Efficient Data Dissemination in Wireless Mesh Smart Grids with Software Defined Network

author 1 *, Author 2†, Author 3 † and Author 4 †
* Affiliation 1
† Affiliation 2
Email: email@example.com

***Abstract*—Wireless mesh networks (WMNs) are getting an important attention in the transmission and distribution of Smart Grid power systems to create self-organized electricity communication superhighway capable of monitoring its own health and performance as well as performing efficient trouble notifications. However, current wireless routing protocols have been influenced by the ah-hoc network flavors and routing in LAN, which makes them fairly limited and their extensions to the smart grid power systems very difficult. Several key challenges should be addressed to enable customizable and programmable wireless mesh networks in smart grids. Although Software Defined Networking (SDN) has been envisioned as a new approach to enable network programmability throughout an intelligent orchestration and provisioning systems, however, SDN research to date had predominantly focused on wired networks.**

This paper presents a novel approach to address those challenges by enabling SDN in wireless mesh smart grid power systems. To this end, we first modified the NS-3 simulators to support the SDN paradigm and interoperate with Mininet emulator. Second, we implemented an intelligent Smart grid network architecture that provides an efficient and affordable coverage as well as a scalable high bandwidth capacity. Then, we evaluated our approach for various QoS metrics like latency and bandwidth utilization. Finally, the evaluation showed that our solution could accommodate Smart Grid networks.

***Index Terms*—Smart Grid, SDN, Wireless Mesh Networks, Home Area Network.**

I. Introduction

The energy sector is undergoing a massive changes, evolving from traditional grid into a Smart Grid. In particular, the replacement of electromagnetic meters with the Advanced Metering Infrastructure (AMI) which connects remotely readable smart gas, and electricity meters has expanded the efficiency of smart grids. Those smart meters are equipped with transmission technologies to connect to communications networks, measure and report individual electrical usage to a global smart grid system. Wireless networks have been recently discussed as an important key enabling technology to the transmission and distribution of power grids [1]. In particular, Wireless Mesh Networks (WMNs) have been actively considered as one of the most promising wireless technologies to build highly scalable wireless backhaul for Smart Grid power systems [2], renewable energy sources [3] and solar energy harvesting BSs [4]. WMNs are able to construct low-cost, robust, high performance, and secure wireless connectivity. They can also handle low data rate and low power applications as well as high definition video.

Although WMNs can collect information from neighboring smart devices and provide fault tolerant, and highly available network backhaul, current wireless routing protocols are fairly limited and their extensions to power grid systems are very difficult. Routing decisions are taken in a distributed way based on the local knowledge of mesh routers about each of its neighbors, and reflect a partial visibility of the network without given attention to the real network conditions. This local visibility limits the ability of WMNs to perform network engineering in large-scale wireless networks. Additionally, WMNs are difficult to manage and upgrade because their configuration should be done at each mesh router manually, which is difficult task and error-prone.

Recent approaches to bring intelligence towards the future wireless smart grids have envisioned the Software Defined Networking (SDN) paradigm [5]. SDN is perceived to have tremendous potential for refactoring network protocols and provide a programmable data plane that fits the requirements of Smart Grid systems [6] [7]. SDN has been used to implement a multi-rate, multicast network for Phasor Measurement Unit (PMU) data [8]. Similarly, Rinaldi et al. [9] investigated a wired SDN controller to manage the network infrastructure of smart grid and provide a resilient Smart Grid systems [10]. However, all those contribution consider using SDN in a wired smart grid networks.

To enable SDN over wireless mesh smart grid network several enhancement should be provided to support the controversial aspect of the centralized aspect of SDN with the distributed IP-based forwarding in WMNs. To address these issues, we implemented a novel approach towards the creation of an intelligent wireless Smart grid network. Our solution combines the intelligent centralized SDN control along with the IP data forwarding to provide an efficient and affordable coverage as well as a scalable high bandwidth capacity, flexible and network-aware communication.

