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An adaptive and cooperative MAC protocol for safety applications in cognitive radio enabled vehicular Ad-hoc networks

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ABSTRACT

Rapid broadcast of safety message (*sm*) is critical for real-time applications in cognitive radio vehicular ad hoc networks (CR-VANETs). The arrival of primary users (PU) and the relative unpredictability of traffic emerge as network bottleneck constraints, resulting in unreliable broadcast services. The requirement is for a Medium Access Control (MAC) protocol that allows for fair contention, is adaptive, and includes a makeup strategy for rebroadcasting failed transmissions. There are intricate tradeoff optimisation relationships in which a value for the contention window that is inadequate will not result in optimal network performance. In this paper, we develop a dynamic contention window backoff mechanism using Karush–Kuhn–Tucker (KKT) conditions that enhances network performance by modifying the backoff time according to traffic density. Then we amalgamate this algorithm with a cooperative makeup strategy to design a novel adaptive and cooperative MAC protocol that is operable in a dynamic CR-VANET paradigm (ACCRV-MAC). A Markov chain decision model characterises the protocol, and Network Simulator -2 analyses various performance parameters. The study reveals that ACCRV-MAC improves throughput by 38.3% and reduces network latency by 49% compared to existing MAC protocols.

1. Introduction

In the last decade, Intelligent Transportation Systems (ITS) have gained popularity to address the global issue of traffic accidents by conveying life-saving information promptly. This critical and delay-sensitive information, denoted as *sm*, necessitates a rapid, efficient, and dependable broadcast service [1]. The vehicular ad-hoc network (VANET) utilising Dedicated Short-Range Communications (DSRC) technology is implemented in ITS because of its spontaneity and ad-hoc nature [2]. Unfortunately, due to the recent rise in demand, the 75 MHz band designated by the United States Federal Communication Commission to VANET is frequently overloaded [3]. Additionally, the authors of [4] claim that more than 60% of the spectrum below 6 GHz is not being utilised. By combining cognitive radio (CR) technology with VANETs, this pseudo-starvation can be overcome [5]. The CR technology allows unlicensed secondary users (SUs) to access the PU's legacy spectrum while not in use by the PU.

Although in terms of bandwidth utilisation, CR-VANET has been recommended to improve VANET to provide enhanced communication opportunities for all participating nodes [5], there is no assurance that data will be sent efficiently. This issue arises due to high node instability and the relative unpredictability of vehicular positions and topology, which can cause packet collisions. As the transmission is inconsistent, and passengers and pedestrians are at fatal risk, a reliable Medium Access Control (MAC) protocol is necessary to ensure rapid delivery of data (within 100ms [6]) via unlicensed channels in CR-VANET. Due to its MAC layer protocol architecture, CR-VANET technology improves spectrum efficiency but does not alleviate the latency issue. Furthermore, poor information delivery in dynamic topologies has been caused by unstable (unacknowledged data delivery) communication and the lack of a makeup strategy in the data link layer. Cooperation in the MAC layer is utilised to overcome these aforementioned issues [7]. Even in unfavourable channel conditions, the combination of cooperative MAC and CR-VANET allows for dependable *sm* broadcasting [7]. When the intended SU fails to receive a packet, cooperative transmission (CT) at the MAC layer utilises helper nodes to rebroadcast the *sm*. The helpers are the source and destination nodes' mutual neighbours, and they higher likelihood of carrying a transmission successfully than the sender and receiver nodes [8,9]. Cooperative transmission can rebroadcast failed transmissions and aid proactive handoff in case of PU appearance. As a result, user interference and energy consumption are reduced. In our previous work [7], we introduced a cooperative and

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contention-based MAC protocol (CCRV-MAC) in CR-VANET, which offered a makeup approach for smooth retransmission and timely data delivery. The protocol used a back-off counter that varied from the Contention Window (CW) value to zero, with nodes being assigned a minimum window upon starting contention; however, it had a few shortcomings which are addressed in this work.

1.1. Motivation

Contention-based protocols, compared to contention-free protocols, are better suited to dynamic topologies in terms of MAC protocol design. Because eliminating unused transmission slots in a contention-free MAC protocol is difficult, while in the contention method, it is organically dispersed and adjusts to traffic loads [10]. While centralised scheduling can resolve conflict, it is not scalable to a large number of nodes, and it is also unfeasible in a highly dynamic and dispersed CR-VANET scenario where minimising the delay is the primary concern [9]. Idle waiting and collisions during the contention phase are two major causes of excessive latency in contention-based systems [11]. A conventional broadcast network features a random back-off and Listen Before Talk (LBT) [12]. A random waiting period is selected from a CW for the back-off. When a transmission attempt fails, the CW size is doubled until it reaches the maximum specified size. Regardless of network conditions, such as the number of contending vehicular nodes, the CW will be reset to the minimum assigned CW after each successful transmission. Even if the vehicle density has risen dramatically, the SUs will all utilise the same initial CW. As a result, packet collisions occur, increasing the likelihood of packet loss. If there is a data collision, the nodes will have to contend for the window once more, increasing the latency significantly. Hence, using a fixed CW for all nodes increases the system's latency and reduces the system performance [13]; instead, an adaptive CW should be utilised in the back-off process to alleviate this problem.

