SDN-Based Link Recovery Scheme for Large-Scale Internet of Things

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***Abstract*—In this paper, we propose *SD-Reco*, a Software-Defined Network (SDN)-based centralized AP and relay node re-configuration scheme for link recovery in IEEE 802.11ah networks. The proposed scheme identifies the overlapping regions and congestion of a network and re-configures Relays, APs, and SDN core nodes for reliable data transmission. Taking advantage of redundant links, the SDN controller triggers a node to receive/transmit frames using the best relay/AP for reliable and low latency delivery. The stations use redundant available links to relay/AP for any failure, not meeting the Quality of Service (QoS) requirement and congestion. Our solution use a relay placement scheme to know topology of the network for centralized controlling. An AP node determines the congestion status of each relay and itself and updates the same to the SDN controller. Accordingly, the controller selects an AP/relay and places flow-rules from overlapping regions for forwarding the traffic dynamically. SD-Reco improves packet delivery ratio up to 18.7% and latency up to 33.3%, compared to the existing state-of-the-art.**

***Index Terms*—Software-Defined Network (SDN), IEEE 802.11ah, Link failure, Internet of Things (IoT)**

I. Introduction

The emerging IEEE 802.11ah overcome several IoT communication issues by handling complexity and coexistence and making the network easier to manage [1], [2]. For example, in an agriculture monitoring and alarming system, a single IEEE 802.11ah network provides an efficient service for preventing crops' damage by wildlife. Otherwise, we need multiple communication technologies for supporting the required data-rate and coverage range making it more complex to manage. However, with the growing demands of the application, a network may deploy multiple Access Points (APs) and relay APs (RAPs) for bearing scalability and larger coverage. For provisioning Quality-of-Service (QoS) in different IoT applications, such network faces challenges such as (i) congestion near AP or relays, (ii) interference detection and recovery near remote stations (STAs), and (iii) channel inefficiency. Recently, Software-Defined Network (SDN)-based access networks show appropriateness to reconfigure different parameters such as channels, bandwidth, and flow-rules, from the available global network view it has [3].

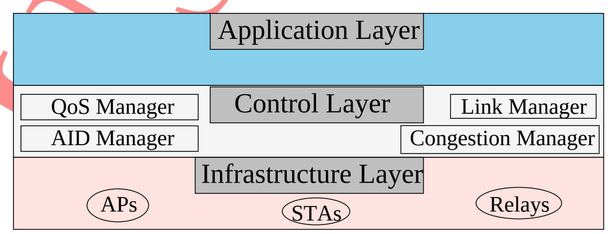

Fig. 1. SDN-based reliable network architecture for IoT

This work proposes an SDN-enabled AP and relay reconfiguration mechanism to support reliable IoT communication in a large-scale IEEE 802.11ah network. Our work attempts to address the issues of link failure and congestion in such a network by proposing a QoS-aware link recovery and flow-placement scheme. The proposed scheme finds the redundant link with the help of the location and coverage area of the relays and AP nodes. We enhance the existing SDN controller with additional modules such as link manager, congestion, and Association IDentification (AID) manager for link recovery, congestion, and AID control in the network.

A. Motivation

Being the leader of the IEEE 802.11 standardization group's new amendment 'ah' has proven to be suitable for scalable IoT connectivity [1], [4]. With the use of sub-1GHz and different Modulation and Coding Schemes (MCSs), 802.11ah is able to achieve up to 1Km of coverage range in 1-hop. It allows up to 8,191 devices to be associated with an AP using a hierarchical AID scheme. Different applications such as smart grid, smart city, and smart monitoring of agricultural field, require a huge number of devices to be deployed [5]. IEEE 802.11ah also proposes a relay node feature for multi-hop and significant coverage. For QoS in terms of latency, scalability, and energy-efficiency, perspective point-of-view requires more relays and APs in the network. The possibility of redundant

