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EVP-STC: Emergency Vehicle Priority and Self-Organising Traffic Control at Intersections Using Internet-of-Things Platform

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ABSTRACT This paper presents an Internet-of-Things-based platform for emergency vehicle priority and self-organised traffic control (EVP-STC) management at intersections. With the increasing number of automobiles, traffic jams in urban areas are becoming a critical issue. Traffic jams, especially those at intersections, not only increase delays for drivers but also increase fuel consumption and air pollution. We propose a novel platform and protocol called EVP-STC that contains three main systems. The first system, called the intersection controller, is installed at traffic lights and collects emergency vehicle position information and vehicle density data at each road segment approaching an intersection. The intersection controller then adjusts the timings of traffic lights based on detected real-time traffic. The second system is installed at each road segment and contains force resistive sensors to detect vehicles. It transmits the detected information to the intersection controller via ZigBee. The third system is installed in emergency vehicles and provides GPS coordinates to the intersection controller to avoid any waiting time for emergency vehicles at intersections. Simulation results demonstrate the effectiveness of the proposed platform, which minimises total delays, lane opening times, and waiting times for emergency vehicles.

INDEX TERMS Traffic light, Internet-of-Things, intersection, Zigbee, vehicle priority management.

I. INTRODUCTION

Traffic light controllers play a significant role in maintaining smooth traffic flows in city environments. The sequences and durations of traffic light signals are two key factors that must be considered when designing a traffic light controller. In many countries, most traffic light controllers feature fixed sequences and durations of light signals, which do not consider dynamically changing traffic environments. Such fixed traffic light control methods are only suitable for stable and regular traffic, and not for dynamic traffic situations. Therefore, traditional traffic light controllers are one of the main factors contributing to severe road congestion in urban areas [1]. In addition, facilitating and prioritising the transit of emergency vehicles in urban areas comprises an important safety issue. However, in traditional traffic light controllers, light sequences are determined without considering the presence of emergency vehicles. Therefore, emergency vehicles such as ambulances, police cars, and fire engines must wait at intersections, which increases their delays and leads to the loss of lives and property [2].

Improving emergency response times is extremely critical, particularly for fire and health-related incidents. However, when the number of vehicles increases at an intersection, this not only increases the response times of emergency vehicles but also increases the likelihood of accidents occurring when emergency vehicles enter intersections at high speed. For example, in Ireland, an average of 700 fatalities are recorded every year because of late ambulance responses [3]. The National Highway Traffic Safety Administration in the US released a report regarding accidents that involved emergency vehicles such as fire trucks, ambulances, and police cars [4]. The agency studied the number of ambulance accidents over the 20-year period of 1992–2011 and estimated that an average of 1,500 accidents involving ambulances occurred each year, wherein 33 people were killed and 2,600 people were estimated to be injured. According to the report, fire engine accidents are the second leading cause of death for firefighters. There were roughly 31,600 accidents involving fire vehicles over a 10-year period in which 630 firefighters were killed. In addition, it is reported that there are approximately 300 fatalities in the US each year during police pursuits, where 30% of the fatalities comprise people not involved in a pursuits. Therefore, reducing emergency response times by minutes or even seconds is crucial in emergency situations. An intelligent traffic management system is mandatory for effectively avoiding emergency vehicle accidents at intersections by presenting green and red signals to emergency vehicles and non-emergency vehicles, respectively, based on an intelligent priority algorithm.

Therefore, in this paper, we propose an emergency vehicle priority and self-organised traffic control (EVP_STC) protocol, which prioritises the arrival of emergency vehicles at intersections to reduce their response times in emergency situations. In addition, EVP-STC prioritises all four approaches at intersections and determines the sequences and the durations of traffic light signals based on the estimated arrival times of emergency vehicles and the density of vehicles on each approach. Force-resistive sensors are installed to count the number of vehicles approaching the intersection. This information is then transmitted via Zigbee to an intersection controller which controls the traffic light duration based on the changing traffic environment.

The remainder of this paper is organised as follows. Section II describes related work. Section III presents the flow charts and algorithms for the microcontrollers installed in the intersection controller, as well as the emergency vehicle and transmitter setup. Section IV describes our simulation environment and compares the performance of EVP-STC with that of a fixed-time-slot traffic control protocol. Finally, Section V provides some conclusions.

II. RELATED WORK

Accidents involving emergency vehicles represent a significant problem that is growing worldwide. Most emergency vehicle accidents occur at intersections because emergency vehicles travel at higher speeds in urgent situations, which can lead to severe injury or death. To prioritise the transit of emergency vehicles and organise traffic flows at intersections, a number of traffic management schemes have been proposed by researchers [5]. In [6]–[9], intelligent traffic control systems were proposed to provide priority to emergency vehicles. In [10], cameras were installed at intersections to measure traffic conditions, which were then utilised to estimate the sequences of traffic lights.

Shaikh and Chandak [11] utilised recent technologies, such as infrared cameras and GPS, to detect the presence of emergency vehicles and calculate the real-time traffic density. In [12], RFID tags were utilised to identify the presence of emergency vehicles and the inductive loop method was adopted to count vehicles. It was reported in [6] that recent technologies, such as RFID, Bluetooth, ZigBee, and the global system for mobile communication, can be utilised to design intelligent traffic control systems. In [13] and [14], vehicular sensor networks were utilised to provide promising solutions for traffic management by utilising localisation algorithms to determine the locations of vehicles containing wireless sensor network nodes.

Emergency vehicle pre-emption techniques were proposed in [15] and [16], where sensors were installed at each intersection to identify the presence of emergency vehicles. Then, the traffic light controller presented a green light in the direction of an emergency vehicle until it exited the intersection. An RFID- and GPS-based automatic lane clearance protocol for ambulances was proposed in [17]. The objective of this protocol was to minimise the travel times of ambulances by clearing lanes prior to an ambulance reaching an intersection.

In [18], a cellular automata model was established for intersections to analyse the different characteristics of vehicles in two different environments (i.e., a non-vehicle networking environment and Internet of Vehicles (IoV) environment). This model considers the speed effects of leading vehicles, influence of brake lights, and many other rules to accurately reflect the operation of traffic flows at an intersection. A comparison of traffic parameters, such as vehicle speed, traffic flow, and average travel time, was conducted via numerical simulations for the two environments. The results revealed that in an IoV environment, a vehicle's queue length is shorter, congestion dissipates faster, and traffic runs more smoothly.