1.2. Problem statement

The fact that a node's bandwidth share is determined by its CW size, as well as the CW sizes of other competing nodes in the network, makes developing an effectively distributed contention mechanism challenging. While an individual node may manage the size of its CW, it has no control over the sizes of other nodes' windows. Furthermore, by altering its CW size, the node directly impacts the bandwidth share of other nodes. Changing CW at various nodes without thorough coordination might lead to an unstable system [14]. Although the notion of adaptive CW has been utilised numerous times in CR and VANETs individually [15,16], it has not yet been implemented in the CR-VANET paradigm. Hence, to ensure reliable and timely delivery of critical *sm*, three requirements for the design of an efficient MAC Protocol must be met: first, the protocol should use both unlicensed and licensed spectrum; second, a make-up strategy ensured by the helper nodes, which can be used during cooperative transmission (DT), and third, a non-rigid design facilitated by an adaptive CW in the back-off process.

1.3. Contributions

In this paper, we expand on our prior work, CCRV-MAC [7], to overcome its limitations of providing a fixed CW for the contention process. The key contributions are:

- An adaptive and cooperative MAC protocol (ACCRV-MAC) supporting a dynamic CW is proposed.
- The KKT criterion is utilised to define and solve a novel CW size optimisation problem based on the CR-VANET's instantaneous traffic density.
- The improved protocol is constructed using a Markov Chain Decision Model (MCDM) with an adjustable CW in the back-off process.
- Real-time traffic is simulated using Network Simulator-2 (NS-2). Additionally, the throughput, packet delivery ratio (PDR), and average latency of the CR-VANET are determined under varied conditions demonstrating the performance enhancement of the proposed protocol over CCRV-MAC and other contemporary protocols based on CR-VANET.

1.4. Paper organisation

Section 2 discusses related work and the research gap. Section 3 provides background information on the proposed protocol's system architecture and mechanism. The CW optimisation problem is defined in Section 4. The MCDM, the solution to the optimisation problem, and the analysis of ACCRV-MAC's performance are described in Section 5. The numerical outcomes produced via simulation on NS-2 are discussed in Section 6. Finally, in Section 7, this paper is concluded with recommendations for future research.

2. Related works and research gap

Although significant research has been done to address numerous challenges in CR and VANET communication networks, CR-VANET technology has not been extensively examined by researchers regarding the design of the MAC protocol. Selected CR-VANET, CR, and VANET MAC protocols are included in the literature survey to understand the research gap better.

Authors of [17] propose a technique that proactively monitors channel sensing results and offers quick access to data, but it lacks PU control and is vulnerable to packet loss. The authors of [18] provide a cluster-based MAC method for determining the best *sm* broadcasting channel. In [19], a prediction technique for finding the exact channel most likely to be accessible for the CR-VANET is presented. Although channel status is calculated proactively in [20] to solve dynamic spectrum sensing difficulties by decreasing overhead, the technique consumes bandwidth in CR-VANET in the event of low traffic density. Even though all of the protocols mentioned here have a high throughput, they lack collision detection and makeup techniques for unsuccessful broadcasts, which has a detrimental impact on the delay an *sm* packet suffers throughout the broadcast.

In our previous work [7], we devised a makeup approach based on cooperative transmission for failed transmissions. In addition, a cooperative relay technique for the proactive information dissemination of PU's presence was implemented for the first time in the CR-VANET. However, there was no consideration for an adaptive contention architecture, finding it challenging to implement in a delay-sensitive real-time paradigm with elastic traffic. A MAC protocol developed for a specific number of vehicular nodes and constant CW size, as indicated in the introductory section, cannot be stretched to a dynamic environment owing to bandwidth restrictions. Despite the paucity of studies on adaptive contention mechanisms in the CR-VANET, protocols developed for CR and VANET applications with similar structures can give helpful information. The authors of [15] strive to coordinate the collision probability in VANET by increasing the CW size to double the vehicle density. Even though this technique does not employ a fixed CW, it fails to improve network latency. Just doubling the CW size does not offer the precise CW necessary for maximum throughput without raising delay due to extra slots for contention. The authors of [16] employ a dynamic CW to reduce contention-based MAC delays and energy consumption in a CR network. However, this technique requires several additional signals for hand-shaking and does not function in broadcasting; thus, it cannot be used for *sm* dissemination.