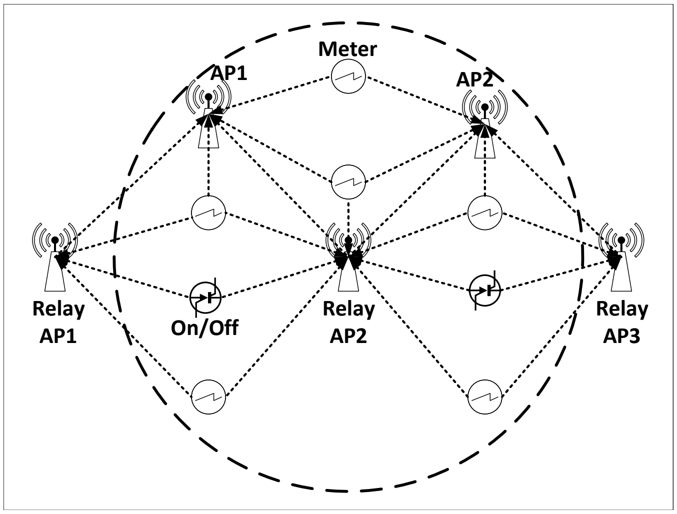

Fig. 2. An example scenarios of overlapping association in 802.11ah-based Smart-grid network

links in the network is very high. As shown in Fig. 2, the location of meters and switches of a smart grid application is within the range of multiple APs and relay APs. However, detecting congestion/link failure and recovery is challenging with multiple networks and APs.

In many cases, SDN is suitably used for achieving network-wide user mobility, control of QoS, AP virtualization, and security on AP nodes [6]. The network infrastructure can be with AP and relay, providing support for communication among the stations (maybe mobile or static). Following are the challenges that need to handle by a large-scale network like 802.11ah:

1) Link failure: IEEE 802.11ah is a centralized multi-hop network without considering any mesh management. In the case of a multi-hop network covering a larger distance, remote monitoring and resolving network issues is a challenge.
2) Co-existence: Fast-growing number of different heterogeneous wireless devices complete with their different wireless communication protocols. Allowing all the radios, protocols, and standards to operate without causing problems within the same connected environment is still challenging.
3) Generally, due to many stations and traffic volume, the considered network faces congestion issues a the relay or AP node. Therefore, forwarding the traffic through the connected AP or relay, as per the QoS requirements of applications, is not suitable.
4) QoS and load-balancing: Efficient utilization of bandwidth among the network is important, but this needs an SDN-based approach that can monitor the overall network and process many intelligence decisions.

B. *Contributions*

The key *contributions* of this work are as follows:

1) We propose a centralized AP and relay node re-configuration mechanism for 802.11ah-based large-scale IoT. Our solution identifies interfacing regions in the proposed network and re-configures relays, APs, and SDN core nodes for reducing packet loss and latency.
2) A link-recovery scheme is proposed to deal with large-scale and multi-hop IEEE 802.11ah network. SDN controller triggers a node to receive/transmit frames through the best relay/AP for reliable delivery. The stations can use redundant available links to relay or AP for any failure or not meeting the QoS requirement.
3) We propose a link failure and congestion detection mechanism by monitoring the recent traffic map and transmission status of a particular AP or relay.

II. Related Works

The authors in the existing literature consider QoS in different IoT applications. We discuss a few works that are related to the IEEE 802.11ah-based mechanisms and SDN-based access networks proposed for reliable and low latency communications.

The QoS is defined as a set of quality criteria for a particular service [7]. Most of the application follows periodic uplink traffic for monitoring the status of the environment in a home or industry area. For automation and control, low rate downlink traffics is created by the alarms/commands from the control center to corresponding authorities/actuators. For example, there may be a huge amount of on-demand reporting type of traffic from thousands of smart-grid stations [8]. In the power outage situation, a huge number of stations simultaneously try for reporting due to the shortage of battery [9]. Prior scheduling is important for improving reliability for such even-driven traffic. Seferagic *et al.* [10] proposed a network adjustment scheme by finding a suitable control loop for the better delay and jitter requirements. However, it is difficult to delay and jitter requirements for such application when the network is saturated and multi-hop in nature.

