



# On Minimizing TCP Traffic Congestion in Vehicular Internet of Things (VIoT)

M. Joseph Auxilius Jude<sup>1</sup> · V. C. Diniesh<sup>1</sup> · M. Shivaranjani<sup>2</sup> ·  
Suresh Muthusamy<sup>3</sup> · Hitesh Panchal<sup>4</sup> · Suma Christal Mary Sundararajan<sup>5</sup> ·  
Kishor Kumar Sadasivuni<sup>6</sup>

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## Abstract

The performance of end-to-end wireless link congestion control algorithm in the vehicular internet of things network is plagued by the inherent limitations of spurious rate control initiation, slow convergence time, and fairness disparity. In this article, the delay assisted rate tuning (DART) approach is proposed for the vehicular network that implements two algorithms, utilization assisted reduction (UAR) and super linear convergence (SLC), to overcome the transmission control protocol (TCP) limitations. The UAR algorithm is responsible for initiating the proportionate rate control process based on the bottleneck prediction parameter, thereby regulating the needless rate control during non-congested losses. In the congestion recovery mode, the SLC algorithm executes a dynamic rate update mechanism that enhances the flow rate and minimizes bandwidth sharing disparity among TCP flows. An analytical model was developed to study the DART convergence rate and fairness performance against the existing algorithm. The vehicular simulation outcome also confirms significant enhancement in average transmission rate, average message latency, and average bandwidth sharing performances of the DART algorithms against the RFC 6582, TCP-LoRaD, and CERL + congestion avoidance algorithms under varying traffic flows and node movement scenarios.

**Keywords** Vehicular internet of things (VIoT) · Transmission control protocol (TCP) · Vehicular communication network · Intelligent transportation system (ITS) · Wireless access in vehicular environments (WAVE)

## 1 Introduction

An emerging connected vehicle paradigm, the VIoT [1–5], interconnects vehicles with other vehicles, humans, and machines for optimal sharing of traffic and non-traffic-related information for safe and comfortable commuting. VIoT was formed as an inevitable division of the intelligent transportation system (ITS) [6–8] to improve data sharing and better

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✉ M. Joseph Auxilius Jude  
jude2193@gmail.com

Extended author information available on the last page of the article

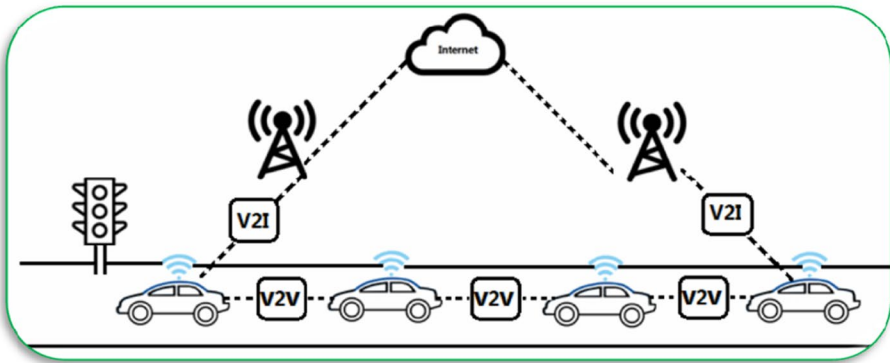


Fig. 1 V2X communication networks

resource management for semi or fully autonomous vehicles. V2X shares the vehicle information from the intelligent embedded sensors to the cloud or a diverse group of users through a fixed hotspot or roadside unit (RSU). The vehicle-to-everything (V2X) paradigm [9–11] of V2X solely relies on dedicated short-range communications (DSRC) [12–16] for device-to-device (D2D) information exchange.

The V2X operates in a 5.9 GHz radiofrequency with 10 MHz seven non-overlapping channels operating in a 75 MHz radio spectrum. V2X also caters to support non-vehicle safety services, such as file sharing, mailing service, toll payment, e-shopping, e-payment, and acts as a mobile hotspot for last-mile wireless internet connectivity. The internet remains the backbone of the V2X ecosystem; the boundless global web traffic and data center traffic depends on TCP [17–19] to deliver data packets between end systems. Figure 1 displays the vehicular transmission model in different modes.

TCP incorporates flow control [20], congestion control [21], and error control mechanisms, ensuring the successful in-sequence transmission of each information byte between sender-receiver processes. TCP's bottleneck control mechanism comprises a slow start (SS), congestion avoidance (CA), and CR mode. In the SS mode, the source device fixes the SS threshold ( $SS_{Thresh}$ ) and doubles the source window ( $Wnd$ ) rate for each successful acknowledgment. On exceeding the  $SS_{Thresh}$  the source device initiates the CA phase and gradually increments the transmission rate by one data packet for each RTT. TCP starts the transmission rate control process when the source device infers packet loss by a timeout or three duplicate acknowledgments (3DUPACK). The source device trims down the  $Wnd$  rate of TCP connections during the congestion control process by a commensurable rate reduction factor of 0.5. In the CR phase, the  $Wnd$  increments one packet per RTT until the equilibrium point. Figure 2 displays the  $Wnd$  growth or transmission pattern of additive increase and multiplicative decrease (AIMD) traffic connection for each iteration or RTT.

The majority of web servers around the globe widely adopt RFC 6582 [22] congestion control approach due to its lesser implementation complexity and faster mechanism to detect incipient network bottleneck conditions. In addition, the proper functioning of the congestion control algorithm in each phase results in optimal throughput performance. However, the existing RFC 6582 implementation remains inappropriate for the vehicular environment due to the following deficiencies.

*Spurious rate control initiation:* The RFC 6582 algorithm invokes rate control based on the timeout condition. This assumption results in triggering a spurious rate decrement process for

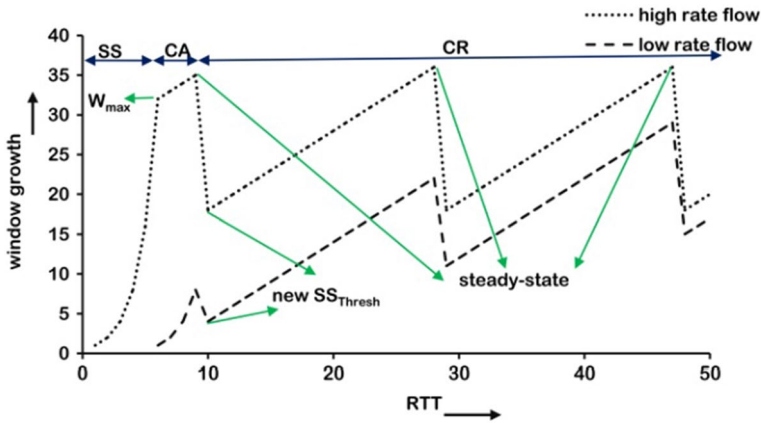


Fig. 2 Transmission pattern of RFC6582 traffic connections

non-congested RTT jitter or packet losses that arise due to frequent route breakage and radio channel losses. The spurious rate control phenomenon severely destabilizes the throughput stability of TCP traffic flow in the wireless links.

