Soft-Safe: Software Defined Safety-as-a-Service for Intelligent Transportation System

Ruelia Saha[‡], Chandana Roy[†], *Student Member, IEEE*, and Sudip Misra[§], *Senior Member, IEEE*
[‡ §]Department of Computer Science and Engineering, [†] Department of Industrial & Systems Engineering,
[‡†§]Indian Institute of Technology Kharagpur, India
{[‡]rueliasahacse, [†]chandanaroy, [§]sudipm }@iitkgp.ac.in

***Abstract*—In this work, we propose Soft-Safe, a Software Defined Safety-as-a-Service (Safe-aaS) model for provisioning safety-related decisions to the registered end-users. In Safe-aaS, the end-users register to the infrastructure, provide their initial and destination location, select certain decision parameters, and make payment through a Web portal. As the safety-related decisions are time-critical in nature, therefore timely delivery of these decisions is essential. Considering these facts and road transportation as the application scenario of Safe-aaS, we address the problem of efficient decision delivery to the end-users in two stages. In the first stage, we propose a Software Defined Safe-aaS platform to address the problems of heterogeneity among the SDN switches present in the edge layer. Further, based on the utility of each of the SDN switches present within the vicinity of the end-users, we optimally select a suitable SDN switch among the available ones, for delivering them decisions. To obtain the maximum utility for delivering decisions to the end-users, we map the interactions between the SDN controller and SDN switches as a *Non-cooperative Single Leader Multiple Follower* game. Then, we estimate the optimal delay incurred by an SDN switch applying the Lagrangian function and Karush-Kuhn-Tucker (KKT) conditions. Exhaustive simulation results illustrate that the energy consumed and delay incurred using our proposed scheme, Soft-Safe, is reduced compared to the existing schemes, Traditional Safe-aaS and MoRule.**

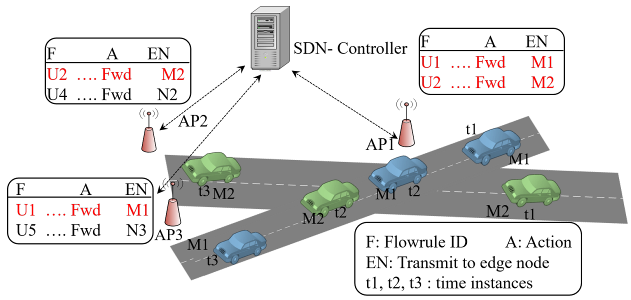
***Keywords*—Safety-as-a-Service (Safe-aaS), Software Defined Network (SDN), Stackelberg game, Decision Virtualization, Road Transportation, Safety**

I. Introduction

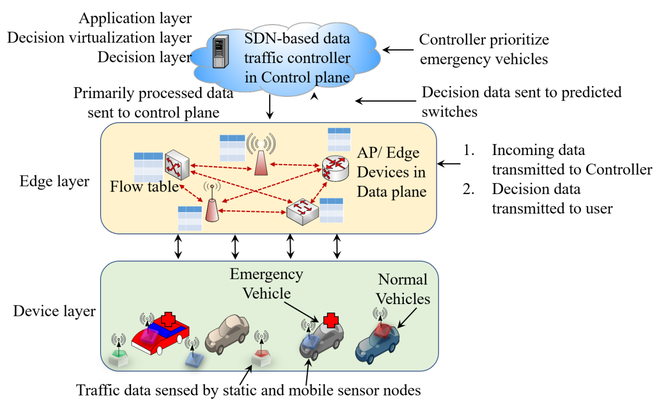
With the increase in the number of on-road vehicles, the rate of rise in traffic congestion, accidents, and casualties have increased significantly. Internet of Vehicles (IoV), an application of Internet of Things (IoT) in the field of road transportation, allows the transfer of data in real-time [1]–[3]. Further, to improve the on-road safety of drivers as well as vehicles, various safety-related schemes such as Advanced Driver Assistance Systems (ADAS) [4]–[7] and Intelligent Transportation Systems (ITS) [8]–[11] have attained a popularity for provisioning assistance to the drivers and management of traffic. However, the prior intimation of on-road safety-related information to the drivers results in the reduction of accidents to a considerable extent. Safe-aaS [12]–[15] is a unique platform, which provides safety-related information to multiple end-users simultaneously, founded on the concept of decision virtualization. Considering road transportation as the application scenario of Safe-aaS, we propose an SDN-based Safe-aaS infrastructure to address the resource-constrained nature of sensor and edge nodes, and efficiently manage the available resources.

Typically, the end-users register, provide the source and destination details, select certain decision parameters, and make payment through a Web portal. Based on their selected decision parameters, a decision is provided to them. The heterogeneous types of static and mobile sensor nodes present in the device layer sense and transmit data to the edge layer/cloud, depending upon the time-critical nature of the sensed data. The mobile sensor nodes are attached to the vehicles, while the static ones are deployed at a particular geographical location. On the other hand, the nodes present in the edge layer are resource-constrained in nature. The number and type of edge nodes present within the vicinity of the end-users change with their mobility. For better management of the network and these heterogeneous edge devices, we propose a software defined Safe-aaS infrastructure. We assume the edge nodes as the SDN switches, which primarily process the time-critical nature of the raw sensed data and transmit them to the decision layer for decision generation. Additionally, these SDN switches deliver decisions to the end-users, based on their locations. To deliver the decision, the flow rule is updated at the selected SDN switch. The SDN controller acts as the centralized entity present in the control plane, which provides a global view of the network. In our proposed scheme, Soft-Safe, we consider that the SDN controller performs the functionalities of the decision, decision virtualization, and application layer of Safe-aaS. Therefore, the interactions between the SDN controller and the switches permit the updating of flow rule at the selected SDN switch, among the available ones present within the vicinity of an end-user.