In [19], a traffic signal control framework was proposed for determining the signal control settings that minimise total travel times at intersections. The proposed framework integrates the double-queue traffic flow model into a signal-controlled traffic network to capture queue spillbacks. Furthermore, driver route choices in response to changes in traffic signal control were captured using Wardrop's first principle model. A solution based on a heuristic genetic algorithm was implemented to solve the proposed nonlinear programming problem with time-varying delay terms.

In [20], a joint adaptive routing and traffic signal control algorithm was proposed to improve traffic operations in a vehicular ad-hoc network environment. Drivers could access real-time traffic information through a vehicle-to-vehicle infrastructure to make route choices at each intersection based on a hyper-path trees model. It is known that a driver's route choices are affected by traffic control strategies. To study the effects of incoming traffic and current queues on traffic signal operation, two traffic signal control strategies (i.e., phase selection control and modified max pressure control) were proposed.

In [21], a novel paradigm for traffic signal control, called 'self-organising signals', was proposed based on a local actuated controller with additional rules and coordination mechanisms. New rules were proposed for extending green signal times to serve imminently arriving platoons. In addition, a dynamic coordination mechanism was incorporated in which small groups of closely spaced traffic signals communicate with each other to cycle synchronously at critical intersections in order to reduce transit delays.

In [22], a multi-modal traffic signal priority problem was discussed under the assumption that vehicle-to-infrastructure communication is available for different traffic modes. Priority eligible vehicles, such as emergency vehicles, transit buses, commercial trucks, and pedestrians were able to send requests for priority to a traffic signal controller when approaching a signalised intersection. It is likely that multiple vehicles and pedestrians will send such requests, meaning that there may be multiple active requests simultaneously. A request-based mixed-integer linear program was formulated to explicitly accommodate multiple priority requests from different modes of vehicles and pedestrians.

In [23], a traffic light control system utilising a co-simulation-based optimisation approach was proposed to provide traffic light priority to trucks. This system assumes that there is continuous communication between trucks and intersection controllers. When a truck approaches a signalised intersection, it reports its arrival to the intersection controller by sending its real-time information (velocity, location, size, etc.). The intersection controller then estimates the truck arrival time at the intersection and assigns the highest passing priority to the truck.

Huang *et al.* [24] proposed a traffic control system using Timed Petri Nets (TPN). The proposed system gives priority to emergency vehicles, allowing them to pass through intersections with less delay. A reachability graph analysis was utilized to prove the liveness and reversibility of the proposed TPN model. In [25], Petri nets (PNs) were utilized to model traffic-light control system for intersections. Cameras were utilized to detect accidents at intersections in order to prevent large-scale congestion induced by these accidents. The proposed model recovers deadlocks, prevents livelocks, and resolves conflicts to ensure safety at an intersection. In [26], a set of algorithms were proposed to plan traffic signal timings through deep reinforcement learning. A deep neural network (DNN) was arranged to learn from the sampled traffic control inputs and the corresponding traffic control outputs. Based on the obtained DNN, an optimal traffic signal timing plan was constructed for the complex dynamics of vehicles at intersection.

Recently, a novel traffic-management concept called the virtual traffic light (VTL) was proposed [27], [28]. In a VTL system, vehicles self-organise to elect a leader to serve as a VTL infrastructure. The leader is responsible for broadcasting traffic light messages in order to resolve traffic conflicts at intersections. The leader vehicle should present a green signal to one approach and a red signal to the remaining approaches. Once the VTL leader detects that the approach with a green light has no additional vehicles attempting to cross the intersection, that approach is interrupted and the green light is given to the next approach. When the green light is in the leader's approach, a new leader must be elected to maintain the VTL.However, in VTL systems, sending 'hello' messages increases the communication overhead. In addition, the implementation costs of VTL systems are very high, as each vehicle needs to be equipped with a dedicated short-range communication (DSRC) device, a digital road map and a global positioning system (GPS). Münst *et al.* [29], Shi *et al.* [30], Ferreira and d'Orey [31], Fathollahnejad *et al.* [32], and Wang *et al.* [33] proposed various schemes based on VTL.

Existing protocols either propose techniques to resolve the issue of prioritising emergency vehicles at intersections, or resolve the issue of managing the sequences and durations of traffic light signals according to the vehicle densities on particular road segments or approaches. Our previous work in [34] focuses only on adjusting the timings of green traffic lights in accordance with the detected real time traffic, without considering the presence of emergency vehicles at an intersection. To the best of our knowledge, very few protocols exist that resolve both issues (i.e., prioritise emergency vehicles at intersections and estimate the durations of traffic light signals according to vehicle density). Therefore, the major contribution of this study comprises a system that both prioritises emergency vehicles at intersections and manages the sequences and durations of traffic light signals based on the vehicle density on each approach, which is measured by utilising force-resistive sensors. This work builds on our previous work in [34] by incorporating the presence of emergency vehicles at intersection. In addition, we provide details of algorithms performed by emergency vehicles, transmitting systems installed at intersections and intersection controllers. In addition, extensive simulations are preformed to demonstrate how the proposed scheme accommodates the arrival of emergency vehicles in order to reduce the response times of emergency vehicles at intersections.

III. ARCHITECTURE OF THE PROPOSED EVP-STC PROTOCOL

This section presents the architecture of the proposed EVP-STC protocol, which aims to reduce the average waiting times of both emergency and non-emergency vehicles at intersections by utilising the following key features:

- Intersection controller: The intersection controller manages the arrival of emergency and non-emergency vehicles. It prioritises emergency vehicles at intersections and assigns the highest priorities to high-density roads or approaches
- Force resistive sensors: Sensors are installed at a distance of 25 m from an intersection to transmit vehicle count information to the intersection controller via ZigBee.
- Emergency vehicle: An emergency vehicle approaching an intersection communicates with the intersection controller via ZigBee for priority assignment.