*Slow convergence rate:* TCP implementation in the CR phase is plagued by the slow *Wnd\_* update function that leads to additional RTTs to finish the flows, results in increased communication latency between end systems.

*Fairness disparity among TCP flows:* From Fig. 1, it is observed that the existing *Wnd\_* growth in the CR phase maintains a fairness disparity among the concurrent TCP flows, i.e., flows with higher and lower transmission SS rates maintain a massive variation in sharing the network bandwidth.

The DART implementation proposed in this article modifies the rate adjustment model and *Wnd\_* growth function to overcome the limitations of TCP connections under the VIoT environment. The later part of the article is arranged into five sections. Section 2 briefs contemporary literatures on independent congestion control algorithms developed for wireless scenarios. Section 3 narrates the operation of the UAR+SLC algorithms in vehicular networks, and Sect. 4 explicates the fairness and convergence model of the DART approach based on the optimization theory. Section 5 briefly outlines the vehicular simulation outcomes of the proposed and existing algorithms under diverse scenarios. Finally, Sect. 6 presents the proposed UAR+SLC implementation conclusion and discusses the future direction of the work.

## 2 Background and Related Works

Over three decades, TCP's congestion avoidance algorithm has undergone several modifications [23] to sustain a stable data rate among multiple traffic flows under both wired and wireless conditions. This literature briefly reviews the recent developments of independent congestion avoidance approaches developed to improve TCP's throughput stability in lossy wireless links. CERL+[24] method derives two parameters (queuing delay and RTT delay) for predicting the bottleneck wireless link. The sender initiates rate adjustment when the derived delay parameter is higher than the threshold level. Rather than of reacting to packet drop, CERL+ relies on delay

parameter estimation for *Wnd\_* deflation. However, the *Wnd\_* growth function in the CR phase is similar to the RFC 6582 approach, resulting in a slow convergence rate.

TCP Wave [25] approach implements a unique burst-based transmission of packets instead of traditional *Wnd\_* based packet transmission. The WAVE algorithm tracks the wireless network dynamics based on  $\Delta RTT$  computation, derived from average RTT and minimum RTT ( $RTT_{min}$ ) values. The source node initiates a reduction in burst size when the derived  $\Delta RTT$  is higher than the tolerated bottleneck level  $\beta$ .

FIT [26] algorithm is yet another derivative of RFC6582, where a newer *Wnd\_* increment mechanism is introduced in the CR phase based on the traffic flows. Furthermore, FIT implements a new rate adjustment mechanism instead of the traditional rate halving method. However, the FIT algorithm reacts to non-congested losses of lossy radio links that cripple TCP's throughput capability. TCP-LoRaD [27] predicts the bottleneck wireless link based on the queuing delay parameter. However, the *Wnd\_* growth pattern of TCP-LoRaD in the CR phase resembles the RFC6582 model resulting in a slower convergence and bandwidth sharing inequality among multiple traffic flows.

ACC [28] is yet another method to improve AIMD traffic flow under lossy radio conditions. The ACC approach solely relies on packet latency to initiate the transmission rate adjustment process. First, the sender derives the queuing delay of a wireless link by computing the RTT values of the current and old packet. The source device starts the rate adjustment process where the threshold value lesser than the obtained RTT ( $\zeta \times q_{max}$ ). In the CR phase, the ACC algorithm implements a linear *Wnd\_* increase similar to RFC 6582, resulting in a slow data throughput to attain the steady state or maximal point.

Vegas [29, 30] based end-to-end congestion avoidance implementation estimates RTT delay parameter to invoke the rate adjustment process. However, the Vegas approach fails to update the latest  $RTT_{min}$  value for wireless topology change. The discrepancy in computing  $RTT_{min}$  leads to spurious initiation of a congestion control process that cripples TCP's throughput performance. Pegas [31], modification of Vegas algorithm implements a particle swarm approach in fixing the new  $RTT_{min}$  value for dynamically changing topology. Pegas captures dropped packet count,  $RTT_{min}$ , and current transmission rate as the input parameter for setting the dynamic  $RTT_{min}$  value for each packet interval. However, PSO implementation at the sender side requires more computation parameters for obtaining a new  $RTT_{min}$  value for each packet interval. Similarly, G-vegas [32] employs grey prediction theory, and D-TCP [33] uses the cuckoo search optimization technique to estimate the dynamic  $RTT_{min}$  value based on the wireless dynamics.

However, the Vegas-based approaches perform worse under diverse TCP traffic conditions due to RTT fluctuations [26] in wireless conditions. Table 1 summarizes the behavior of recent AIMD congestion avoidance algorithms under lossy wireless networks. However, the AIMD approaches *Wnd\_* growth pattern severely compromise the steady-state convergence of the TCP flows. The additive *Wnd\_* growth in the CR phase cripples the throughput rate and requires additional RTTs to complete the TCP flow.

**Table 1** Comparison of AIMD congestion avoidance approaches

TCP	<i>Wnd_</i> pattern	Rate reduction factor	Congestion prediction parameter
CERL+	Additive increase	$Wnd_ * 0.5$	$0.5 * [(RTT - RTT_{min}) * BW]_{max}$
TCP-LoRaD	Additive increase	$Wnd_ * 0.8$	$(RTT_{max} - RTT_{min})$
WAVE	Based on receiver <i>wnd_</i>	$\geq 3$ segments	$\Delta RTT > \beta$
ACC	Additive increase	$Wnd_ * 0.5$	$RTT > \zeta \times q_{max}$
FIT	Additive increase	$Wnd_ - (2 / (3N + 1)) * Wnd_$	Packet loss event

### 3 The Proposed DART Approach

The DART implements UAR and SLC algorithms which require modification in TCP’s congestion control and recovery mechanisms. The UAR algorithm is a three-step process responsible for the rate tuning at the sender side. Step 1 implements a bottleneck prediction ( $T_{bottle}$ ) parameter to determine the incipient link congestion instead of a packet loss effect. The  $T_{bottle}$  parameter is computed based on the average RTT ( $RTT_{avg}$ ) and  $RTT_{R_{min}}$  values. As mentioned in [34], the  $RTT_{avg}$  values are computed from the recent five samples. The  $RTT_{R_{min}}$  is the minimum RTT value among the recent five samples that minimize the impact of RTT fluctuation in  $T_{bottle}$  prediction. When the estimated  $T_{bottle}$  rate is superior (0.7) than the threshold ( $\gamma$ ) rate, the sender begins the rate adjustment process. The  $\gamma$  value is fixed as 0.7 based on the repeated trials using wireless internet RTT measurements. Lesser  $\gamma$  value results in a spurious timeout due to frequent RTT fluctuations. A higher  $\gamma$  value allows the sender to respond slowly to bottleneck conditions. The  $T_{bottle}$  parameter is derived as

$$T_{bottle} = \frac{RTT_{avg} - RTT_{min}}{RTT_{avg}} \tag{1}$$

Step 2 implements the utilization prediction ( $W_{utility}$ ) parameter to initiate a proportionate reduction mechanism during the rate adjustment process. The sender identifies low and high rate TCP flows based on the  $\delta$  threshold value ( $\delta=0.5$ ), estimated based on the current  $Wnd\_level$  ( $W_i$ ) and maximum receiver capacity  $W_{max}$  or initial  $SS_{Threshr}$ . The source node implements two rate decrement factors based on the utilization levels. The  $W_{utility}$  parameter and rate decrement factor is derived as

$$W_{utility} = \frac{W_i}{W_{max}} \tag{2}$$

$$\begin{aligned} W_{utility} < \delta; \text{ low rate flow} \\ W_{utility} \geq \delta; \text{ high rate flow} \end{aligned} \tag{3}$$