Existing research works on road safety reveal various aspects of provisioning safety-related information such as weather conditions, driver assistance systems, and road conditions to the drivers and pedestrians [5], [8], [9], [16]. Safe-aaS is a newly designed, unique platform, which provides customized safety-related decisions dynamically to the end-users. Founded on the concept of decision virtualization, the same decision is provided to multiple end-users. Heterogeneous types of static and mobile sensor nodes are present in the device layer of Safe-aaS. These sensor nodes sense and transmit data to the edge layer/cloud, depending upon the time-criticality of data. Further, the edge nodes are also heterogeneous in terms of their specifications. The sensor and edge nodes are also resource-constrained in nature. With the variation in the geographical location of the vehicles, the sensor nodes attached to them attain mobility. Therefore, the number and type of edge nodes present within the communication range of these mobile sensor nodes also fluctuate. The integration of SDN with Safe-aaS eliminates the problems associated with the heterogeneity of the edge nodes. We model the edge nodes present in the edge layer as switches. In another aspect, SDN decouples the data plane from the control



(a) Motivating Scenario



(b) The System Architecture

Fig. 1: Soft-Safe

plane and assists in the efficient management of the resources. Therefore, the selection of the appropriate switch is necessary to provide the decision to the end-users with their variation in location. This results in minimization of delay incurred in the delivery of the generated decisions. The redundant utilization of the resources such as energy, bandwidth, and storage space, for updating the flow rules in each of the available switches, is also avoided. Therefore, a Software-Defined Safe-aaS is one of the possible solutions, for the selection of the appropriate SDN switch to deliver a decision to the end-user, in terms of delay incurred and efficient management of the resources.

Motivating Scenario: In Fig. 1(a), we depict a network which comprises static and mobile sensor nodes, SDN switches/APs, and a SDN controller. $M1$ and $M2$ belong to the end-users of Soft-Safe. Both the end-users are unknown to the road, so they register to the Safe-aaS platform for road condition and shortest path. At time instant, $t2$, both these vehicles were at the same location. The SDN-based traffic controller transmits their decision to the APs after processing the sensed data, as per the end-users requirement. The APs are resource-constrained in nature, hence updating the flow rule in all the APs, present within the vicinity of the end-user, consumes unnecessary storage space, energy, and bandwidth. Therefore, the SDN controller implements the cost function for the selection of the optimized edge node to store the flow rule. Further, the generated decision within the AP is transmitted to the end-user. As per the decision transmitted by AP1, $M1$ and $M2$ change their route, at time instant $t3$. Therefore, the flow rule for the packet containing the decision is stored in AP2 and AP3, respectively.

In this proposed scheme, Soft-Safe, we primarily aim to resolve the following issues associated with the Safe-aaS infrastructure: a) How to eliminate the heterogeneity that exists among the edge nodes? b) How to update the flow table at the SDN switches, such that the resource-constrained nature of these switches is efficiently handled using the present geographical location of that end-user? To address these issues, we propose an SDN-based Safe-aaS infrastructure. The specific contributions of this work are as follows:

- We propose a Software-Defined Safe-aaS platform to eliminate the heterogeneity issues faced by the edge nodes present in the edge layer. We consider these edge nodes as SDN switches, which are placed at the data plane.
- We design the SDN-based traffic controller in the control plane that provides flow control to the SDN switches as well as processes the data and generates decisions for the end-users. The SDN controller performs functionalities of the decision, decision virtualization, and application layer of Safe-aaS, as shown in Fig. 1(b).
- We apply *Non-Cooperative Single Leader Multiple Follower Stackelberg* game to model the interactions among the SDN controller and SDN switches, present within the vicinity of the end-user. Further, we design the optimization function to estimate the maximum utility in the selection of the appropriate SDN switch, depending upon the residual energy, bandwidth, available storage space, and delay incurred. To simplify the function, we use Lagrangian Multiplier and apply Karush-Kuhn-Tucker (KKT) conditions to solve it. Finally, the optimal delay incurred by the SDN switch is selected for delivering the generated decision to the end-user.
- Through extensive simulation, we analyze the proposed scheme and observe that the delay incurred and energy consumed for transmitting the data to the end-users is reduced significantly, compared to the traditional Safe-aaS [12] and MoRule [17]. Additionally, Soft-Safe provides maximum utilization of the memory space available at the SDN switches.

The rest of this paper is organized as follows – Section II discusses the prior research works on road safety and SDN, Section III illustrates the problem scenario, mathematical analysis, and solution approach, Section IV describes the simulation setup, results, and benchmarks, and Section V concludes the proposed work.

II. Related Work

In this section, we discuss some of the prior research works undergone in the field of on-road safety in Intelligent Transportation System (ITS) [1], [12]–[14], [18]–[21] and their various applications in Software Defined Networks (SDNs) [22]–[29].

Lu *et al.* [19] surveyed on the available wireless technologies along with the potential challenges for providing connectivity among "Vehicle-to-X". The authors discussed the various challenges associated with the wireless solutions specially for the infrastructure connectivity between Vehicle-to-Sensor, Vehicle-to-Vehicle, Vehicle-to-Internet, and Vehicle-to-Road. On the other hand, vehicular cloud computing (VCC) is an emerging hybrid technology, in the field of traffic management and road safety, which makes utilization of diverse vehicular resources to deliver on-road information. Similarly, Whaiduzzaman *et al*. [30] considered the various challenges in vehicular networks and performed an extensive survey on VCC. The authors highlighted the extensive applications, cloud formations, key management, and inter-cloud communication systems. Additionally, they also discussed these above-mentioned issues in terms of privacy and security and compared the mechanism of VCC with Cloud Computing (CC). Further, Tassi *et al*. [20] proposed a new theoretical model on mmWave-based highway communication networks, where the authors considered a highway scenario, in the presence of heavy vehicles. They considered these heavy vehicles as a blockage in the slow lanes and applied the stochastic geometry tool to derive the approximations for Signal-to-Interference-plus-Noise Ratio (SINR) outage probability. Additionally, the authors discussed that a reduction in the horizontal beam from 90° to 30° resulted in the reduction of the SINR outage probability. On the other hand, Peng *et al*. [21] presented an overview on vehicular communication, from the network layer perspective. The authors explained the applications, driving pattern classification, and highlighted the unique characteristics of the vehicular communication network. Further, Mendiboure *et al*. [29] proposed SDN-based Pub/Sub middleware for content dissemination. Recently a unique platform was proposed by Roy *et al*., termed as Safety-as-a-Service infrastructure [12]–[14], which provides customized on-road safety-related decisions dynamically to the registered end-users, through the Web portal. The authors discussed a pay-per-use model, using which the registered end-users select the decision parameters to receive on-road safety-related decisions, based on their requirements. Additionally, they coined the term decision virtualization, depending upon which the virtualized decisions were delivered to the multiple end-users simultaneously. Further, Roy *et al*. [15] considered the energy-constraint nature of the sensor nodes and proposed a scheme for provisioning energy-efficient safety-related decisions to the end-users.