Fig. 1 illustrates a four-way road intersection where force resistive sensors are installed on each lane at a distance of 25 m from the intersection. The 25 m distance was selected for testing purposes, but this distance can be increased and

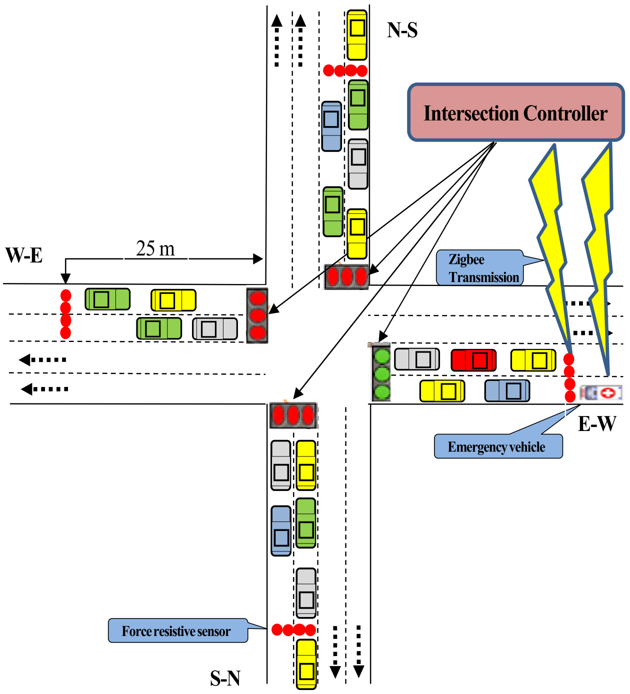


FIGURE 1. Four-way road intersection.

is highly application dependent, especially in dense urban areas where long vehicle queues form at intersections. It is indicated in Fig. 1 that both the force resistive sensors and emergency vehicles communicate wirelessly with the intersection controller via ZigBee. The intersection controller manages the operation of all the traffic lights installed at the intersection. Fig. 2 presents a flow chart for the vehicle detection system installed at each approach. The vehicle detection system includes force resistive sensors, a microcontroller, and a Zigbee module. Each approach consists of two lanes, and each lane is equipped with force-resistive sensors. Force-resistive sensors are utilised to detect vehicles at each approach. The microcontroller is utilised to transmit vehicle count information to the intersection controller through a Zigbee module. As shown in the flowchart, a predefined timer and count variable are initialised, and the microcontroller waits for an event to occur. When an event occurs, the controller will check the event type. If a vehicle is detected, then the count variable is incremented by one, and the microcontroller returns to the event detection state. However, if a 'timer expired' event is detected, then a message containing the vehicle count information is transmitted to the intersection controller.

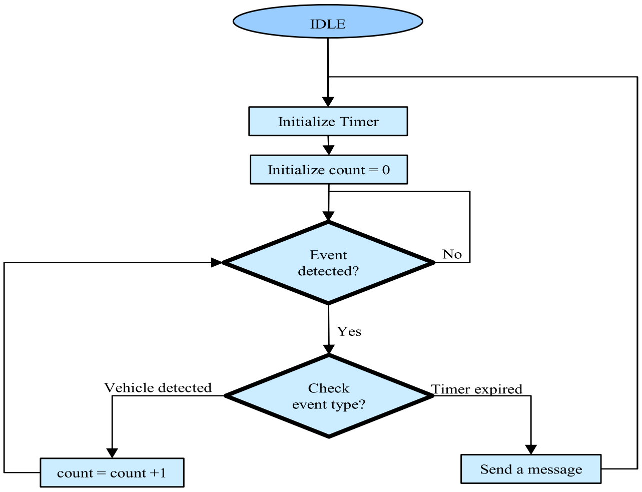


FIGURE 2. Flow chart for the vehicle detection system installed at each approach.

Fig. 3 presents a flow chart for the system installed in emergency vehicles. An emergency vehicle announces its presence by periodically sending emergency priority request (EPR) messages (containing location coordinates and velocity information) to the intersection controller. When an EPR message is received by the intersection controller, it sends an 'EPR granted' message to the emergency vehicle. If an emergency vehicle receives this message, then it continues to move towards the intersection at constant speed. To calculate the time an emergency vehicle requires to reach the intersection, the microcontroller in the intersection controller utilises the Haversine formula [35] to determine the distance between the emergency vehicle and intersection.This process is defined by the following equation (1):

$$dist = 2r\sin^{-1} \times \sqrt{\sin^2\left(\frac{\Delta Ø}{2}\right) + \cos\left(Ø_1\right) * \cos\left(Ø_2\right) * \sin^2\left(\frac{\Delta\delta}{2}\right)} \tag{1}$$

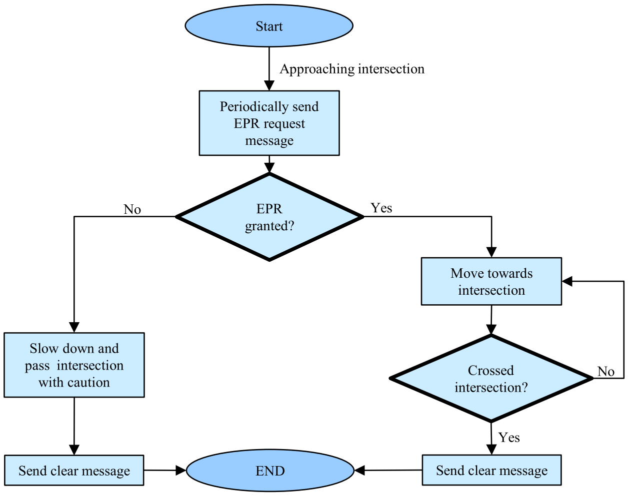


FIGURE 3. Flow chart fo the system installed in emergency vehicles.

where Ø is the latitude, δ is longitude (in radians). Finally, equation (2) is utilised to calculate the time required for an emergency vehicle to reach the intersection. The calculated time value is then utilised by the intersection controller to present a green signal at the appropriate time to an approaching emergency vehicles.

$$\text{Time} = \frac{\text{dist}}{\text{velocity}} \quad (2)$$

The intersection controller interacts with both the vehicle detection system and the system installed in emergency vehicles. A Zigbee module in the intersection controller receives messages from all four approaches and emergency vehicles, and then forwards them to the microcontroller. The microcontroller controls the operation of all traffic lights based on the received information. If a message is received from an emergency vehicle, the normal operation of the traffic lights is interrupted and priority is granted to the approach from which the arrival of emergency the vehicle is expected. However, in the absence of an emergency vehicle, the microcontroller prioritises the four approaches based on the vehicles density on each approach and switches the approaches on or off accordingly.

Algorithm 1 presents the code for the microcontroller in the transmitter system installed at each approach. A predefined timer T_{pd} and count variable Cnt_{veh} are initialised and the microcontroller waits to detect events. When an event occurs, the controller will check the event type. If a vehicle is detected by a force resistive sensor, then Cnt_{veh} is incremented by one and the controller returns to the event detection state. However, if the timer T_{pd} expires, then an ET_{pd} event is detected. A message containing the vehicle count information is then transmitted to the intersection controller. After sending a message, the microcontroller of a transmitter system will reset both the predefined timer T_{pd} and count variable Cnt_{veh}. The same process is then repeated. The format of the message (shown in Fig. 4) includes the sensor ID, message ID, and vehicle count information.

