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HIFFR: Hybrid Intelligent Fast Failure Recovery Framework for Enhanced Resilience in Software Defined Networks

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***Abstract*—Deploying new optimised routing policies on routers in the event of link failure is difficult due to the strong coupling between the data and control planes and the absence of topology information about the network. Because of the distributed architecture of traditional Internet protocol networks, policies and routing rules are spread in a decentralised way, resulting in looping and congestion problems. Software-defined networking (SDN) enables centralised network programmability. As a result, data plane devices just focus on packet forwarding, leaving the control plane's complexities to be managed by the controller. Thus, the controller centrally installs the policies and rules. Considering the controller's knowledge of the global network architecture, central control enhances the flexibility of link failure identification and restoration.**

Therefore, this paper uses SDN architecture to enhance network resilience against link failures by introducing the Hybrid Intelligent Fast Failure Recovery (HIFFR) framework, which aims to improve the speed and effectiveness of network failure recovery.

***Index Terms*—Software-Defined Networking (SDN), Resilience, Link Failure, Routing Protocols, Graph Neural Network (GNN)**

I. INTRODUCTION

Numerous objects in our surrounding environment have the potential to be integrated into intelligent systems that gather data and provide various services, thereby significantly increasing network deployment size as well as the volume of network traffic [1]. To develop a link between specific entities, it is necessary to have a well-established network topology and a real communication medium for the efficient transfer of data packets. To effectively manage and maintain the network, it is necessary to focus on ensuring the reliability and availability of network services, especially critical ones, which must be available at all times, by ensuring no delayed or undelivered data that may have harmful implications.

Software-defined networking (SDN) [2] was devised as an intelligent technology offering a new viewpoint. It optimises traditional networks' operating management by separating the control plane and the data plane. In network management architecture, the control plane operates under a centralised controller with a global topology view. This feature enables the controller to manage different and complex challenges. On the contrary, the data plane is solely tasked with carrying out basic forwarding functions. Intercommunication between the control and data planes is commonly facilitated using the OpenFlow protocol [3].

The controller is the central component, crucial in managing and orchestrating network traffic [4]. In the event of a link failure, the SDN controller promptly detects this disruption through real-time monitoring mechanisms. Once detected, the controller triggers a sequence of automated actions to minimise the effects of the link failure. It dynamically adjusts the network topology by rerouting traffic from the affected link, ensuring uninterrupted connectivity and minimising downtime. Through its centralised network view, the SDN controller efficiently redirects it along alternate paths or dynamically adjusts forwarding rules across network devices.

When implementing Software-Defined Networking (SDN) for network device management, particularly with OpenFlow switches, plenty of opportunities arise to enhance network management and efficiency. Despite these opportunities, this architectural shift also brings new challenges, one of the most critical being the management of link failures. Therefore, SDN architectures should possess fault tolerance capabilities to mitigate the impact of such failures.

A failure occurs due to one or more errors causing network misbehaviour [5]. Failure management can be divided into two primary methods: detection and recovery. In the context of SDN, detection methods can be categorised as periodic or event-based. In contrast, failure recovery strategies can be divided into two groups: proactive (protection) and reactive (restoration) [6]. However, when it comes to link failure, these two approaches handle failures in distinct ways, each having its own implementation mechanism and duration of execution.

An efficient flow installation process is essential to address the issue of failures. Reactive flow installation is employed after a failure has occurred. This process, critical for directing network traffic, experiences significant delays. These delays mainly stem from the time needed for switch-controller communication when a switch lacks a corresponding rule in its flow table for incoming traffic. During reactive flow installation, the latency of signalling messages sent to the SDN controller increases, particularly when the switch simultaneously processes multiple flow rules received from the controller.

Another strategy is proactive, employed before failures occur. This approach involves the SDN controller's static pre-installation of flow rules, enabling faster recovery from link failures than the reactive strategy. By pre-emptively installing these rules, latency is significantly reduced, a critical factor for the deterministic communication necessary in real-time systems. However, while this approach reduces latency, it lacks the flexibility to adapt to dynamic network state changes, potentially resulting in performance issues and increased storage overhead for switches due to storing backup paths.

