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Dynamic Routing Protocol Selection in Multi-hop Device-to-Device Wireless Networks

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***Abstract*—Until now, multi-hop device-to-device (MD2D) routing in mobile wireless networks has been designed to operate over a single-protocol routing framework. Consequently, to the best of our knowledge, no framework has been developed to enable the dynamic deployment and switching of multiple MD2D routing protocols under one framework. This paper proposes a multi-protocol framework to introduce the idea of clustering a cell and deploying different MD2D routing protocols for each cluster based on the cluster requirements. To this end, four clusters are developed with varying network conditions (i.e., node density, mobility rate, and the number of flows). Then, the performance of our two previously designed multi-hop routing protocols, namely hybrid SDN architecture for wireless distributed networks (HSAW) and source-based virtual ad hoc routing protocol (VARP-S), are investigated in each cluster in terms of energy consumption, end-to-end (E2E) delay, packet loss, and cellular-band overhead. Based on the achieved simulation results, a multiple-criteria decision-making (MCDM) approach based on the analytic hierarchy process (AHP) is developed to choose the most suitable protocol for each cluster to provide the best performance. The simulation results indicate that our proposed multi-protocol framework provides better performance compared to traditional single-protocol architectures.**

Keywords: 5G, multi-hop routing, multi-hop D2D, software-defined networking, wireless networking.

I. Introduction

Today, wireless cellular networks have been facing several challenges: 1) increasing demand from mobile users for a better quality of service (QoS) and quality of experience (QoE), 2) the growing interest in machine-to-machine (M2M) applications and the internet of things (IoT) to connect a large number of devices, 3) costly and timely network upgrade due to proprietary hardware and protocols, and 4) compatibility issues between various existing heterogeneous networks and difficulties in their management. Several emerging technologies are integrated into 5G and beyond networks to address the aforementioned challenges and enhance the capacity, flexibility, and scalability of the network, including software-defined networking (SDN), network function virtualization (NFV), multi-hop device-to-device (MD2D) communications, massive multiple-input multiple-output (MIMO), mobile edge computing (MEC), millimeter wave (mmWave) communications, and deploying ultra-dense small cells [1]–[6]. The main focus of this study is on SDN-based multi-hop routing in cellular networks.

SDN provides logically centralized control over a network via separating the control plane from the data plane. It employs open application programming interfaces (APIs) between different layers to facilitate network programmability. In the SDN architecture, vendor-specific configurations, control decisions, complexity, and computational overheads are taken from the data plane. Data plane devices are programmable forwarding elements receiving instructions from the control plane to relay data traffic. All network functionalities, such as performance monitoring, traffic management, network discovery, routing, load balancing, and security appliances, are applications running on top of the controller [7]–[9]. Hence, SDN can provide service providers with simplified network management, smooth service and application deployments, dynamic resource configuration and management, fast integration of different heterogeneous radio technologies, and enhanced QoS and QoE through fine-grained control over resources. Mobile devices in an SDN-based cellular network can be configured through open APIs. SDN enables intelligent network traffic management by directing the multi-interface mobile users to employ the most suitable wireless technology for communications [10]–[12].

Significant research has been conducted on SDN-based cellular networks [13]–[16]. However, to the best of our knowledge, no publications can be found on the dynamic selection of routing protocols under varying network conditions. The motivation of this study is to design inclusive multi-protocol architecture which can fully utilize the complementing strengths of individual routing protocols in different network conditions. This is important for supporting the dynamic selection of routing protocols, adapting to network conditions.

In this paper, we design a multi-protocol framework to maximize the overall network performance. In the proposed framework, an SDN controller provides oversight of the entire cell and initially clusters the cell based on the various traffic densities (i.e., sparse, semi-dense, and dense) observed in different parts of a cell. The SDN controller identifies which routing protocol can provide better end-to-end connectivity within each cluster. To this end, the controller analyzes each cluster based on parameters that impact the protocols' functionalities, such as the average mobility rate of the devices, number of flows, and traffic density. Subsequently, the controller selects a protocol with better end-to-end connectivity for each cluster.

To investigate which protocol suits which network condition, we first analyze the performance of the protocols in each cluster in terms of different network performance criteria, such as E2E delay, energy usage, cellular overhead, and packet loss. Furthermore, we evaluate other factors, such as the high-demand services and energy-dependency of the devices, when selecting a routing protocol. We employ the AHP method to choose the best protocol for each cluster based on the level of importance of each performance criterion. For example, suppose the high-demand services in a cluster are delay-sensitive services. In this case, a routing protocol that better supports these services and introduces the least E2E delay is selected.

The contributions of this paper are summarized as follows:

- A novel framework is developed to integrate MD2D and cellular systems under a unified framework. The framework introduces a joint clustering and dynamic selection strategy for MD2D routing in cellular networks and supports diverse traffic conditions and requirements.
- The proposed framework streamlines the decision-making process and facilitates using computationally efficient decision-making approaches. An AHP-based method is developed to assist in the protocol selection. A set of important network performance criteria are identified with the importance level of each criterion varying based on the cluster requirements, hence making the AHP model fit for purpose.
- An extensive simulation study is conducted to evaluate the proposed framework in comparison with the state-of-the-art routing frameworks. The proposed framework has the potential to integrate and orchestrate current and emerging MD2D routing protocols.

The rest of this paper is organized as follows. Section II gives a thorough review of previous studies on the integration of multi-hop communications and the SDN paradigm with cellular networks. Section III provides a detailed description of the proposed multi-protocol framework. Section IV presents the proposed AHP-based decision-making model for the multi-protocol framework. Section V presents the channel, energy and network model used to implement the multi-protocol framework. Section VI demonstrates the simulation results and emphasizes the potential benefits of the framework. Finally, Sections VII and VIII present the concluding remarks of this paper and the future works.

II. Related Work

In cellular networks, users experience lower data rates and QoS levels when their distance from the base station (BS) increases. This is mainly due to signal attenuation and the existence of different obstacles and interferers. Increasing the number of BSs could help extend the cellular coverage, but it imposes additional operational and deployment costs. Integrating MD2D or ad hoc networks with the cellular network can be an advantageous solution with no need for extra hardware expenditure. MD2D communications in cellular networks enable wireless devices in close proximity to communicate directly instead of traversing through the cellular network. This will enhance the cellular network scalability, system capacity, resource allocation, energy efficiency, spectrum utilization, transmission delay, and interference management. The reason is that devices in MD2D communications consume less energy and experience high-speed data transfer over short-distance hop-by-hop connections than long-distance one-hop connections with the BS. Further, the traffic load on the cellular network is reduced, and consequently, the cellular capacity is increased by offloading the cellular traffic to MD2D communications. The devices in the areas with poor cellular coverage can use MD2D connections to reach the BS. In addition, the usage of the unlicensed frequencies for multi-hop connections enables a mobile user to have simultaneous cellular and MD2D connections. The applications of MD2D in the cellular networks are content distribution, local advertisements, proximity-based social networking applications, machine-to-machine (M2M) applications, and emergency scenarios in which cellular infrastructure is damaged or not available [17]–[21]. 3G Partnership Project (3GPP) Release 12 also employed D2D communications in LTE networks for applications, such as public safety, proximity-based services, and network offloading by integrating IEEE 802.11 technologies into cellular networks. 3GPP Release 13-15 approved two-hop communication to further increase the network capacity. However, the development of routes over more than two hops has not yet been supported by 3GPP [22]–[24].

Significant research has been conducted on developing techniques to enhance interface management, power efficiency, cellular coverage expansion, resource allocation management, spectrum utilization, and QoS for MD2D communications in cellular networks [25]–[29]. The proposed strategies were based on fixed or mobile relay nodes for uploading and downloading to and from a BS to increase the network throughput and capacity. Regardless of the proposed solutions and techniques, a variety of constraints still exist. First, there is inflexibility and a high cost of equipment due to proprietary hardware and protocols. Second, the vendor-specific configuration of interfaces and devices makes the network upgrade costly and complex. Third, the tight coupling of control and data planes in the equipment complicates the network and service deployments. Fourth, there is a lack of fine-grained control over resources and centralized data plane functions in the core entity of long-term evolution (LTE) networks resulting in scalability issues. Finally, there is poor support for virtualization [30]–[32]. 5G wireless and beyond has addressed these issues, by integrating SDN and NFV at the core and the edge. Integrating SDN and NFV into cellular networks provides an open and reprogrammable framework to facilitate rapid and cost-effective service deployment.