The remainder of this paper is organized as follows: Section II details an in-depth discussion about SDN and Smart Grid and examines the synergies between them. Section III compares our work with related works. Section IV details the design rational and the implementation for our architectural decisions. Section V evaluates our solution enabling flexible data delivery and low latency communication overhead. Section VI presents concluding remarks alluding to lessons learned and future work.

II. Synergies Between SDN and Wireless Smart Grids

In this section, we present a motivating use case to enable WMNs in smart grid and discuss how SDN can bring significant benefits to wireless Smart Grids.

A. Use Case: Extending smart grid to rural regions

Since rural areas in emerging or developed countries are suffering of the absence of power grid or the frequent occurrence of power outage, renewable green energy sources such as solar and wind energy, become a viable alternative to power houses. The primary reason for this inability to access power grids is economic; power grids require the installation of expensive wired network backbone such as optical fiber, and thus there is no large motivation to make so large investments in poor and rural regions. To mitigate the higher costs of deploying wired backbone and extend the network coverage in rural regions, WMNs present an attractive solution due to their cost-effective deployment and their multi-hop wireless connectivity. Moreover, WMNs can be used for fast deployment of an urgency that occurs in areas affected by disasters. Figure 1 illustrates a WMN exploiting green energy harvesting BS's to extend smart grid and provide a stable power service to rural and disasters regions.

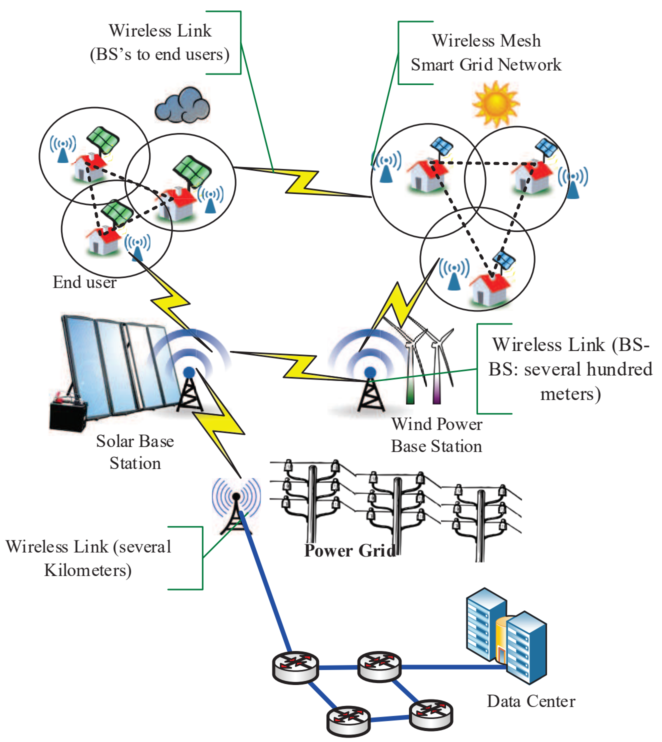

Fig. 1: Wireless mesh smart grid network exploiting green energy harvesting BS's for providing sustainable communication service by expanding communication coverage in rural areas

As common requirements for end users in rural regions are their demands for stable network connectivity to support constant data delivery, voice call service with consistent quality. As shown in Figure 1, with the absence of power grid in this rural area houses will use green energy sources such as solar and wind powers. These energy-constrained sources should coordinate their communication to provide the required power to neighbors in cloudy or rainy days.

The wireless mesh smart grid network connecting those rural houses assumes a hierarchical structure composed of Home Area Networks (HAN), Neighbor area networks (NAN), whose plugged to a Network Gateway (NG) to access to wide area networks (WAN). HAN connects a group of sensing devices to smart meters that record the energy consumption for a given home and transmit the collected data to a Meter Controlling Cystems (MCS). NANs connect multiple MCSs of HAN that are geographically close and interact with cloud services in wide area networks (WANs) for various kinds of data collection and analytics.