Algorithm 1 Microcontroller at Transmitting System

```
Input: E_v (vehicle detected by sensor)
Output: MSG (message containing sensor ID, message ID, and Cnt_veh)

Procedure:
Step 1: defining and initialising variables
        $T_{pd}$ = (Predefined timer) = 2 min
        $Cnt_{veh}$ = (counts vehicles detected by sensor) = 0
        $ET_{pd}$ = $T_{pd}$ Expired
Step 2: detecting events
        -While (1) do
            if ($E_v = true$)
                -$Cnt_{veh} = Cnt_{veh} + 1$
            -End if
            -if ($ET_{pd} = true$)
                -send MSG
                -$Cnt_{veh} = 0$
            -End if
        -End While
```

Header	Sensor ID	Message ID	Count	Trailer

FIGURE 4. Message format.

Algorithm 2 presents the code for the microcontroller in an emergency vehicle. An emergency vehicle announces its presence by periodically sending EPR messages to the intersection controller. If the intersection controller receives an EPR message from an emergency vehicle, then it sends an EPR granted message to the emergency vehicle. Once the emergency vehicle receives this message, it continues moving towards the intersection at constant speed. In the unlikely event that an emergency vehicle reaches an intersection and has not yet received an EPR granted message, it slows down and carefully observes other vehicles before crossing the intersection. As soon as the emergency vehicle crosses the intersection, the event CR_{int} is detected. The vehicle then broadcasts a clear message CL_{msg} to allow the intersection controller to resume normal traffic operation.

Algorithm 2 Microcontroller in Emergency Vehicle

```
Input: $EPR_{gnt}$ (EPR granted message)
Output: $EPR_{req}$ (EPR request message) $CL_{msg}$ = Clear message

Procedure:
Step 1: defining and initialising variables
        $CR_{itn}$ = Crossed intersection
Step 2: detecting $EPR_{gnt}$ message
        -While (1) do
            Periodically send $EPR_{rq}$ message
            -if ($EPR_{gnt} = true$)
                -move towards the intersection at constant speed
            -End if
            - if ($EPR_{gnt} = false$)
                -slow down and cross the intersection with caution
            -End if
            -if ($CR_{itn} = true$)
                -send $CL_{msg}$
            -End if
        -End While
```

Algorithm 3 presents the code for the microcontroller at the intersection controller. This controller waits for different types of events to occur. If an EPR request (EPR_{req}) message arrives from an emergency vehicle approaching the intersection, the controller sends an EPR granted (EPR_{gnt}) message back to the emergency vehicle. In addition, the controller stops the current sequence of traffic light signals and calculates a green signal time for the emergency vehicle using equation (2), to present a green signal GS_{rp} to the approach containing the emergency vehicle and red signals to all remaining approaches. Once the emergency vehicle crosses the intersection, it sends a clear message CL_{msg} to the

Algorithm 3 Microcontroller at Intersection Controller

```
Input: $EPR_{rq}$ (EPR request message)
       $MSG$ (message containing Sensor ID, message ID,
       and $Cnt_{veh}$), $CL_{msg}$ (clear message)
Output: $EPR_{gnt}$ (EPR granted message)

Procedure:
Step 1: defining and initialising variables
        $GS_{rp}$ = Green signal to proper approach
        $RS_{rp}$ = Red signal to proper approach
        $Cnt_{msg}$ = count no. of MSGs received
        $Array_{msg}$ = Array containing received MSGs
        $T_{GS}$ = Green signal time calculated using (3).
        $ET_{GS}$=$T_{GS}$ Expired
Step 2: detecting events
    -While (1) do
        -if $(EPR_{req} = true)$
            - Send $EPR_{gnt}$
            - Calculate green signal time using (2)
            - Show $GS_{rp}$
        -End if
        - if $(CL_{msg} = true)$
            - Resume normal operation
        -End if
        - if $(MSG = true)$
            - Store MSG in $Array_{msg}$
            - $Cnt_{msg} = Cnt_{msg} + 1$
        -End if
        - if $(Cnt_{msg} = 4)$
            - Sort $Array_{msg}$ in descending order
              of the value of $Cnt_{veh}$
            - Push MSG's into a Queue.
            -While (Queue not empty)
                - Pop MSG from the queue.
                - Extract sensor ID and
                  $Cnt_{veh}$
                - Calculate and start $T_{GS}$
                - Show $GS_{rp}$
                -if $(ET_{GS} = true)$
                    - Show $RS_{rp}$
                -End if
            -End While
        -End if
    -End While
```

controller. After receiving the clear message, the controller resumes normal operation. In contrast, if the detected event is the arrival of a message from the transmitter system that is installed at each approach, then this message is initially stored in an array ($Array_{msg}$), and the count variable Cnt_{msg} is incremented by one. If Cnt_{msg} is equal to four (i.e., all four transmitting systems have sent their respective messages containing vehicle counts for their respective approaches), then these four messages are sorted in descending order of the value of Cnt_{veh}. The messages are then pushed into a queue in descending order of the value of Cnt_{veh}. Next, a loop is initiated to process all four messages until the queue is empty. First, the message with the highest vehicle count value Cnt_{veh} is popped from the queue. Thereafter, a timer T_{GS} is initialised by utilising equation (3), where T_{GS} represents the time required for the vehicles on a particular approach to cross the intersection, S is the distance between the force-resistive sensor and the intersection (25 m in our simulations), V is the average velocity of the vehicles crossing the intersection, Cnt_{veh} is the number of vehicles per lane, and N_M is the maximum number of vehicles that can be accommodated per lane. After calculating the timer T_{GS}, a green signal GS_{rp} is presented to the correct approach. The green signal will remain active as long as the timer T_{GS} has not expired. Once the timer T_{GS} expires (ET_{GS}), a red signal RS_{rp} is presented to that approach, and the next message is popped from the queue. This process is repeated until all four messages have been processed and the queue is empty. Once the queue is empty, a new set of four messages is pushed into the queue and the entire process is repeated.

$$T_{GS} = \frac{S}{V} \times \frac{Cnt_{veh}}{N_M} \tag{3}$$

IV. PERFORMANCE EVALUATION

In this section, the performance of EVP-STC is compared with a fixed-time-slot traffic signal controller and a VTL scheme based on simulations of various traffic conditions.

