These rules are defined by packet headers, input ports, priorities and instructions associated with each input flow.

Route computation in a centralized way by an OpenFlow controller is similar to the *Network Manager* used in ISA100.11a, WirelessHART and 6TiSCH [19]; although the latter also supports distributed and hybrid approaches. The *Network Manager* is certainly the main component of those architectures and is responsible for configuring the network resources and managing routing between devices. “Thanks to the centralized approach, field device complexity is kept low” [20]. Similarly, the OpenFlow controller is able to create, by using a common control interface, redundant paths based on the network status and information received from the network devices.

Regarding the failover capability of an OpenFlow network, the authors of [21] summarized different approaches that make these networks more robust, such as using multiple controllers, backup forwarding rules, as well as delegating the failure detection to the network devices. Taking advantage of the programmability provided by SDN technologies, previous work [22] proposes to use this paradigm in IEC 61850-based systems in order to implement QoS, traffic filtering, load balancing, etcetera.

In relation to the object of study, SDN is being proposed [23] to transparently manage hybrid networks, where wireless and wired systems interact. Also, Reference [24] uses OpenFlow for the mobility management in Wireless Mesh Networks. The OpenRoads project [25] uses OpenFlow to actively establish redundant wireless links, whether under Wi-Fi and WiMAX technology, achieving an uninterrupted communication in roaming situations. The detection and removal of duplicate packets by the receiver is performed by a Linux kernel module (*nf_mobility*). This module provides a sequence number for connection (based on the 5-tuple: protocol, source and destination IP addresses and TCP/UDP ports). However, this method, in contrast to PRP, is not compatible with those protocols that send data directly into lower layers; as occurs, for example, in the services defined by the IEC 61850 standard: GOOSE and SV. They both transport critical information and are mapped directly on Layer 2 frames.

The combination of PRP and the OpenFlow protocol has been proposed in a previous work [26]. This paper aimed to improve the performance offered by traditional networks to which the PRP nodes are connected, which are generally based on spanning tree protocols, such as RSTP (IEEE 802.1 D). For example, multiple network failures are supported by establishing more than two paths on the same network, which is not feasible under spanning tree protocols. However, it is necessary to study the benefits that this combination can offer to wireless networks, where connections are more susceptible to interference.

5 A proposal for managing redundant wireless links

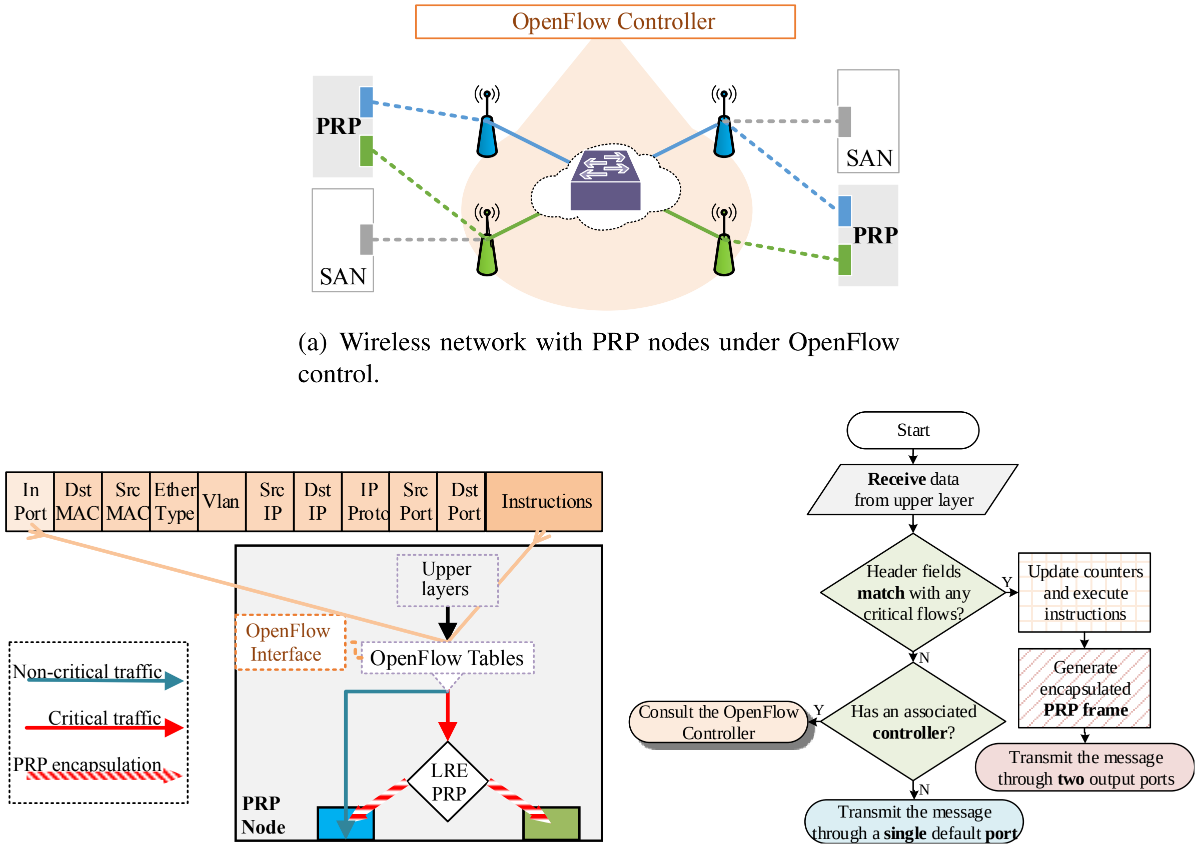
In the proposed solution, end nodes are redundantly connected to one or several access points, and an OpenFlow controller establishes the forwarding rules in the networking devices (Fig. 2(a)). Additionally, end nodes also include an OpenFlow pipeline that allows them to distinguish data flows. Thus, end-to-end redundancy provisioning is based on traffic criticality. That is to say, unlike for non-critical traffic, parallel routes between sender and receiver nodes are established for those frames that require very high availability. Therefore, the network control plane is aware of the needs of PRP nodes, unlike what happens in traditional networks.

