Combining In-band SDN and Wireless Mesh Networks for Internet Provisioning in Rural Areas

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***Abstract*—This paper presents a novel solution to bridging the digital divide in remote areas by integrating Software-Defined Networking (SDN) with wireless mesh networks. This approach leverages the flexibility and scalability of mesh networks, along with the efficient control and traffic management capabilities of open-source SDN, to provide a cost-effective solution for Internet provisioning. In our solution, the APs (i.e., mesh nodes), which connect each other via wireless mesh, are SDN-capable and connected to the SND controller via in-band connections (i.e., sharing infrastructure with data transmission). Unlike traditional methods such as 5G, LTE, or satellite Internet, which may not always be feasible in remote regions, this approach offers an affordable alternative. We used an emulator (i.e., mininet-wifi) and an SDN controller (i.e., POX) to build the network to demonstrate its feasibility. IEEE 802.11s wireless links are adopted for access points (APs)' wireless links and the routing and forwarding are done by a software module on POX. We created and evaluated a medium-sized network using basic transport protocols (i.e., TCP and UDP) and essential services, including VoIP and video streaming. The results confirm the effectiveness of the proposed solution.**

***Index Terms*—SDN, Mesh, Rural, Internet Provisioning**

I. INTRODUCTION

A significant portion of the global population remains unconnected to the Internet [1]–[3]. Approximately 2.7 billion people worldwide still lack Internet access, a critical issue highlighted by initiatives like the Connecting the Unconnected Summit in 2022. This digital divide is particularly severe in rural areas, where limited connectivity exacerbates challenges such as long commutes for children attending school. Addressing this issue requires a cost-effective, efficient, and scalable network solution. While wired networks, LTE, and 5G are potential candidates for network expansion, their deployment costs and potential revenues often hinder or slow down progress. Cellular networks, though widespread, still face coverage challenges in difficult terrains due to high infrastructure costs. Similarly, while satellite Internet can reach remote locations, it comes with high operational costs. Low-cost, widely available commodity hardware like Bluetooth and Wi-Fi are limited to short-range, low-throughput applications, making them unsuitable for broader Internet services.

This work addresses the limitations of existing rural Internet access solutions by exploiting Software-Defined Networking (SDN) and wireless mesh networks, aiming to offer a flexible, scalable, and cost-effective solution for remote regions. Wireless mesh networks (IEEE 802.11s), utilizing readily available hardware and unlicensed frequency bands, provide a practical and economical foundation for rural connectivity. Their decentralized architecture and self-healing capabilities make them ideal for areas with limited or expensive traditional infrastructure. SDN, a paradigm that decouples the control plane from the data plane, enables centralized management and dynamic network optimization [4]. By combining these technologies, we aim to create a robust and adaptable network that can meet the evolving connectivity needs of rural communities.

Previous research has identified the potential benefits and current limitations of SDN integration in wireless mesh networks [5], [6]. This work advances these findings by combining SDN with wireless mesh networks to create a new SDN wireless mesh. The proposed system establishes wireless links (using IEEE 802.11s) between access points (APs), which provide connections to nearby stations, similar to standard Wi-Fi. In this setup, the APs function as SDN data planes controlled by an SDN controller that manages traffic flows over the mesh network. The controller's ability to handle complex instructions and programmable network configurations further enhances the network's performance and reliability. We use an in-band solution to maintain communication between the data planes and the control plane (i.e., the OpenFlow channel). More specifically, the controller only needs to directly connect to one device (or data plane), on which we use TCP forking to redirect the TCP connection of the OpenFlow channels between other devices and the controller.

We use mininet-wifi [7] and POX controller [8] to build the conceptual network. While the former creates wireless links and data planes (i.e., APs), the latter has discovery and forwarding modules to guarantee TCP/IP communication on the networks. We then evaluate the performance of transport protocols (i.e., TCP and UDP) and essential services (i.e., VoIP and video streaming) in an assumed Internet provision scenario with different network conditions. The evaluation shows that under normal and low loss rate conditions, the network can provide sufficient TCP and UDP throughput and guarantee the performance of VoIP and video streaming. Under severe conditions, the network must be improved to efficiently

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provide Internet services.