Rate reduction procedure for high bandwidth utilized TCP flow is computed as

$$W_{i(k+1)} = W_i * .0.5 ; W_{utility} \geq \delta \tag{4}$$

Rate reduction procedure for low bandwidth utilized TCP flow is computed as

$$W_{i(k+1)} = W_i * \left\{ \left( 1 - \frac{W_i}{W_{max}} \right) \right\}; W_{utility} < \delta \tag{5}$$

Step 3, the UAR algorithm implements a modified fast retransmit mechanism during the packet loss state, resulting in retransmission of missing data packets within the current RTT without invoking the rate reduction process.

The SLC algorithm is responsible for the  $Wnd\_increment$  mechanism in the CR phase with a faster recovery rate and minimum fairness disparity among traffic flows. The SLC algorithm introduces a new dynamic  $Wnd\_update$  pattern that allows the traffic flow to enter the steady-state transmission point at a faster rate with the least fairness disparity. The steady-state point is an equilibrium state where the source device transmission rate matches the link capacity. The  $Wnd\_increase$  pattern of the CR phase is given as

$$W_{i(k+1)} = W_{i(k)} + \frac{(4 * W_{max})}{W_{i(k)}} \tag{6}$$

The DART approach finite state machine (FSM) model is represented in Fig. 3. The FSM model specifies interactions among different transition states and their impact on the transmission rate.

### 3.1 Fairness and Convergence Efficiency Analytical Validation

The proposed DART approach’s bandwidth fairness and transmission efficiency performance are validated using an analytical model and compared against CERN+, TCP-LoRaD, and RFC 6582 approaches. The fairness and convergence efficiency analytical equations are derived based on Jain’s model [35]. In wireless conditions, the fairness performance of TCP flow is influenced by  $Wnd\_$  growth pattern and channel conditions [36, 37]. The DART implementation practices a packet latency/ $T_{bottle}$  parameter to initiate the  $Wnd\_$  decrement process. Let  $\gamma(t)$  be the  $T_{bottle}$  threshold value;  $r_s$  represents the source node dispatching rate,  $r_m$  represents the highest attainable dispatching rate of the source node,  $WL_c$  represents the wireless link capacity and  $R_{Target}$  is the steady-state point. The source device dispatching rate matches the wireless link capacity

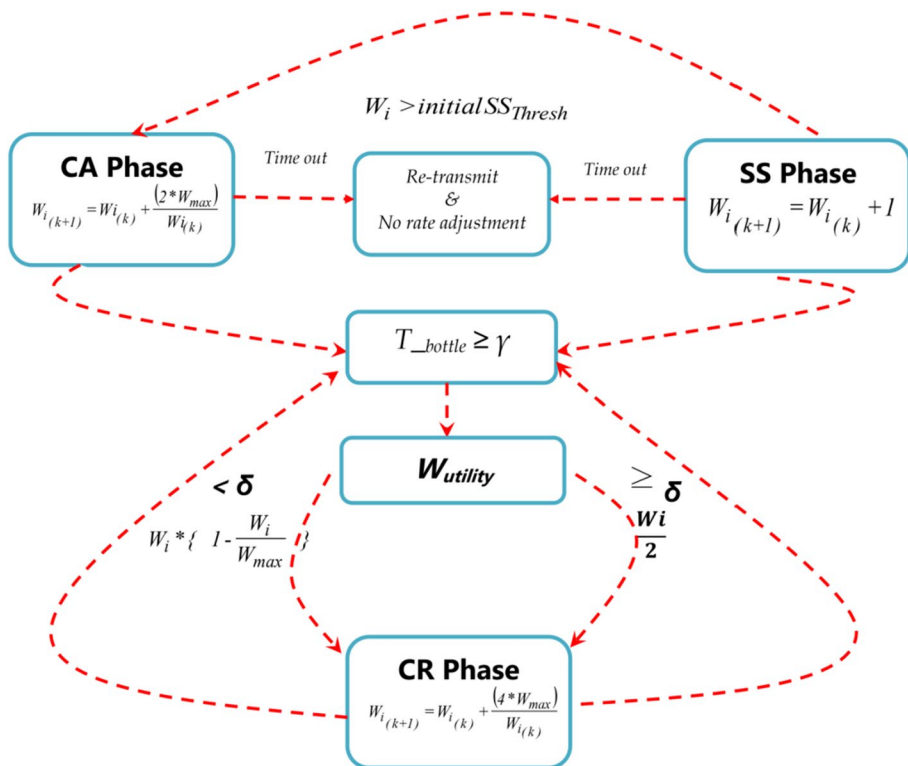


Fig. 3 FSM model of DART approach

( $R_{Target} = WL_c$ ) in the steady-state point. The  $R_{Target}$  value is taken as the maximum dispatching rate ( $r_m$ ) attained by the sender and expressed as the function of time

$$r_s(t) = \{ r_{y_1}(t), r_{y_2}(t), r_{y_3}(t), \dots, r_{y_m}(t) \} \tag{7}$$

The source node increment  $r_s$  for non-congested state  $\gamma(t) = 0$  ( $\gamma < 0.7$ ) and lessen  $r_s$  for an increase in network load  $\gamma(t) = 1$  ( $\gamma \geq 0.7$ ).

$$\begin{aligned} \gamma(t) &= 0, \text{ non congested state} \\ &1, \text{ congested state} \end{aligned} \tag{8}$$

Figure 4 illustrates the communication model of the proposed DART approach.