Several studies have been conducted to integrate SDN into the existing cellular architecture. The proposed solutions focus on replacing the main forwarding entities of the LTE architecture with inexpensive and simple programmable components managed and controlled by the SDN controller. This introduces higher network throughput, enhanced handover management, less energy consumption, lower latency, and a significant reduction in the deployment and operational cost of infrastructure used by the cellular network [12]–[15], [33]–[36]. Further, a few studies focused on SDN-based D2D[1] and MD2D routing

[1]In D2D routing, there is only one relay node between BS and mobile device. The relay node could be a mobile user or an AP.

in the cellular networks [37]. In [38], a three-tiered SDN architecture was proposed, namely management, controller, and physical. In this architecture, BSs perform basic packet-processing functions and receive instructions from applications running on a centralized controller. Two different frequencies were used for offloading the traffic: one for the macro BS and the other for the femtocells. Moreover, data-plane rules defined by operators were distributed over multiple low-cost network switches to make the network more scalable and minimize the overhead of the core entity. In [39], a QoE enhancing algorithm was presented based on one-hop D2D communication in software-defined multi-tier LTE-advanced (LTE-A) networks to facilitate Internet access and enhance the QoE of users for uploading and downloading transmissions. In the proposed algorithm, the defined application modules on the SDN controller collaborate to establish a one-hop D2D link. The load balancer and resource allocator modules determine which eNodeB can provide the best QoE for each UE. If no idle eNodeB is found, mobility management, load balancer, resource allocator, and routing setup modules collaborate to establish a one-hop D2D link using a relay node between mobile devices and the BS for uploading and downloading transmissions. The authors in [40] proposed a hierarchical D2D communication architecture with a centralized SDN controller that communicates with the cloud head (local controller) to minimize the number of LTE requests. The authors believe that the proposed cloud-based architecture improves energy consumption and scalability and helps with public safety applications through multi-hop routing under the management of the SDN controller. In [41], an SDN-based routing scheme was designed, called low-overhead D2D routing (LODR), for multi-hop D2D communications of mobile nodes in wireless networks using SDN techniques. In the proposed architecture, each user equipment (UE) is equipped with OpenFlow switch capabilities. An OpenFlow controller controls the multi-hop routing behavior of UEs. Their simulation results showed a better performance for the proposed scheme compared to traditional ad-hoc networks in terms of control overhead and network convergence. In [42], a software-defined communication layer within mobile devices was designed, referred to as WASP (WiFi, ad-hoc, software-defined networking, and personal-mobile), for hybrid wireless networks. Mobile nodes in the proposed architecture forward their neighboring information to an SDN controller. The acquired information is used by the SDN controller to instruct mobile devices to relay traffic. Their experimental results demonstrated better performance for WASP compared to traditional ad hoc networks in terms of scalability with a minimum trade-off of energy. They also presented a content distribution scheme using WASP to minimize the load on cellular networks. The authors in [43] proposed a multi-layer SDN-based architecture to efficiently interconnect multi-interface mobile users (LTE/WiFi). In the proposed architecture, a global controller manages the entire LTE/WiFi network with the assistance of multiple local controllers. Each local controller monitors and manages a specific area. The global controller manages the radio resource allocation by collecting information from the local controllers and makes the offloading decision when traffic load on a local controller is high. Authors in [44] designed a software-defined cooperative offloading model (SDCOM) in which an SDN controller is deployed at the packet data network (PDN) gateway of the LTE-A architecture and performs a centralized task scheduling to reduce access links traffic and energy usage of the mobile devices. In the proposed model, mobile users execute tasks cooperatively and share the results. In [45], a hierarchical D2D communication architecture was proposed that improves power consumption by reducing the number of LTE communication channels. In the proposed architecture, mobile clouds are created using D2D to facilitate various services. A global SDN controller registers the formed mobile clouds in the network and has a global view of the services offered by the served clouds. Hence, the controller can set up the clouds against users' requests. The controller interacts with the cloud heads and determines the routing paths between the cloud heads by considering the link quality between the cloud heads and their residual batteries.

In our previous studies [46]–[48], an SDN-based framework was proposed to offload traffic from the cellular network to multi-hop D2D routing. In the proposed architecture, the SDN controller has a global view of the entire network using the received neighbor information from the mobile nodes. The controller determines how mobile users direct their data traffic. The proposed framework supports various multi-hop routing protocols. Taking advantage of this feature, two types of routing strategies were designed in the proposed framework: proactive and reactive. For the proactive approach, the HSAW protocol was proposed wherein the SDN controller broadcasts traffic policies and the ink-state database (LSDB) of the entire network [47]. Thus, mobile nodes can make routing tables to forward traffic. In the reactive approach, the controller provides forwarding information to the mobile nodes for any active route in the network. For this strategy, two different routing protocols were proposed: VARP-S [46] and SDN-based multi-hop D2D routing protocol (SMDRP) [48]. In the VARP-S, the controller provides the source node with forwarding information. Subsequently, the source node attaches the full path to the data packets and forwards the packets to the next hop. In the SMDRP, the controller assigns a unique flow identity (ID) to each active flow and broadcasts the forwarding information. Only the nodes involved in the flow store the flow information in their flow tables. Unlike VARP-S, in SMDRP, the source node only attaches the flow ID to each data packet. Intermediate nodes forward data packets to the next hop based on the flow ID attached to the packets. Our studies indicated that the proposed framework significantly reduces the network overhead compared to traditional ad hoc networks. Further, for densely populated networks, the reactive approach performs better than the proactive approach in terms of cellular overhead and energy consumption.

In contrast to existing work which primarily focus on single-protocol structure, we propose a novel unified multi-

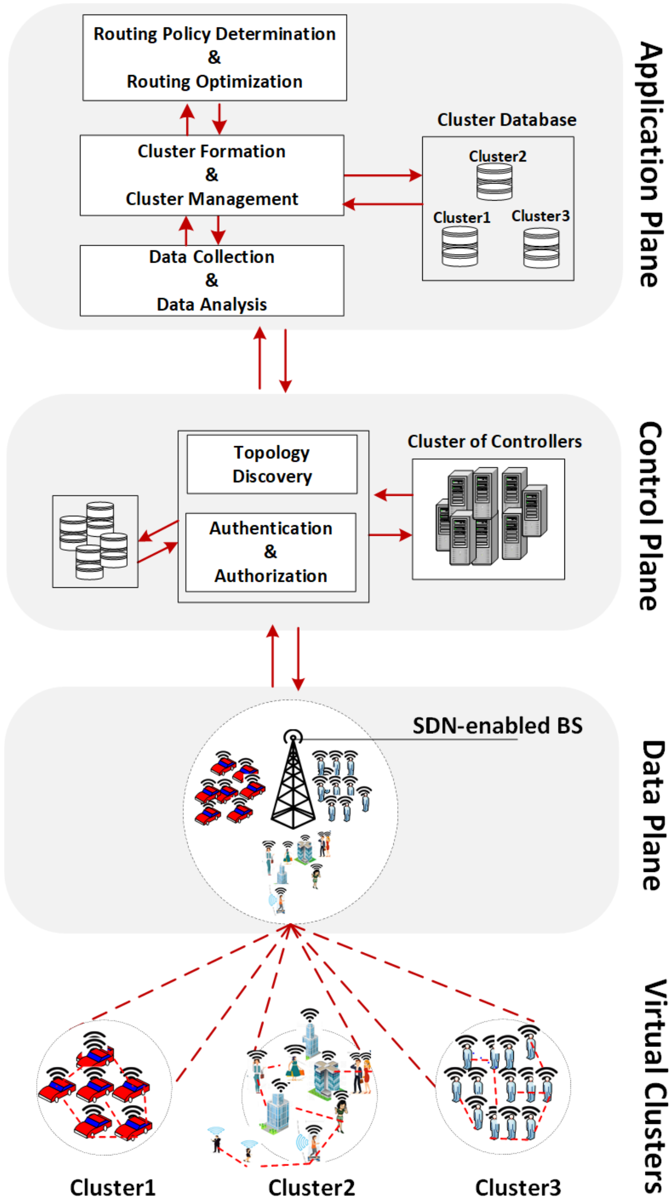

Figure 1: *Multi-protocol framework for SDN-based cellular networks.*

protocol architecture enabling the integration of MD2D and cellular networks. Furthermore, the framework empowers the BS controller to seamlessly switch or select the best protocol based on network conditions and requirements. The use of multiple protocols in one framework can maximize the overall performance when different network conditions exist.

III. Proposed multi-protocol SDN-based framework for cellular networks

Figure 1 presents the proposed multi-protocol framework. Initially, an SDN-based BS[2] logically splits the cell into multiple clusters based on the traffic density. The BS has global knowledge of the network and can dynamically determine which routing protocol is suitable for each cluster. Depending on the cluster condition, the SDN controller dynamically updates the routing protocol used by mobile nodes and the routing parameters. For example, the HSAW routing protocol may be used in one cluster, while another may use the VARP-S protocol. Routing parameters, such as Hello packet intervals, may differ between clusters to support various mobility rates. If the condition of a cluster changes, then the controller instructs nodes to switch to a new selected protocol. However, this switching should occur in a non-real-time manner to prevent unnecessary route flapping. The controller uses the collected historical data to decide whether switching is required for a cluster and when switching should occur.