The remainder of this paper is as follows. Section II introduces related research. Section III provides the methodology. Section IV presents the comparison results. Finally, Section V concludes the paper.

II. RELATED WORK

Fusing SDN with mesh networks presents transformative possibilities for enhancing connectivity in remote areas. Rademacher et al. (2017) provide a comprehensive review of the state and challenges of SDN, emphasizing the flexibility and management benefits SDN brings to traditional mesh network architectures [5]. Similarly, Gilani et al. (2020) discuss SDNMesh, an SDN-based routing architecture tailored for mesh networks, showcasing improvements in network management and scalability [6]. While Rademacher explores the integration of SDN with traditional mesh network architectures, the in-band SDN mesh network approach developed in this study advances this concept by specifically tailoring SDN's dynamic management capabilities directly within the mesh topology. This allows for flexibility and real-time resource optimization, which is essential for maintaining robust connectivity in remote, infrastructure-scarce areas.

The potential of SDN to enable rural connectivity has been increasingly recognized. Hasan et al. (2012) explore how SDN can bridge the connectivity gap in underserved areas, offering a scalable and cost-effective solution to extend network services [9]. Building on this, the in-band SDN mesh network utilizes the centralized control of SDN to manage decentralized mesh networks, reducing operational costs and enhancing scalability without requiring extensive physical infrastructure. This approach provides a cost-effective method to extend high-quality internet access into rural regions, leveraging SDN to minimize the complexity and cost typically associated with expanding traditional network infrastructures. The work by Chafla Altamirano et al. (2022) further investigates a QoS-aware network self-management architecture based on SDN for remote areas, highlighting the adaptability of SDN in diverse and challenging environments [10].

Practical evaluations of SDN controllers and their performance in network setups are crucial for real-world applications. Noman and Jasim (2020) evaluate the POX controller and OpenFlow protocol using the Mininet emulator, providing insights into SDN's performance bottlenecks and operational efficiencies in controlled environments [8]. This is complemented by the work of Patel et al. (2022), who discuss the implementation of an SDN network using the POX controller, emphasizing its effectiveness in network management and configuration flexibility [11].

In contrast to the discussed related works, the in-band SDN mesh network provides a unique solution for internet provisioning in remote areas. It not only harnesses the strengths of SDN for dynamic network management and scalability but also optimizes these features within a mesh network framework for enhanced reliability and cost efficiency. This makes it an ideal approach for extending internet connectivity to rural and remote areas, where traditional methods may falter due to logistical and economic constraints.

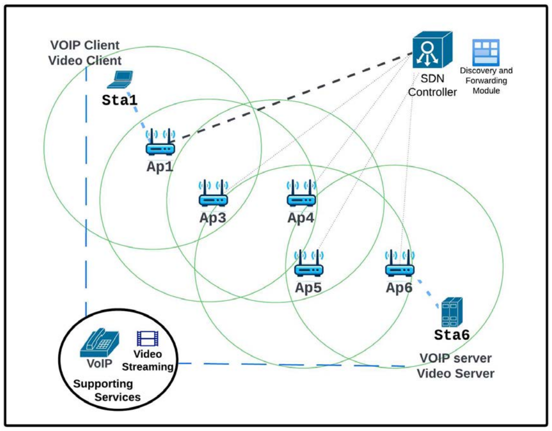
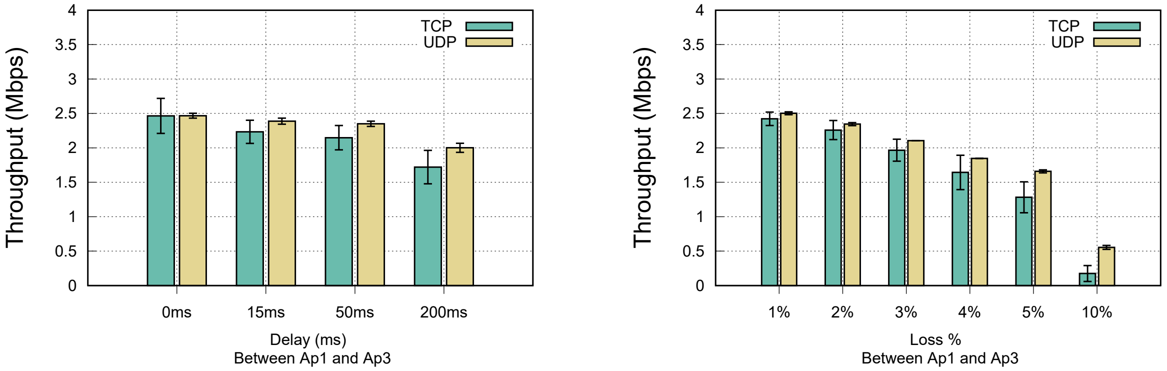