SDAN caters to different features such as configurability, programmability, virtualization, and traffic shaping in a WLAN. As an initial work on SDAN, Murty *et al.* [11] considered different network metrics such as packet loss, the Received Signal Strength Indicator (RSSI), channel utilization, and neighborhood size to take association and channel allocation decisions in their proposed solution. Further, Smith *et al.* [12] proposed an SDN architecture, which configures mobility, security, and QoS provisioning for improving network performances. In another work, Suresh *et al.* [13] designed a handoff mechanism for SDAN and measured its performance in a test-bed. The author successfully analyzed the developed module over the OpenWrt router. Kim *et al.* [3] proposed an on-demand interference control mechanism for reducing energy consumption at APs. Ethanol [14] implements slim APs and shifts most of the MAC functionalities to the centralized controller.

After a detailed literature survey on QoS-aware and SDN solutions in IEEE 802.11ah and access network, the key network control solutions identified are dedicated forwarding, association control, and energy-saving. However, these solutions are incompatible to deal with the link failure, congestion, and end-to-end QoS in a large-scale IEEE 802.11ah network. Enhancement to the existing network 802.11ah and SDN architecture is important for supporting reliable and low-latency communication.

III. SD-Reco: The Proposed Protocol

We propose an SDN-based dynamic reconfiguration mechanism for an 802.11ah network with multiple APs and relays. The design of the proposed protocol is influenced by the availability of multiple channels of 1 and 2 MHz bandwidth in sub-1 GHz and flexible MCSs proposed in IEEE 802.11ah. Due to such coverage, there may be a large number of available links for connecting APs and relays. The STAs can choose an alternative link to send their traffic outside the network. However, such a decision is possible only if the network topology view is available. Our approach uses an SDN controller to trigger a node to sends its traffic through different AP/relay with a dynamic AID placement scheme.

A. Network Topology

The RAP nodes are be connected with the AP using multi-hop distances. Fig. 3 shows a typical IoT network architecture using IEEE 802.11ah where three IoT networks are connected to the Internet.

The architecture can be thought of as a combination of sensor, relay, and core networks. The overall network can be represented as a set $N(C, A, R, E)$, where C is the SDN controller, A is the set of AP node ($A = A_1, A_2, ..., A_j$), R is the set of RAP nodes ($R = R_1, R_2, ..., R_n$), and E is the set of end nodes (sensor/actuator) ($E = E_1, E_2, ..., E_m$). A takes the responsibility of initialization, synchronization, slot assignment, and channel allocation of the whole network. The Rs are the owners of channels and hold the responsibility of forwarding data from Es to A and vice versa. The IEEE 802.11ah standard uses the macro model of propagation [15] for Tx/Rx. With a height of 15 meters above the rooftop, the propagation loss (in dB) in this model can be calculated as:

$$L(d) = 8 + 37.6log_{10}(d) + 21log_{10}\left(\frac{f}{900MHz}\right) \quad (1)$$

where d is the wireless distance between the sender and the receiver node, and f is the carrier frequency. The AP node in IEEE 802.11ah transmits beacon which also broadcast RAW Parameter Set (RPS) information in the preceding. In the interval, there may be one or more number of RAW for a group of stations. Stations belonging to a RAW group are allowed for contention within the assigned slot duration. Getting a slot is dependent on a mapping function as mentioned below:

$$x = (i + offset)\%l \quad (2)$$

Where, x is the slot number in the RAW frame of size l, the offset value is for improving fairness among the STAs in a RAW, and i is the position index or AID of the station. If the