In another aspect, SDN is an emerging technology, which brings forth programmability, agility, and centralized management of the network. Bera *et al*. [25] performed a comprehensive survey on the various aspects of SDN for fulfilling the requirements of the Internet of Things (IoT)-based technologies in the different networking aspects such as edge, access, core, and data center networking. On the other hand, Sadio *et al*. [23] designed and implemented a prototype of an SDN in the real-life scenario. The authors used OpenFlow switches to design the SDN-based backbone. Further, they tested the SDN-based radio access on WiFi Access Points which supported OpenvSwitch/OpenFlow and Click Modular Router. Finally, the authors implemented OpenFlow switch functionalities on a Single Board Computer which was used as an On-Board Unit (OBU). Rego *et al*. [28] proposed a hybrid IoT-SDN based architecture for smart cities. In another work, Salahuddin *et al*. [22] presented a novel roadside unit (RSU) cloud and a vehicular cloud, as the operational backbone of the vehicle grid in the Internet of Vehicles (IoV) environment. The proposed RSU cloud architecture consisted of both traditional and specialized RSUs employing Software-Defined Networking (SDN) to dynamically replicate, instantiate, and migrate services. The authors configured these services and data forwarding information was dynamically hosted in the network to efficiently serve the underlying demand from the vehicular grid.

Synthesis: From the existing research works on road safety, SDN and its diverse applications, in the field of cloud computing, we observed that there exists a research lacuna in the field of SDN-based Intelligent Transportation System with the integration of cloud/fog architecture, for handling the time-critical data in the IoT scenario. The existing works consider SDN-based IoV architecture for providing optimized flow rule placement [24], [27] and enhanced network management [26]. Further, research is also performed on Vehicular cloud computing for handling time-critical data. However, a single architecture for the management of both time-critical nature of data as well as resource-constrained nature of the edge devices, is not yet addressed.

III. Problem Scenario

A. Architecture

We consider an Intelligent Transportation System (ITS), where Safe-aaS [12]–[15] infrastructure is implemented. Typically, Safe-aaS is a unique platform, which provides customized safety-related decisions to the end-users. Safe-aaS is a five-layered architecture – *device*, *edge*, *decision*, *decision virtualization*, and *application*. The device layer comprises heterogeneous types of static and mobile sensor nodes. These sensor nodes sense and transmit data to the edge nodes/cloud, based on the time-critical nature of data. The primarily processed data from the edge nodes/cloud are transmitted to the decision layer for decision generation. The decisions generated are a combination of multiple sensor data. Further, the mapping of these generated decisions with the end-users requests are done in the decision virtualization layer. On the other hand, the application layer acts as the interface between the end-users and the Safe-aaS platform. The end-users register themselves, select certain decision parameters, and make payment, through the Web portal. A Safety Service provider (SSP) is the centralized entity, who provides safety-related decisions to the end-users. The other two important entities – sensor and vehicle owners – rent their sensor nodes to the Safe-aaS infrastructure. In return, these sensor and vehicle owners receive an amount from the SSP as rent.

In Safe-aaS, the edge layer comprises heterogeneous types of edge nodes. We represent these edge nodes as SDN switches, which form the data plane in the SDN-enabled Safe-aaS. These SDN switches transmit a packet-in signal to the SDN-enabled traffic controller. The decision, decision virtualization, and application layer together form the control plane, where the SDN controller is centrally placed. Additionally, the controller possesses a global view of the network, designs flow rules for the unknown data packets, and applies certain machine learning (ML) algorithms. As the location of the end-users changes with their mobility, the number and type of access points present within their vicinity also fluctuates. The downlink transmission of the data packets to the selected nearest SDN switch of the end-user is performed by the SDN controller. Based on their available energy, storage space, bandwidth used, and delay incurred in the delivery of the decisions, the appropriate SDN switch is selected among the ones present within the vicinity of the end-user. Finally, the flow rule is updated at the selected SDN switch and the decision is delivered to the end-users.

B. Mathematical Formulation

Suppose, $\mathbb{O} = \{O_1, O_2, \cdots, O_m\}$ be the set of owners (sensors/vehicles owners) present in the scenario, who deploy heterogeneous types of static and mobile sensor nodes at different geographical location and/or into the vehicles. These sensor nodes sense and transmit their data to the edge nodes/cloud, based on the time-critical nature of data and are represented as $\mathbb{S} = \{S_1, S_2, \cdots, S_n\}$. We consider $\mathbb{E} = \{E_1, E_2, \cdots, E_p\}$ as the set of SDN switches present in the network for primary processing the data, update the flow rules at the selected SDN switch, and deliver the generated decision to the appropriate end-user through the selected switch. Further, the total energy, $\mathbb{E}_i^t$, consumed by the i^{th} SDN switch is denoted as the combination of the energy required to transmit the data to the controller, active ports of the switch, and processes the flow rules. Mathematically,

$$\mathbb{E}_i^t = \mathbb{E}_{trans}^t + \mathbb{E}_{port}^t N_a + \mathbb{E}_{fr}^t N_{fr} \tag{1}$$

where $\mathbb{E}_{trans}^t$, $\mathbb{E}_{port}^t$, and $\mathbb{E}_{fr}^t$ represent the energy required to transmit the sensed data, the energy required by the active ports, and the energy required to maintain and update a flow rule. Further, the number of active ports and flow rules available at the SDN switches are denoted by N_a and N_{fr}, respectively.

