TiME: Time-sensitive Multihop Data Transmission in Software-Defined Edge Networks for IoT

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Abstract. This work addresses the problem of optimal data transmission in a multi-hop edge network. In edge networks, IoT devices need to transmit data to the local processing units. However, having a short-range communication capacity, it is hard for IoT devices to transmit the data to the concerned processing edge devices. Hence, they mostly rely on multi-hop communication. There is no such scheme for multi-hop communication at the edge while ensuring timeliness. We envision that software-defined networking can help in solving the aforementioned problem. Hence, we proposed a software-defined edge architecture and designed a game theoretic model for optimal multi-hop data transmission. We use a dynamic coalition game to identify the optimal paths for data transmission in edge networks for IoT. The performance of the proposed scheme is also evaluated and compared with the existing literature.

Keywords: Edge networks · Multi-hop · IoT · Coalition · Game Theory

1 Introduction

Software-Defined Networking (SDN) is envisioned to overcome the constraints of traditional networking. In conventional networking, each device is configured with low-level and frequent vendor-specific instructions. Fault dynamics and load fluctuations in the network environments follow this configuration complexity. Real-time reconfiguration and response mechanisms are almost nonexistent in IP networks. Therefore, the researchers mentioned that SDN can play a crucial role. SDN separates the data plane from the control plane, making the network switches simple forwarding devices. This results in implementing the control logic in a logically centralized controller [12]. SDN simplifies policy enforcement, network reconfiguration, and evolution by implementing the control logic in physical

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devices depending upon the application-specific requirements in real-time [4]. On the other hand, in the presence of numerous Internet of Things (IoT) devices, the amount of data generated increases significantly, which is to be delivered with a predefined time duration in the edge network. This is one of the essential issues in software-defined edge networks (SDEN).

In the existing literature, Mondal *et al.* [18] considered that the IoT devices are directly connected with the switches at the data plane. However, in reality, it may not always be possible. Therefore, the IoT devices at the edge rely on multi-hop communication. In this scenario, the intermediate IoT devices act as relay nodes and forward packets to the SDN switches in multiple hops [1]- [6]. Additionally, multi-hop communication is essential for transferring data to the SDN switches from ad-hoc IoT devices while ensuring reduced energy consumption. However, IoT data transmission in edge networks is challenging and fails to provide a global overview of the network topology. The end-to-end delay in data transmission also varies significantly in edge networks in the presence of mobile IoT devices. Hence, there is a need to design a scheme for time-sensitive data transmission in SDEN.

As observed by Fedor and Collier [8], introducing multiple hops in the path increases the network lifetime of the IoT networks. Though IoT-based real-time applications mainly rely on the reception of IoT data in a timely manner, data arrival is an exogenous process with less control over its arrival. The network performance depends on the data generation rate and transmission path parameters. In the existing literature, viz. [1,4,8,25], the researchers studied the optimal data generation rate. However, the effects of optimal path selection on timely data transfer are not studied extensively. An ideal situation would be to receive an update at the destination the moment it was generated at a source, but this is not possible because of the fact that the other updates queued up waiting for their own transmission. Additionally, a stale data packet cannot be used [24]. Hence, we argue that high throughput and minimal delay are not enough to measure the timeliness of an update, so another metric was introduced by Kaul *et al.* [9,10] known as the Age of Information (AoI) that measures the time that has passed since the freshest generated packet of data. This motivates us to devise a scheme for optimal flow-rule placement in SDEN that ensures the timeliness of end-to-end data transfer. We propose a dynamic coalition formation game theoretic scheme for time-sensitive multi-hop data transmission in SDENs. To summarize, the contributions in this work are as follows:

1. We designed a time-sensitive multi-hop data transmission scheme, named TiME, for the software-defined edge networks. We used a dynamic coalition formation game to model the proposed scheme mathematically.
2. We evaluated the performance of TiME through simulation while comparing it with the existing scheme.

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2 Related Work

The existing literature is divided into flow-rule placement and flow-space utilization which are discussed in this section.