B. The role of SDN in Smart Grids

The separation of packet forwarding logic from the data plane to an external controller which embeds all the network intelligence renders SDN easy to configure. OpenFlow, the dominant SDN technology, uses abstracted flow table to populate simple rules to process packets, forward them to another table, send them to an output port or simply drop them. Accordingly, full network configuration is possible by installing flow processing rules in OpenFlow switches.

The value of SDN in Smart Grid lies specifically in the ability to provide network virtualization and automation. SDN network virtualization provides a powerful way to run multiple concurrent virtual slices over a shared substrate. Accordingly, it will be advantageous to bring the SDN benefits to run multiple wireless smart grid networks inside a single physical wireless access points, each virtual wireless slice could has its own hardware resources, radio configuration and capabilities of advertisement.

The centralized up-to-date view makes the controller suitable to perform network management functions while allowing easy modifications of forwarding functions through the centralized control plane which maintains a wide view of the network. Considering the recent advances of wireless Smart Grids, which should be able to support an increasingly diverse set of new and yet unforeseen services and applications, all with extremely diverging requirements, it could extremely beneficial to enhance grid networks through intelligence and bring the advantages of SDN.

Additionally, since most of the data collected by MCSs will be directed to the WAN, the concentration of the traffic on NANs may increase the network load on certain links and may generate buffers overflows. Because gateways in NANs will act as central point of attachment to the WAN, they likely become a potential bottleneck in wireless mesh smart grid network. To overcome those limitations, SDN can use load balancing techniques to adapt the traffic forwarding to network load and absorbs temporary picks in the network. Pushing the traffic engineering algorithms in a separate SDN controller enhance the traffic management and helps in selecting best end-to-end path between WANs and end devices such as MCSs.

III. Related Works

During the past five years, SDN has received unprecedented attention by the research community for developing network support for wired and cloud networks. However, there are a limited effort to leverage the potential of SDN for Smart Grid communication. Jianchao et al. [6] discussed the opportunities that brings SDN to support potential use cases in Smart Grid. Similarly, Dong et al. [10] studied the benefits of SDN to improve network resilience in Smart Grid. Rinaldi et al. [9] proposed using a wired SDN controller to simplify and automate the network management in power grids. Cahn et al. [11] presented the SDECN framework for self-configuring IEDs for substation automation. Likewise, Dorsch et al. [7] presented fast recovery and load management algorithms for the distribution and the transmission power grids. Similarly, multicast Phasor Measurement Unit (PMU) has been investigated [8]. Thomas et al. [12] proposed using a SDN-enabled multicast scheme to support flexible and fault-tolerant group communication in power systems.

Furthermore, smart-meters communication advocates delivering meter-reading information to the cloud-hosted services for performing load shedding and data reporting and analyzes. To this end, Guo et al [13] proposed a SDN framework to aggregate multiple smart-meters flows at a joining concentrator points [14] along the path to the remote cloud infrastructure. The proposed framework uses a reactive OpenFlow approach to aggregate and schedule individual flows. However, the reactive OpenFlow incurs several performance and scalability degradation. In particular, the joining concentrator should generate *PACKET_IN* messages to the SDN controller for every new flow arriving at its incoming ports and wait for the controller rules to to program its software pipelines. The problem is further exacerbated for mice flow matching in latency-sensitive because of an explosion in the number of forwarding states. Likewise, authors in [15] enhanced a SDN controller by implementing a Multi-Agent System as a northbound interface for handling overloads and guaranteeing grid stability. The approach is further enhanced by a fast failover mechanisms [16] to enable instant local recovery and optimal route updates.

Although the previous works enabled SDN in smart grids, they however consider only wired communication. In contrast to wired networks which are known to be stable and robust, our contribution addresses wireless mesh smart grid network to extend power systems to rural and disaster regions. Our solution provides an efficient and affordable coverage as well as a low-latency and flexible and network-aware communication.

IV. Implementation Details

Our architecture is composed of three components: i) mesh clients, which include wide range of user devices including smart gas and electricity meters. Data from those smart sensors are relied by mesh routers; ii) mesh routers are deployed as low cost, flexible static access points with minimal mobility to perform routing and maintenance operations in the network; and iii) gateways are Internet access devices that route all information to the network backbone.