Faced with these challenges, we propose expanding our strategy to include both pre-failure and post-failure stages of network management. The pre-failure stage focuses on predicting and preventing network link failures. This stage aims to identify links at risk of failure, utilising monitorable network metrics, allowing for pre-emptive measures to mitigate potential disruptions. The post-failure stage, conversely, is activated when a failure occurs to quickly determine and implement the most optimal routing solutions to ensure network resilience and maintain service continuity [7]. To effectively manage these stages, we explore applying advanced deep learning techniques, specifically Graph Neural Networks (GNN), to enhance our predictive and reactive capabilities within the network infrastructure.

Furthermore, to address the fast recovery process while considering latency issues and enhancing network adaptability, we introduce the Hybrid Intelligent Fast Failure Recovery (HIFFR) framework. This approach dynamically redefines the optimal path in response to network link failures and status changes, leveraging continuous monitoring to minimise the time required to compute the optimal path and reduce the communication overhead between switches and the SDN controller. By utilising a hash table to store flow rules based on the current minimum path latency within the memory space of the SDN controller, we aim to alleviate the controller's load significantly. This strategy ensures the swift calculation of forwarding paths for recovery. It facilitates the achievement of high availability, reliable packet delivery, and minimal latency, thereby addressing both the pre-emptive and reactive aspects of network management in the context of SDN.

The remainder of the current report is organised as follows: Section II presents a comprehensive examination of relevant studies documented in existing literature. This section provides valuable perspectives on the research conducted within this domain. Section III illustrates and explains our proposed HIFFR system architecture with pre-failure detection. Section IV elaborates on our proposed HIFFR system architecture with detailed post-failure management to facilitate better comprehension. Finally, in Section V, we provide our conclusions, outlining the benefits of our contribution in summary.

II. RELATED WORK

Several studies have investigated managing failures in software-defined networking (SDN). Two main popular recovery strategies are applied: reactive, which is applied after the failure occurs, and proactive, which works before a failure happens.

A significant number of studies have employed a reactive approach to recovery. The paper [8] presents a rapid port failure recovery solution for OpenFlow networks that utilise traditional Internet routing protocols such as Border Gateway Protocol (BGP) and Open Shortest Path First (OSPF). The authors in [9] discussed that periodically monitoring the link to detect failures before setting up a backup path may strain the controller. To mitigate this, the monitoring responsibility should shift from the controller to the OpenFlow switch, yet this contradicts SDN principles. The study conducted in [10] Created a localised fast reroute (LFR) technique to facilitate faster recovery while minimising the controller's involvement. The system combines fragmented traffic patterns into a unified large flow and dynamically computes an alternative local routing.

Similarly, several studies have been conducted using a proactive approach to recovery. The study in [11] introduces a Group Table-based Rerouting (GTR) technique designed to improve the recovery process from link failures in SDN. It utilises OpenFlow's Fast Failover (FF) group table capability to optimise memory usage and reduce resource utilisation. The authors of [12] propose a proactive recovery approach to reduce controller processing load and ensure an effective failure recovery system. They develop a mixed-integer Integer Linear Programming Model for pre-computed backup recovery paths, considering QoS indicators. In their follow-up work [13], The authors expand on their previous research by incorporating a failure rerouting technique using Multiprotocol Label Switching tags and an extended version of OpenFlow, making it incompatible with current networks and hardware switches. The study by [14] proposes a system to reduce controller communication and implement local actions using two approaches for bypass pathways. However, this could cause load imbalance and congestion and hinder network reconfiguration due to large updates.

Several studies have utilised the Ryu [15] controller to evaluate SDN architecture's performance, deeming it an optimal choice. For instance, the study [16] explores implementing a database-centric SDN architecture with configuration engines utilising the REST API provided by the Ryu controller to achieve flexible and efficient network administration. Similarly, another study [17] evaluates the efficacy of the Ryu controller in optimising network resources and improving traffic routing to enhance network performance. The authors in [18] demonstrate the effectiveness of the Ryu controller in dynamically monitoring and capturing network traffic statistics for better network performance.