5.1 Traffic filtering policies in PRP nodes

This proposal enables the possibility of using the PRP protocol as needed, which optimizes available resources. Traffic control in the end nodes is based on priority policies, that is, critical services will be protected with the PRP frame format; while services that tolerate communication disruptions will be transmitted without PRP encapsulation through one of the available interfaces. For example, some of the entries configured on a node PRP could include:

```
{"OpenFlow switch": {
  "id": "prp1",
  "entries": [
   {"dl_type":"0x88b8","actions":"output:lre_prp"},
   {"in_port":"prp1-eth0","dl_type":"0x88b8","actions":"output:lre_prp"},
   {"in_port":"prp1-eth1","dl_type":"0x88b8","actions":"output:lre_prp"},
   {"dl_type":"0x0800","nw_dst":"192.168.60.2",
    "nw_proto":"17","tp_dst":161,"actions":"output:prp1-eth0"}]}}
```

Specifically, the first rule determines that the incoming traffic with Ethertype *0x88b8*, corresponding to GOOSE frames, will be forwarded to the inner port *lre_prp*, which will append an RCT trailer to the frames and send them to the physical interfaces *prp1-eth0* and *prp1-eth1* (the following two rules set up the reverse path). On the other hand, the last rule determines that the UDP traffic, with IP destination address *192.168.60.2* and destination port *161*, will be directly forwarded by the *prp1-eth0* port.



(a) Wireless network with PRP nodes under OpenFlow control.

(b) PRP node with traffic filtering based on OpenFlow.

(c) Processing of PRP and OpenFlow node.

Figure 2: Combination of PRP and OpenFlow technologies in wireless networks.

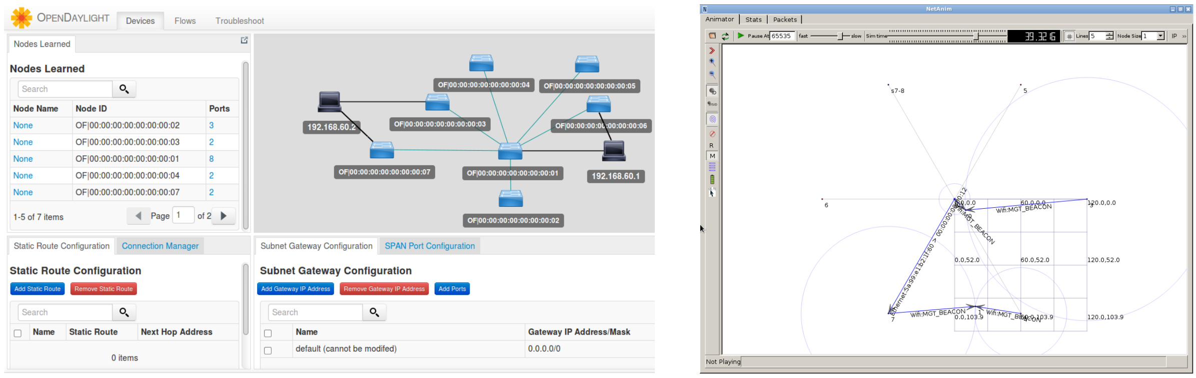
Fig. 2(b) and 2(c) represent the data-flow processing in PRP nodes, along with match fields that may serve to distinguish critical and non-critical traffic. Although these policies are installed by using OpenFlow messages, the end nodes may be beyond the control of the Controller.