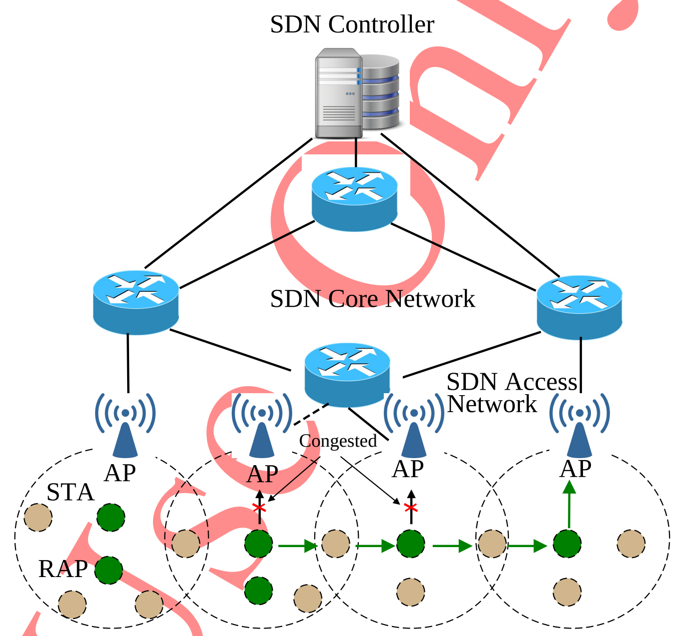

Fig. 3. Network architecture

station has already paged, uses AID, otherwise position index is used. The slot duration (T_x) is calculated from slot duration count (S_c) specified in RPS as-

$$T_x = 500\mu s + S_c \times 120\mu s \quad (3)$$

where, S_c is depended on the k ($S_c = 2^k - 1$), which is the number of bits in sub-filed. If the slot format field set to 0, $k = 11$ otherwise for 1, $k = 8$.

(i) For $k = 11$, the minimum value of $T_x = 500\mu s$ when $C = 0$, whereas the maximum of it is $T_x = 500\mu s + (2^{11} - 1).120\mu s = 246.14ms$
(ii) For $k = 8$, the maximum value of T_x is 31.1ms.

Again, the size of S_{RAW} is calculated as 2^{14-y} from a 14-bit field, hence the maximum number of slots in a RAW is 8 for $k = 11$, and 64 for $k = 8$. In this way, group size will be $T_{RAW} = T_x \times S_{RAW}$, and maximum time frame size of group for $k = 11$ is 1.96s and 1.99s for $k = 8$. The slot allotment is also considered in the relay nodes. As per the Traffic Indication Map (TIM) and Delivery TIM (DTIM), a station follows its slot and starts for contention. If the contention is successful, the station can send/receive a frame.

B. Association and Controller Discovery

The STAs in the network use a centralized scheme [16] for association with AP or RAP. However, if there are multiple hops, a STA or another RAP (from the next level) joins with the RAP having the highest RSSI value. An example scenario of RAP association can be seen in Fig. 4. Although, node 5 receives beacons from Node 3 and Node 4, due to higher RSSI value, node 5 joints with node 3.

The value of d (in Eq. 1) can be calculated as, $d = 10^{(T_{xp} - T_{rss})/20}$ [17], where T_{rss} is the Received Signal