The sender updates its dispatching rate  $r_s(t+1)$  based on  $\gamma(t)$  and follows an additive  $W_{nd}$ \_ increment pattern for  $\gamma(t) = 0$  and multiplicative  $W_{nd}$ \_ decrement pattern for  $\gamma(t) = 1$ . The  $W_{nd}$ \_ increment and decrement patterns are expressed as

$$\begin{aligned} r_s(t+1) &= W_I + r_i(t), \gamma(t) = 0 \\ &= W_D * r_i(t), \gamma(t) = 1 \end{aligned} \tag{9}$$

The  $r_i(t)$  represents the current dispatching rate,  $r_m(t)$  is the maximum dispatching rate,  $W_I$  and  $W_D$  denotes additive  $W_{nd}$ \_ increment pattern and multiplicative decrement pattern. For the DART approach,  $W_I$  and  $W_D$  are derived from the Eq. (4), (5), and (6) as

$$W_I = \frac{4 * r_m}{r_i} \tag{10}$$

$$\begin{aligned} W_D &= 1 - \frac{r_m}{r_i}; r_i(t) \leq \delta \\ &= \frac{1}{2}; r_i(t) > \delta \end{aligned} \tag{11}$$

On substituting (10) and (11) in (9), the equation can be modified as

$$\begin{aligned} r_s(t+1) &= \frac{4 * r_m}{r_i} + r_i(t), \quad \gamma(t) = 0 \\ &= 1 - \frac{r_m}{r_i} * r_i(t); \quad r_i(t) \delta \gamma(t) = 1 \\ &= \frac{1}{2} * r_i(t); \quad r_i(t) > \delta \gamma(t) = 1 \end{aligned} \tag{12}$$

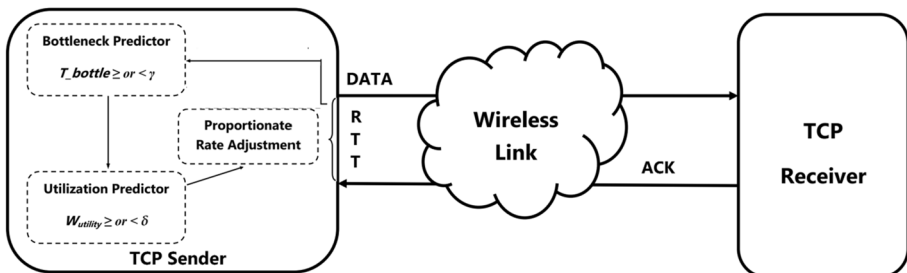


Fig. 4 DART approach communication model

The DART approach flow efficiency equation is developed based on the TCP fairness and convergence vector diagram displayed in Fig. 5. Let  $r_{s1}$  (x-axis) and  $r_{s2}$  (y-axis) are the two source devices sharing the bottleneck wireless link. The midpoint on the graph represents the efficiency of the two flows. The region below the efficiency midpoint is the underutilization, and above is the congested state. The flows ( $r_{s1}$  and  $r_{s2}$ ) attain its transmission efficiency when  $r_{s1} = r_{s2} = R_{Target} = WL_c$ . The convergence rate is an essential component in attaining the efficiency of the TCP flow. The convergence rate denotes the pace at which the source device transmission rate attains the equilibrium state. The dispatching rates of the TCP flows get lessened when  $r_s(t)$  reach the equilibrium condition and again attain the steady-state point in repeated cycles.

The condition for the convergence efficiency of TCP flow is derived as

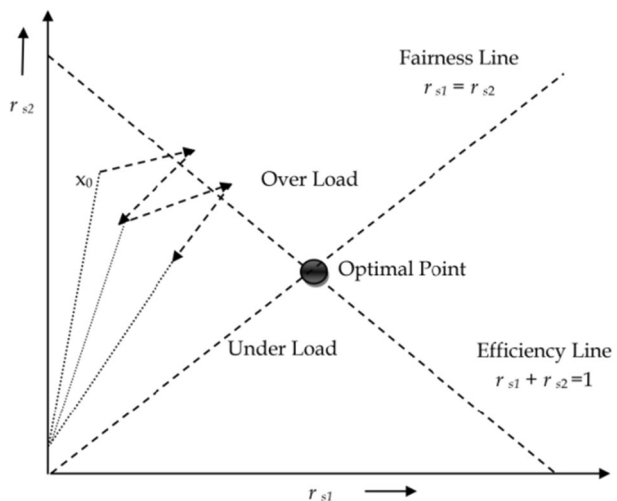
$$\begin{aligned} \gamma(t) = 0 &\Rightarrow \sum r_s(t+1) > r_m(t) \\ \gamma(t) = 1 &\Rightarrow \sum r_s(t+1) < r_m(t) \end{aligned} \tag{13}$$

The independent congestion avoidance algorithm’s efficiency is crippled severely by negative feedback phenomena due to spurious rate decrement process for packet loss conditions. However, the DART approach invokes rate adjustments solely based on the  $T_{-bottle}$  parameter, which considerably minimizes negative feedback phenomena and improves the TCP flow efficiency in wireless conditions. The convergence efficiency of the DART approach is derived by substituting Eq. (12) in (13)

$$\gamma(t) = 0 \left( \frac{4 * r_m}{r_i} + r_i(t) \right) > r_m(t) \tag{14}$$

$$\begin{aligned} \gamma(t) = 1 &\Rightarrow \left( 1 - \frac{r_m}{r_i} \right) * r_i(t) < r_m(t); r_i(t) < \delta \\ &= 1 \Rightarrow \left( \frac{1}{2} * r_i(t) \right) < r_m(t); r_i(t) > \delta \end{aligned} \tag{15}$$

**Fig. 5** Efficiency and fairness vector representation





Equation 15 denotes the utilization level based on the proportionate reduction for  $\gamma(t) = 1$  condition. Equation 14 represents the  $Wnd\_$  increment pattern for  $\gamma(t) = 0$ , which results in a quicker convergence pace towards the midpoint efficiency line. Similarly, the efficiency equation for RFC 6582 based TCP flows (CERL+ and TCP-LoRaD) are derived as

$$\gamma(t) = 0 \Rightarrow \left( \frac{1}{r_i(t)} + r_i(t) \right) > r_m(t) \tag{16}$$

$$\gamma(t) = 1 \Rightarrow \left( \frac{1}{2} * r_i(t) \right) < r_m(t) \tag{17}$$

Figure 6 displays the convergence efficiency analysis of RFC 6582 and DART in the CR phase. The convergence efficiency Eqs. (14, 15, 16 and 17) are validated by substituting the values  $r_m = 36$  and the initial  $r_i$  value = 18. The  $Wnd\_$  growth oscillates between the minimum and steady-state point in repeated cycles. The graph shows that DART accomplishes a faster convergence pace than RFC 6582, i.e., the DART algorithm reaches efficiency midpoint within fewer RTTs.