Depending upon the decision parameters selected by the registered end-users, the decisions are generated and delivered to them at their present geographical location. Further, the updating of flow rule at each of the SDN switches result in unnecessary energy wastage, bandwidth consumption, and available storage space. Therefore, the required flow rule is necessary to be updated at the selected SDN switch, present within the vicinity of the end-users. Motivated by the concept of operating cost of the APs [24], we design our utility function for updating the flow rule at the SDN switches. Considering the delay incurred to transmit data and update the flow rule, available storage space, residual energy, and bandwidth for transmitting data, the utility function of any SDN switch is mathematically represented as,

$$\mathbb{U}_{ij}^t = \left(\lambda_1 S_i^{t,eff} + \lambda_2 B_i^{t,eff} + \lambda_3 E_i^{t,eff}\right)\left(\frac{\lambda_4}{D_{ij}^{eff}}\right) \tag{2}$$

where λ_1, λ_2, λ_3, λ_4, and λ_5 represent the weight factors, such that $\forall \lambda_i$, $0 < \lambda_i < 1$. The effective storage space, S_i^{eff}, is expressed as the ratio of the available storage space of the i^{th} switch at time instant, t, to the maximum storage space of the switch, $\mathbb{S}_t^{max}$. Therefore,

$$\mathbb{S}_i^{t,eff} = \frac{\mathbb{S}_i^{init} - \mathbb{S}_i^t}{\mathbb{S}_i^{max}} \tag{3}$$

where $\mathbb{S}_i^{init}$ and $\mathbb{S}_i^t$ represent the initial storage space and the storage space required to store the newly designed flow rule. Further, we estimate the effective bandwidth, $\mathbb{B}_i^{t,eff}$ of the i^{th} switch as the ratio of the available bandwidth for transmitting data to the maximum bandwidth, $\mathbb{B}_t^{max}$ at the time instant, t.

$$\mathbb{B}_i^{t,eff} = \frac{\mathbb{B}_i^t}{\mathbb{B}_t^{max}} \tag{4}$$

On the other hand, the effective residual energy of the i^{th} SDN switch is represented as the ratio of the available remaining energy after updating the flow rule at the i^{th} SDN switch to the maximum available energy $\mathbb{B}_t^{max}$, at time instant, t. Therefore,

$$\mathbb{E}_i^{t,eff} = \frac{\mathbb{E}_i^{init} - \mathbb{E}_i^t}{E_i^{init}} \tag{5}$$

where $\mathbb{E}_i^{init}$ and $\mathbb{E}_i^t$ denote the initial energy available and the energy required for updating the flow rule at the i^{th} SDN switch during time instant, t. Further, the effective delay incurred, $\mathbb{D}_{ij}^{eff}$, to transmit the generated decision is represented as the ratio of the delay incurred to transmit the sensed data and update the flow rule in the corresponding flow table, to the maximum delay incurred. Mathematically,

$$\mathbb{D}_i^{t,eff} = \frac{\mathbb{D}_{trans,i}^t}{\mathbb{D}_{trans}^{max}} + \frac{\mathbb{D}_{s,i}^t}{\mathbb{D}_s^{max}} \tag{6}$$

where $\mathbb{D}_{trans,i}^t$ and $\mathbb{D}_{s,i}^t$ represent the delay incurred in transferring and updating the data at the SDN switches, respectively. $\mathbb{D}_{trans}^{max}$ and $\mathbb{D}_s^{max}$ denote the maximum delay that may occur during the time of transmission and updating the flow rule at the switches, respectively. Therefore, the delay incurred during transmission of data directly depends on the distance, where the switch is located. The delay incurred during transmission $\mathbb{D}_{trans,i}^t$ is mathematically represented as, $\mathbb{D}_{trans,i}^t = \gamma_1 \mathbb{L}_i^t$, where γ_1 represents the delay incurred to travel per unit distance and $\mathbb{L}_i^t$ denotes the distance between the i^{th} switch from the SDN controller at any time instant, t. Similarly, the maximum delay incurred to transmit data to the SDN switches is expressed as: $\mathbb{D}_{trans}^{max} = \gamma_2 \mathbb{L}_i^t$, where γ_2 is the maximum delay incurred during transmission.

C. Game Formulation

In the Safe-aaS infrastructure, the end-users receive safety-related decisions based on the decision parameters selected, and the source and destination details provided by them, during registration. As the end-users change their geographical location, the number and type of access points (APs), through which the decisions are delivered to them, fluctuates. In the proposed scheme, we consider a Software Defined-Safe-aaS platform, where the edge layer acts as the data plane, and decision is delivered to the end-users through the SDN switches. Therefore, we map the interactions between the SDN controller and SDN switches with the *Single Leader Multiple Follower* game-theoretic fabric. The SDN controller acts as the leader and the SDN switches act as the followers.