This section details the design decisions of our architecture for enabling OpenFlow-based mesh nodes as well as how they interact with the IP forwarding protocol. Then, we details the behavior of the SDN controller to handle the request from mesh clients.

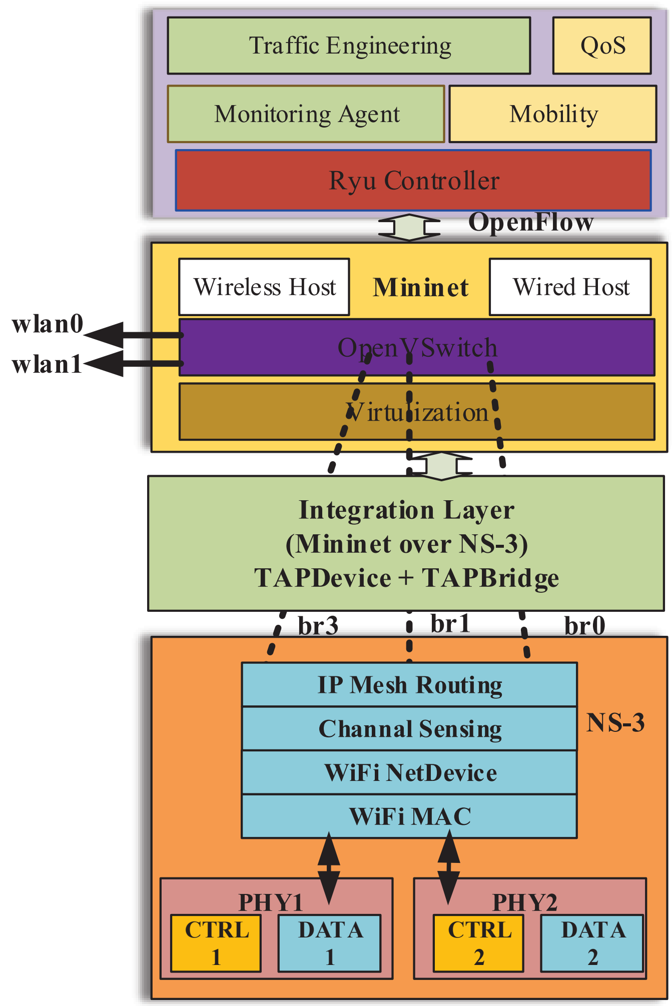

Fig. 2: Design of the OpenFlow-enabled mesh router

A. Integrating NS-3 with Mininet

To enable both NS-3 and Mininet communicating with each other, we implemented the integration layer shown in Figure 2. The main reason behind this integration is that NS-3 provides real-time emulation, so that the real network can process packets generated by a client. Besides, NS-3 does not support SDN simulation natively so we need to enhance it with Mininet emulator to integrate the SDN controller along the OpenFlow-enabled switch, i.e., the OpenVSwitch.

B. Design decision for mesh nodes

To enable multiple virtual wireless networks inside each mesh node, we equipped each mesh routers with two physical interfaces for increasing the transmission capacity. As shown in Figure 2, we programmed each physical interface to support two virtual SSIDs so that one SSID is used to forward data messages and the other one handle control messages.

Additionally, due the variation of the link quality, the network topology changes more frequently and the current OpenFlow protocol does not support autonomous discovery neither enable data forwarding over air interfaces. In order to address this challenge, we foresee that a IP-based connectivity in such wireless mesh smart grid network is required to enable node discovery and identification. The main reasons for using basic IP forwarding in this work are to provide better performance in terms of scalability, lower overload, and layer three functionalities. Forwarding SDN packets can be performed using the OpenFlow in-band approach, so that the OpenFlow interface can be connected to the SDN controller. The IP interface is connected to OpenFlow via virtual interfaces, i.e., *br* interfaces in Figure 2. Thus, individual nodes can use basic IP messages to compute next hop destinations and forward signaling messages throughout the IP routing information by using IP internal routing table. Data packets, i.e., measurements of individual smart meters, can be forwarded based on the routing protocol we implemented inside the SDN controller.