The motivation behind partitioning a cell into different clusters and using a specific routing protocol for each cluster is because each routing protocol differs in terms of complexity and routing overhead, and consequently, is suitable for networks with specific features. The use of a single routing protocol may not be suitable for networks experiencing various network conditions in different areas. Hence, the controller investigates each area in terms of factors affecting the functionality and performance of the multi-hop routing protocols, such as average mobility rate, node density, and the number of flows. The SDN controller then selects the suitable routing protocol for each cluster by having sufficient knowledge of each protocol and its routing parameters and capabilities. The following example is provided to better clarify the purpose of the clustering in our framework: in urban environments, assuming a stadium full of users and comparing it with the surrounding areas. While the stadium network is fully congested, the surrounding areas might experience a lower traffic density. If we assume two separated clusters for the stadium and surrounding areas, then the network requirements of one cluster are entirely different from the other one. Therefore, the two clusters can be virtually separated: one fully congested with almost static behavior and the other with low density and relatively high mobility rates. Accordingly, a suitable routing protocol must be identified for each cluster based on the cluster requirements.

The SDN controller identifies each cluster by a unique ID, referred to as cluster-ID, and communicates with each cluster using an individual multicast address. When a node attaches to the BS, the controller sends the cluster ID and multicast address to that node while confirming the node association. The controller maintains a table called ClusterTable, which keeps cluster information. The 5G and WiFi frequencies are utilized for cellular and MD2D communications, respectively. The cellular channel is used to exchange control traffic between mobile nodes and the controller, download and upload from and to the BS to connect to the Internet or other networks that are not reachable through MD2D routing or MD2D cannot provide the required quality for that data flow compared to the cellular data transmission. The WiFi channel is used to exchange data traffic via multi-hop connections.

Mobile devices in our proposed framework can be programmed using two approaches: active and passive. In active

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[2]In this study, the terms BS and controller are used interchangeably.

programming, the SDN controller dictates the forwarding information to the cluster, whereas in passive programming, the functionality of the existing ad hoc routing protocols remains unchanged. The controller provides the information required for the protocols self-optimization, such as the maximum number of hops in an MD2D connection, routing metrics and parameters (e.g., hello intervals and topology control intervals). This significantly improves the overall functionality of the network. The focus of this paper is active programming, and comparing the functionality of the proposed approaches is beyond the scope of this study and is deferred to our future work.

In active programming, the controller is engaged in multi-hop routing and provides forwarding information to mobile nodes. The controller decides on the multi-hop routing strategy to be used in a cluster, considering the cluster requirements and features. The forwarding information sent by the controller can vary depending on the selected routing method, reactive or proactive. In both reactive and proactive routing approaches, the controller builds an LSDB of the entire cluster. In our previous studies, we designed different routing strategies for active programming in cellular networks, namely HSAW [47], VARP-S [46], and SMDRP [48]. If a proactive routing approach is selected, such as HSAW, the controller multicasts the LSDB to the cluster. The controller also multicasts traffic policies carrying a list of traffic types, selected metrics for each type, and maximum allowed end-to-end cost for multi-hop routing. Each mobile node then builds the LSDB of the cluster. The source node of a data packet runs Dijkstra´s algorithm to find the least-cost path to the target and forward the data to the next hop. The controller periodically updates the mobile nodes with lost or newly added links to the cluster. In reactive approaches, such as VARP-S or SMDRP, mobile nodes are not required to maintain the LSDB of the cluster. If a node has a data packet, it sends a flow request message (FREQ) to the controller. The controller then provides forwarding information for each active flow. Further, the controller updates the involved nodes of a flow if any link failure occurs.

In this paper, it is assumed that all nodes are under the coverage of the BS. The routing procedure for the nodes that are out of cellular coverage and the communication between mobile nodes in adjacent clusters are planned for future study.

IV. DECISION-MAKING PROCEDURE FOR MULTI-PROTOCOL FRAMEWORK

We use the MCDM approach based on AHP [49] to select the best routing protocol for each cluster in terms of different network performance criteria and the high-demand services in a cluster. The following sections summarize the AHP-based decision-making procedure in the multi-protocol framework.

A. Overview of AHP-based Decision-making Procedure

In a decision-making process, there are several criteria and alternatives to be chosen from. MCDM evaluates explicitly multiple conflicting criteria in the discrete decision spaces, examines the alternative options based on the preference, and selects the best option. We employ the AHP method as it can be applied to various types of decision-making problems.

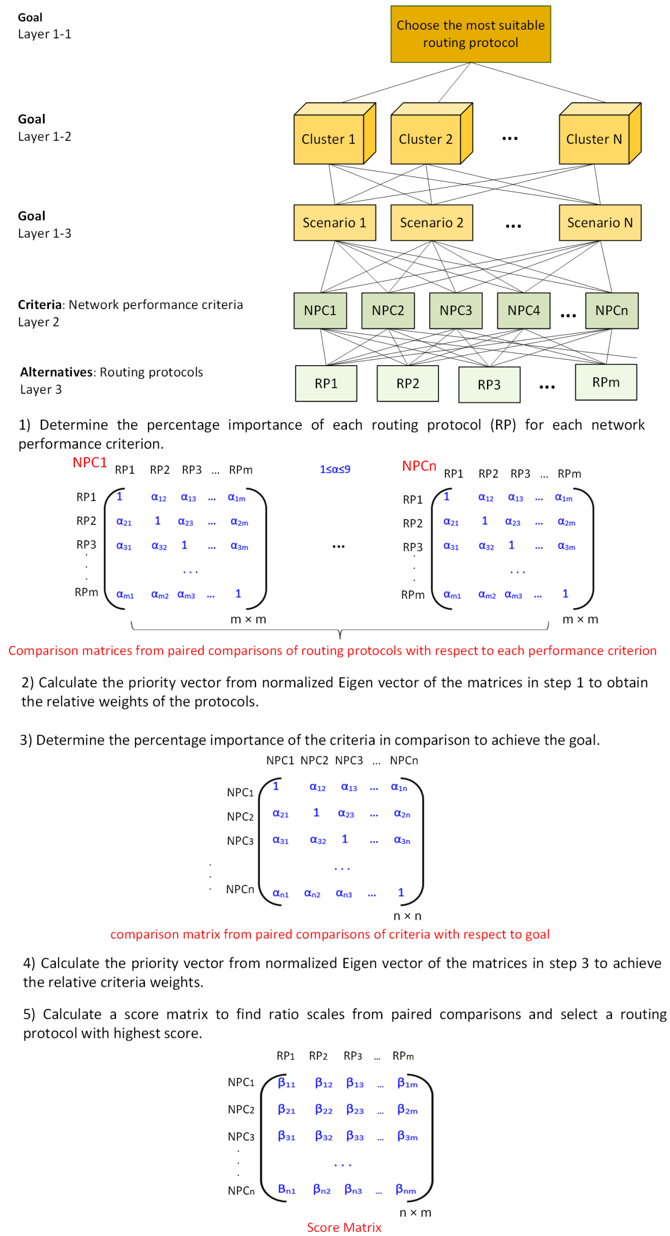


Figure 2: AHP-based decision-making model for multi-protocol framework.

The AHP model is based on a hierarchical structure and was developed by Saaty [49] as a potential tool to manage qualitative and quantitative multi-criterion elements involved in decision-making behaviors. In this method, a fundamental scale in [49] is used to determine the importance level of each criterion compared to the others; and the preference level of its alternatives compared to one another for each criterion. The following steps are taken to conduct the AHP: 1) creating a hierarchy of the problem, 2) giving a nominal value to each level of the hierarchy, and 3) creating a pairwise comparison judgment matrix. The steps are detailed in the following paragraphs.

To make a decision based on the AHP method, first, we determine the goal of decision-making (level 1 – Goal), i.e., selecting the most suitable protocol for a cluster, decision indicators (level 2 – Criteria), i.e., network performance criteria, and decision choices (level 3 – Alternatives), i.e., MD2D routing protocols. Next, we assign weights to the criteria based on their relative importance. A pairwise comparison matrix is generated, and a normalized eigenvector of the matrix is calculated to achieve the required relative weights of the criteria. To this end, a score/weight from the fundamental scale is given to each criterion to determine the importance level of each criterion compared to the others to achieve the goal. The score/weight ranges from 1 to 9, and higher values are preferable to smaller values. The size of the comparison matrix is $n \times n$, where n is the number of criteria. Then, the alternatives (i.e., routing protocols) are compared for each of the criteria to determine the percentage importance distribution of the alternatives. Consequently, n comparison matrices with size $m \times m$ are generated if the number of alternatives is m and there are n criteria for each alternative. Subsequently, the priority vectors of the created matrices are computed. After that, a scoring matrix with size of $n \times m$ is calculated to find the ratio scales from paired comparisons. This matrix is the overall composite weight of each alternative derived from the level-2 and level-3 weights. The overall weight is achieved by normalizing the linear combination of multiplication between the priority vector and weight. Finally, each alternative is ranked based on the score matrix [50], [51].

B. AHP-based Decision-making Model for Multi-protocol Framework

Figure 2 summarizes the proposed AHP-based decision-making process for the multi-protocol framework. The goal is to select the most suitable routing protocol for each cluster based on the cluster condition and requirements (e.g., node density, traffic density, average mobility rate, and high-demand services). The criteria are network performance parameters that determine the cluster performance, including E2E delay, packet loss, and energy usage. The alternatives are the available MD2D routing protocols operating differently in various network conditions. The importance of each performance criterion for a cluster, and the performance level of each routing protocol for each performance criterion, are evaluated using AHP. A score matrix is obtained from the AHP evaluation that indicates the most suitable protocol (i.e., the protocol with the highest score).