Fairness study measures the bandwidth distribution among two separate TCP traffic flows ( $r_{s1}$  and  $r_{s2}$ ) sharing the same bottleneck wireless link of  $WL_c$ . The fairness convergence is attained among the competing flows when the fairness index  $F(r_s)$  moves towards unity, i.e.,  $r_{s1} = r_{s2}$ . The dispatching rate of the  $r_{s1}(t)$  or  $r_{s2}(t)$  is below/above the fairness line in graph (Fig. 5) results in unfairness among sharing network bandwidth the competing flows. The  $F(r_s)$  index is derived using Jain's equation as

$$F(r_s) = \frac{(\sum r_{si})^2}{n(\sum r_{si}^2)} \tag{18}$$

The Eq. 18 can be modified as

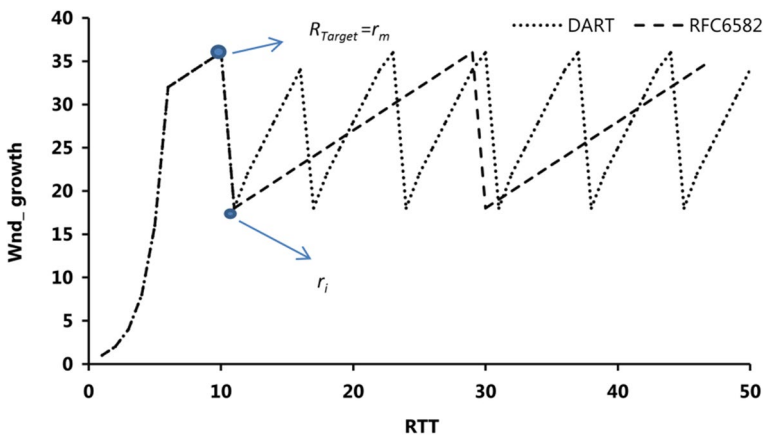


Fig. 6 Efficiency Convergence of DART vs. RFC6582  $Wnd\_$  growth

$$F(r(t + 1)) = \frac{(\sum r_{si}(t + 1))^2}{n(\sum r_{si}(t + 1)^2)} \tag{19}$$

Altering Eq. (19) based on  $W_I$  and  $W_D$  variables

$$F(r(t + 1)) = \frac{(\sum W_I + W_D r_i(t))^2}{n \sum (W_I + W_D r_i(t))^2} \tag{20}$$

where

$$W_I \geq 0, \quad 0 \leq W_D < 1 \tag{21}$$

By substituting Eq. (14) and (15) in (20), the fairness index of the DART approach is derived as

$$F(r(t + 1)) = \frac{\sum \frac{4*r_m}{r_i} + 1 - \frac{r_m}{r_i} * r_i(t)^2}{n \sum \frac{4*r_m}{r_i} + 1 - \frac{r_m}{r_i} * r_i(t)^2}, \quad r_i(t) \leq \delta \tag{22}$$

$$F(r(t + 1)) = \frac{\sum \frac{4*r_m}{r_i} + \frac{1}{2} * r_i(t)^2}{n \sum \frac{4*r_m}{r_i} + \frac{1}{2} * r_i(t)^2}, \quad r_i(t) > \delta \tag{23}$$

Table 2 displays the fairness and efficiency analytical equations of proposed and existing approaches.

Figure 7 displays the  $Wnd\_growth$  function of RFC 6582 and DART approaches in the CR phase based on the fairness equations in Table 2. The  $r_m$  value is taken as 36; the initial  $r_i$  value for high utilized flow is taken as 18, and the low utilized flow is taken as 6. The graph shows that DART accomplishes a minimum disparity among the competing flows within fewer RTTs.

**Table 2** DART, CERL+, RFC6582 and TCP-LoRaD fairness and efficiency equations

TCP variants	Efficiency equation	Fairness equation
DART	$\gamma(t) = 0 \Rightarrow \sum \left( \frac{4*r_m}{r_i} + r_i(t) \right) > \sum r_m(t)$	$\frac{\sum \frac{4*r_m}{r_i} + 1 - \frac{r_m}{r_i} * r_i(t)^2}{n \sum \left( \frac{4*r_m}{r_i} + 1 - \frac{r_m}{r_i} * r_i(t)^2 \right)}, \quad r_i(t) \leq \delta$
	$\gamma(t) = 1 \Rightarrow \sum \left( 1 - \frac{r_m}{r_i} \right) * r_i(t) < \sum r_m(t); r_i(t) \leq \delta$	$\frac{\sum \frac{4*r_m}{r_i} + \frac{1}{2} * r_i(t)^2}{n \sum \frac{4*r_m}{r_i} + \frac{1}{2} * r_i(t)^2}, \quad r_i(t) > \delta$
	$= 1 \Rightarrow \left( \frac{1}{2} * r_i(t) \right) < \sum r_m(t); \sum r_i(t) > \delta$	
CERL+ TCP – LoRaD } RFC 6582	$\gamma(t) = 0 \Rightarrow \left( \frac{1}{r_i(t)} + r_i(t) \right) > \sum r_m(t)$	$\frac{\sum \frac{1}{r_i(t)} + r_i(t) + \frac{1}{2} * r_i(t)^2}{n \sum \frac{1}{r_i(t)} + r_i(t) + \frac{1}{2} * r_i(t)^2}$
	$\gamma(t) = 1 \Rightarrow \left( \frac{1}{2} * r_i(t) \right) < \sum r_m(t)$	

Conversely, RFC 6582 has a slower flow convergence rate and larger fairness disparity gap between high and low-rate TCP flows.

The pseudocode for DART implementation in SS, CA and CR phases are given as.

**Algorithm : SS phase , CA Phase and CR Phase**

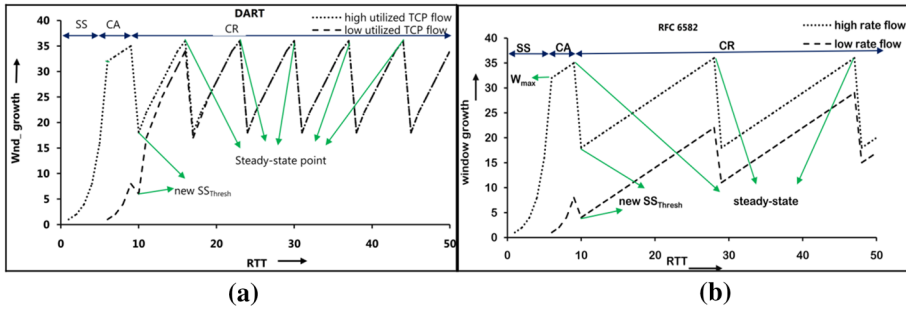
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If ( $W_i \leq \text{initial } SS_{Thresh}$ )
     $W_{i(k+1)} = W_{i(k)} + 1$  for each ACK
else ( $W_i > \text{initial } SS_{Thresh}$ )
     $W_{i(k+1)} = W_{i(k)} + \frac{(2 * W_{max})}{W_{i(k)}}$ 
end
end
For (Timeout or 3DUPACK)
    if ( $T_{bottle} < Y$ )
        Re-transmit lost packet & No rate reduction
    Else ( $T_{bottle} \geq Y$ )
        if ( $W_{utility} \geq \delta$ )
            set  $newSS_{Thresh} = 0.5 * W_i$ 
             $W_{i(k)} = newSS_{Thresh}$ 
             $W_{i(k+1)} = W_{i(k)} + \frac{(4 * W_{max})}{W_{i(k)}}$ 
        else  $W_{utility} < \delta$ 
            set  $newSS_{Thresh} = W_i * \{ 1 - \frac{W_i}{W_{max}} \}$ 
             $W_{i(k)} = SS_{Thresh}$ 
             $W_{i(k+1)} = W_{i(k)} + \frac{(4 * W_{max})}{W_{i(k)}}$ 
        end
    end
end
end
end