As a promising direction in developing 6G and future networks [19], SDN plays a crucial role. It allows for dynamic control, scalability, and security, which are essential for creating highly efficient and adaptive communication systems in the future. Several research efforts have been conducted to address the integration of SDN with 6G. For instance, in [20], the authors emphasise incorporating SDN-based unmanned aerial vehicles systems (SDUAVs), developing networking technologies, and service requirements for 6G services. Their study provides a thorough assessment of the possibilities of SDUAV networks for next-generation wireless communication. Additionally, another survey [21] provides a comprehensive overview of SDN technology in 5G and 6G networks. It was conducted to highlight the potential of SDN for revolutionising mobile communications and addressing key network performance requirements for future generations.

Several recent studies have integrated graph neural network (GNN) technology with SDN. RouteNet [22] is a Graph Neural Network model for network modelling and optimisation in SDN. It accurately estimates performance metrics like delay and jitter, outperforming traditional schemes like Open Shortest Path First (OSPF). It has potential applications in routing optimisation and Service Level Agreement (SLA) maintenance. In the follow-up study [23], the authors introduce a novel approach that uses GNN to predict key performance indicators (KPIs) like delay, jitter, and loss in SDN. It incorporates probabilistic modelling, packet loss ratio prediction adaptation, residual connections for training facilitation, and computation cost improvements. The Shapley Explainer method [24] is a new approach to interpreting GNN in SDN. It uses Shapley values and a soft discrete mask matrix to provide scores of fair importance to input nodes, effectively predicting network performance metrics in the RouteNet model.

In summary, previous studies have proposed various approaches and methodologies to address failure recovery. The availability of TCAM (Ternary Content Addressable Memory) space often limits the effectiveness of proactive strategies in managing network traffic. Proactive strategies typically involve creating rules in the TCAM table to identify and manage traffic flows. However, limited TCAM space can restrict the number of rules that can be implemented, potentially hindering the effectiveness of these strategies. Conversely, reactive solutions encounter notable latency issues, as the controller must promptly update failed routes.

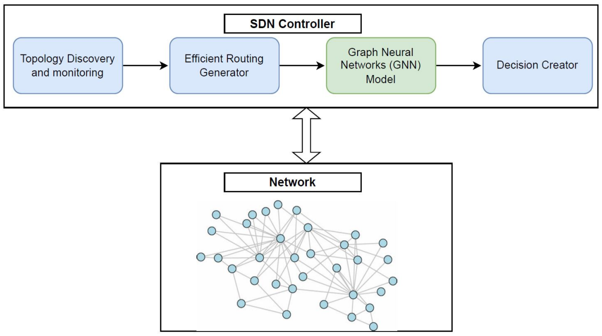

Fig. 1: HIFFR System Architecture with Pre-Failure Detection.

As a result, a hybrid strategy that combines the advantages of both recovery strategies with the Ryu controller is adopted. This approach incorporates machine learning techniques to address the link failure issue efficiently.

III. HIFFR SYSTEM ARCHITECTURE WITH PRE-FAILURE DETECTION

The HIFFR System Architecture is designed to provide a resilient and robust network infrastructure capable of anticipating potential failures through advanced detection techniques. This comprehensive framework ensures optimised protocol use across different stages, enhancing network reliability and performance, as shown in Fig. 1.

This system's topology discovery and monitoring serve as intermediaries between the SDN controller and the physical network. Their responsibility lies in facilitating the exchange of information between the SDN controller and the network. Initially, topology discovery is used to gather and update diverse networking information from switches and routers in real-time. Subsequently, transmission requests are forwarded to the efficient routing generator for optimal path calculation and decision-making.

Graph Neural Networks (GNN) [25] are used by the system to improve the prediction of potential connection failures at the stage preceding any failure. To anticipate failures and find vulnerabilities in the network before they affect the entire system, this approach analyses the graph structure of the network. Then, it sends the analysed result to the decision creator. The decision creator then transmits the configurations to the network switches and routers via a flow table. By continuously monitoring and analysing the network graph, the GNN can predict possible connection failures, enabling proactive actions to reduce risks. By identifying underperforming links or nodes, the system can reroute traffic or adjust configurations to maintain optimal network performance. GNN provides a deeper understanding of network dynamics, improving the overall resilience of the network infrastructure against potential disruptions.