V. System Model

Three major parts of our implementation model are explained in this section, namely, the channel estimation, energy model, and network model. First, the cellular channel capacity is estimated using MIMO technology. Second, the link data rate is calculated based on the estimated channel. Third, the total energy consumed by each node to send or receive packets is computed. Finally, the specifications of the network model are detailed.

A. Cellular Channel Model

Our model integrates MIMO technology into the BS to increase the overall network performance and address challenges, such as signal propagation, increased number of users, and growing demand for low-latency communications. Further, we estimate the channel and the maximum data rate required for each user to establish a link to the BS. The following notations are used in our channel estimation and link capacity: $\mathbf{A}$, $\mathbf{a}$, and α represent matrix, vector, and scalar, respectively, and $\mathbf{A}^{-1}$ and $\mathbf{A}^H$ are the inverse and Hermitian (conjugate transpose) of matrix $\mathbf{A}$.

In MIMO, once the transmitted signal reaches the BS, each antenna receives multiple copies, which may be affected by scattering, shadowing, or pathloss. However, signals with the highest amplitude/power are selected for our channel estimation as proposed by [52], [53]. There are precoding matrices at both the transmitter and receiver to mitigate the channel effect and improve the QoS. To obtain the precoding matrices, we first model the communication channel between a mobile station (MS) and the BS as a collection of signals that are affected by multipath propagation, which is calculated as follows:

$$\mathbf{H}(\tau) = \sum_{l=1}^{L} \mathbf{C}_l \delta(\tau - \tau_l), \tag{1}$$

$$\mathbf{C}_l = \begin{bmatrix} c^l_{1,1} & c^l_{1,2} & \cdots & c^l_{1,N_{BS}} \\ c^l_{2,1} & c^l_{2,2} & \cdots & c^l_{2,N_{BS}} \\ \vdots & \vdots & \ddots & \vdots \\ c^l_{N_{MS},1} & c^l_{N_{MS},2} & \cdots & c^l_{N_{MS},N_{BS}} \end{bmatrix}, \tag{2}$$

where δ is the Dirac delta function, $\mathbf{C}_l$ is the complex channel gain matrix consisting of the l^{th} path which are delayed in time with τ_l, and $c^l_{N_{MS},N_{BS}}$ is the channel coefficient between the antennas of both sides (i.e., the k^{th} BS antenna and the m^{th} MS antenna for the corresponding l^{th} path). It is assumed that $c^l_{N_{MS},N_{BS}}$ is Rayleigh distributed.

The MIMO channel singular value decomposition (SVD) is calculated to estimate the precoding matrices, as below:

$$\mathbf{H} = \mathbf{U}\mathbf{S}\mathbf{V}^H, \tag{3}$$

where $\mathbf{S}$ is a non-negative singular diagonal matrix with values of $\mathbf{H}$. $\mathbf{U}$ and $\mathbf{V}$ are the unitary matrices with sizes $N_{RX} \times N_{RX}$ and $N_{TX} \times N_{TX}$, respectively. In the downlink scenario, N_{RX} is referred to as the number of MS antenna (N_{MS}), and N_{TX} is the number of BS antennas (N_{BS}). The resulting matrices from SVD, $\mathbf{U}$, and $\mathbf{V}$ are the precoding matrices used at the transmitter ($\mathbf{F}_T = \mathbf{U}$) and receiver ($\mathbf{W}_R = \mathbf{V}$) in the MIMO system, respectively. The channel capacity is estimated based on the obtained precoding matrices as follows:

$$R = \log_2 |\mathbf{I}_{N_p} + \frac{P}{N_p}\mathbf{R}_n^{-1}\mathbf{W}_R^H\mathbf{H}\mathbf{F}_T\mathbf{F}_T^H\mathbf{H}^H\mathbf{W}_R|, \tag{4}$$

$\mathbf{I}_{N_p}$ is the unitary matrix, P/N_p is the normalized total transmitted power, N_p is the number of transmitted packet symbols,

P is the average total transmission power, and $\mathbf{R}_n$ is the noise covariance matrix.

Given the channel rate in $b/s/Hz$, the MIMO channel data rate (DR) between the transmitter and receiver is:

$$DR = N_{TX} BW R, \tag{5}$$

where BW is the channel bandwidth in Hz, and N_{TX} is the number of antennas at the transmitter.

Based on the achieved data rate, the transmission delay (TD) of the link is estimated as below:

$$TD = \frac{S}{DR}, \tag{6}$$

where S is the packet size in bits.

B. Energy Consumption Model

In our simulation, a classical first order radio model is used to calculate the energy consumed by the nodes for transmitting and receiving data [54], [55]. It is assumed that the power loss is based on multipath fading and free-space power loss. Based on the proposed energy model, the energy consumed by node$_i$ for transmitting or receiving a packet is calculated as below:

$$E_{i\in N}^{TX} = \begin{cases} e_{TX} S_i + e_{mp} S_i d^4, & if\ d > a; \\ e_{TX} S_i + e_{mp} S_i d^2, & if\ d < a; \end{cases} \tag{7}$$

$$E_{i\in N}^{RX} = S_i(e_{RX} + e_{da}), \tag{8}$$

where e_{TX} and e_{RX} are the consumed power by the electronic devices, S_i is the packet size that node$_i$ tries to transmit or receive ($i \in 1, 2, ..., N$), e_{da} is the data aggregation energy, d is the distance between the transmitter and receiver, and a is a threshold distance for the transmit power that determines the selection of a multipath or free-space model in the calculation. The value of a is defined as below:

$$a = \sqrt{\frac{e_{fs}}{e_{fm}}}, \tag{9}$$

where e_{fs} and e_{fm} are the amplifier constants for the free-space model and multipath model, respectively. If the value of a is less than the distance between two nodes, the multipath model is selected. Otherwise, the free-space model will be employed.

Based on (7) and (8), let E_T denotes the total power consumed by N nodes in the network and is calculated as follows:

$$E_T = \sum_{i=1}^{N} E_i^{TX} + \sum_{i=1}^{N} E_i^{RX}, \tag{10}$$

C. Network Model

Two different frequency bands are used in our model: one with a licensed frequency for cellular communication (5G standards) and the other with unlicensed frequency for MD2D communications (IEEE 802.11g [3]). Further, four clusters are

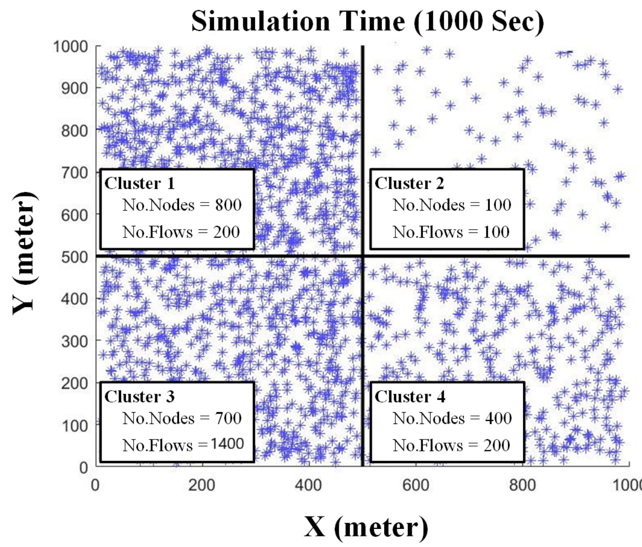


Figure 3: *2D representation of clusters.*

Table I: Simulation parameters.

Parameters	Value
Simulation tool	MATLAB
Simulation area	1 Km × 1 Km
Simulation time	1000 sec
Routing protocols	HSAW, VARP-S
Node mobility model	Random waypoint mobility
Wireless standard	IEEE 802.11g
Max BS antennas	64
Max MS antennas	4
Pathloss constant	3
Carrier frequency	5 GHz
Max bandwidth	80 MHz
Packet size	50 Mbits
Number of nodes	100, 400, 700, and 800
Node transmission range	75 m
Node speed	3, 10, and 20 (m/s)

initially developed with varying node densities and mobility rates. The cluster density is categorized as sparse, semi-dense, and dense. Fig. 3 shows the 2-dimensional view of our framework, and the specifications of the clusters are presented for each area. Clusters 1 and 3 are considered dense networks, and clusters 2 and 4 are considered sparse and semi-dense networks, respectively. Different mobility speeds are specified to model pedestrians and vehicles of various types, i.e., $3m/s$ for the pedestrian network, and mobility of $10m/s$ and $20m/s$ for vehicles such as bicycles, scooters, and cars. The mobility pattern of mobile nodes is the random waypoint mobility model. Two different network scenarios, energy-independent and delay-sensitive, are assumed for the clusters to take into account the type of devices and the high-demand services when selecting a protocol. The performance of HSAW and VARP-S is compared for each cluster separately to identify which protocol is the potential candidate for each cluster. The AHP method is used to determine the most efficient protocol based on the simulation results. Subsequently, the selected protocol for each

[3]The proposed architecture can use other IEEE 802.11-based radio standards and is not limited to IEEE 802.11g.

cluster is run on the mobile nodes of that cluster to evaluate the total throughput of the network.