A. SIMULATION ENVIRONMENT

The fixed-time-slot protocol was implemented by utilising the PTV Vissim (version 9.00) simulator [36], and tested based on an intersection scenario. The same configuration data was utilised for the proposed EVP-STC protocol and the VTL scheme. The intersection has four approaches. Each approach has two lanes in both the approaching and exiting directions. To maintain a variable vehicle load on each approach, four different vehicle densities were considered for each approach. In the west-east (W-E) approach, the densities of the vehicles were 700, 1,200, 1,700, and 2,200 during different simulations. In the south-north (S-N) approach, the densities of the vehicles were 800, 1,300, 1,800, and 1,900. In the east-west (E-W) approach, the densities of the vehicles were 900, 1,400, 1,500, and 2,000. Finally, in the north-south (N-S) approach, the densities of the vehicles were 1,000, 1,100, 1,600, and 2,100. The loads on all approaches were distributed in such a manner that each approach experiences minimum, average, and maximum vehicle loading during different simulation runs. For the fixed-time-signal control protocol, one stage for each approach was defined with a green signal time of 10 s. An inter-stage time of 5 s was defined to switch from a green to an orange signal and from an orange to a red signal. After 15 s, the next approach will be presented with a green signal. Therefore, the total cycle time for the four approaches is 60 s. For the EVP-STC protocol, the transmitter setup was installed at a distance of 25 m from the intersection. It is assumed that a 25-m road segment accommodates a minimum of six and maximum of 12 vehicles per lane. For the VTL scheme, each vehicle is equipped with a GPS system and DSRC radios with a transmission range of 200 m. The vehicles move at a speed of 10 km/h to cross the intersection. The simulation parameters are summarised in Table 1.

TABLE 1. **Simulation parameters.**

PARAMETERS	Value
Simulation scenario	Intersection
No. of Lanes	2
Vehicle density (W-E)	700, 1,200, 1,700, 2,200
Vehicle density (S-N)	800, 1,300, 1,800, 1,900
Vehicle density (E-W)	900, 1,400, 1,500, 2,000
Vehicle density (N-S)	1,000, 1,100, 1,600, 2,100
Green signal time	10 s
Inter-stage time	5 s
Cycle duration	60 s
Transmitter setup	25 m
No. of vehicles in 5 m/lane	6,8,10,12
Vehicle velocity	10 km/h
VTL DSRC range	200 m
Simulation duration	10,000 sec

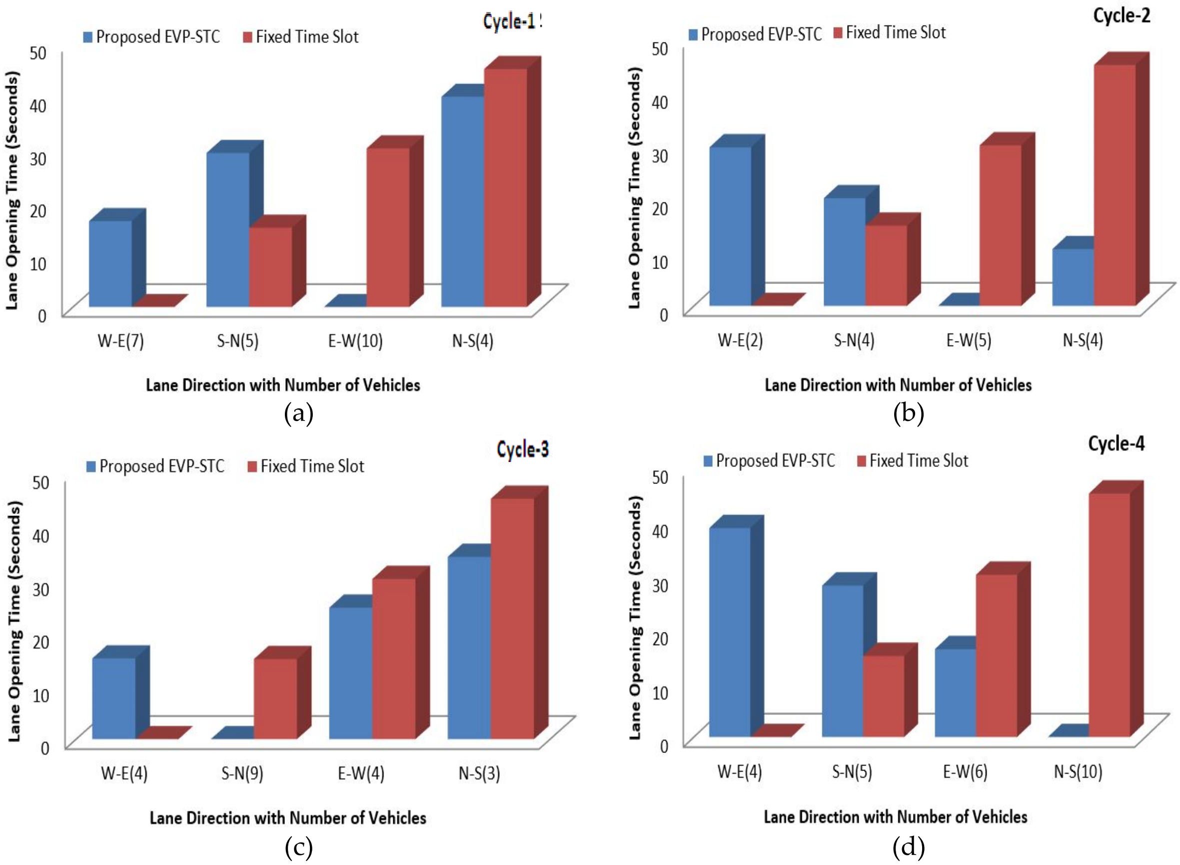
B. PERFORMANCE METRICS

To investigate the performance of the EVP-STC protocol, the following metrics were utilised:

- Lane opening time: The time at which a particular approach is presented with a green traffic signal to let vehicles cross the intersection.
- Total delay experienced: The cumulative sum of all the cycle delays incurred during the simulation, where the cycle delay refers to the time required to complete one cycle for all four approaches at the intersection. This value is constant for fixed-time traffic signals and variable for the EVP-STC protocol.
- Total overhead: The total number of control messages sent during the simulation of EVP-STC and VTL.

1) LANE OPENING TIME

Fig. 5 compares the lane opening times for EVP-STC and the fixed-time-slot traffic signal controller according to the vehicle density on each approach. Fig. 5(a) presents the lane opening times during the first cycle. In the case of fixed time slots, it is shown that the W-E approach is opened at second zero. Then, after 15 seconds, the S-N approach is opened. Similarly, the E-W and N-S approaches are opened after exactly 30 and 45 s, respectively. However, in the case of EVP-STC, the lane opening time depends on the vehicle density on each approach. Fig. 5(a) indicates that the E-W approach is opened first because there are more vehicles (10) on the E-W approach compared to the remaining approaches.