IV. HIFFR SYSTEM ARCHITECTURE WITH POST-FAILURE MANAGEMENT

In efforts to enhance the performance of SDN networks, a proposed modification involves reinforcing the controller by integrating specific applications designed to efficiently manage packet rerouting processes in the event of link failures, as shown in Fig. 2.

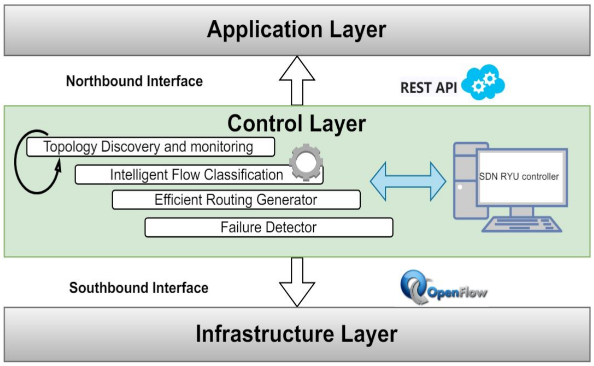

Fig. 2: HIFFR System Architecture with Post-Failure Management.

In response to link failures, a new optimal path is selected from a pre-computed list of paths to enhance the speed of calculations and decrease the load on the SDN controller. Flows are classified as most or less frequently used. Depending on this classification, backup paths are stored either in the controller's hash table or the switch's flow table. This adaptation aims to optimise the overall management of the network system, thereby enhancing its efficiency and resilience.

A. The Application Layer

The application layer is the top layer in the HIFFR architecture [26]. It is the layer in which services and applications determine network behaviour. Multiple network apps transmit information regarding network policies and distinct functionalities. These applications communicate with the underlying SDN control layer using northbound APIs. Applications at this layer include security policies, load balancing, and traffic engineering tools. The application layer acts as an intermediary between network operators and the foundational SDN architecture, facilitating the implementation of smart and adaptable networking solutions.

B. The Control Layer

The control layer of HIFFR is centralised in a logical manner through the controller or network operating system. This system is responsible for managing requests originating from the infrastructure layer. The control layer is responsible for setting up elements, assigning data paths and configuring policies. The control plane [27] serves as the avenue for dictating the behaviour of the network. This plane regulates rules for the operation of the entire network. Each network functions as per the responses and commands issued, and it is the task of the control plane to process and execute these demands. The communication process with the infrastructure layer encompasses enforcing behaviour and fulfilling low-level control alongside capability discovery. In this layer, the SDN controller acts as the central intelligence of the network, simplifying network administration.

Within the HIFFR system, the Ryu SDN controller is considered in the framework's design. Four main applications are integrated with the SDN controller to enhance the detection and recovery process in the event of link failure.

- **Topology Discovery and monitoring Application**
  The Topology Discovery function of our architecture identifies the network structure and provides information about the sensor nodes and links available.
  It begins as soon as the network connects to the SDN controller. We use the Link Layer Discovery Protocol (LLDP) [28], a vendor-neutral, standardised protocol (IEEE 802.1AB) designed for discovering and advertising information about neighbouring devices on a local area network (LAN). It helps us find where network devices are located and use the Packet_In messages to gather information about registered nodes and transform data packets so that the SDN controller can work with them. It also utilises the Flow_Mod method to prepare the packets for OpenFlow, making them suitable for processing by the SDN controller. Using NetworkX (a Python package), a graph will be generated. This graph will then be stored in the SDN controller's memory to facilitate efficient rerouting processes.

- **Intelligent Flow Classification Application**
  In this innovation application, the SDN controller employs Graph Neural Network (GNN) algorithms to analyse the network structure and traffic patterns represented as graphs received from the topology discovery application. The aim is to distinguish between the most and least utilised data flows. By identifying features in the network graph, GNNs efficiently categorise data flows based on their frequency of use and significance. This categorization enables the SDN controller to prioritise how network resources are allocated. Essential flows, such as real-time communication or critical data, which are frequently used, are given priority to store their backup paths in the

switches' flow table. This ensures access to low latency and requires less computational time. Conversely, less frequently used flows store backup paths in the controller's hash table to reduce switch overhead. GNN-based flow classification enables the system to adapt dynamically to evolving network conditions, thereby enhancing the overall efficiency and performance of the SDN infrastructure.