VI. Simulation Results and Performance Analysis

This section presents the performance analysis of the HSAW and VARP-S protocols for each cluster in terms of various network performance criteria. Then, the AHP decision-making procedure to select the most appropriate protocol is described, and the performance of multi-protocol is compared with a single-protocol framework. The simulation parameters are listed in Table I. For simplicity of analysis, the following assumptions have been made:

- The controller has oversight of the entire cell and initially has clustered the cell (i.e., 4 clusters) based on the traffic density.
- All nodes are under the coverage of the BS.
- The energy specifications of all nodes are the same, and the nodes in the network have the same initial energy. For the HSAW protocol, the energy consumed by the mobile nodes to run Dijkstra´s algorithm is ignored.
- Three average mobility rates are considered for mobile nodes: 3 m/s, 10 m/s, and 20 m/s.

A. Simulation Analysis of HSAW and VARP-S Routing Protocols

At the initial stage of our simulation, a random number of flows with different sources and destinations are generated. The controller then provides different forwarding information to nodes according to the selected routing protocol for the cluster (i.e., HSAW or VARP-S). In the case of VARP-S, the source node sends a flow request for a specific target to the controller, and the controller replies with forwarding information (i.e., a list of intermediate hops to the target). Then, the source node attaches the full route to the data packets and forwards the packet to the next hop. In HSAW, the controller multicasts the LSDB of the entire cluster. Subsequently, if a node has a data packet to send, it runs Dijkstra's algorithm to find the next hop to the target of the data packet. Each protocol acts differently in response to the link failure. In HSAW and VARP-S, the upstream node of the failed link forwards the broken link information to the controller, and subsequently, the controller multicasts that information to the cluster. In HSAW, the upstream node determines a new route to the target by running Dijkstra's algorithm on the cluster LSDB. In VARP-S, the source node waits to receive the updated forwarding information from the controller. However, HSAW is a proactive protocol in nature. Hence, all the nodes continually update their LSDB and calculate routes whenever any changes occur in the cluster.

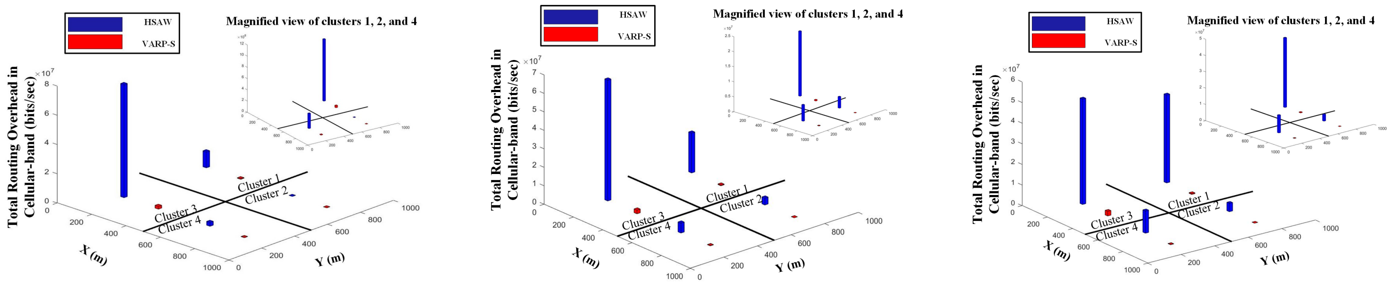
Figures 4, 5, 6, and 7 demonstrate the functionality of the routing protocols for 4 clusters based on four network performance criteria: cellular routing overhead, E2E delay, energy consumption, and packet loss. Each figure includes three subfigures presenting the performance of the protocols for three mobility rates. Each cluster experiences various traffic densities and number of flows as detailed in Fig. 3.

*1) **Overhead**:* Figure 4 presents the cellular routing overhead of the protocols. As highlighted in the figure, HSAW produces a significant overhead on the cellular channel in all the clusters compared to VARP-S. Since in HSAW, the LSDB of the whole cluster will be multicast by the controller. Therefore, for a large number of nodes, the size of LSDB increases, leading to higher overhead. Whereas in VARP-S, only route request and route reply control messages are exchanged between the source node and the controller for the demanded targets. For HSAW, cluster 1 experiences higher overhead than clusters 2 and 3 due to more node density. However, cluster 3 shows significant routing overhead compared to the other clusters because of high network density and data traffic. It can be concluded that for highly dense networks, VARP-S operate better as fewer control messages are required for route discovery and route maintenance. Moreover, overhead increases exponentially as the mobility rate increases due to frequent link failure and the need for more updates.

*2) **End-to-end delay**:* The HSAW provides better E2E delay compared to VARP-S, as shown in Fig. 5. In the HSAW for route discovery and maintenance, nodes run Dijkstra's algorithm to determine the route to the target and do not wait for forwarding information from the controller. In VARP-S, the source node has no knowledge of the cluster and must wait for the controller instructions. Cluster 3 experiences the highest E2E delay compared to other clusters as node density and the number of flows are high. The least E2E delay can be seen in cluster 2 because of low traffic density. The figure also shows that by increasing mobility, the E2E rises accordingly.

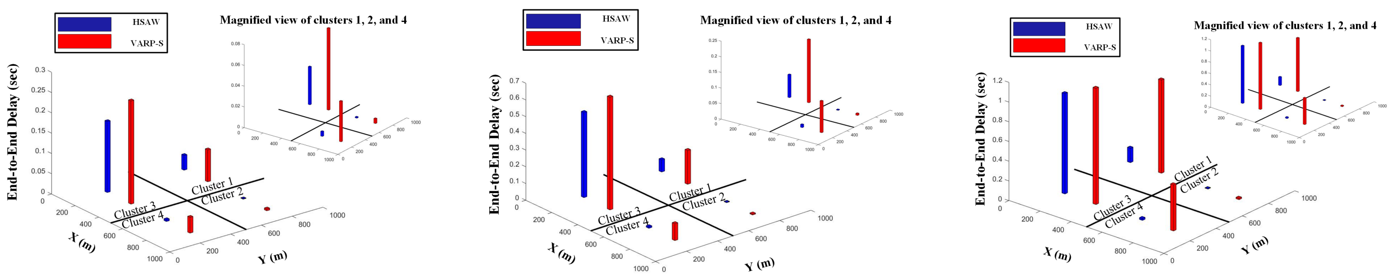
*3) **Energy**:* Figure 6 shows the energy consumed by mobile nodes for data delivery, route discovery and maintenance in HSAW and VARP-S protocols. As shown, nodes running the HSAW protocol consume more energy than those running VARP-S. In HSAW, nodes dissipate more energy to receive the LSDB of the whole cluster, and overall network energy consumption increases as the number of nodes grow (increasing the number of nodes means increasing the LSDB size). Further, due to the mobility of the nodes and dynamic changes of the cluster condition, nodes experience more frequent LSDB updates, leading to more consumed energy. In contrast, mobile nodes consume much less energy in VARP-S compared to the HSAW. Because in VARP-S, if any changes occur in the cluster impacting the data delivery of the existing flows, the controller only informs the relay nodes of the affected flows. Fig. 6 also shows that energy consumption increases by increasing mobility. Since the topology changes and the link failure will likely occur more frequently for higher mobilities. In overall, cluster 3 experiences significant energy consumption compared to others due to a large number of nodes and data traffic.

It is notable that in HSAW, nodes must run Dijkstra´s algorithm more frequently in response to the topology changes, which leads to more processing overhead and further energy consumption. However, this is not taken into account in this analysis.



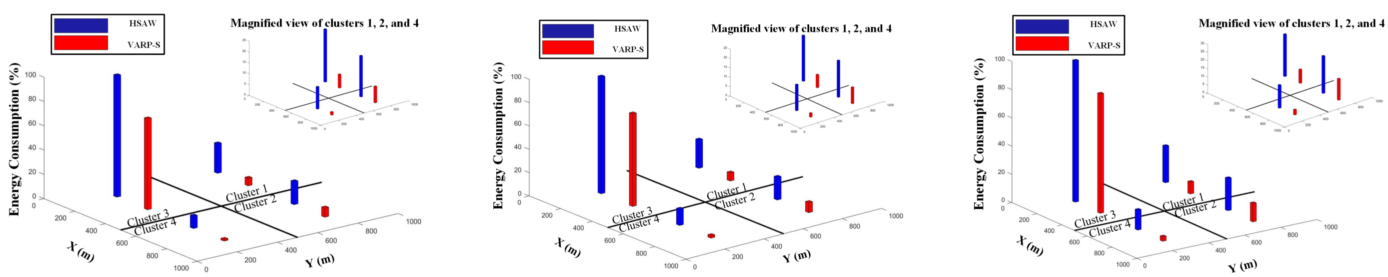
*(**a**) Node´s velocity = 3 m/s* *(**b**) Node´s velocity = 10 m/s* *(**c**) Node´s velocity = 20 m/s*