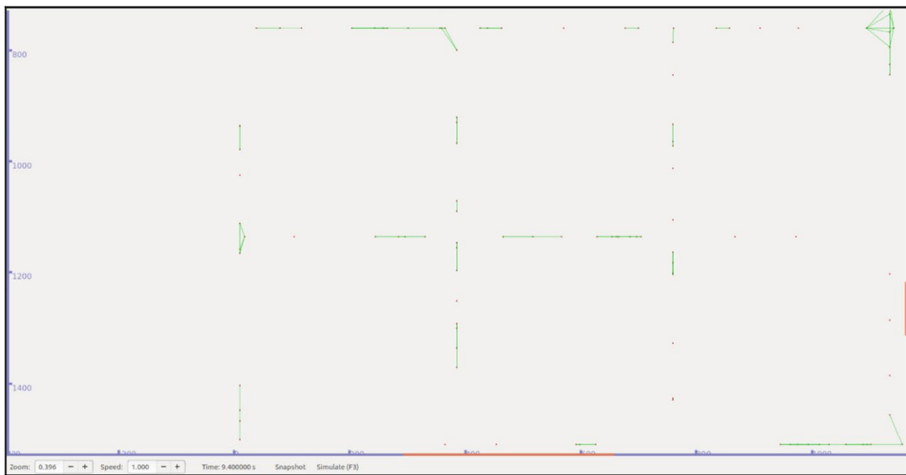
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**3.2 Simulation Results and Analysis**

The DART approach performance is validated using the vehicular simulation approach under varying node mobility and varying traffic load scenarios. The DART, RFC6582, CERN+, and TCP-LoRaD congestion avoidance algorithms are evaluated based on average throughput, average end-to-end packet latency, fairness, and transmission efficiency metrics. The experiments conducted using the network simulator (NS-3) [38, 39] in a



**Fig. 7** Fairness Convergence of DART vs. RFC6582 **a** DART *Wnd\_growth* and **b** RFC6582 *Wnd\_growth*



**Fig. 8** Closed road formation scenario in PyViz [43, 44] visualizer

closed road formation, as shown in Fig. 8. The vehicle mobility traces are generated using VanetMobiSim [40, 41] and ported into the simulation. The vehicular network features are incorporated using WAVE library modules [42]. Table 3 summarizes the parameters of vehicular simulation experiments.

### 3.3 Mobility Analysis

The mobility analysis measures the congestion avoidance algorithm performance under varying vehicle speed conditions. The vehicle speed varies between a minimum of 5 m/s to a maximum of 20 m/s in closed road simulation experiments, and Fig. 9 displays the simulation outcomes. The DART approach achieves an average throughput of 9.82 Mbps in low speed road conditions and yields an improvement of 26.57, 11.91, and 9.26% against the RFC6582, TCP-LoRaD, and CERL+ approaches. In the 20 m/s vehicle speed condition, the DART attains an average throughput of 5.57 Mbps, and the existing methods encounter a throughput lag of 49.55% (RFC6582), 36.98% (TCP-LoRaD), and 34.11% (CERL+). In vehicular networks, frequent connection failure occurs due to vehicle mobility conditions,

**Table 3** Vehicular simulation parameters

Simulation parameters	
Vehicles	250
Simulation duration	900 s
Simulation area	1500 × 1500 m
Radiation pattern	Omni Directional
Antenna elevation	1.5 Meters
Antenna gain	5dBi
Receiver sensitivity	− 95 dBm
Propagation type	Nakagami
Channel width	10 MHz
MAC	IEEE 802.11p
Data rate	27 Mbps
Modulation	QAM
Coding rate	3/4
Transmission technique	OFDM
Subcarriers	52
Sub carrier frequency	156.25 kHz
Symbol interval	8 μsec
Control channel	50 ms
Service channel	50 ms
Operating frequency	5.9 GHz
System loss	1
Vehicle speed	5, 10, 15 and 20 m/s
Traffic	2, 4, 6, and 8
Wnd_ size	256
Packet size	1400 Bytes

triggering timeout at the sender side. Under such circumstances, the DART approach re-transmits only the lost packet without invoking the rate adjustment that considerably stabilizes the throughput rate. Furthermore, the DART rate adjustment based on  $T_{bottle}$  prediction and faster convergence rate in the CR phase improves the throughput rate than the existing approaches. However, the TCP-LoRaD and CERL+ in high mobility conditions attain a lesser average throughput performance due to its slow convergence rate in the CR phase.

Similarly, the DART approach yields a lesser mean delay during packet transmission compared to the other approaches. The DART approach attains a 19.67, 14.74, and 9.26% lesser RTT packet delay than RFC6528, TCP-LoRaD, and CERL+ approaches in the low vehicle speed conditions. The DART approach attains similar mean delay performance in the high speed conditions. During simulations, it is noted that the rate adjustment based on  $T_{bottle}$  prediction allows the sender to push more data packets when the link delay is low, minimizing mean packet latency during transmission. Conversely, the slow convergence rate and RTT fluctuation in bottleneck prediction of CERL+ and TCP-LoRaD increase the mean delay of data packets to finish the flow.

The number of successful data packets delivered to the destination determines the transmission efficiency. The wireless link quality and the queuing delay are the two prime factors

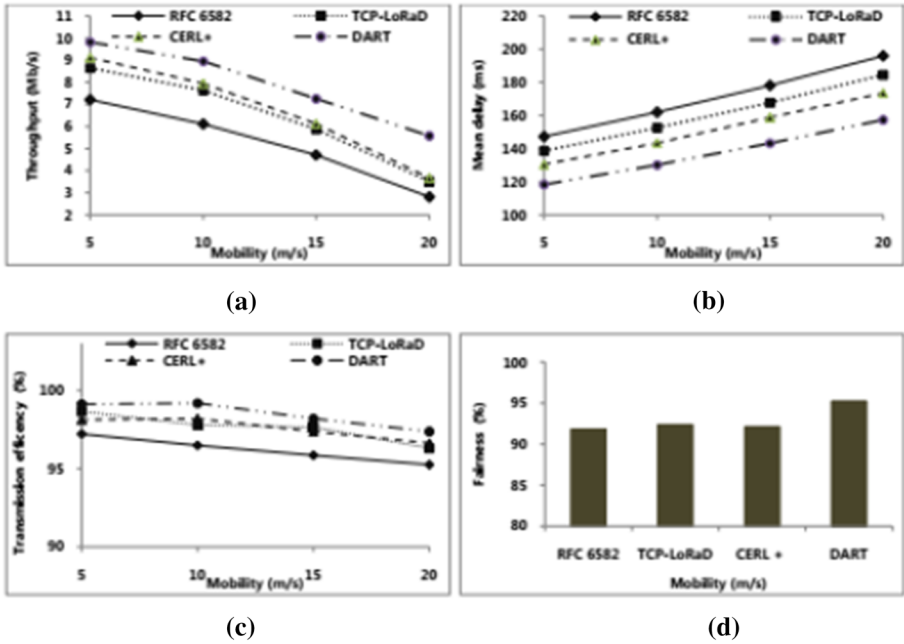


Fig. 9 Congestion avoidance approaches performance under mobility conditions **a** average throughput **b** mean delay **c** transmission efficiency and **d** fairness