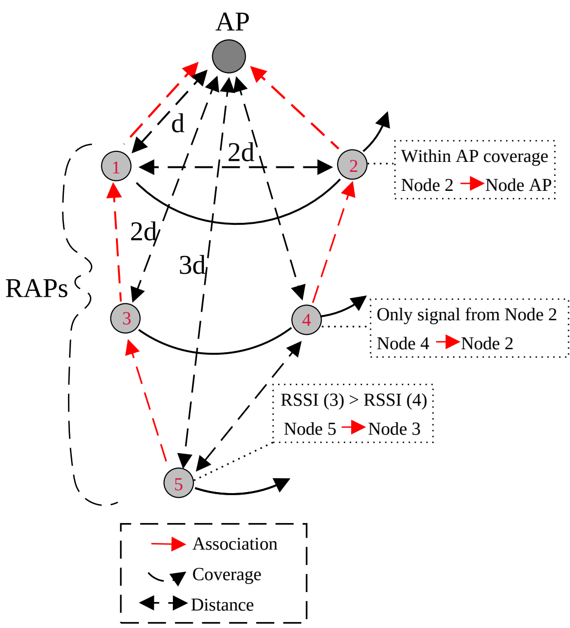

Fig. 4. An example of multi-hop association procedure

Strength Indicator (RSSI), it depends on gains, loss, sensitivity, fading effect, and carrier frequency band. T_{xp} is the transmission power of an 802.11ah node. For improved coverage, a node at the edge of d coverage converts its mode of operation to RELAY mode. Enhancing the work of [18], another relay node is selected using angular separation, which can be calculated as:

$$\Delta\theta = \frac{360^0 \times 2D}{2\pi d} \tag{4}$$

where D is the RAP node coverage. As the coverage of RAP and AP are same, the value of d and D are also same, hence, $\Delta\theta = \frac{360^0}{\pi}$. Different relays and their positions are known to the parent AP, which further sends this information to the SDN controller. Fig. 5 shows the association procedure as followed by a STA. APs update information related to location, RSSI value, and last time transmitted to the controller.

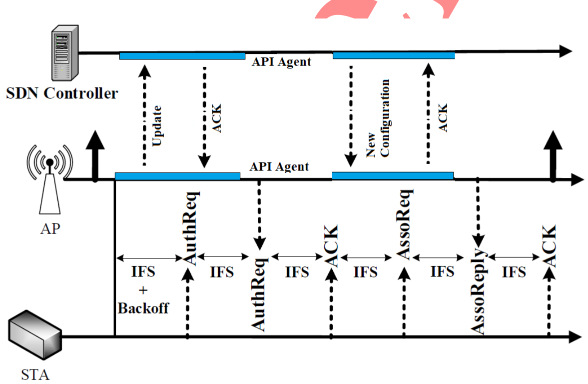

Fig. 5. Station and AP association procedure[1]

C. Link Failure and Congestion Detection

From the set of RAW slots $slot = \{s1, s2, \cdots, s_l\}$. In each slot s_i, station generates, sends, and receives their traffic using the slots as provided by the respective AP or relays. If $\gamma(s_i), \alpha(s_i)$, and $\beta(s_i)$ denote the rates of data generation, reception, and transmission in the slot s_i. The individual congestion index of relay and AP is calculated with the help of total transmitted data over total generated and received data, which is calculated as:

$$X_i^{RAW} = \frac{\sum_{s\in slot} \alpha(s_i)}{\sum_{s\in slot}(\gamma(s_i) + \beta(s_i))} \tag{5}$$

The SDN controller periodically checks for congestion index of an AP/relay. If the value of X_i^{RAW} is below 1, the AP or relay is considered to be congested. Once the required TIM or DTIM bitmap is prepared by the relay or AP nodes, they monitor the possible link failure by checking the upcoming transmission. If the station failed to send its frame in the allocated slot, a link failure is considered. It then request the SDN controller for alternative links.

D. QoS-aware Link Recovery and Forwarding

The SDN controller handles link failure and QoS by a dynamic AID allocation and flow-rule placement scheme. Generally, dynamic AID allocation is initiated by a non-AP node by sending an AID switch request. To enable this, STAs are programmed with *dot11DynamicAIDActivated* equal to true. In our scheme, the SDN controller sends a new configuration to the prevAP (i.e., AP/relay, where link failure detected) and newAP (e.g., neighbor AP/relay) to remove and add AID, respectively. During the search for newAP, the controller also checks the current congestion index. After that, an AID switch frame is sent to a target station. Controller places required flow-rules in the relay, parent AP, and core network. The Controller keeps track of the latency-sensitive applications, such as telemetry and Voice of IP (VoIP). The proposed flow placement solution prioritizes the traffic dealing with such an application. For which we use the existing priority field of OpenFlow protocol [19].