2.1 Flow-rule placement

Bera *et al.* [2] devised an adaptive flow-rule placement scheme and solved as a max-flow-min-cost optimization problem using a greedy heuristic approach. They also used Integer Linear Programming (ILP) to select the optimal flow rules to minimize the number of exact-match flow rules in the network. Lastly, a rule distribution algorithm was formulated to assign a more significant number of flows in the network, thereby decreasing rule congestion in the network. In [17], Mondal *et al.* proposed a scheme, FlowMan, using generalized Nash bargaining game to ensure high throughput and low delay in a heterogeneous Software-Defined Internet of Things (SDIoT) environment. The authors observed that FlowMan could effectively boost network throughput while reducing network delay while optimizing the flows in each hop. In another work, Bera *et al.* [3] proposed a mobility-aware adaptive flow-rule placement scheme, Mobi-Flow, for Software Defined Access Networks (SDANs) that predicted the future location of users by using the Markov predictor. Based on these predicted locations, flow rules are installed at those access points (APs), minimizing delay, and controlling overhead, energy consumption, and cost in the network. In [11], Khoobbakht *et al.* proposed a hybrid rule placement algorithm to effectively utilize the flow table's limited space and decrease the controller's load. The proactive and reactive methods are combined in the algorithm to reduce the signaling overhead on the controller, reducing the network's reaction time to network changes. In Ref. [13], Kyung proposed a mobility-aware prioritized flow-rule placement scheme that classifies delay-sensitive flows in SDAN directly affecting the users' QoS experience. The prioritized delay-sensitive flows are pre-installed into the target forwarding devices minimizing unnecessary rule placement.

Nguyen *et al.* [19] applied deep reinforcement learning (DRL) to design an adaptive flow-rule placement system, DeepPlace, in SDIoT networks. This scheme provided a very detailed analysis on the network traffic along with increasing the QoS in traffic flows in the network. Another rule placement algorithm using Deep Reinforcement Learning (DRL) and traffic prediction is studied by Bouzid *et al.* [5]. The authors used Long Short-Term Memory (LSTM) prediction method and ILP to solve the flow-rule placement problem. Misra *et al.* [16] designed a traffic forwarding scheme for a software-defined healthcare network. They used machine learning to identify the criticality of the flow in the presence of mobile devices. In [22], Saha *et al.* devised a QoS-aware adaptive flow-rule aggregation scheme in SDIoT network. This scheme uses a Best-fit heuristic approach for fast aggregation and sufficient reduction in the number of flow rules without degrading the QoS of IoT traffic. In another work, Saha *et al.* [23] proposed a QoS-aware flow-rule aggregation scheme for a generic network topology for improving the QoS of IoT applications by aggregating the flow

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rules adaptively. The proposed scheme applies a path selection heuristic to increase the total number of flow rules that can be accommodated in the network and a flow-rule aggregation scheme, concurrently enhancing the QoS of fresh IoT flows. Mimidis-Kentis *et al.* [15] devised a flow-rule placement algorithm that utilized both the software and hardware flow tables. The authors devised a placement algorithm to implement for the Open Network Operating System (ONOS) SDN controller, and it was validated on an SDN testbed. A larger number of flows could be accommodated at the SDN switches without much degradation in the network performance and no packet loss. Saha *et al.* [21] proposed a traffic-aware QoS routing scheme in SDIoT network, which considers two types of routing techniques- delay-sensitive that deals with delay-sensitive flows and loss-sensitive, that deals with loss-sensitive flows for incoming packets from the applications. This scheme is proposed to reduce end-to-end delay and the percentage of flows. The optimal forwarding path is computed based on a greedy method, and the SDN controller implements sufficient flow rules at the forwarding devices in the network.

2.2 Flow-space utilization

Lu *et al.* [14] proposed a scheme known as TF-IdleTimeout that configures the flow entry lifecycle following the real-time traffic network in an SDN-based data center network. Two criteria- Flow Entry Missing Number and Flow Dropping Number were applied in this scheme to improve the utilization efficiency of ternary content-addressable memory (TCAM) capacity in SDN. In [20], Panda *et al.* proposed a dynamic way to allocate a hard timeout value for each flow entry. This flow entry considers both predictable and unpredictable flow properties. The dynamically assigned hard timeout method proves more effective than the statically assigned hard timeout. Chen and Lin [7] devised a scheme for flow-rule placement for maximum packet throughput. This can reduce the TCAM utilization as a whole but also increase the link bandwidth if the packet gets dropped before it reaches the switch where its associated rule is already placed. So, this study offers a trade-off between the space utilization of TCAM and bandwidth exhaustion in SDN. The authors in [26] presented a routing scheme to ensure minimal entries at the switches and high resource utilization.