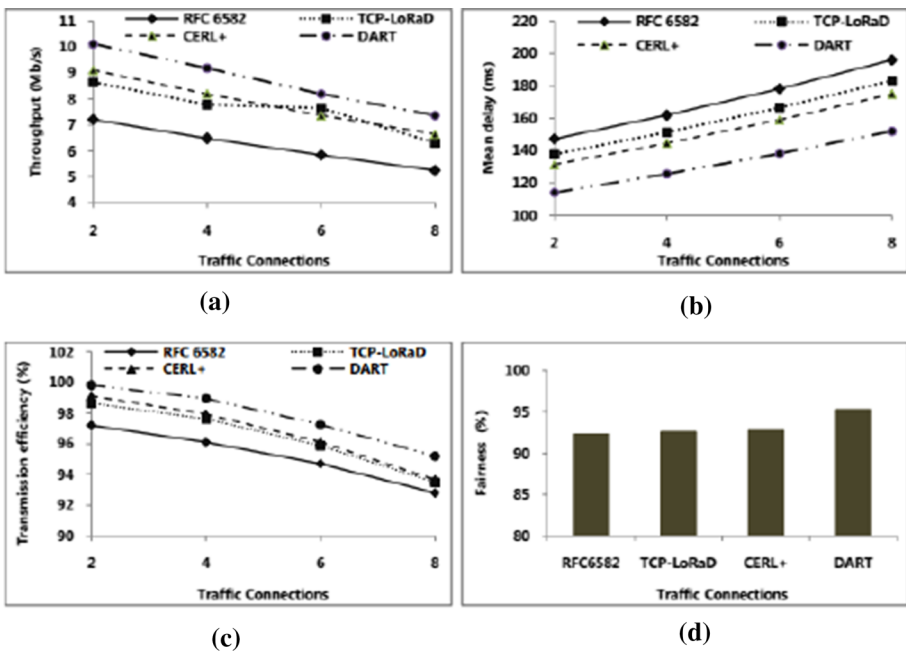


Fig. 10 Congestion avoidance approaches performance under traffic load conditions **a** average throughput **b** mean delay **c** transmission efficiency and **d** fairness

determining packet transmission efficiency in vehicular networks. The DART approach attains an average efficiency between 97.31 and 99.12%, and the existing approaches reach efficiency between 95.25 and 98.11% in diverse mobility conditions. The fairness metric evaluates equitable bandwidth distribution among the competing TCP flows in the network. The DART approach attains average bandwidth fairness of 95.25% in diverse mobility.

Conversely, the existing approaches achieve 92.09% bandwidth fairness among traffic flows in mobility conditions. The DART approach proportionate rate adjustment and SLC algorithm significantly contribute to the equitable sharing of network bandwidth among different flows. However, the fairness capability of the existing approach is crippled primarily due to its flat-rate decrement mechanism and  $Wnd\_$  growth pattern in the CR phase.

### 3.4 Traffic Load Analysis

The traffic load analysis measures the performance of the congestion avoidance approach under varying TCP traffic conditions. The experiments were conducted by increasing the traffic load from two to eight pairs of a source–destination process with an average vehicle speed of 10 m/s. Figure 10 displays the outcomes of the proposed and existing approaches. The DART approach attains the average throughput rate of 10.12 and 7.37 Mbps under minimum and maximum traffic load conditions, with 29.11, 12.68, and 10.23% improvement against RFC6582, TCP-LoRaD, and CERL+ approaches under varying load conditions. Furthermore, the DART approach congestion prediction assisted proportionate rate adjustment, and a faster convergence rate considerably contributes to achieving a higher throughput rate.

During packet transmission under diverse traffic load conditions, the DART approach attains 22.44, 17.04, and 13.09% lesser mean delay than RFC6528, TCP-LoRaD, and CERL+ approaches. The DART approach  $Wnd\_$  growth pattern allows the sender to the swift packet transfer during the low link delay conditions that minimize mean packet delay. Conversely, the existing approaches' slow transfer rate in the CR phase increases the mean delay of data packets to finish the flow.

The DART packet transmission yields a higher efficiency of 95.32–99.12% in diverse load conditions due to its capability to infer queuing delay that minimizes packet loss associated with buffer overflows. However, transmission efficiency is degraded due to radio channel loss that induces considerable packet drop in the DART and existing approaches under vehicular networks. Similarly, DART proportionate rate decrement and SLC algorithm in the CR phase allow multiple flows to attain a 95.32% fair distribution of resources. However, the traditional  $Wnd\_$  growth pattern of similar AIMD approaches achieves 92.56% fairness under diverse traffic conditions.

## 4 Conclusion

The DART congestion avoidance approach proposed in this article intends to improve TCP traffic throughput, convergence rate, and equitable bandwidth distribution under VIoT networks. The DART initiates a proportionate rate adjustment mechanism based on the  $T\_bottle$  parameter that considerably lessens needless throughput reduction during packet losses in wireless conditions. Furthermore, the modified  $Wnd\_$  growth pattern in the CR phase significantly boosts the convergence rate and maintains the equitable distribution of network bandwidth among low and high utilized flows. The analytical equations derived based on Jain's model verifies the improvement in fairness and convergence rate performance over the existing

schemes. The experiment outcome under two scenarios proves that DART attains considerable throughput, transmission efficiency, and equitable bandwidth distribution improvement with the least mean delay in packet transmission. The proposed DART approach's future variant is customized to support the multipath TCP implementation under vehicular networks.

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**Data Availability** The datasets analyzed during the current study are not publicly available, compromising our future research programs. Still, they are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors hereby acknowledge that there is no conflict of interest.

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**M. Joseph Auxilius Jude** received his B.E in Electronics and Communication Engineering, M.E with specialization in Digital Communication and Networking, and Ph.D. under Anna University, Chennai, India, in 2005, 2007, and 2019 respectively. He is working as Associate Professor and associated with the Self Organized Networking Group (SONG) of the ECE department at Kongu Engineering College. He is closely related to developing advanced wireless networking lab and organized funded industryaligned training programmes in alliance with the Defence Research & Development Organisation (DRDO), Department of Science & Technology (DST), and Industry Insitute Partnership Cell. He is a peer reviewer for IEEE Access, IEEE Sensor Letters, Wiley International Journal of Communication Systems, and Springer Wireless Personal Communications. He also acted as a mentor for the collaborative project on vehicular communication with UTP Malaysia. His research interests include design, testing, and validating scheduling algorithms for wireless sensor networks, congestion control algorithms (TCP and AQM) for the MANET and VANET. He is a

member of IEEE (Computer Society and Sensor Council), a life member of IETE, and institution chair of IEEE computer society.