Fig. 1: Combining SDN and Wireless Mesh Networks

III. METHODS

This section introduces our methodology for building the SDN-based wireless mesh network to provide Internet connectivity in remote areas. The conceptual network is shown in Fig. 1, which shows a client (i.e., Sta1) using Internet services running on a server (i.e., Sta6). An example of our solution in practice is as follows. When families move into a remote community, a new node, represented by an AP, is assigned to that area. This AP becomes part of the mesh network, extending the network's reach. The family or individuals in that area become stations connected to the network, allowing them access to Internet services. SDN (or OpenFlow), which decouples the control plane from the data plane of a network device, enables dynamicity and programmability on the network. Note that SDN was originally designed for wired networks; hence, data planes are normally called SDN switched. In our networking solution, the SDN data plane is extended to be applied to access points. This adaptation is significant as it extends the benefits of SDN to wireless networks, which are typically more complex than wired ones.

The access points serve as a backbone for the constructed network, which extends the Internet connection. More specifically, the network's physical and data link layers are based on the IEEE 802.11s mesh standard for the wireless links between APs and other IEEE 802.11 for AP-station connections. The stations, which include end-user devices such as laptops and smartphones, need no modification to connect to the nearest AP and use Internet services. Meanwhile, the wireless APs enable IEEE 802.11s communication between APs and the service provider by forming a mesh topology. Each node on the mesh can communicate with its neighbor wirelessly to extend network coverage. This communication through mesh wireless links creates a network with multiple paths for data transmission, improving resilience and availability. The IP and upper layers in the network are managed by the SDN controller,



(a) When varying delay

(b) When varying loss

Fig. 2: UDP and TCP throughput

TABLE I: Devices and Settings

`OS`	Ubuntu 20.04.3 LTS
`Mininet-WiFi`	Version 2.6
`Openflow`	Version 1.1
`Pox Controller`	POX gar Branch

which, in principle, manages the routing, forwarding, and other related functions across the network. In our solution, we build the SDN controller's two most important software modules: discovery and routing. The discovery component identifies network devices, links (between ports of different devices), and their status. Meanwhile, the routing module learns the expected communication, for example, from a station, and then creates forwarding rules and installs them into the access points via the OpenFlow protocol.

The OpenFlow protocol operates on the OpenFlow channel, which is a secure TCP connection between the controller and data planes. Hence, in SDN, it is important to have the physical paths between the planes. The out-of-band solution (i.e., a private network for the OpenFlow channel) is not suitable in this case due to the construction and deployment costs. Hence, the in-band (i.e., running OpenFlow protocol on the same infrastructure with data communication) is adopted in this case. In our proposal, the SDN controller connects physically to one AP and logically to all APs, creating an in-band connection. The in-band approach reduces the need for extra hardware and infrastructure, making deploying and maintaining the network in remote areas more accessible.