IV. Performance Evaluation

We evaluate the proposed protocol using Network Simulator (NS-3) [20] and Mininet emulator [21] platform. The Tapbridge object of NS-3, effectively allows the system's host (running native applications) and protocol stacks to integrate with the NS-3 simulator. Tapbridge sends the packets from Mininet host to the NS-3-based IEEE 802.11ah's NetDevice and transmitted over the NS-3 emulated channel. This allows us to simulate the large-scale network behavior not necessarily supported by Mininet. We use POX [22] as the controller for the proposed control operations. Required system and simulation-related parameters are shown in Table I.

[1]Communication between STA and AP is adopted from IEEE 802.11ah

TABLE I
SIMULATION PARAMETERS USED IN THE PERFORMANCE ANALYSIS

Parameter	Value
SDN Controller	POX [22]
Basic data rate	300 Kbps
Payload size	256 Bytes
Radio propagation model	Outdoor (macro [5])
Modulation and Coding	MCS0
$[W_0, W_m]$	[15, 1023]
Initial backoff window	64
Traffic Types	HTTP (TCP), VoIP (UDP)
HTTP Connection Type	Multi-transactions, STA hosted
Simulation area	3000 m × 3000 m Flat-grid
Bandwidth	1 MHz
Channels	1
Number of APs	5
Number of Relay APs	100
RAW size	15
Group size	8
Hops (Max.)	3
Beacon interval	100 ms
Number of nodes	5000
Number of SDN Core Nodes	10 (Mininet)

A. Benchmark and Performance Metric

The existing SDN-based schemes such as [13], [12], [23], considering IEEE 802.11a/b/g/n for WLANs, are not suitable for large-scale IoT. Therefore, we compare SD-Reco with IEEE 802.11ah-based WLAN, *SD-Ah* (with multiple APs and RAPs). The proposed scheme is evaluated using the following performance metrics:

1) Latency: Per frame Latency is the time required to successfully send a frame from the station to the local system (required communication is enabled by Tap-bridge). In our experiments, this communication starts from NS-3's 802.11ah station to the local system through relay AP, AP, and Mininet Switch.
2) Packet Delivery Ratio (PDR): It is the ratio between the successfully received packet and total number of pcket sent.

B. Simulation Results

We generate best-effort traffic (HTTP) from in both directions (i.e., Internet to STA and vice-versa) for the first set of experiments. The station uses the same random rate of frame generations. With an increasing number of stations, traffic load also increases. Fig. 6 shows the packet delivery ratio of the proposed scheme is compared to SD-Ah. Due to the congestion and packet loss, with an increasing number of stations, PDR decreases. However, our solution shows better results, which shows an improvement of up to 18.7%. This is due to the consideration of link recovery and dynamic flow-placement in SD-Reco.

In the same network traffic scenario, we check the per frame latency in both schemes. A significant portion of the delay in the network may come due to retransmission and complete failure during transmission. SD-Ah does not detect any packet failure and congestion in the network. As a result, latency