**V. C. Diniesh** received his B.E in Electronics and Communication Engineering and M.E with specialization in Embedded and Real Time System under Anna University, Chennai, India in 2009 and 2011 respectively. He is currently pursuing PhD in the area of wireless ad-hoc and sensor networks. He is with Self Organized Networking Group (SONG) of the ECE department at Kongu Engineering College. He is closely connected with the routing protocol development and training for tactical wireless networks especially for disaster and battlefield management, organized funded programmes in collaboration with DST and Industry Insitute Partnership. His research interests include designing, testing and validation of routing protocols for mobile ad-hoc network and wireless sensor network. He is a member of IEEE and life member of IETE.



**M. Shivaranjani** completed her Master Degree in Communication Systems, from Kongu Engineering College affiliated to Anna University, Chennai. She received her Bachelor Degree in Electronics and Communication Engineering from Kongu Engineering College affiliated to Anna University, Chennai. She is with Self Organized Networking Group (SONG) and currently working as an assistant professor in Velalar College of Engineering and Technology. Her current research focuses on designing Transmission Control Protocol (TCP) for Wireless Multi-hop Networks especially vehicular ad hoc network and Mobile ad hoc network.



**Suresh Muthusamy** received the bachelor's degree in Electrical and Electronics Engineering and the master's degree in Power Electronics and Drives during the year 2009 and 2011 from Anna University, Chennai and Anna University, Coimbatore respectively. Currently, he is working towards the Ph.D. degree in Electrical Engineering at Anna University, Chennai in the area of Hybrid Renewable Energy Systems. He worked as Assistant Professor in the Department of Electrical and Electronics Engineering at Kongu Engineering College (Autonomous), Perundurai, Erode during the period June 2011 to January 2020. From January 2020 onwards, he has been working as Assistant Professor Senior Grade in the Department of Electronics and Communication Engineering at Kongu Engineering College (Autonomous), Perundurai, Erode. He published more than 85 research articles in well reputed and refereed international journals like Elsevier, Springer, Taylor & Francis, SAGE, ASME, ASTM international, MDPI, etc & indexed in SCI, SCIE, ESCI, Scopus and Web of Science with good impact factor. He presented several research articles in national and

international conferences and also serving as the reviewer, editor for about 52 international journals including IET Renewable Power Generation, IET Journal of Engineering, etc. To his credit, he has filed and published 28 Indian patents in IPR website, governed by Ministry of Commerce & Industry, Government of India. His areas of interests include hybrid renewable energy systems, power electronic converters, hybrid electric vehicles and battery management systems.



**Hitesh Panchal** received the bachelor's degree in Mechanical Engineering from Government Engineering College, Modasa, Gujarat during the year 2004 and the master's degree in Internal Combustion Engines and Automobile from L.D. College of Engineering, Ahmedabad, Gujarat during the year 2006. He then received the Ph.D degree in Mechanical Engineering in the area of Solar Thermal Engineering from K.S.V. University, Gandhinagar, Gujarat in 2015. Dr. Panchal has published more than 150 research articles in reputed National and International Journal publications like Taylor and Francis, Springer, Elsevier, ASME, SAGE, etc. and also received 5000+ Google Scholar citations with h-index of 47 and i-10 index of 113. Dr.Panchal received many prestigious awards like Best Ph.D Thesis Award, Bharat Excellence Award, Young Scientist Award, Bright Researchers Award and many more from various organizations. Dr.Panchal has completed 2 Research projects from GUJCOST, DST of 15 lakhs and currently working on one Research project from DTE. Dr.Panchal has filed 24 full patents & 10 Industrial designs and

among them 2 patents & 7 industrial designs has been granted. Dr.Panchal has been selected in "Top 2% Indian Scientist under the energy category" published by Stanford University for the year 2020 and 2021.










**Suma Christal Mary Sundararajan** received the master's degree in Computer Science and Engineering from Francis Xavier Engineering College, Tirunelveli and Ph.D. degree in Computer Science and Engineering from Kalasalingam University, Srivilliputhur in 2016. She is currently working as Professor in the Department of Information Technology at Panimalar Engineering College, Poonamallee, Chennai. She has published more than 25 research articles in Scopus, SCI indexed journals and presented 40 papers in national and international conferences. She has received Young Scientist award from Computer Society of India and received Best Project award from Dr.Kalam Educational Trust, Best Teacher Award from IEAE. Her areas of interest include Network Security, Neural Networks, IoT, Virtual reality and Soft Computing, etc.



**Kishor Kumar Sadasivuni** is working in Center for Advanced Materials, Qatar University. He has published 82 Journal papers, 12 book chapters, 7 books edited and 3 patents filed. He has about 10 years of experience in synthesis & characterization of nanoparticles and also in manufacturing nanocomposites for industrial applications. His areas of interest include different types of nanocomposite fabrication, modifications, designs and their applications especially sensors, piezoelectrics, actuators, energy storage, Dielectrics, 3D-Printing and flexible electronics

## Authors and Affiliations

**M. Joseph Auxilius Jude**<sup>1</sup>  · **V. C. Diniesh**<sup>1</sup>  · **M. Shivaranjani**<sup>2</sup>  ·  
**Suresh Muthusamy**<sup>3</sup>  · **Hitesh Panchal**<sup>4</sup>  · **Suma Christal Mary Sundararajan**<sup>5</sup>  ·  
**Kishor Kumar Sadasivuni**<sup>6</sup> 

V. C. Diniesh  
vcdiniesh@gmail.com

M. Shivaranjani  
ranjani093@gmail.com

Suresh Muthusamy  
infostosuresh@gmail.com

Hitesh Panchal  
engineerhitesh2000@gmail.com

Suma Christal Mary Sundararajan  
sumasheyalin@gmail.com

Kishor Kumar Sadasivuni  
kishor\_kumars@yahoo.com

<sup>1</sup> Vinton Network Lab, Self Organised Networking Group (SONG), Department of Electronics and Communication Engineering, Kongu Engineering College (Autonomous), Perundurai, Tamil Nadu, India

<sup>2</sup> Department of Electronics and Communication Engineering, Velalar College of Engineering and Technology (Autonomous), Thindal, Erode, Tamil Nadu, India

<sup>3</sup> Department of Electronics and Communication Engineering, Kongu Engineering College (Autonomous), Perundurai, Erode, Tamil Nadu, India

<sup>4</sup> Department of Mechanical Engineering, Government Engineering College, Patan, Gujarat, India

<sup>5</sup> Department of Information Technology, Panimalar Institute of Technology, Poonamallee, Chennai, Tamil Nadu, India

<sup>6</sup> Centre for Advanced Materials, Qatar University, Doha, Qatar