Non-Cooperative Game: The Justification: The end-users first register to the Safe-aaS platform, provide their source and destination details, and select certain decision parameters through the Web portal. However, as the end-users change their location, their nearest APs also vary. The number of available APs/SDN switches changes randomly with the variation in the geographical location of that end-user. In such a dynamic scenario, the selection of the appropriate AP/SDN switch to deliver the safety-related decisions incurring maximum utility, based on the available storage space, the delay incurred, the available energy, and the bandwidth, is indispensable. Therefore, we map this situation with a Non-Cooperative Single Leader Multiple Follower game-theoretic approach, where the SDN controller acts as the leader and the SDN switches act as followers. Depending upon the strategies put forth by the leader, the flow rule is updated at the specific SDN switch among the available ones, to deliver the decision to the end-user. As a result, the unnecessary energy, bandwidth, and storage space, consumed at the switches reduce significantly. Therefore, the optimization function for the utility of the i^{th} SDN switch is mathematically represented as,

$$\underset{D_i^{t,eff}}{\text{argmax}} \quad \mathbb{U}_{ij}^t \tag{7}$$

subject to, $0 \leq \mathbb{S}_i^{t,eff}, \mathbb{B}_i^{eff}, \mathbb{D}_{ij}^{eff}, \mathbb{E}_i^{t,eff} \leq 1$.

Theorem 1. *The utility function of the i^{th} SDN switch is concave in nature.*

Proof: Suppose, there exists a set of points $(y_1, y_2) \in \mathbb{U}$. Therefore, the utility function is considered to be concave in nature, iff $f(\lambda y_1 + (1-\lambda)y_2) \geq \lambda f(y_1) + (1-\lambda)f(y_2)$, such that the values of $\lambda \in (0,1)$. In the similar manner, the utility of the SDN switches a and b, is represented as, $\mathbb{U}(\mathbb{S}_a^{t,eff}, \mathbb{B}_a^{eff}, \mathbb{D}_{aj}^{eff}, \mathbb{E}_a^{t,eff})$ and $\mathbb{U}(\mathbb{S}_b^{t,eff}, \mathbb{B}_b^{eff}, \mathbb{D}_{bj}^{eff}, \mathbb{E}_b^{t,eff})$. Mathematically,

$$\begin{aligned} &\mathbb{U}(\lambda(\mathbb{S}_a^{t,eff}, \mathbb{B}_a^{eff}, \mathbb{D}_{aj}^{eff}, \mathbb{E}_a^{t,eff}) + (1-\lambda)(\mathbb{S}_b^{t,eff}, \\ &\mathbb{B}_b^{eff}, \mathbb{D}_{bj}^{eff}, \mathbb{E}_b^{t,eff})) \geq \lambda \mathbb{U}(\mathbb{S}_a^{t,eff}, \mathbb{B}_a^{eff}, \mathbb{D}_{aj}^{eff}, \mathbb{E}_a^{t,eff}) \\ &+(1-\lambda)\mathbb{U}(\mathbb{S}_b^{t,eff}, \mathbb{B}_b^{eff}, \mathbb{D}_{bj}^{eff}, \mathbb{E}_b^{t,eff}) \end{aligned} \tag{8}$$

Further, the first order differential equation of the utility function of the a^{th} SDN switch w.r.t $\mathbb{D}_{aj}^{eff}$ is represented as,

$$\frac{\partial(\mathbb{U}_{aj}^t)}{\mathbb{D}_{aj}^{eff}} = -\left(\lambda_1 \mathbb{S}_a^{t,eff} + \lambda_2 \mathbb{B}_a^{t,eff} + \lambda_3 \mathbb{E}_a^{t,eff}\right) \frac{\lambda_4}{(\mathbb{D}_{aj}^{eff})^2} \tag{9}$$

Similarly, the first order derivative of the utility function of the b^{th} SDN switch w.r.t. $\mathbb{D}_{aj}^{eff}$ is, $\frac{\partial(\mathbb{U}_{bj}^t)}{\mathbb{D}_{bj}^{eff}} = -\big(\lambda_1 \mathbb{S}_b^{t,eff} + \lambda_2 \mathbb{B}_b^{t,eff} + \lambda_3 \mathbb{E}_b^{t,eff}\big) \frac{\lambda_4}{(\mathbb{D}_{bj}^{eff})^2}$. Therefore,

$$\begin{aligned} &(\mathbb{D}_{aj}^{eff} - \mathbb{D}_{bj}^{eff})\Big(\bigtriangledown \mathbb{U}(\mathbb{S}_a^{t,eff}, \mathbb{B}_a^{eff}, \mathbb{D}_{aj}^{eff}, \mathbb{E}_a^{t,eff}) \\ &\quad - \bigtriangledown \mathbb{U}(\mathbb{S}_b^{t,eff}, \mathbb{B}_b^{eff}, \mathbb{D}_{bj}^{eff}, \mathbb{E}_b^{t,eff})\Big) \leq 0 \end{aligned} \tag{10}$$

$$\begin{aligned} &\left(\mathbb{D}_{aj}^{eff} - \mathbb{D}_{bj}^{eff}\right)\left(\frac{\lambda_4}{(\mathbb{D}_{bj}^{eff})^2}\left(\lambda_1 \mathbb{S}_b^{t,eff} + \lambda_2 \mathbb{B}_b^{t,eff} + \lambda_3 \mathbb{E}_b^{t,eff}\right)\right. \\ &\left. \quad -\frac{\lambda_4}{(\mathbb{D}_{aj}^{eff})^2}\left(\lambda_1 \mathbb{S}_a^{t,eff} + \lambda_2 \mathbb{B}_a^{t,eff} + \lambda_3 \mathbb{E}_a^{t,eff}\right)\right) \leq 0 \end{aligned} \tag{11}$$

Therefore, from Equations (10) and (11), we conclude that the utility function of any i^{th} SDN switch is concave in nature. ■

Theorem 2. *There exists a unique solution for the maximum value of utility function incurring optimal delay to deliver the decisions to the end-users.*

Proof: In the proposed scheme, the SDN controller performs the functionalities of the decision, decision virtualization, and application layer, and decides through which SDN switch the decision is to be delivered to the end-user. Based on the available storage space, residual energy, bandwidth, and delay incurred, the SDN switch is selected to deliver the decision incurring maximum utility. Therefore, to select the appropriate SDN switch present within the vicinity of the end-user, we solve Equation 7.