Figure 4: *Total routing overhead in cellular-band (bits/s).*



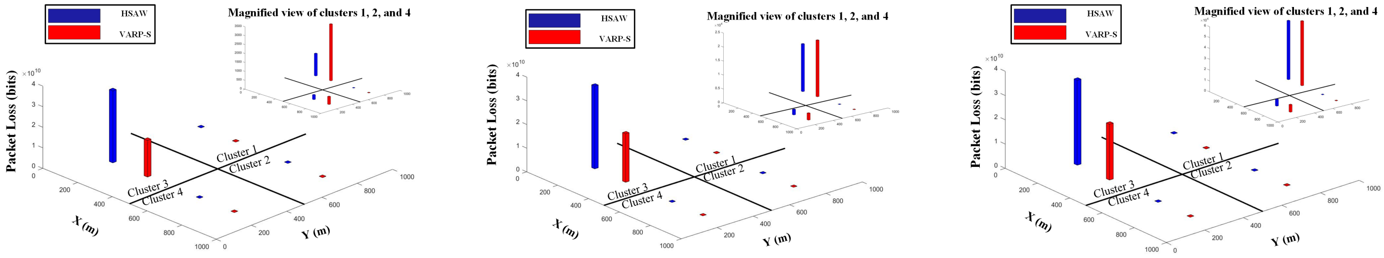
*(**a**) Node´s velocity = 3 m/s* *(**b**) Node´s velocity = 10 m/s* *(**c**) Node´s velocity = 20 m/s*

Figure 5: *End-to-end delay (sec).*



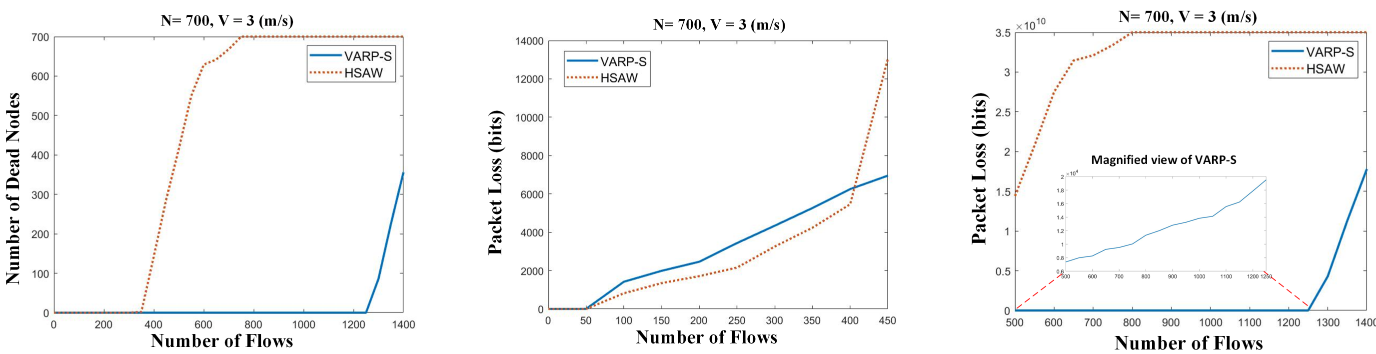
*(**a**) Node´s velocity = 3 m/s* *(**b**) Node´s velocity = 10 m/s* *(**c**) Node´s velocity = 20 m/s*

Figure 6: *Energy consumption of nodes (%).*



(a) Node´s velocity = 3 m/s *(b) Node´s velocity = 10 m/s* *(c) Node´s velocity = 20 m/s*

Figure 7: *Packet Loss.*



(a) No.Dead nodes vs. No.Flows *(b) Packet loss vs. No.Flows (0-450 flows)* *(c) Packet loss vs. No.Flows (500-1400 flows)*

Figure 8: *Packet loss over a densely populated network.*

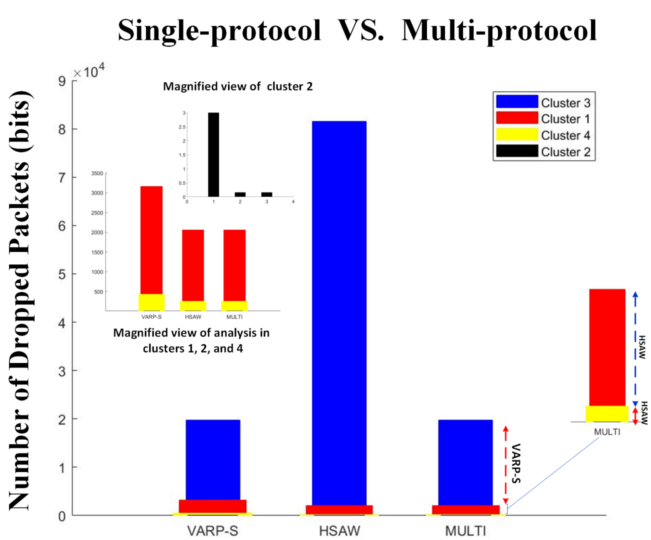


Figure 9: *Performance analysis of multi-protocol framework vs. single-protocol framework in terms of Packet loss.*

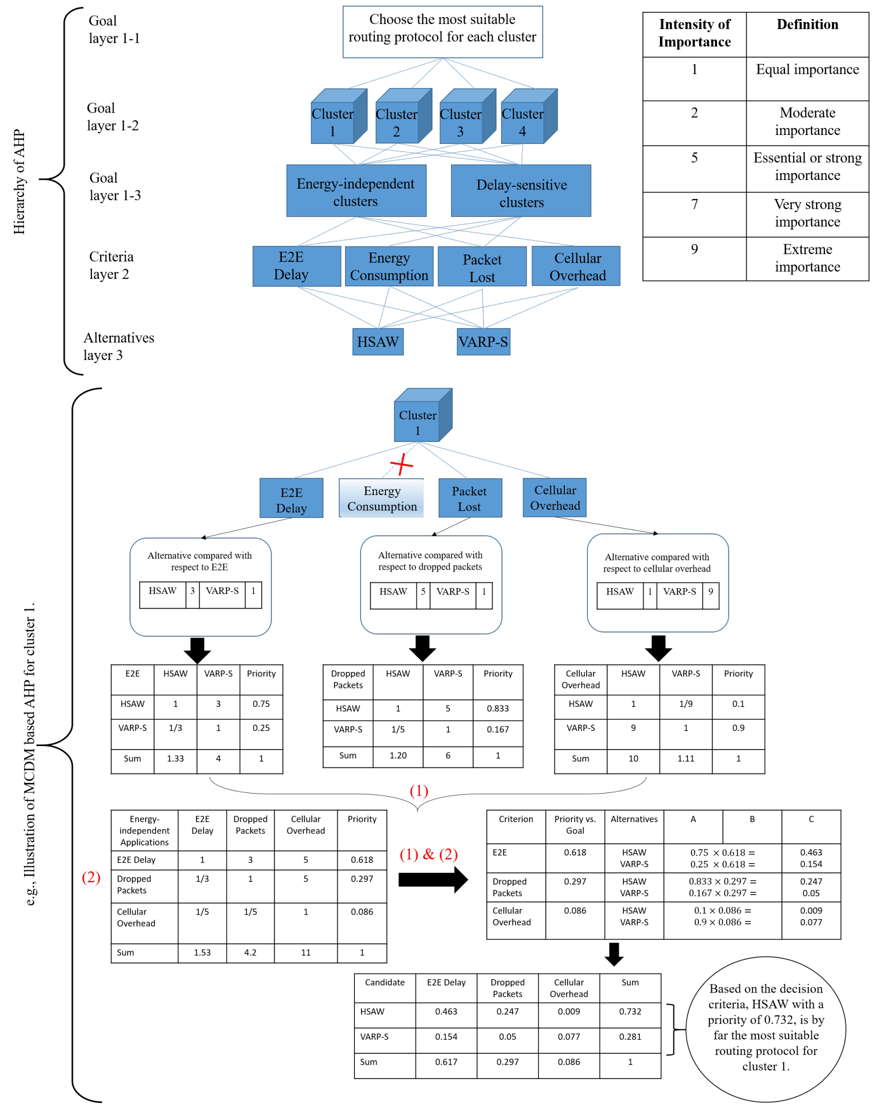


***Figure 10:** AHP decision-making process to select the most suitable routing protocol for each cluster.*

Table II: Suitable protocol for energy-independent and delay-sensitive clusters based on the AHP decision-making.

Decision / Cluster	Decision Strategy	
	Energy-independent clusters	**Delay-sensitive clusters**
Cluster 1	HSAW	HSAW
Cluster 2	VARP-S	VARP-S
Cluster 3	VARP-S	VARP-S
Cluster 4	HSAW	HSAW

*4) **Packet loss**:* Figure 7 demonstrates the functionality of the protocols in terms of packet loss. Except cluster 3, HSAW provides more reliable data delivery than VARP-S because it has a faster response to the link failure, as explained in Sec. VI-A2. In cluster 3, the network experiences a higher number of flows leading to nodes consume more energy in HSAW compared to VARP-S, as depicted in Fig. 6. Consequently, nodes run out of the battery, which leads to more packet loss and link failure in HSAW. Fig. 7 also shows that by increasing the mobility rate, the packet loss increases due to frequent link failure.