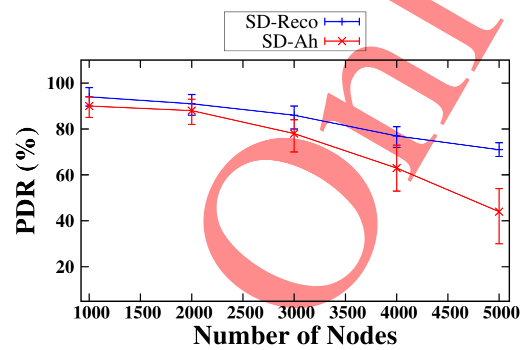

Fig. 6. Packet delivery ratio (%) with increasing number of stations

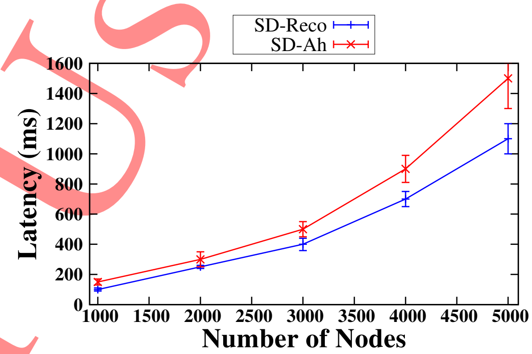

Fig. 7. Average per frame Latency with increasing number of stations

significantly increases with an increasing number of stations. On the other hand, SD-Reco can dynamically reconfigure the AID and flow table in the handling AP and SDN core nodes. Due to this, the latency in the proposed scheme shows an improvement of up to 33.3% as compared to the SD-Ah (Refer 7). The availability of redundant links depends on the number of relay APs and APs in the network. To see this behavior, we change the number of relay nodes from 10 to 60. Initially, not much PDR improvement can be seen in the proposed scheme. However, with an increasing number of relays in the network, the percentage improvement of PDR increases significantly. The results are presented in Fig. 8 considering 5000 number of stations.

In another network scenario, we consider VoIP along with existing HTTP traffic as generated or sent by or to the stations. Fig. 9 shows the latency of the proposed scheme with both types of traffic. The flow-rule placement scheme uses the priority value to specially process the VoIP traffic over the Openflow enable APs and SDN core nodes. Therefore, the latency of such traffic is lesser than HTTP traffic. Also, sending VoIP traffic over the proposed network does not provide any priority. Consequently, SD-Ah shows the highest latency as compared to other approaches.

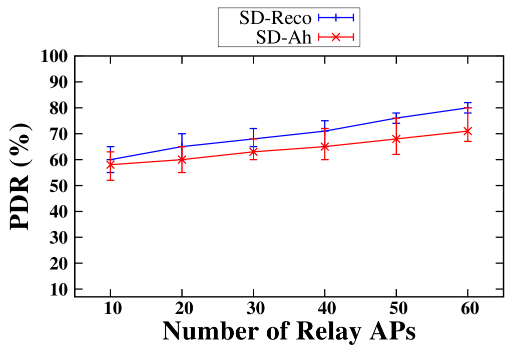

Fig. 8. Packet delivery ratio (%) with increasing Relay APs

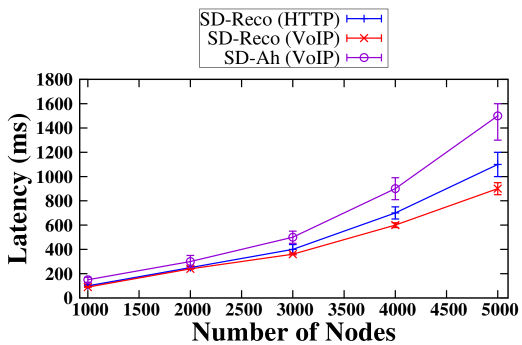

Fig. 9. Average per frame Latency of HTTP and VoIP traffic with increasing number of stations

V. Conclusion

This paper presented SD-Reco, an SDN-based link recovery scheme for relay-based IEEE 802.11ah network. SD-Reco overcomes the issues of link failure and congestion in large-scale wireless IoT networks. The proposed scheme places the relay nodes in the network considering location and coverage range. As per the locations of relays and APs, the SDN controller keeps records of overlapping regions and uses the alternative link for reliable data transmission. Our solution dynamically forwards traffic through alternative relay/AP in case of link failure and congestion at AP/relay. The proposed scheme shows improvement in terms of latency and packet delivery ratio. In the future, we plan to propose an optimized network configuration considering the energy, latency, and jitter requirements of different IoT applications.

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