C. Network Monitoring and configuration

The monitoring agent illustrated in Figure 2 performs flexible and robust monitoring built atop a the SDN controller. It communicates with the controller using REST northbound interfaces. The controller can supervise the internal of its connected mesh routers to install new OpenFlow rules. The monitoring agent communicate network policies with the control plane to query optimal policy decisions that should be installed in the forwarding plane, i.e., the OpenFlow-enabled mesh nodes. Moreover, using REST interfaces enables gathering statistics, faults, and errors from the underlying layers as well as retrieving operational states of the network.

D. Routing approach

As the SDN approach foresees that all routing policies should implemented inside an external controller, we enhanced the Ryu controller [17] to support our routing and traffic engineering mechanisms.

Figure 4 shows the load balancing algorithm we implemented to perform traffic engineering. First, the controller is configured with the default parameters, i.e., the OpenFlow rules allow forwarding traffic across the link *a* connecting router 1 and router 4 in Figure 3. Once the controller can establish the communication, the client 1 send *TCP* data packet with higher transmission rate to induce network congestion. As soon as the link becomes congested, the load balancing algorithm is activated in the controller side, i.e., the traffic engineering block in Figure 2.

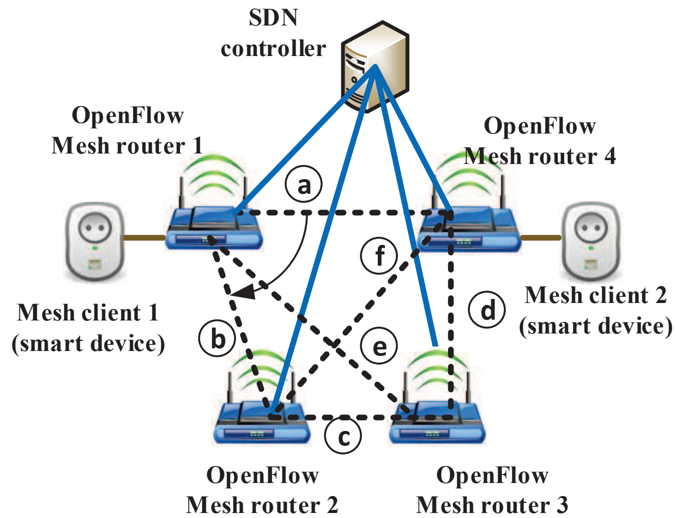

Fig. 3: Scenario

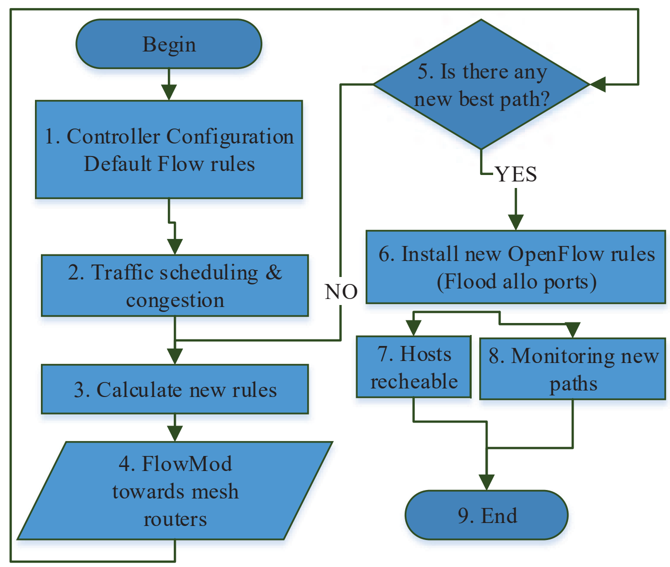

Fig. 4: The framework for the load balancer

Since the controller have a centralized view of the network, he can easily decide the network bottleneck and switch data to the best available new path. To do so, the controller calculates the new rules, i.e., the MAC and IP addresses for the new mesh routers in the new path and send OpenFlow FlowMod messages to select the new end-to-end path. Thereafter, it floods all the ports towards the selected mesh routers, open the TCP connection to allow mesh clients reach each other's, while it continue performing node discovery for monitoring the network topology.