To further investigate the impact of the number of flows on the packet loss in dense networks, in Fig. 8, we compare the performance of the protocols for cluster 3 with 700 nodes, when the number of flows increased from 0 to 1400. As shown, HSAW provides better performance when the number of flows is less than 450 (see Fig. 8b). However, when the number of flows exceeds 450, nodes in HSAW deplete their batteries, resulting in a high number of dead nodes in the cluster (see Fig. 8a). This significantly increases the packet loss in the HSAW. Consequently, VARP-S is a better choice for cluster 3 when the number of flows is greater than 450 (see Fig. 8c).

B. Routing Protocol Decision-making for Each Cluster

We use the MCDM approach based on AHP [49] to select the best routing protocol for each cluster in terms of the defined criteria (i.e., E2E delay, packet loss, energy consumption, and cellular overhead). Further, the high-demand services and energy-dependency of the devices in the cluster are taken into account when selecting the routing protocol. The selection of protocols is investigated for two different scenarios to demonstrate the advantages of having a multi-protocol framework when different protocols are selected for each cluster based on the cluster requirements. The first scenario is for the clusters where nodes are energy-independent, such as vehicular networks. The second scenario is for clusters wherein the high-demand services are delay-sensitive applications that time matters most, such as hospitals or public safety scenarios. In such applications, the level of importance of cellular overhead is very low and can be ignored in AHP decision-making.

As shown in Fig. 10, the AHP hierarchy architecture is adapted to our model. The goal is to select the best routing protocol for each cluster based on the defined scenarios in Sec. VI-B. The criteria are E2E delay, packet loss, energy consumption, and cellular overhead. Two potential routing protocols, VARP-S and HSAW, are shortlisted alternatives for each cluster. Due to space constraints, we only demonstrate the AHP process for cluster 1 for the first scenario that nodes are energy-independent. For such applications, we can ignore the energy criteria because the weight of this criterion is too small and its impact on the overall decision is negligible. The AHP online calculator [56] is used to calculate the priorities of the criteria and alternatives. Based on the decision criteria, HSAW with a priority of 0.732 is by far the most suitable routing protocol for cluster 1. Similarly, the same process can be applied to the other clusters. The results of decision-making are summarized in Table II for the previously defined scenarios: energy-independent and delay-sensitive. The most suitable protocol for each cluster is concluded in the "Decision Strategy" section of Table II based on the AHP results.

C. Performance Analysis of Multi-protocol Framework vs. Single-protocol Framework

From the simulation results, it is concluded that for a sparsely distributed cellular network, both protocols perform well as neither are pushed to their operational limits. However, there are clear distinctions between the protocols when either traffic flow or node density is high. To clarify and show how a specific network performance parameter can be improved using our proposed multi-protocol framework, we investigate the framework performance in terms of packet loss. At first, one type of protocol is run in all the clusters to determine the performance of each protocol (see bars VARP-S and HSAW in Fig. 9). As shown in Fig. 7, except cluster 3, HSAW provides better performance than VARP-S, owing to its faster response to network failures, as discussed in Sec. VI-A4. The "Multi" bar in Fig. 9 represents the advantage of leveraging the best features of both protocols to provide reliable data delivery. This is achieved by running the most efficient protocol in each cluster, i.e., VARP-S for cluster 3 and HSAW for other clusters, to minimize the total packet loss in the entire network.

VII. Conclusions

This paper presented a novel SDN-based multi-protocol routing architecture to enable the use of multiple MD2D routing protocols under one framework. In this paper, an SDN controller split the network into different clusters based on the observed network geometry. Moreover, the performance of the selected protocols, HSAW and VARP-S, was analyzed in each cluster in terms of energy, E2E delay, packet loss, and cellular overhead. Building on our analysis and results, the AHP MCDM method was used to choose the most suitable routing protocol for each cluster. Our results showed that our proposed framework provides better performance when compared to traditional single-protocol network scenarios.

VIII. Future Work

This study has the potential to be a steppingstone for exploring the integration of different multi-hop routing protocols into a multi-protocol framework, wherein each protocol is used in its suitable network environment. In the future, we will analyze the proposed passive programming and compare its performance with active programming approaches. We will also extend our simulation study and perform a detailed comparison with other existing routing frameworks.

We also intend to explore the potential integration of our proposed multi-protocol framework over O-RAN. O-RAN specification defines a unified software-defined service-oriented infrastructure for 5G and beyond wireless networks, which has opened the pathway towards developing and integrating novel network applications for cellular networks [57]–[59]. O-RAN provides open-source software for modeling and developing protocols for the RAN. This enables us to develop novel network applications and protocols, in the form of NFVs (also referred to as rApps and xApps in the O-RAN architecture) over the RAN.

References

[1] A. Ahad, M. Tahir, M. Aman Sheikh, K. I. Ahmed, A. Mughees, and A. Numani, "Technologies trend towards 5g network for smart health-care using iot: A review," *Sensors*, vol. 20, no. 14, p. 4047, 2020.

[2] K. Samdanis and T. Taleb, "The road beyond 5g: A vision and insight of the key technologies," *IEEE Network*, vol. 34, no. 2, pp. 135–141, 2020.

[3] M. Kumhar and J. Bhatia, "Emerging communication technologies for 5g-enabled internet of things applications," in *Blockchain for 5G-Enabled IoT*. Springer, 2021, pp. 133–158.

[4] A. Dogra, R. K. Jha, and S. Jain, "A survey on beyond 5g network with the advent of 6g: Architecture and emerging technologies," *IEEE Access*, vol. 9, pp. 67 512–67 547, 2020.

[5] X. You, C.-X. Wang, J. Huang, X. Gao, Z. Zhang, M. Wang, Y. Huang, C. Zhang, Y. Jiang, J. Wang *et al.*, "Towards 6g wireless communication networks: Vision, enabling technologies, and new paradigm shifts," *Science China Information Sciences*, vol. 64, no. 1, pp. 1–74, 2021.

[6] S. Manap, K. Dimyati, M. N. Hindia, M. S. A. Talip, and R. Tafazolli, "Survey of radio resource management in 5g heterogeneous networks," *IEEE Access*, vol. 8, pp. 131 202–131 223, 2020.

[7] T. Li, J. Chen, and H. Fu, “Application scenarios based on sdn: An overview,” in *Journal of Physics: Conference Series*, vol. 1187, no. 5. IOP Publishing, 2019, p. 052067.

[8] K. Nisar, I. Welch, R. Hassan, A. H. Sodhro, and S. Pirbhulal, “A survey on the architecture, application, and security of software defined networking,” *Internet of Things*, p. 100289, 2020.

[9] S. H. Haji, S. R. Zeebaree, R. H. Saeed, S. Y. Ameen, H. M. Shukur, N. Omar, M. A. Sadeeq, Z. S. Ageed, I. M. Ibrahim, and H. M. Yasin, “Comparison of software defined networking with traditional networking,” *Asian Journal of Research in Computer Science*, pp. 1–18, 2021.

[10] S. Faid and M. Moughit, “The benefits of sdn integration on 5g mobile network,” in *International Conference on Artificial Intelligence and Symbolic Computation*. Springer, 2019, pp. 266–276.

[11] S. K. Tayyaba and M. A. Shah, “5g cellular network integration with sdn: Challenges, issues and beyond,” in *2017 International Conference on Communication, Computing and Digital Systems (C-CODE)*. IEEE, 2017, pp. 48–53.

[12] M. Hicham, N. Abghour, and M. Ouzzif, “5g mobile networks based on sdn concepts,” *International Journal of Engineering and Technology (UAE)*, vol. 7, no. 4, pp. 2231–2235, 2018.

[13] A. Abdulghaffar, A. Mahmoud, M. Abu-Amara, and T. Sheltami, “Modeling and evaluation of software defined networking based 5g core network architecture,” *IEEE Access*, vol. 9, pp. 10 179–10 198, 2021.

[14] H. Fall, O. Zytoune, and M. Yahyai, “to radio resource distribution approach in wireless cellular software defined networking,” *International Journal of Advanced Intelligence Paradigms*, vol. 13, no. 3-4, pp. 449–461, 2019.

[15] C. N. Tadros, M. R. Rizk, and B. M. Mokhtar, “Software defined network-based management for enhanced 5g network services,” *IEEE Access*, vol. 8, pp. 53 997–54 008, 2020.

[16] Z. Zhou, J. Gong, Y. He, and Y. Zhang, “Software defined machine-to-machine communication for smart energy management,” *IEEE Communications Magazine*, vol. 55, no. 10, pp. 52–60, 2017.

[17] H. H. Hussein, H. A. Elsayed, A. El-kader, and M. Sherine, “Intensive benchmarking of d2d communication over 5g cellular networks: prototype, integrated features, challenges, and main applications,” *Wireless Networks*, vol. 26, no. 5, pp. 3183–3202, 2020.