- **Efficient Routing Generator Application**
  In this primary SDN controller application, alternative backup paths for various flows in the network are periodically calculated using the Open Shortest Path First (OSPF) routing protocol [29]. OSPF, a standardized link-state protocol, facilitates the exchange of routing information within a single autonomous system (AS). It determines the shortest path for packet routing by using the Dijkstra algorithm and sharing routing information among all OSPF-enabled routers in the network. This process ensures efficient and reliable packet forwarding by dynamically adjusting to network changes and optimizing routes. The application will continue calculating alternative paths even if no link failures have occurred. These calculations rely on the existing network topology, and the controller identifies alternative paths for each flow, considering flow classification and latency factors.

- **Failure Detector Application** The failure detector function continuously monitors the network for link failures using the Bidirectional Forwarding Detection (BFD) protocol [30]. BFD is specifically designed to quickly identify issues in the communication path between two network devices, checking not only the interfaces and data links but also the forwarding engines themselves. It is commonly used in conjunction with other routing protocols. Its primary goal is to provide efficient and rapid failure detection with minimal overhead and short duration. Upon detecting a link, switch, or port failure, the SDN controller is promptly informed of the issue, initiating a fast failure recovery process.

C. The Infrastructure Layer

The infrastructure layer, the data plane, encompasses network components like switches, routers, and all other resources that interact with the user and application traffic [31]. Due to the functioning of the logically centralised control system, networking equipment like switches and routers carry out the task of routing data packets according to instructions provided by the SDN controller. These devices commonly employ forwarding tables or flow tables to determine the handling and transmission of incoming packets. The infrastructure layer handles the packet forwarding task following the flow instructions. The controller installs the flow policies using the OpenFlow protocol. As a result, this plane's operation depends on the other planes' effectiveness in fulfilling their respective roles and the interfaces that facilitate communication and data exchange.

D. Tools and Technologies for Simulation

1) SDN Controllers and Simulation Tools: Ryu [15], [16] is a flexible network management and simulation tool that can be used for simulating SDN controllers.
2) Deep Learning and Data Analysis Tools: TensorFlow [32] is a free and open-source software library for machine learning and artificial intelligence and can be used for developing and training GNN models, and NetworkX [33], a python library, can be utilised to analyse and visualise the network's graph structure.
3) Network Emulation and Testing: To effectively evaluate network performance and resilience under various conditions, Mininet [34] and GNS3 [35] are utilised for network emulation and testing.

E. Implementation

The implementation of the project is currently a work in progress. So far, the experimental setup has been completed, and several key components have been developed and tested. This section outlines the completed work as well as the planned future work.

- **Network Topology Design:** The topology chosen to implement the proposed system is the HiberniaUK topology [36]. It is a significant part of the internet infrastructure in the United Kingdom. Custom Python script is used to create a network topology using Mininet.

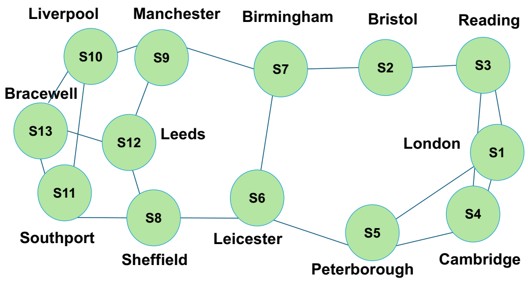

Fig. 3: Network Topology

- **SDN Controller Configuration:** The SDN controller, built on the Ryu framework, has been configured. Core functionalities have been implemented, including packet handling, flow rule installation, and LLDP packet processing.