To simplify the optimization function given in Equation 7, we utilize *Lagrangian* function, which is represented as:

$$\begin{aligned} \mathbb{L}_i = \mathbb{U}_{ij}^t - \mu_1(1 - S_i^{t,eff}) - \mu_2(1 - D_{ij}^{eff}) - \\ \mu_3(1 - B_i^{t,eff}) - \mu_4(1 - E_i^{t,eff}) \end{aligned} \tag{12}$$

where μ_1, μ_2, μ_3, μ_4, and μ_5 denote the *Lagrangian Multipliers*. We further apply *Karush-Kuhn-Tucker* (KKT) conditions to solve the Lagrangian function and obtain the optimal value of $D_i^{t,eff}$ incurred in the delivery of decisions to the end-users. The *dual feasibility* and *complementary slackness* conditions are as follows:

$$\bigtriangledown_{D_i^{t,eff}} L_i = 0 \tag{13a}$$

$$\mu_i(X) = 0 \text{ and } \mu_i \geq 0, \forall i = 1,2,3,4,5 \tag{13b}$$

where X represent the constraints of Equation (7). On solving Equation (13), we obtain the optimal value of the delay incurred, as given in Equation (14).

$$\mathbb{D}_i^{t,eff*} = \sqrt{\left(\frac{\lambda_4}{\mu_2}\right)\left(\lambda_1 S_i^{t,eff} + \lambda_2 B_i^{t,eff} + \lambda_3 E_i^{t,eff}\right)} \tag{14}$$

Therefore, a unique optimal value of the delay incurred exists, at which the decision is delivered to the end-users for the maximum utility of the selected SDN switch. ■

Algorithm 1 provides the comprehensive view regarding the transmission of decision from the controller to the j^{th} end-user. Step 2 describes that the time-critical sensed data is transmitted from the j^{th} sensor node to the i^{th} edge node. Further, the primarily processed data is transmitted to the controller placed in the control plane. Steps 3-5 describes that based on the selected decision parameters, the controller generates a decision in the decision layer. Finally, the flow table is updated by the controller in Step 6. In Step 7, the i^{th} switch transmits the decision to the k^{th} end-user.

Algorithm 1 Soft-Safe

INPUTS: $\mathbb{O}$, $\mathbb{S}$, and $\mathbb{E}$
OUTPUT: Transmitting decision to the k^{th} end-user
PROCEDURE:
1: **for** k = 1 to q **do** ▷ q: Number of end-user
2: Transmitting the sensed data from S_j to the edge nodes E_i
3: E_i transmit data to controller
4: Controller generates decision, based on selected parameter by O_j
5: Controller generate utility function for each E_i and select the appropriate E_i using Equation 7
6: Controller update the flow table in the selected E_i
7: E_i transmits the generated decision to the end-user
8: **end for**

IV. Performance Evaluation

A. Simulation Design

To evaluate the performance of our proposed scheme, Soft-Safe, we consider the presence of 100–500 heterogeneous type of sensor nodes deployed over a region of $500 \times 500 m^2$. In Safe-aaS platform, we consider the presence of mobile sensor nodes, which attain mobility with the variation in the geographical location of the vehicles. Therefore, mobility acts as one of the important factors. To design the speed and direction of the sensor nodes, we apply Gauss Markov mobility model, which is mathematically represented as:

$$s_n = \alpha s_{n-1} + (1-\alpha)\bar{s} + \sqrt{(1-\alpha^2)} \times s_{x_{n-1}} \quad (15a)$$

$$d_n = \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)} \times d_{x_{n-1}} \quad (15b)$$

where α is the tuning parameter. $\bar{s}$ and $\bar{d}$ denote the mean speed and direction. $s_{x_{n-1}}$ and $d_{x_{n-1}}$ represent the random variable from a Gaussian distribution that assigns randomness to the speed and direction of the sensor node. Table I illustrates the various simulation parameters considered for the simulation of the proposed scheme.

TABLE I: Simulation Parameters

Parameter	**Value**
Simulation area	500 × 500 m^2
Number of sensor nodes	100–500
Number of switches	5–350
Number of port switch ports	12 – 48
Number of flow rules	8000–16000
Deployment of APs	static
Sensor deployment type	random

B. Benchmark

In order to evaluate and compare our proposed scheme, Soft-Safe, we consider two other existing schemes as benchmarks – traditional Safe-aaS [12] and MoRule [17]. Roy *et al*. [12] proposed a unique infrastructure, Safety-as-a-Service (Safe-aaS), for provisioning customized safety-related decisions to the end-users. Safe-aaS is a five-layered infrastructure – device, edge, decision, decision virtualization, and application. The heterogeneity of the edge nodes gives rise to various issues. Our proposed Software-Defined Safe-aaS platform helps to eliminate these problems. On the other hand, Li *et al*. [17] considered the mobility of users and rule capacity constraint, and designed an efficient rule placement scheme for mobile users. We represent the traditional Safe-aaS as Safe-aaS [12] and rule placement scheme as MoRule [17]. We observe that the energy consumed and delay incurred is reduced compared to the existing schemes, Safe-aaS and MoRule. Further, the number of flow rules required is significantly reduced in Soft-Safe compared to the traditional Safe-aaS platform.