6 Simulation results

6.1 Technical implementation

Various open-source software projects have been used in the validation:

- OpenDaylight has been used as OpenFlow controller. It is responsible for device and network topology discovery, route calculation and loop prevention.
- Open vSwitch (OVS) [27] has been used as OpenFlow networking device (wireless access points and switches). Furthermore, OVS is also incorporated in the PRP nodes for filtering flows.
- End nodes use a software implementation of PRP stack, which runs in the Linux user space.
- The OpenNet [28] simulation tool adds functionalities of the ns-3 simulator to the Mininet emulator. As a result, wireless connections and mobile nodes can be evaluated.



(a) OpenDaylight GUI. (b) NetAnim visualization tool.

Figure 3: Tools used in the emulation process.

Fig. 3 shows two graphical user interfaces used in the testbed: *a*) The OpenDaylight management application, which displays the network topology, information about the discovered devices and the installed flow rules. *b*) The NetAnim tool shows the transmitted frames and the movement of the nodes within the network, which allows us to carry out a further analysis.

With respect to the testbed configuration, the results presented here are obtained using the following topology and network conditions:

- Using 802.11g transmission standard, which operates in the 2.4 GHz band and at 22 Mbit/s average throughput.
- The channel assignment scheme allows two wireless interfaces of PRP nodes to operate on different channels. The frequency diversity would increase if the nodes worked in different bands, eg, 2.4 GHz and 5 GHz.
- Wireless nodes operate in an infrastructure mode served by several access points, which are star-wired to a distribution network through 100 Mbit/s full-duplex interfaces, without any additional delay.
- The OpenFlow control traffic is transmitted over an out-of-band configuration.

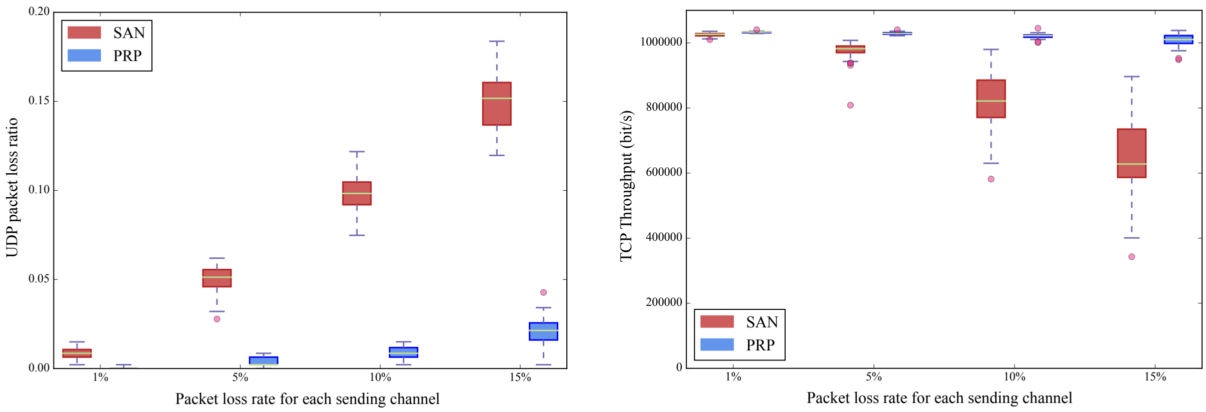
Next, two study cases show how employing parallel connections increases the successful communication probability.

6.2 Higher robustness against packet loss

As mentioned before, PRP ensures that no messages are lost if one of the two established paths fails, avoiding downtime. This does not depend on using OpenFlow, but it corresponds to the overall availability of parallel systems, as in (1):

$$A_p = 1 - \prod_{i=1}^{N} (1 - A_i) \tag{1}$$

The unavailability ($U = 1 - A$, $U \in [0, 1]$) of subsystems is directly associated with the overall packet loss rate. Therefore, a PRP system reduces such rate with respect to a non-redundant



(a) Packet-loss robustness. (b) TCP Throughput.

Figure 4: Influence of lossy wireless links on reliable and unreliable transport protocols.

system. For a parallel chain with unavailability q_1 and q_2,

$$U_{non-redundant} = q_1 \geq U_{parallel} = q_1 * q_2 \tag{2}$$

To show the robustness against interference, the availability of a service is studied when the probability of packet loss is the same (statistically independent) for each wireless link which a node PRP is connected to. Fig. 4(a) plots a comparison of the packet-loss robustness for a SAN and a DAN. Tests have been conducted with UDP traffic (unreliable transport protocol) under different packet loss rates.