- **LLDP Packet Transmission:** The function (as shown in Snippet 1) for sending Link Layer Discovery Protocol (LLDP) packets from the controller to the switches has been implemented. This allows the controller to gather topology information from the network.

```
def send_lldp_packet(self, datapath, port):
   ofproto = datapath.ofproto
   parser = datapath.ofproto_parser
   pkt = packet.Packet()
   pkt.add_protocol(ethernet.ethernet(ethertype=
        ether_types.ETH_TYPE_LLDP,src=datapath.
        ports[port].hw_addr,dst=lldp.
        LLDP_MAC_NEAREST_BRIDGE))
   pkt.add_protocol(lldp.lldp(tlvs=[lldp.ChassisID
        (subtype=lldp.ChassisID.
        SUB_LOCALLY_ASSIGNED,
   chassis_id=b’datapath_id’), lldp.PortID(subtype
        =lldp.PortID.SUB_LOCALLY_ASSIGNED,
   port_id=b’port_no’)]))
   pkt.serialize()
   self.logger.debug("----------------Sending␣LLDP
        ␣packet:␣%s", pkt)
   actions = [parser.OFPActionOutput(port)]
   out = parser.OFPPacketOut(datapath=datapath,
        buffer_id=ofproto.OFP_NO_BUFFER, in_port=
        ofproto.OFPP_CONTROLLER, actions=actions,
        data=pkt.data)
   datapath.send_msg(out)
```

Snippet 1: LLDP Packet Transmission

- **Bidirectional Forwarding Detection (BFD) Integration:** A function to handle BFD packets has been implemented as shown in Snippet 2. This enables rapid detection of link failures between network devices, improving network resilience and performance.

```
  # Start BFD session between switches with a
       link between them
   for link in net.links:
      node1, node2 = link.intf1.node, link.intf2.
           node
      if isinstance(node1, OVSKernelSwitch) and
           isinstance(node2, OVSKernelSwitch):
         switch1 = node1
         switch2 = node2
         # Check if there is a direct link between
              switches
         bfd_session_cmd = ’ovs-vsctl␣set␣
              Interface␣’ + link.intf1.name + ’␣
              bfd:connect=’ + link.intf2.name
         result = switch1.cmd(bfd_session_cmd)
         if result.strip():
            print("Output␣from␣BFD␣session␣start␣
                 cmd:␣" + result)
         else:
            print("BFD␣session␣started␣between␣
                 switches" + switch1.name + "␣and␣
                 " + switch2.name)
```

Snippet 2: Bidirectional Forwarding Detection (BFD)

- **Spanning Tree Protocol (STP) Activation:** A function to enable STP on all switches in the network has been implemented and tested (as shown in Snippet 3). This prevents network loops, maintaining a stable and efficient network topology. For each switch, it runs the command to set the (stp_enable) property to true. It checks the result of the command execution. If there is any output, it prints the output. If there is no output (indicating success), it prints a success message.

```
def enable_stp(net):
#Enable STP on the switch
 for switch in net.switches:
   result = switch.cmd(’ovs-vsctl␣set␣Bridge’,
        switch,
   ’stp_enable=true’)
   if result.strip():
   print("Output␣from␣switch:", result)
   else:
   print("STP␣enabled␣on␣switch:␣" + switch.name)
```

Snippet 3: Spanning Tree Protocol (STP) Activation

- **Future Work:** Extensive testing should be conducted to validate the functionality and performance of the implemented features. Additionally, stress testing is necessary to ensure the network's robustness and reliability under various conditions.

V. CONCLUSION

In this work, we introduced the Hybrid Intelligent Fast Failure Recovery (HIFFR) framework. This approach dynamically redefines the optimal path in response to network link failures and status changes, leveraging continuous monitoring to minimise the time required to compute the optimal path and reduce the communication overhead between switches and the SDN controller. By utilising a hash table to store flow rules based on the current minimum path latency within the memory space of the SDN controller, we aim to alleviate the controller's load significantly. This strategy ensures the swift calculation of forwarding paths for recovery, facilitating high availability, reliable packet delivery, and minimal latency, thereby addressing both the pre-emptive and reactive aspects of network management in the context of SDN.

Integrating software-defined networking (SDN) and machine learning technologies with routing protocols has enhanced failure recovery, particularly in real-time networks. Consequently, intelligent Graph Neural Networks (GNN) has emerged as an innovative paradigm. These smart GNNs aim to uniquely enhance the SDN architecture for pre-failure detection and post-failure management. The proposed HIFFR for SDN effectively addresses failures by leveraging machine learning techniques. By combining rapid recovery mechanisms with intelligent decision-making, this framework significantly enhances network resilience. Our research augments the existing SDN architecture by integrating additional applications, which improve routing efficiency, reduce latency, and ensure data availability and reliability.

VI. ACKNOWLEDGMENT

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