(a) (b)

(c) (d)

FIGURE 5. **Lane opening times during four different cycles.**

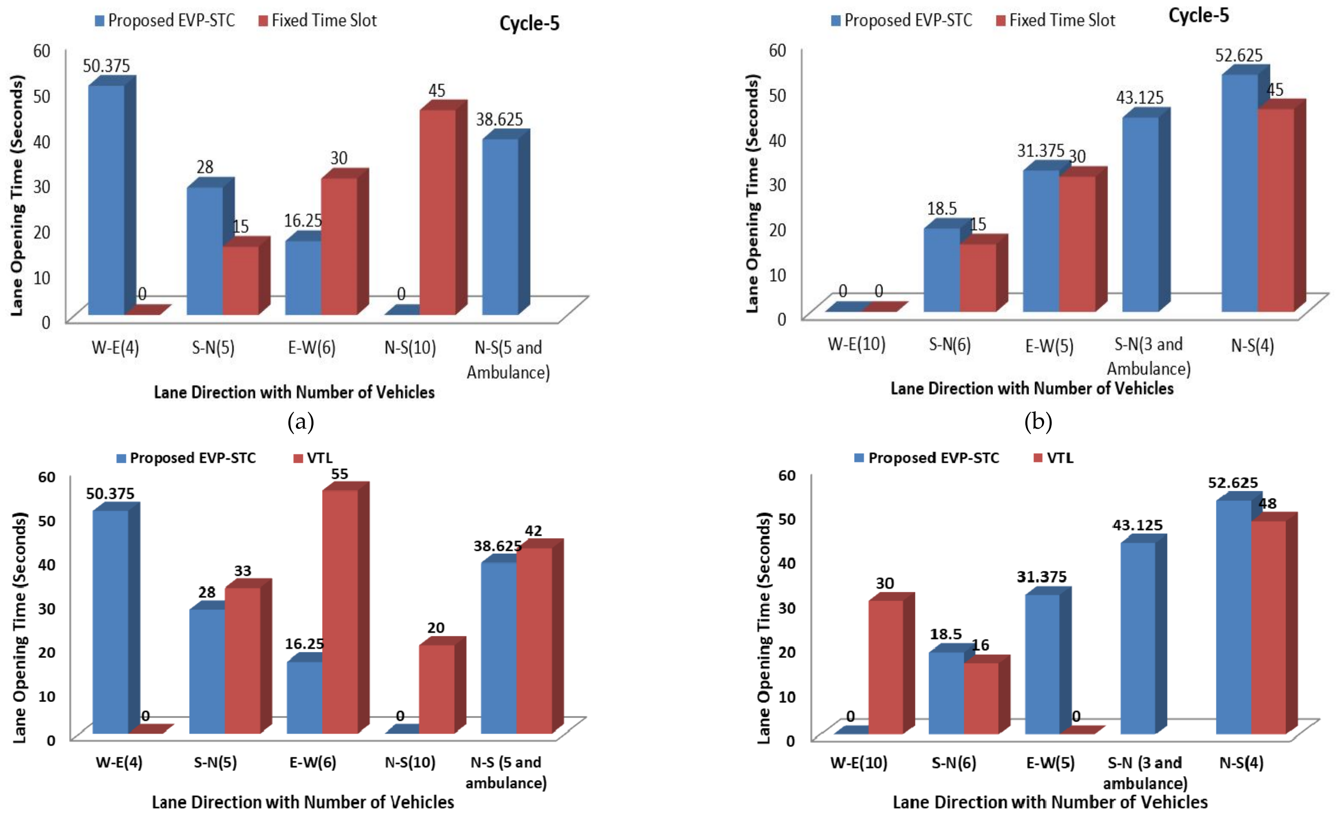
The duration of the green signal is calculated based on the number of vehicles on the E-W approach, as shown in equation (3). Then, the W-E, S-N, and N-S approaches are opened with seven, five, and four vehicles per lane, respectively. In EVP-STC, owing to the variable-time signal controller, the lane opening time for the last N-S approach is 41 s, in contrast to the 45-s opening time in the case of fixed time slots.

In Fig. 5(a, b, c, d), it is shown that in the case of fixed time slots, the lane opening time for the last approach is 45 s for all four cycles. This is because the lane opening time is fixed for all four approaches and does not depend on the vehicle density. However, Fig. 5(a, b, c, d) shows that in the case of EVP-STC, the lane opening time for the final approach is variable during all four cycles and depends on the number of vehicles on that particular approach. In the case of EVP-STC, the minimum lane opening time for the final approach was 32 s and the maximum was 41 s.

In Fig. 5, it is also shown that in EVP-STC, the maximum lane opening time for a particular approach is always less than the maximum lane opening time for fixed time slots. Therefore, in the proposed EVP-STC scheme, the highest priority is assigned to the approach with the highest vehicle density, which leads to a reduction in the queue lengths at intersections, which eventually reduces the waiting times of vehicles and avoids the formation of long queues of vehicles at intersections.

2) LANE OPENING TIME CONSIDERING EMERGENCY VEHICLES

Fig. 6 presents the lane opening times when an emergency vehicle, such as an ambulance, arrives on a particular approach. In the case of fixed time slots, it is shown in Fig. 6 (a, b) that the W-E approach is always opened at second zero. Then, in 15-s intervals, the remaining S-N, E-W, and N-S approaches are opened. Therefore, the cycle time for fixed time slots is always 60 s. This is because each of the four approaches is opened after exactly 15 s. However, in the case of EVP-STC, the lane opening time for any approach depends on the vehicle density on that approach. In Fig. 6 (a), it is shown that the N-S approach is opened at second zero because there are more vehicles (10) on the N-S approach compared to the remaining approaches. Then, the E-W and S-N approaches are opened after 16.25 and 28 s with six and five vehicles per lane, respectively. Following the S-N approach, the next approach to open is the W-E approach with four vehicles per lane. Meanwhile, an ambulance arrives on the N-S approach with five additional vehicles. The intersection controller is made



(a)

(b)

(c)

(d)

FIGURE 6. Lane opening time considering emergency vehicles.

aware of the arrival of the ambulance via Zigbee transmission and prioritises its approach by opening the N-S approach at 38.625 s instead of opening the W-E approach, thereby reducing the waiting time for the ambulance at the intersection. If it is assumed that the ambulance arrives at 35 s on N-S approach, then according to the fixed-time protocol, the N-S approach is opened at 45 s, thereby increasing the waiting time of the ambulance at the intersection by 6.5 s compared to the lane opening time of the ambulance in the EVP-STC protocol. Once the ambulance passes through the intersection, the W-E approach is opened at 50.375 s.