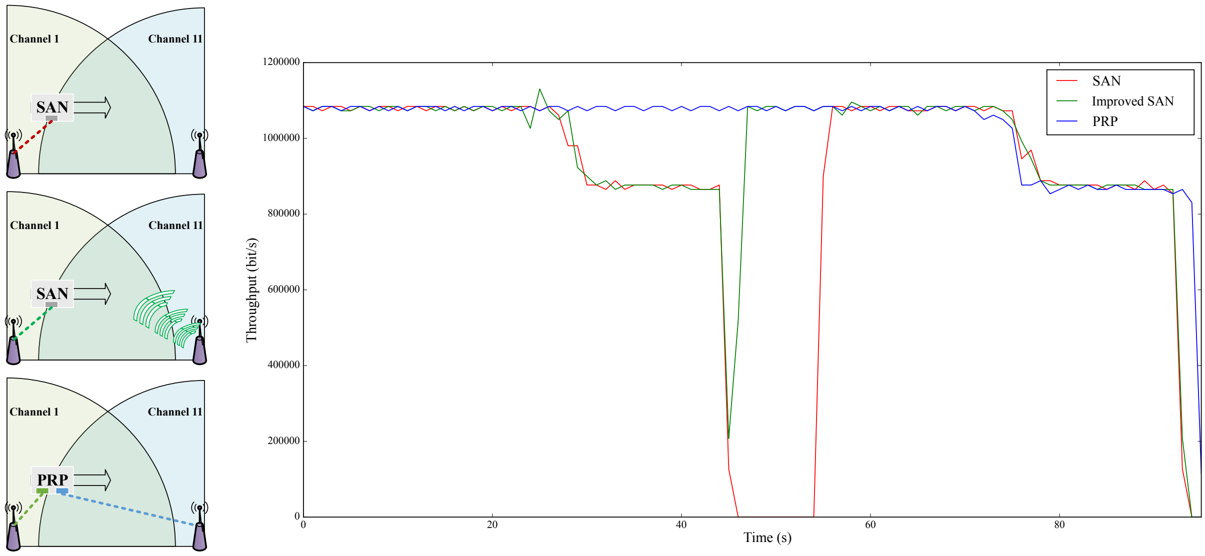
To highlight the increase in the availability of TCP services (reliable transport protocol), Fig. 4(b) shows the throughput of a TCP connection, limited to 1.05 Mbit/s by the sender. Box plots including minimum, first quartile, median, third quartile and maximum value correspond to 30 samples from which information is collected for 10 seconds using the *Iperf* tool.

6.3 Seamless roaming

This experiment illustrates the continuity of service during a handover process when simultaneous connections are established to different access points. As discussed in [29], the OpenFlow/SDN technologies can optimize the provision of resources based upon predicting handover occurrences. Therefore, it is also considered the possibility of proactively transmitting data before a change in the end node/access point connection. However, the scanning and connection processes involves, in any case except when using PRP, a communication interruption, as shown in Fig. 5(b). It is necessary to note that OpenNet does not yet support IEEE 802.11r Fast Roaming or prescan mechanisms that selects new access points before disconnection of current link to further shorten handover latency [28]. Particularly, Fig. 5(a) represents three cases, in which a node receiving UDP traffic moves between two access points operating in different 802.11g channels.

1. Node with a single interface (SAN):

   (a) The controller installs OpenFlow rules in the network elements so they operate as a traditional learning switches. This implies that a longer recovery time is seen, since



(a) Study cases. (b) UDP throughput.

Figure 5: Node connectivity in an access point roaming scenario.

the controller has to react to the data in a different link with the installation of new rules and changing or deleting the old ones.

(b) The controller installs rules in the network elements so that the traffic is redundantly forwarded to the destination node by the access points in order to reduce the interruption period.

2. Node with two interfaces (DAN) connected to two access points between which it moves. Thus, the node remains connected at all times, until it is out of range.

These three examples also serve to represent that one node supports the simultaneous transmission of PRP encapsulated and non-encapsulated frames, depending on the criticality of the data and network status. This means that, in non-critical flows, there is no longer a need for duplicating frames.

7 Conclusions

Despite being in an early stage, wireless solutions offer numerous advantages for the industry automation, such as rapid deployment and enabling mobile nodes. On the other hand, there are numerous applications that demand high available topologies. Taking into account that PRP provides a high level of failure tolerance, this paper examines the benefits obtained in IEEE 802.11 networks in which nodes are redundantly connected, and whose traffic is controlled via OpenFlow. In addition, PRP nodes include forwarding rules to differentiate flows requiring active protection from those which do not. In particular, robustness of parallel systems is analyzed, even in mobile environments where critical data can be transmitted without dropping frames.

With regard to future research, it would be interesting to analyze the performance on IEEE 802.11s mesh networks, and considering QoS extensions, as well as to assess the impact of the control traffic on network performance.

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