V. Performance Evaluation

In this Section, we present the results of the experiments we conducted to validate our claims in supporting the technical challenges we identified in Section II. First, we focus on the communication overhead in the wireless mesh smart grid

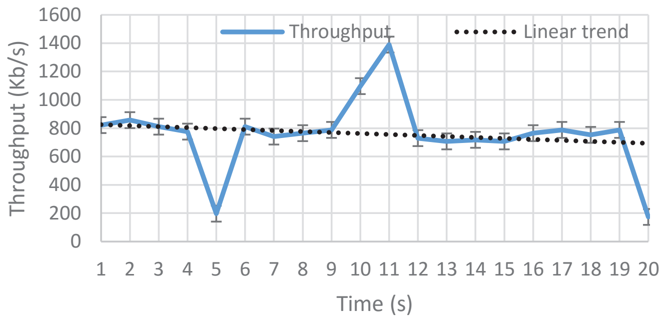

Fig. 5: Evaluating The Load Balancer with Traffic Redirection

caused by the network congestion. Then, we evaluate the end-to-end latency to verify the stability of our solution.

A. Evaluating the traffic redirection

Figure 3 shows a typical scenario of four mesh routers connected in the mesh smart grid network. Assume that links *a*, *b*, *c*, *d*, *e*, and *f* establish the communication between those routers, so that the first best path between smart clients 1 and 2 is illustrated by link *a* between *router 1* and *router 4*. If the mesh client 1 experiences unexpected conditions, such as network congestion or channel interference, the SDN controller install new OpenFlow rules on each router to enable selecting the new path, i.e., links *b, f* and c, d.

Figure 5 shows the TCP flow between client 1 and client 2. At time 4 seconds a network congestion occurs in mesh router 1 which induced the performance degradation, i.e, the throughput decreased from 800 kB/s to 200 kB/s. At 5 seconds the load balancing algorithm in the controller is activated to redirect the traffic from the link *a* to links *b* and *f*. The controller now removes the old OpenFlow rules in router 1, i.e., those used for sending the traffic across link *a*. Then, the IP and MAC addresses of router 2 are added in the new rules. The bow in Figure 3 shows the new path selected by the controller by installing new OpenFlow rules in node 1.

B. Evaluating the Network Latency

The performance of our solution is now measured in terms of end-to-end latency between two end mesh clients. We foresee that this cumulative latency includes the forwarding delay and the queuing delay to show how faster response the total measurement delay over all elements of the solution is.

We show in Figure 6 the latency captured with Wireshark network protocol analyzer. The average network latency between the smart device 1 and the smart device 2 is close to 20 milliseconds (the maximum latency expected in close to 50 milliseconds). These results underscore another benefit of our solution: additional network processing delays are not incurred since OpenFlow messages sent by the controller to install new routing rules do not affect the performance of the communication.