Fig. 6(b) presents another scenario involving the arrival of an ambulance. The W-E approach is opened at second zero because it has the highest number of vehicles. Then, the S-N and E-W approaches are opened at 18.5 s and 31.375 s with 6 and 5 vehicles per lane, respectively. After the E-W approach, the next approach to open is the N-S approach with four vehicles per lane. Meanwhile, an ambulance arrives on the S-N approach with three additional vehicles. The intersection controller is made aware of the arrival of the ambulance via Zigbee transmission and prioritises its approach by opening the S-N approach at 43.125 s to reduce the waiting time of the ambulance at the intersection. If it is assumed that the ambulance arrives at 35 s on the S-N approach, then according to the fixed-time protocol, the S-N approach is opened on the next cycle at 70 s, thereby increasing the waiting time of the ambulance at the intersection by nearly 27 s compared to the lane opening time of the ambulance in the EVP-STC protocol. Once the ambulance passes through the intersection, the N-S approach is opened at 52.625 s.

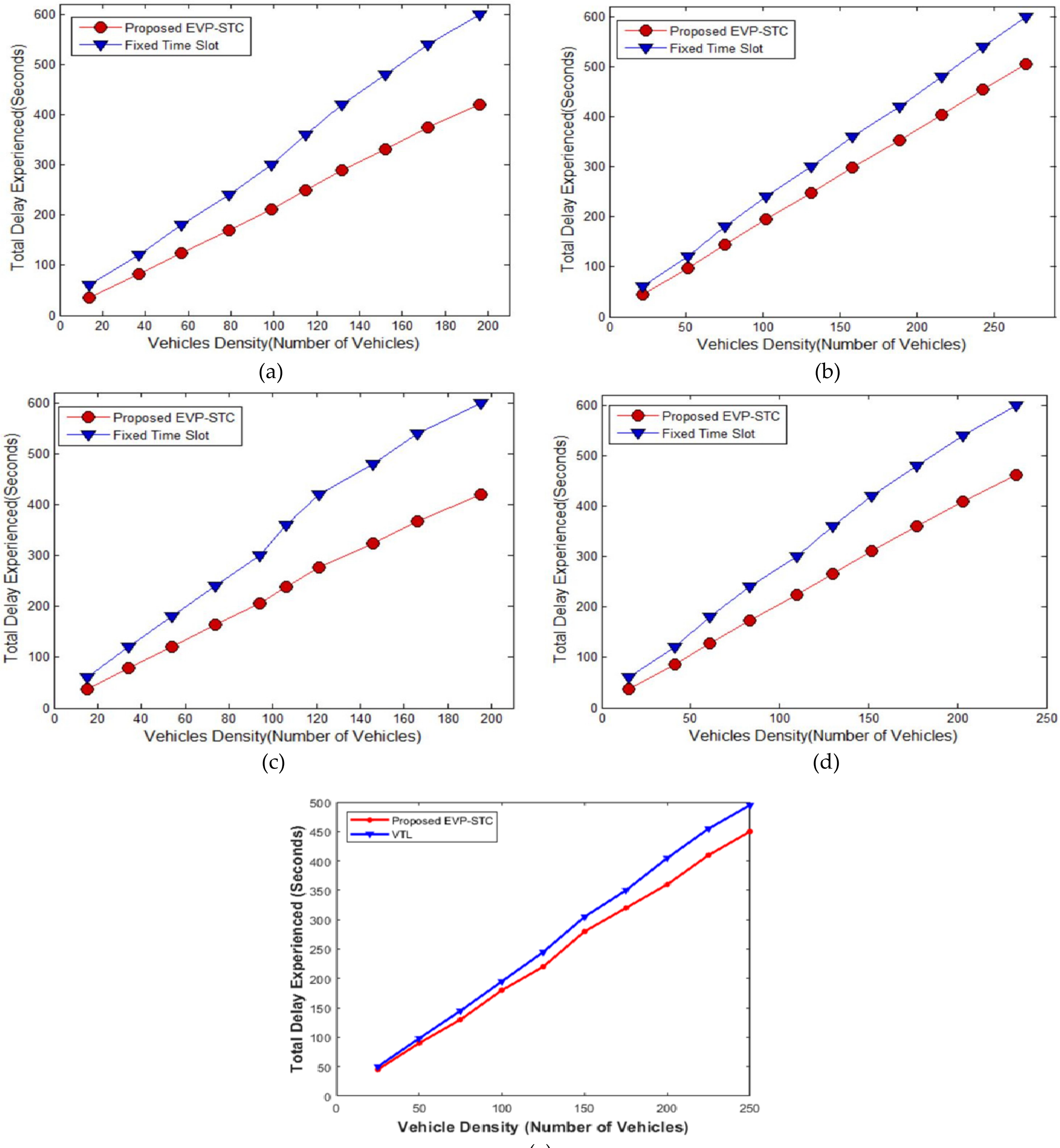
Fig. 6 (c) compares the proposed EVP-STC with the VTL scheme. The lane opening times of EVP-STC are similar to those in Fig. 6 (a). In Fig. 6 (c), it is shown that for VTL, the W-E approach is opened at second zero, because the leader vehicle shows a green signal to W-E approach. Then, N-S and S-N approaches are opened after 20 and 33 s, respectively. As described earlier, in VTL, the leader assigns green light to next approach when it detects that the approach with a green light has no additional vehicles attempting to cross the intersection. Hence, in VTL, the green signal time for a particular approach depends on the presence of vehicles on that approach which in turn increases the waiting times of vehicles on other approaches at the intersection. Following the S-N approach, the next approach to open is the E-W approach. Meanwhile, an ambulance arrives on the N-S approach. According to VTL scheme, the ambulance is given priority by opening the N-S approach at 42 s instead of opening the E-W approach, thereby reducing the waiting time of the ambulance at the intersection. Once the ambulance passes through the intersection, the E-W approach is opened at 55 s. In Fig. 6 (c), it is shown that the lane opening time for the emergency vehicle in the proposed EVP-STC comprises the lower time of 38.6 s compared with 42 s in the case of VTL. This is because in VTL, a particular approach remains open for traffic flow as long as vehicles are present on that approach, thereby increasing the waiting times of other approaches. Second, owing to the exchanges and collisions of hello messages between vehicles in the VTL scheme, the leader vehicle is unable to correctly estimate the presence of vehicles on a particular approach. These estimation errors in VTL might lead to prolonged green signal times for some approaches which in turn increase the waiting times of emergency vehicles.