C. Result

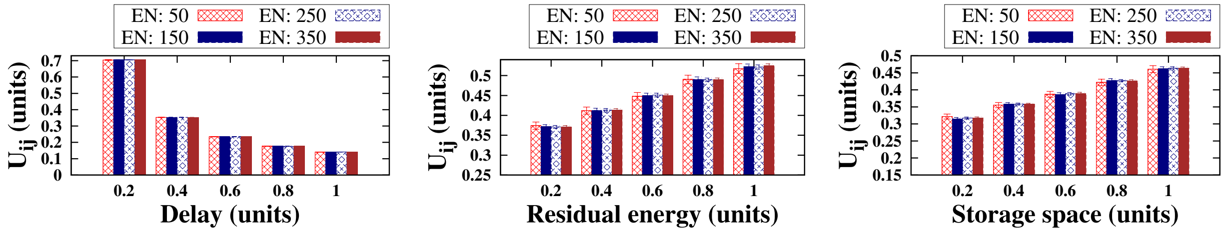
We use different performance metrics such as energy consumption, delay incurred, available storage space, number of packets transmitted, number of flow rules present, and utility, for optimal selection of the switches, which are discussed as follows:

Utility: The primary objective of the proposed scheme is to minimize the number of flow rules within the SDN switches and effectively utilize the storage space for storing these flow rules. Considering this, we design the utility function for the SDN switches. We compute the utility of the SDN switches, as per Equation 2. Fig. 2 illustrates the variations in the utility with the increase in the delay incurred, energy consumed, and available storage space at the SDN switches. In Fig. 2(a), we observe that with the increase in the delay incurred, the utility decreases by 88%–90% (approx.) in the presence of 50–350 edge nodes/SDN switches. On the other hand, in Figs. 2(b) and 2(c), we observe that with the increase in the effective energy consumed and storage space available, the utility of the edge nodes/SDN switches increases by 31%–33% (approx.) and 35%–36% (approx.). The probable reason behind such a trend is that with the rise in the value of effective storage space (TCAM memory) and residual energy at the SDN switches, the number of flow rules to be stored and updated at these SDN switches increases. Further, the increase in the delay incurred in updating these flow rules results in the delay in delivery of decisions, which affects the utility of the switches.

Energy consumption: Fig. 3(a) depicts the variations in the energy consumed at the SDN switches using the proposed scheme, compared to the traditional Safe-aaS [12] and MoRule [17]. We observe that with the increase in the number of edge nodes in the simulation environment from 5–30, the amount of energy consumed reduces by 22% and 45% (approx.) respectively, compared to the existing schemes. One of the possible reasons behind such a trend in energy consumption is that the energy required to transmit the control packet by the SDN controller to the SDN switches present within the vicinity of the end-user is significantly reduced. On the other hand, in traditional Safe-aaS, the appropriate SDN switch is not selected, hence the energy consumed to transmit the sensed data to the edge nodes present within their vicinity, is increased. Additionally, we observe that the existing scheme, MoRule consumes the maximum overall network energy. Fig. 5(b) illustrates that with the increase in the number of flow rules and the active ports of the SDN switch, the energy consumption by the SDN switches increases. We observe the amount of energy consumed increases with the increase in the number of flow rules in the presence of 12, 24, 36, and 48 respectively.

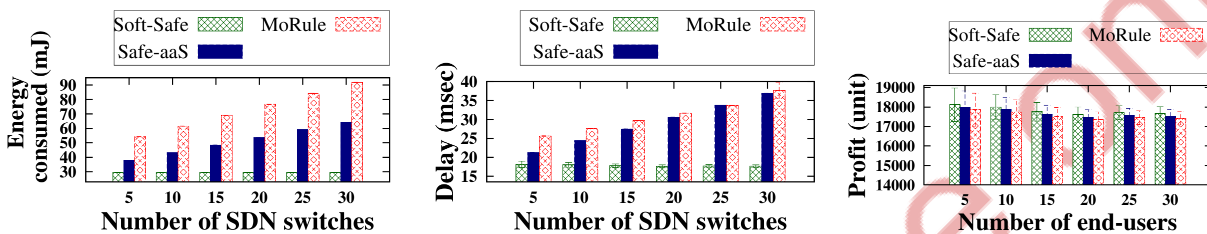
Delay incurred: Fig. 3(b) illustrates the variations in the delay incurred by the network with the increase in the number of SDN switches. We observe that with the increase in the number of SDN switches, the delay incurred by the proposed scheme, reduces by 15% and 29% (approx.), respectively, compared to the traditional Safe-aaS [12] and MoRule [17]. The probable reason behind this is that the delay incurred in transmitting the data packets to the nearby SDN switches is significantly reduced due to the updating of flow rules at the selected SDN switch. Additionally, with the reduction in the delay incurred the number of end-users served by the SDN-enabled Safe-aaS platform increases.

Number of flow rules: Fig. 4 depicts the number of flow rules present within the SDN switches for Soft-Safe and traditional Safe-aaS. As the number of registered end-user increases, the number of data packets containing decisions for the end-users also increases proportionately. Moreover, with the variations in the geographical location of the end-users, the number of SDN switches present within their vicinity also changes. We increase the number of end-users from 0 upto 400. Further, we observe that the number of flow rules required increases with the increase in the number of end-users. In Fig 4, we observe that the number of flow rules required decreases by 9.14% and 50% (approx.) in the proposed scheme, compared to the MoRule and traditional Safe-aaS, respectively. One of the probable reasons behind this is that the particular flow rule is updated at the selected SDN switch, among the ones present within the communication range of the sensor nodes. On the other hand, in the case of a traditional Safe-aaS platform, the flow rule is



(a) Effective delay (b) Effective energy (c) Effective storage space

Fig. 2: Variation of utility of the switches with different parameters



(a) Energy consumed (b) Delay incurred (c) Profit

Fig. 3: Variation of energy consumed, delay incurred, and profit of SSP in Soft-Safe, Safe-aaS [12] and MoRule [17]