Synthesis After a detailed analysis of the existing research work, we observe a research gap in the flow-rule placement schemes while considering multiple hops in SDEN. Multiple hops in the network can reduce power consumption for distant transmissions. However, the existing literature has only focused on single-hop network transmissions. Therefore, we aim to devise an optimal flow-rule placement scheme that ensures end-to-end throughput and minimal delay in SDENs.

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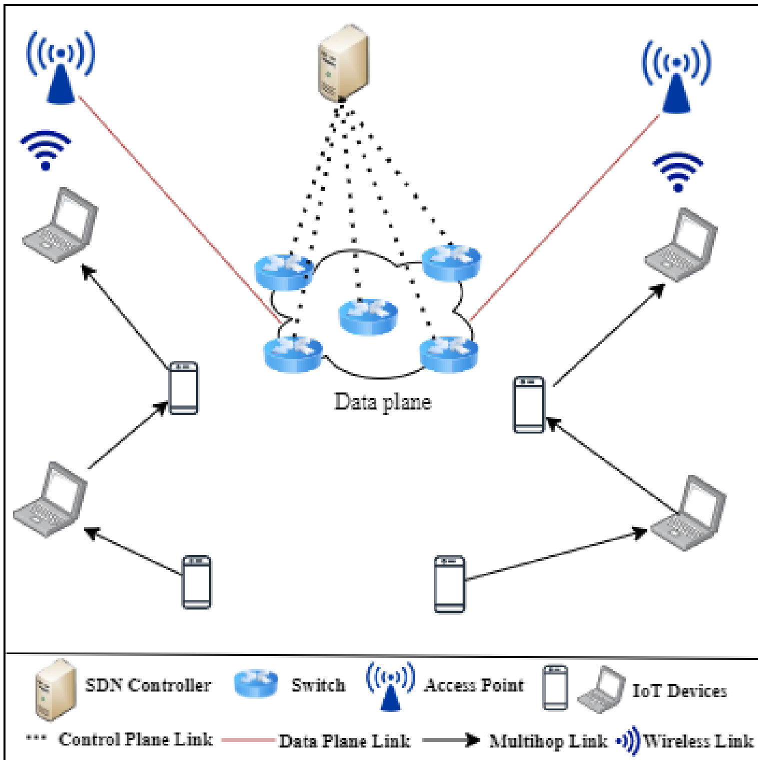

Fig. 1. Schematic Diagram of SDEN Architecture

3 System Model

We consider an SDEN to have a centralized controller that is connected with a set of switches S through the control plane. Figure 1 presents a multi-hop connection between the APs and the terminal IoT devices. We represent the flow association as $F(A, N)$, where A denotes the set of APs and N denotes the set of IoT devices present in the network. Each IoT device $n \in N$ is connected to a switch in the data plane through the APs where each of the APs $a \in A$ communicates with a set of switches s_a where s_a is a subset of S and set of switches is denoted by S. These APs forward the data traffic generated by each IoT device to the SDN switches, where the latter process the data according to the flow rules installed into them by the controller. After processing, the switches transmit the data to the backhaul network for additional processing. In case of a mismatch, metadata for the data traffic is sent to the controller for installing the corresponding flow rules at the switches.

We consider various parameters for each IoT device and the SDN switches, such as energy consumption, data rate, the capacity of each switch, the throughput of each flow, and the delay associated with it. Apart from maximizing the

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throughput and minimizing the delay associated with each flow, low energy consumption and optimal utilization of TCAM space of each SDN switch are also essential for ensuring the QoS of the network. We assume that each IoT device $n \in N$ generates $F_n(t)$ number of flows at time instant t. We consider that there is adequate space in switches S to accommodate $\sum_n F_n(t)$ number of flow rules so that $\sum_n F_n(t) \leq \sum_{s \in S} F_s^{max}$, where F_s^{max} is the maximum number of flow-rules that can be installed at switch s. It is also crucial to generate the optimal data rate to avoid clogging the network or delay in receiving network updates. If the rate of data generation for each flow $f_n(t) \in F_n(t)$ is $r_n(t)$, then the throughput of an SDN switch s can be represented as:

$$T_s(t) = \sum_{f_n(t) \in F_s(t)} r_n(t) \tag{1}$$

where $F_s(t)$ represents the flow rules installed at switch s.