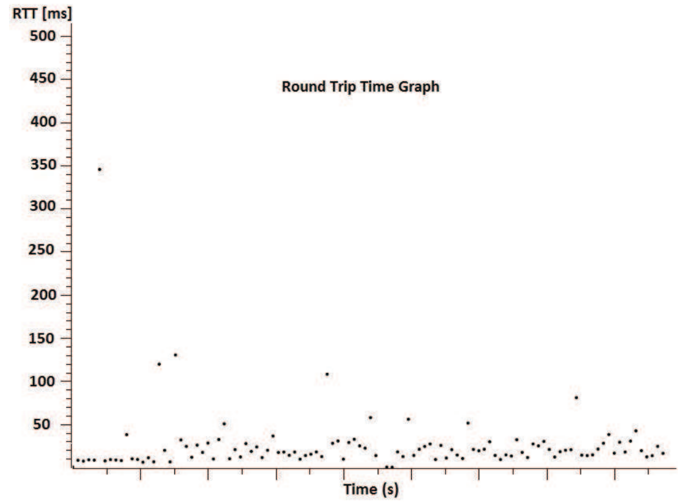

Fig. 6: Time Delay Between Smart Device 1 and Smart Device 2

C. Evaluating the impact of the Packet Loss

In this smart grid scenario, we consider two mesh client exchanging periodic data samples collected by sensing devices, so that if those samples will be lost another new refreshed will be sent in the next period. Figure 7 shows the throughput expected on link *a* between router 1 and router 4 in Figure 3. Additionally, we conducted those experiments to evaluate the impact of the packet loss on the bandwidth and show how much our SDN solution can resist against bandwidth fluctuation.

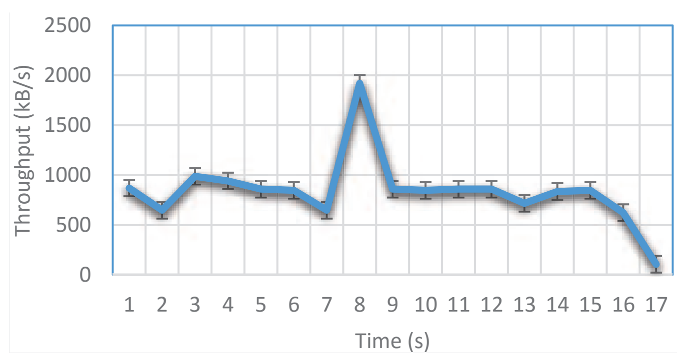

Fig. 7: Impact of the Packet Loss on The Bandwidth Fluctuation

In this experiment, we configured the network with packet dropping rate of 13%. The throughput starts at 900 kB/s and at Time 2.5 seconds, it decreased to 600 KB/s. This is where the load balancing algorithms is activated. The forwarding path between router 1 and router 2 is removed and new one is selected at Time 3 seconds. Similar to TCP communication, the SDN controller notices the bandwidth degradation in link *a*, it activates the load balancer, which remove old OpenFlow rules, i.e., the rules used for selection the path between the router 1 and the router 4. Thus, the controller installs new

OpenFlow rules using the FlowMod messages and adds the new MAC/IP addresses of the router *2* in the new path, i.e., the traffic now show follow links *b* and *f*.

VI. Conclusion

This paper presents a cost-effective SDN-enabled solution to provide wireless mesh smart grid network in rural regions and overcome the higher deployment costs of wired backbone. The performance evaluation shows the ability of our solution to use green energy harvesting BS's for extending smart grid to rural and disasters regions while improving better latency overhead and flexible data forwarding as well as maximizing their wireless connectivity. Our solution is designed with reuse in mind and can easily be adopted in real large-scale testbed. To that end, the source code is made available in open source and can be downloaded here [1].

A. Lessons Learned and Key Insights

We learned following lessons from developing and evaluating our research on SDN-enabled wireless mesh smart grid:

Programming Abstractions for Smart Grid Networks: In its current implementation, our solution relies on OpenFlow to configure and program the underlying wireless devices. Nonetheless, OpenFlow exposes so many details to the programmer, which could turn the network configuration into error-prone "match-action" rules. We believe that more intuitive higher-level abstraction should be provided to simplify the configuration of SDN network devices. As a part of our ongoing works [18], we argue that middleware technologies could be a good candidate to support such a requirements.

Supporting resilient smart grids with SDN: The paper advocates adopting SDN to construct low-cost wireless connectivity in the areas that are not easy to wire. The power grid system should support high information assurance requirements without overloading the overall system. SDN can bring some security risks to smart grids because: i) the SDN controller may contain vulnerabilities in its software; and ii) the centralized control logic can present a single point of failure and subject to DDoS attacks. As SDN is an emerging technology, its security need to be investigated, which form additional dimensions of future work.

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