IV. EVALUATION RESULTS

A. Settings

To build the conceptual SDN-based mesh network, we use Mininet-WiFi and the POX controller and build a network that comprises two types of nodes, five access points, and two stations, as shown in Fig. 1. In the figure, Sta1 and Sta6 act as the client and the server, respectively, aiming to simulate proximity to the closest Internet provider. On the left side of the figure, the icons represent various applications we intend to run. The network also includes two types of links between APs and STAs using WiFi, which have a throughput of 9.155 Mbps and an average delay of 1.3 ms, simulating people connected to the network with end-user devices. The mesh links between APs have a throughput of 12.54 Mbps and an average delay of 1.9 ms. We configured the designated ports to connect to POX, which has software managing the forwarding flow on the APs. More superficially, the controller has written discovery and routing modules, which can discover the available links and create routing paths on the network. The POX controller connects physically to AP1 and logically to all APs, creating an in-band connection.

We utilized popular tools (i.e., ping, iperf3) to assess network performance and the D-ITG tools to emulate the video streaming and VoIP services. We configured the parameters of D-ITG to simulate communication streams in such services for performance evaluation of video streaming and VoIP. As mentioned, we conducted tests simulating Internet provisioning for Sta1 from Sta6, as these are the furthest nodes in the network. We first present the evaluation results of iperf3 for UDP and TCP. In our experimental setup, Sta6 served as the server hosting the iperf3 and other servers. We conducted a series of ten tests, each lasting 10 seconds, to evaluate network performance under varying conditions. We configured the delay and loss on the link between access points AP1 and AP3 to emulate the changing conditions introduced into the network. The experiment settings are detailed in Table I.

B. Evaluation Results

1) TCP and UDP evaluation: The evaluation results with TCP and UDP traffic are shown in Fig. 2, where Fig. 2a, Fig. 2b contains the UDP and TCP throughput with varying delay and loss conditions, respectively. In Fig. 2a, the y-axis represents the throughput (in Mbps), and the x-axis shows the varying delay 0 (no change), 15, 50, and 200 ms to

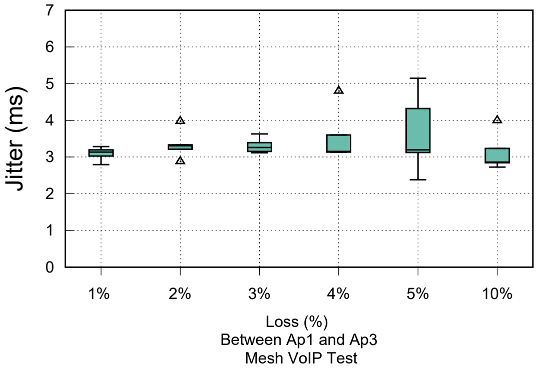


Fig. 3: VoIP's jitter under packet loss variation

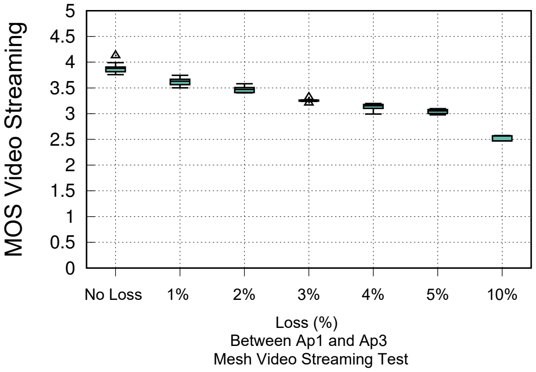


Fig. 4: Video streaming's MOS under varying packet loss

capture the fluctuation in network conditions. The green boxes represent the throughput for UDP, while the yellow boxes show the throughput for TCP. The plot shows a decrease in throughput as latency increases for both protocols, as expected. Despite the increasing delays, the throughput remains stable at approximately 2 Mbps, affirming the network's capability to support internet services under these settings. The results support the hypothesis that SDN mesh networks can be a new solution for Internet provisioning in remote areas. Figure 2b similarly shows TCP and UDP throughputs, but when the loss on the link between AP1 and AP2 changes from 1% to 10%. We can observe that the throughputs decrease when the lost rate increases. Until the rate of 5%, the network still maintains a sufficient throughput (around 1.5Mbps) for basic services. However, under the extreme case of 10% loss, the network can not function properly. Note that this condition rarely happens.