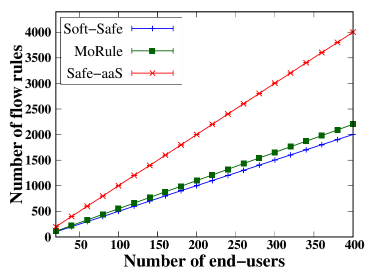
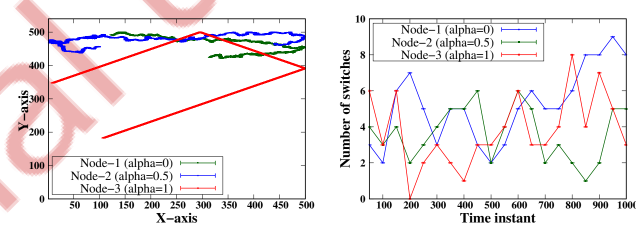
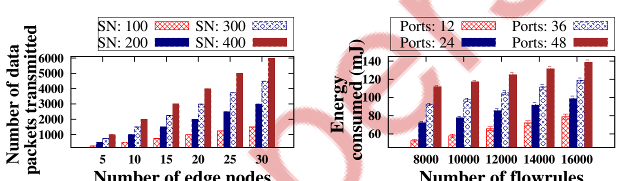


Fig. 4: Variation in the number of flow rules



(a) Mobility trace of vehicles (b) Number of switches

Fig. 6: Variation in the number of edge nodes and mobility path with alpha



(a) Data packets transmitted (b) Energy consumed

Fig. 5: Variation of data packets transmitted and energy consumed

updated at all the edge nodes present within the vicinity of the sensor nodes. Therefore, the number of flow rules required also increases. In the case of MoRule, the rule management scheme optimally places the rules for mobile end-users. However, the appropriate switch is not selected. The redundant storage space occupied, energy consumed, and bandwidth utilized by the SDN switch decreases.

Packet transmission: Fig. 5(a) demonstrates the variations in the number of data packets transmitted with the increase in the number of edge nodes. Along the x-axis, we vary the number of edge nodes from 5–30. We observe that with the increase in the number of sensor nodes from 100–400 in the simulation environment, the number of data packets transmitted by the SDN switch increases by 75% (approx.). In the proposed scheme, the sensed data are processed in an SDN-based traffic controller for processing and delivery of the decision to the end-users. Thereafter, the flow rule is updated at the appropriate switch for the delivery of the safety-related decision to the end-user. On the other hand, with the increase in the demand of registered end-users, the number of decisions delivered by the edge nodes/SDN switches to the end-users increases accordingly.

Mobility: We use the Gauss Markov mobility model to generate the location of the mobile nodes. Fig. 6(a) demonstrates the change in the mobility pattern of the mobile nodes with the change in the value of alpha. From Fig. 6(b) we observe the variations in the number of edge devices present within the vicinity of the mobile devices. The possible reason behind such randomness in the graph is since the mobile devices change their location at different time instants. As the vehicle moves away from the existing nearby edge devices and approaches a new location, some different set of edge devices are present in its communication range. Hence, due to constant change in the location of the devices, the number of available edge devices also varies.

Profit of SSP: A Safe-aaS infrastructure provisions safety-related decisions to the end-users on a pay-per-use basis. Therefore, financial transactions take place among the various actors. Fig. 3(c) depicts the variations in the profit of the service provider using the proposed scheme, compared to the traditional Safe-aaS [12] and MoRule [17]. Motivated by the estimation of profit of the SSP in the traditional Safe-aaS platform [12], we compute the profit of the service provider for Soft-Safe and MoRule. We observe that the profit of the service provider increases by 0.8% and 1.5% (approx.) using Soft-Safe, compared to the traditional Safe-aaS and MoRule, respectively. One of the probable reasons behind this is that with the reduction in the delay incurred, energy consumption, and utilization in the storage space, Soft-Safe provides decisions to more number of registered end-users. Additionally, the amount of penalty charged from the SSP for the delay in providing the decision to the end-users is reduced. On the other hand, the demand of end-users also increases due to the timely delivery of decisions. Consequently, the duration for which the end-users request safety services increases. Thus, the end-users as well as the service provider, both are satisfied.

V. Conclusion

In this paper, we identified and addressed the problem of effective utilization of resources for provisioning Safety-as-a-Service in an SDN-enabled Safe-aaS platform. Safe-aaS infrastructure provides the safety-related decisions to the end-users by processing the data sensed by the sensor nodes. Typically, a Safe-aaS platform comprises five layers – device, edge, decision, decision virtualization, and application. To eliminate the heterogeneity among the edge devices and process the time-critical data, we introduce the concept of SDN architecture. The SDN-enabled Safe-aaS architecture delivers the generated decisions to the end-users through the appropriate SDN switch present within the vicinity of the end-users. As a result, the delay incurred in the delivery of the decisions to the end-users is minimized. Further, the geographical location of the end-users changes with their mobility. In such a situation, updating the flow table in each of the edge nodes present within the vicinity of the end-users leads to redundant usage of available storage space, bandwidth, and energy consumption. Therefore, the selection of the appropriate SDN switch is necessary. Based on the available storage space, residual energy, bandwidth, and delay incurred, we design the utility function for each of the SDN switches and formulate an optimization function. Further, we map the interactions between the SDN controller and SDN switches, as a *Non-cooperative Single Leader Multiple Follower* game. Thereafter, we estimate the optimal delay incurred for the maximum utility of any SDN switch, which is selected for delivering the decision to the end-user. The simulation-based analysis of our proposed scheme, Soft-Safe, illustrates that the energy consumed and delay incurred is minimized, and profit of Safety Service Provider (SSP) is improved, compared to the existing schemes, Traditional Safe-aaS [12] and MoRule [17].

As mentioned in the existing research works, the theoretical modeling of the Safe-aaS infrastructure and the appropriate edge node selection is proposed. In the future, we plan to implement our SDN-enabled Safe-aaS platform in the real-life scenario. Further, deep learning algorithms can be applied for improving the resource management and accuracy in the decisions generated to the end-users. Therefore, we plan to incorporate the deep learning algorithm into the Safe-aaS platform. The consideration of the cost of decision parameters based on the geographical location of end-users is an important matter of concern. We plan to consider the cost of decision parameters and design a pricing scheme in the future.

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