[18] L. Nadeem, M. A. Azam, Y. Amin, M. A. Al-Ghamdi, K. K. Chai, M. F. N. Khan, and M. A. Khan, “Integration of d2d, network slicing, and mec in 5g cellular networks: Survey and challenges,” *IEEE Access*, vol. 9, pp. 37 590–37 612, 2021.

[19] B. Manoj, R. Ananthapadmanabha, and C. S. R. Murthy, “Multi-hop cellular networks: Architecture and protocols for best-effort and real-time communication,” *Journal of Parallel and Distributed Computing*, vol. 65, no. 6, pp. 767–791, 2005.

[20] U. N. Kar and D. K. Sanyal, “An overview of device-to-device communication in cellular networks,” *ICT express*, vol. 4, no. 4, pp. 203–208, 2018.

[21] S. V. A. Amanuel and S. Y. A. Ameen, “Device-to-device communication for 5g security: A review,” *Journal of Information Technology and Informatics*, vol. 1, no. 1, pp. 26–31, 2021.

[22] F. S. Shaikh and R. Wismüller, “Routing in multi-hop cellular device-to-device (d2d) networks: A survey,” *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 2622–2657, 2018.

[23] U. N. Kar and D. K. Sanyal, “A critical review of 3gpp standardization of device-to-device communication in cellular networks,” *SN Computer Science*, vol. 1, no. 1, pp. 1–18, 2020.

[24] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, “An overview of 3gpp device-to-device proximity services,” *IEEE Communications Magazine*, vol. 52, no. 4, pp. 40–48, 2014.

[25] P. K. Malik, D. S. Wadhwa, and J. S. Khinda, “A survey of device to device and cooperative communication for the future cellular networks,” *International Journal of Wireless Information Networks*, pp. 1–22, 2020.

[26] A. H. Alquhali, M. Roslee, M. Y. Alias, and K. S. Mohamed, “D2d communication for spectral efficiency improvement and interference reduction: A survey,” *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 3, pp. 1085–1094, 2020.

[27] G. Zhao, S. Chen, L. Qi, L. Zhao, and L. Hanzo, “Mobile-traffic-aware offloading for energy-and spectral-efficient large-scale d2d-enabled cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 6, pp. 3251–3264, 2019.

[28] S. Jayakumar and S. Nandakumar, “A review on resource allocation techniques in d2d communication for 5g and b5g technology,” *Peer-to-Peer Networking and Applications*, vol. 14, no. 1, pp. 243–269, blue.

[29] A. Asadi, Q. Wang, and V. Mancuso, “A survey on device-to-device communication in cellular networks,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[30] O. Narmanlioglu and E. Zeydan, “Software-defined networking based network virtualization for mobile operators,” *Computers & Electrical Engineering*, vol. 57, pp. 134–146, 2017.

[31] K. Pentikousis, Y. Wang, and W. Hu, “Mobileflow: Toward software-defined mobile networks,” *IEEE Communications magazine*, vol. 51, no. 7, pp. 44–53, 2013.

[32] S. K. Tayyaba and M. A. Shah, “Resource allocation in sdn based 5g cellular networks,” *Peer-to-Peer Networking and Applications*, vol. 12, no. 2, pp. 514–538, 2019.

[33] G. Yu, R. Liu, Q. Chen, and Z. Tang, “A hierarchical sdn architecture for ultra-dense millimeter-wave cellular networks,” *IEEE Communications Magazine*, vol. 56, no. 6, pp. 79–85, 2018.

[34] K. Wang, Y. Wang, D. Zeng, and S. Guo, “An sdn-based architecture for next-generation wireless networks,” *IEEE Wireless Communications*, vol. 24, no. 1, pp. 25–31, 2017.

[35] K. Abbas, M. Afaq, T. Ahmed Khan, A. Rafiq, J. Iqbal, I. Ul Islam, and W.-C. Song, “An efficient sdn-based lte-wifi spectrum aggregation system for heterogeneous 5g networks,” *Transactions on Emerging Telecommunications Technologies*, p. e3943, 2020.

[36] K. Ouali, M. Kassar, T. M. T. Nguyen, K. Sethom, and B. Kervella, “An efficient d2d handover management scheme for sdn-based 5g networks,” in *2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)*, blue, pp. 1–6.

[37] H. B. Valiveti and C. Duggineni, “Software defined device to device communication handover-latest advancements,” in *2021 6th International Conference on Inventive Computation Technologies (ICICT)*. IEEE, 2021, pp. 1079–1083.

[38] I. Elgendi, K. S. Munasinghe, and A. Jamalipour, “A three-tier sdn architecture for densenets,” in *2015 9th International Conference on Signal Processing and Communication Systems (ICSPCS)*. IEEE, 2015, pp. 1–7.

[39] J. Liu, S. Zhang, N. Kato, H. Ujikawa, and K. Suzuki, “Device-to-device communications for enhancing quality of experience in software defined multi-tier lte-a networks,” *IEEE Network*, vol. 29, no. 4, pp. 46–52, 2015.

[40] M. Usman, A. A. Gebremariam, U. Raza, and F. Granelli, “A software-defined device-to-device communication architecture for public safety applications in 5g networks,” *IEEE Access*, vol. 3, pp. 1649–1654, 2015.

[41] R. Jayadi and Y.-C. Lai, “Low-overhead multihop device-to-device communications in software defined wireless networks,” in *2017 International Conference on Soft Computing, Intelligent System and Information Technology (ICSIIT)*. IEEE, 2017, pp. 144–149.

[42] M. Kaplan, C. Zheng, M. Monaco, E. Keller, and D. Sicker, “Wasp: a software-defined communication layer for hybrid wireless networks,” in *2014 ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS)*. IEEE, 2014, pp. 5–15.

[43] J. Park and W. Yoon, “An architecture of multi-layered sdn based lte/wifi network for multi-interface d2d users,” in *2018 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2018, pp. 1161–1163.

[44] Y. Cui, J. Song, K. Ren, M. Li, Z. Li, Q. Ren, and Y. Zhang, “Software defined cooperative offloading for mobile cloudlets,” *IEEE/ACM Transactions on Networking*, vol. 25, no. 3, pp. 1746–1760, 2017.

[45] A. Muthanna, A. A. Ateya, M. Al Balushi, and R. Kirichek, “D2d enabled communication system structure based on software defined networking for 5g network,” in *2018 International Symposium on Consumer Technologies (ISCT)*. IEEE, 2018, pp. 41–44.

[46] M. Abolhasan, M. Abdollahi, W. Ni, A. Jamalipour, N. Shariati, and J. Lipman, “A routing framework for offloading traffic from cellular networks to sdn-based multi-hop device-to-device networks,” *IEEE Transactions on Network and Service Management*, vol. 15, no. 4, pp. 1516–1531, 2018.

[47] M. Abolhasan, J. Lipman, W. Ni, and B. Hagelstein, “Software-defined wireless networking: centralized, distributed, or hybrid?” *IEEE Network*, vol. 29, no. 4, pp. 32–38, 2015.

[48] M. Abdollahi, M. Abolhasan, N. Shariati, J. Lipman, A. Jamalipour, and W. Ni, “A routing protocol for sdn-based multi-hop d2d communications,”

in *2019 16th IEEE Annual Consumer Communications & Networking Conference (CCNC)*. IEEE, 2019, pp. 1–4.

[49] T. L. Saaty, "Decision making—the analytic hierarchy and network processes (ahp/anp)," *Journal of systems science and systems engineering*, vol. 13, no. 1, pp. 1–35, 2004.

[50] H. Taherdoost, "Decision making using the analytic hierarchy process (ahp); a step by step approach," *International Journal of Economics and Management Systems*, vol. 2, 2017.

[51] T. Kardi, "Analytic hierarchy process (ahp) tutorial," *Revoledu. com. Available online: https://tinyurl.com/jpu7pms6 (accessed on 21 September 2021)*, 2006.

[52] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 831–846, 2014.

[53] S. Ashtari, F. Tofigh, M. Abolhasan, J. Lipman, and W. Ni, "Efficient cellular base stations sleep mode control using image matching," in *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*. IEEE, 2019, pp. 1–7.

[54] P. Mishra, C. Gandhi, and B. Singh, "Link quality and energy aware geographical routing in manets using fuzzy logics," *Journal of Telecommunications and Information Technology*, 2016.

[55] M. U. Younus, S. W. Kim *et al.*, "Proposition and real-time implementation of an energy-aware routing protocol for a software defined wireless sensor network," *Sensors*, vol. 19, no. 12, p. 2739, 2019.

[56] D. Goepel, Klaus, "AHP Priority Calculator," 2019, https://bpmsg.com/ahp/ahp-calc.php, Last accessed on 2021-01-20.

[57] S. K. Singh, R. Singh, and B. Kumbhani, "The evolution of radio access network towards open-ran: challenges and opportunities," in *2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*. IEEE, 2020, pp. 1–6.

[58] P. H. Masur and J. H. Reed, "Artificial intelligence in open radio access network," *arXiv preprint arXiv:2104.09445*, 2021.

[59] L. Bonati, S. D'Oro, M. Polese, S. Basagni, and T. Melodia, "Intelligence and learning in o-ran for data-driven nextg cellular networks," *arXiv preprint arXiv:2012.01263*, 2020.

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