2) VoIP and video streaming evaluation:

a) VoIP Performance Evaluation:: This evaluation investigates the Voice over IP (VoIP) communications on the mesh network, detailing the effect of varying packet loss rates, from 1% to 10%, between Station 1 (Sta1) to Station 6 (Sta6). We observe the jitter metric since it quantifies the variability in packet arrival times at the receiver, essential in VoIP. Figure 3 show the results. We can see at lower packet loss percentages, ranging from 1% to 5%, the jitter values remain relatively consistent with median values near 3ms. This indicates a uniform delay pattern in packet delivery within acceptable parameters for VoIP communications. The stability in these measurements reflects the network's capability to manage VoIP traffic effectively under limited network strain. Intriguingly, the jitter exhibits reduced variability at a 10% packet loss rate. This observation can be attributed to the VoIP application's methodology of considering only successfully transmitted packets for jitter calculation. At this higher loss rate, the lower jitter measurement suggests a selective influence where packets facing delayed delivery likely do not reach completion and, thus, are not included in the jitter assessment.

b) Video Streaming Evaluation:: For video streaming, we investigate the Mean Opinion Score (MOS), a widely used metric for assessing the subjective quality of media, particularly in the context of video streaming services. It calculates the perceived quality from the users' perspective, typically scaled from 1 (worst) to 5 (best). This scoring is originally derived from user ratings collected during controlled experiments where participants are asked to evaluate the quality of video or audio samples. However, it can be calculated from the network parameters following the ITU standard [12]. Table 2 illustrates the relationship between MOS values and user satisfaction levels.

TABLE II: Relationship between MOS and user satisfaction

MOS	**User Satisfaction**
4.34	Very satisfied
4.03	Satisfied
3.60	Some users dissatisfied
3.10	Many users dissatisfied
2.58	Nearly all users dissatisfied

Figure 4 graph provides an analysis of the Mean Opinion Score (MOS) for video streaming conducted over a mesh network from Station 1 (Sta1) to Station 6 (Sta6), assessing a range from no packet loss to a 1% loss rate. Initially, with no packet loss, the MOS values exhibit a high median close to 4.5, reflecting an optimal user experience with minimal perceptible disturbances. As packet loss is introduced and increases up to 3%, the MOS demonstrates slight fluctuations but generally maintains high values above 3.5, suggesting that the video streaming quality is perceived as regular despite the onset of minor losses. However, as the packet loss rate escalates beyond 3% to 10%, there is a visible trend of declining MOS values, with the median scores descending towards 3 and lower. This decrease is more pronounced at a 10% loss rate, where the MOS drops significantly, indicating a deterioration in video quality as experienced by users. Factors contributing to this decline could include increased occurrences of buffering, reduced frame rates, and poorer resolution, all of which are more noticeable as the loss percentage rises.

V. Conclusion

This paper presents the effectiveness of leveraging SDN-based mesh networks to address the digital divide and provide internet connectivity in remote and rural areas. The networks inherit the flexibility and programmability of SDN for managing traffic flows. Moreover, they use wireless mesh to form the wireless links between different SDN-capable access points. In the network solution, we newly use an in-band connection for the SDN/OpenFlow channel between the mesh devices and the SDN controller. We realize the conceptual network by creating a network using Mininet-WiFi and the POX controller (with the necessary software). We then evaluate the network using standard TCP and UDP traffic, as well as VoIP and video streaming services. The results show the network can provide sufficient UDP and TCP traffic throughput in various loss and delay conditions. Moreover, it can support essential services such as VoIP and video streaming in such scenarios.

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