Fig. 6(d) also compares the proposed EVP-STC with the VTL scheme and presents an additional scenario involving the arrival of an ambulance. The lane opening times for EVP-STC are similar to those in Fig. 6(b). In Fig. 6 (d), it is shown that for VTL, the E-W approach is opened at second zero. Then, the S-N and W-E approaches are opened at 16 s and 30 s, respectively. After the W-E approach, the next approach to open is the N-S approach. Meanwhile, an ambulance arrives on the S-N approach. However, the VTL leader is unable to detect the arrival of the ambulance owing to the collision of the emergency message with a high density of hello messages exchanged among vehicles at the intersection. Hence, the N-S approach is opened at 48 s, and the ambulance waits at the S-N approach, with its waiting time increased. Therefore, the proposed EVP-STC protocol reduces the waiting times of vehicles at an intersection by incorporating balanced green signal times for all approaches. In addition, the proposed EVP-STC scheme perfectly detects the arrival of emergency vehicles by avoiding exchanges of hello messages among vehicles at an intersection.

3) TOTAL DELAY EXPERIENCED

Fig. 7 illustrates the total delays experienced with respect to the vehicle density. It is shown in Fig. 7(a, b, c, d) that for fixed time slots, the delay increases exponentially. This is because the cycle delay of fixed time slots is always 60 s. However, in the case of EVP-STC, the total delay experienced by vehicles is lower than that in the case of fixed time slots. Fig. 7 (a) illustrates the total delay experienced with an average of eight vehicles per lane. The proposed protocol achieved minimum delays compared to the fixed time slots protocol. Fig. 7 (b) illustrates the total delay experienced when the vehicle density is increased from eight to 12 vehicles per lane. It is revealed that the total delay experienced by vehicles in the proposed scheme is increased compared to the total delay experienced when there were eight vehicles per lane. This is because when the number of vehicles per lane increases at the intersection, the delays of vehicles also increase, as described in equation (3). However, the delay for the proposed EVP-STC scheme is still lower than that of fixed time slots protocol.

Fig. 7(c) and Fig. 7(d) illustrates the total delays experienced when there are 6 and 10 vehicles per lane, respectively. It is revealed that as the vehicle density decreases from 8 to 6 vehicles per lane, the total delay experienced by vehicles in the case of EVP-STC decreases. This is because the proposed EVP-STC estimates the durations of traffic light signals based on the vehicle density on a particular approach.



(a)

(b)

(c)

(d)

(e)

FIGURE 7. Total delay experienced. (a) Eight vehicles/lane. (b) 12 vehicles/lane. (c) Six vehicles/lane. (d) 10 vehicles/lane. (e) 12 vehicles/lane.

Fig. 7 (d) reveals that as the vehicle density decreases from 12 to 10 vehicles per lane, the total delay for the proposed scheme also decreases. This confirms that the proposed EVP-STC effectively manages the durations of traffic signals based on the vehicle density on each approach. The results shown in Fig. 7 indicate that the proposed EVP-STC protocol can reduce the delays of emergency vehicles to a greater extent under light traffic scenarios and to a lesser extent under heavy traffic scenarios. However, this delay is always lower than that incurred by emergency vehicles with fixed-time-slots traffic signals.

Fig. 7(e) shows that in the proposed EVP-STC scheme, the total delay experienced by vehicles is lower than that in the case of VTL. This is because, in VTL, a particular approach remains open for traffic flow as long as vehicles are present on that approach. Such unbalanced green signal times for different approaches increase the total time required for a complete cycle. Furthermore, owing to the exchanges and collisions of hello messages between vehicles in the VTL scheme, the leader vehicle is unable to correctly estimate the presence of vehicles on a particular approach. Therefore, the leader vehicle assigns longer times to some approaches which increase the cycle time at an intersection. Fig. 7 (e) shows that as the vehicle density increases, the increase in the delay for VTL is significant, because of a high rate of collisions among hello messages.

4) TOTAL OVERHEAD

Fig. 8 compares the total overheads of EVP-STC and VTL according to the vehicle density. The overhead appears to scale very well for EVP-STC, especially in heavy traffic conditions. The only overhead in EVP-STC stems from the transmission of messages from all four transmitting systems containing vehicle counts for their respective approaches. However, the overhead resulting from these messages is considerably lower than the overhead resulting from the periodic exchange of hello messages in case of VTL. The total overhead for EVP-STC is approximately 65% lower than that of VTL.

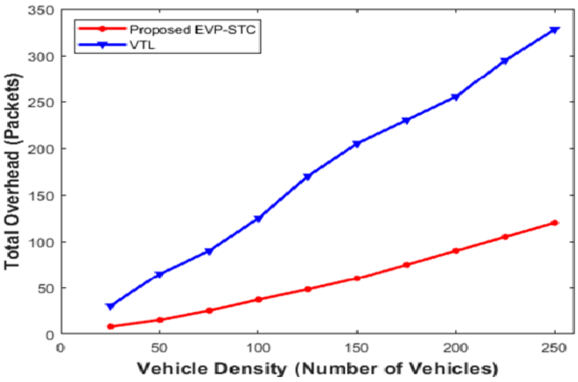


FIGURE 8. **Total overhead.**

V. CONCLUSION

In this study, EVP-STC was proposed to maximise traffic throughput and minimise average vehicle waiting times at intersections. This scheme accelerates emergency response operations, by facilitating the transit of emergency vehicles through intersections in urban areas. In the proposed priority management scheme, an intersection controller communicates with force-resistive sensors and emergency vehicles via ZigBee communication, to resolve potential conflicts at intersections in order to assign higher priorities to specific roads or approaches. The results of our simulations demonstrated that with the proposed EVP-STC scheme, an emergency vehicle can reach the scene of an accident with minimal delay in both light and heavy traffic conditions compared to conventional and virtual traffic light systems. In addition, the proposed EVP-STC protocol reduces the waiting times of non-emergency vehicles compared to those in the fixed-time-slot and VTL schemes by assigning variable durations of traffic light signals to all four approaches based on the number of vehicles on each approach. The proposed EVP-STC protocol assigns the highest priorities to high-density approaches, in order to avoid long queues of vehicles at intersections.

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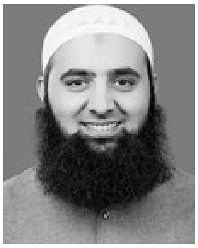

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