We assume that for each IoT device n, there exists a communication range R_n. Hence, the nodes that lie within this range are considered the neighboring nodes. If the amount of energy a node requires to transmit data is E_n, the constraint — $E_n \leq E_r$ — should be satisfied, where E_r is the amount of residual energy of a node. Additionally, the end-to-end delay for each hop must satisfy the constraint — $[\sum_{N-1} d_{ij} \leq D_{N-1}]$, where d_{ij} is the delay associated with the edge that is formed by the i^{th} and j^{th} nodes in the network and D_{N-1} is the delay threshold for a particular application with $N-1$ representing the total number of hops in the network with N as the set of nodes.

4 TiME: The Proposed Time-sensitive Multihop Data Transmission Scheme

In TimE, we try to inculcate optimal flow-rule placement at the switches for time-bound data transfer. To accomplish the same, we use a dynamic coalition-formation game theoretic model. A coalition formation game is said to be dynamic when the nature of the game can alter due to environmental factors such as the mobility of the user nodes or the deployment of new users. We are utilizing a dynamic coalition-formation game theoretic model to control these changes. Two players can be in a particular coalition: the source node and the intermediate node. If cooperating with a user device, i.e., a node, can boost the overall payoff that the participating users can accomplish, then the merging occurs between the devices, starting with the nearest neighbor. If there are two coalitions and the distances of each of the coalitions from a particular AP with co-ordinates (a_x, a_y) are α_i and α_j respectively, applying the Euclidean distance formula, we get-

$$\alpha_i = \sqrt{(x_1 - a_x)^2 + (y_1 - a_y)^2}$$

$$\alpha_j = \sqrt{(x_2 - a_x)^2 + (y_2 - a_y)^2}$$

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where (x_1, y_1) and (x_2, y_2) are the respective co-ordinates of the two coalitions. If $\alpha_i \geq \alpha_j$, then the first coalition is preferred; otherwise, the second coalition is preferred. We form a coalition structure that aims at maximizing the total utility keeping the following points in mind:

- The utility function of a node i where i is an intermediate node signifies the effect of latency incurred during transmission.
- The delay associated with the network has a negative impact on the utility function. The payoff decreases if the delay in the network increases.
- With the increase in the bandwidth-delay product, the payoff also increases, where δB_i represents the bandwidth-delay product associated with the intermediate node i.
- The payoff decreases with the increase in energy consumption associated with each hop.

Therefore, we construct utility function $U_i(t)$ as follows:

$$U_i(t) = \frac{B_{r,i}}{B_i} + \frac{D_{N-1}}{d_{ij}} + \frac{E_{r,i}}{E_i} \tag{2}$$

where $B_{r,i}$ and $E_{r,i}$ represent the residual bandwidth associated with the node i and the residual energy of the node i, respectively.

4.1 Proposed Algorithm

The proposed scheme, TiME, aims to ensure the timeliness of transferring data in SDENs through optimal placement of flow rules, as presented in Algorithm 1. A dynamic coalition-formation game theoretic approach is used for the above objective. The algorithm is formulated on the idea of the *Merge and Split* algorithm, where we merge the players to form a coalition that maximizes the utility function. If the utility is not maximized, we split the coalition and move on to other players for merging to ensure maximum utility in the game.

Complexity Analysis In the algorithm, the time complexity of the outer *for* loop in line 1 is $O(N)$ as it runs for N times. For every iteration of this outer loop, the inner *for* loop in line 2 runs for $(N - i)$ times. The time complexity is $O(1)$ for all other lines. Therefore the overall time complexity of the algorithm is $O(N^2)$.

5 Performance Evaluation

The performance of the proposed scheme is measured by comparing it with the existing scheme, TROD [18]. In TROD, Mondal *et al.* proposed a scheme for dynamic data traffic management in SDNs in the presence of IoT devices ensuring optimal throughput and minimal latency in the network.

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Algorithm 1 Determining throughput ensuring optimal delay

INPUTS:

N ▷ Set of nodes
R_i ▷ Communication range of node i
$B_{r,i}$ ▷ Residual bandwidth associated with the node i
B_i ▷ Bandwidth associated with the node i
D_{N-1} ▷ Delay threshold for an application having $N-1$ hops
$d_{i,j}$ ▷ Delay associated with the edge formed by the i^{th} and j^{th} nodes
$E_{r,i}$ ▷ Residual energy of node i
E_i ▷ Energy consumption associated with node i

OUTPUTS:

U_i ▷ Payoff at equilibrium

METHOD:

for Each $i \in N$ **do**
  for Each $j \in N/\{i\}$ and j lies in R_i **do**
    if $E_j \leq E_{r,j}$, $B_j \leq B_{r,j}$ and $d_{ij} \leq D_{N-1}$ **then**
      Merge and form coalition
      Calculate U_i ▷ using Equation (2)
    end if
    split coalition to form the next coalition
  end for
  Choose the coalition with the maximum utility
  Continue until a particular AP is reached.
end for
return U_i

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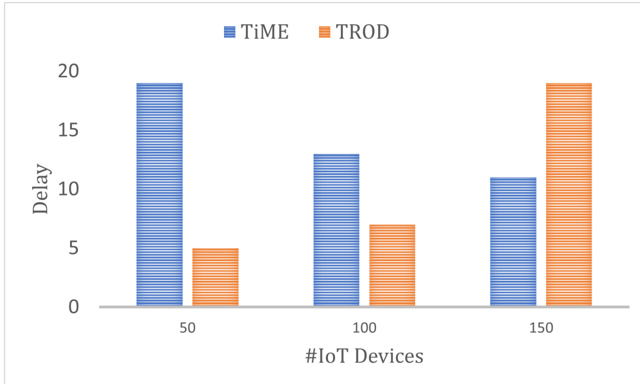
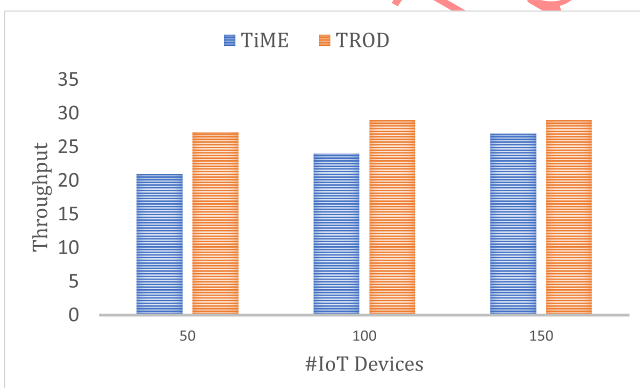
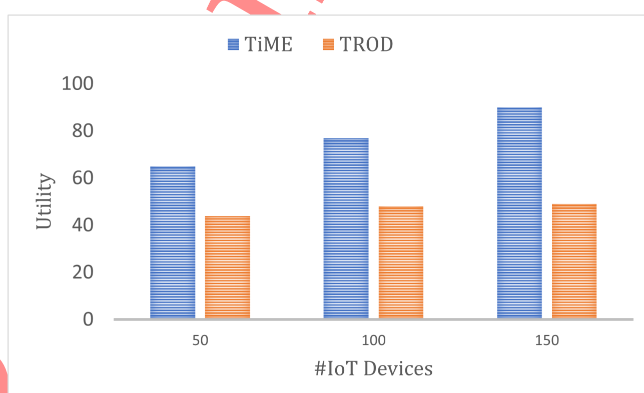


(a) Delay



(b) Throughput



(c) Utility

Fig. 2. Performance Evaluation

Using the proposed scheme, TiME, with the increase in the number of IoT devices, we observed that the overall delay of the network dropped more compared to using TROD. This is due to the fact that with the increase in the number of IoT devices, finding an optimal set of intermediate IoT devices becomes efficient. However, for the same reason, the throughput of TiME is less than TROD. In TROD, the nodes are to be chosen to maximize the throughput, and delay is not considered a constraint parameter. Using the dynamic coalition-formation game-theoretic model and *Merge and Split* algorithm, we formed coalitions with the user devices by merging in case of maximum payoff and splitting in case of a decrease in overall payoff in the multihop communication network. This resulted in an overall increase in the utility and minimal latency in the network.

6 Conclusion

We proposed a time-sensitive data transmission scheme for edge networks in the presence of IoT. While considering IoT devices are connected with edge computing nodes in multi-hop communication, we evaluated the significance of SDN in edge networks for IoT. Thereafter, we proposed a game theory-based mathematical model, TiME, to identify the optimal path between the source and destination edge nodes. We highlighted the choice of a dynamic coalition game for the same. Thereafter, we evaluated the performance of the proposed scheme, TiME, while comparing it with the existing scheme. We observed that TiME improves the performance latency significantly while ensuring optimal throughput.

In the future, this work can be extended to improve the throughput of the multi-hop edge networks while serving delay-critical applications. This work also can be extended while considering the dependency among the edge devices.

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