To the best of our knowledge, no algorithms meant to offer configurable CW sizes that have been suggested up until the time of this paper's submission can be extended to function in cooperative as well as non-cooperative CR-VANET scenarios. As a result, there is a research gap for CR-VANET in terms of implementing an adjustable CW to offer rapid *sm* dissemination and maintaining this performance in highly dynamic traffic density, as well as optimising vehicular node performance.

The protocols mentioned above and their attributes are summarised in Table 1. The characteristics of ACCRV-MAC and its potential to facilitate rapid cooperative communication in the CR-VANET paradigm are clearly illustrated in the table.

3. Proposed protocol

3.1. System design

This study considers a VANET that uses CR, with the premise that the PUs are external entities that can become active at any moment in the network, and the SUs are vehicular nodes. For each broadcast, SUs employs a control channel and several data channels. The SU analyses the spectrum and refreshes its data by overriding the status of previous *T* seconds. Cooperation allows the SU to share this information with other vehicle nodes, allowing the SU to detect the arrival of PU in the channel and conduct handoff opportunistically.

3.2. Protocol mechanism

3.2.1. Contention

The proposed protocol deals with sm dissemination, which is time-sensitive and should be handled swiftly. As a result, a contention-based spectrum access methodology is used because it is flexible according to the number of SU's contenting for the spectrum at a given time, whereas in contention-free access technology, the number of slots considered is rigid and is not flexible according to the number of SU's wanting to gain access at a time, wasting slots which results in delay [7]. In ACCRV, the SU does a quick scan for spectrum holes at the onset of communication. It then senses the spectrum and transmits the data if it is free for DIFS. Otherwise, it initiates a back-off timer procedure with an adaptive CW defined by the number of vehicular nodes in the proximity of the SU in question. The back-off counter is halted if the channel is perceived as busy. If a PU is present, the timer is reset to a fresh value before hand-off. If SU observes the channel as free, the timer value is decremented until it reaches zero, signalling that the SU has won contention.

3.2.2. Direct transmission mode

The timer is decremented until it reaches zero if the SU perceives the channel to be free, as discussed in the contention phase. This indicates that the SU has won the contention, and the SU reserves the channel as a result. After the channel reservation (CHR), the sender nodes immediately broadcast the *sm* and, then wait for the reception of a negative acknowledgement (NACK) signal. To prevent the system from overwhelming due to multiple acknowledgement signals, the protocol is designed only to acknowledge undelivered messages using NACK. The broadcast is deemed successful if the sender node does not sense NACK before a broadcast timeout t_o. In case NACK is received before t_o, the transmission mode switches to cooperation.

Table 1
Comparison of some existing MAC protocols.

Refs. and Year	Network Type	CT	Makeup Strategy	Adaptive CW	Performance Optimization
[7] 2021	CR-VANET	✓	✓	×	×
[15] 2020	VANET	×	×	✓	×
[16] 2019	CR	×	×	✓	✓
[17] 2016	CR-VANET	×	×	×	×
[18] 2019	CR-VANET	×	×	×	×
[19] 2015	CR-VANET	×	×	×	×
[20] 2016	CR-VANET	×	×	×	×
Proposed	CR-VANET	✓	✓	✓	✓

CR = Cognitive Radio, CT= Cooperative Transmission, CW= Contention Window

3.2.3. Cooperation

The mutual neighbour SUs of the sender-receiver pair checks the statuses in their information tables after sensing the broadcasted NACK, and the SU with the best connectivity is chosen among the potential helpers [8]. The selected node broadcasts a ready-to-assist (RTA) signal that all the vehicular nodes in the vicinity can sense. The helper node detects the spectrum once and rebroadcasts *sm*. If RTA is not detected before time-out, it is assumed that nodes cannot help with the rebroadcast, and the *sm* is discarded. In this case, the sender has the option of retransmitting the packet or abandoning it after a few failed efforts.

3.2.4. PU Arrival

If any SU detects PU in the environment during the contention, direct, or cooperative data transmission phase, the SU instantly broadcasts a PU-presence report (PPR). The PPR contains the identified PU's legacy information and identification number. On sensing PPR, all SUs update their status tables and, in turn, rebroadcast the PPR. This procedure continues until all of the SU in the region are aware of the presence of the legacy user. The SUs can conduct channel switching proactively since they are aware of the existence of the PU. This previous knowledge of the licensed user's existence aids in the seamless spectrum handoff process and, in turn, decreases the delay experienced by *sm*.

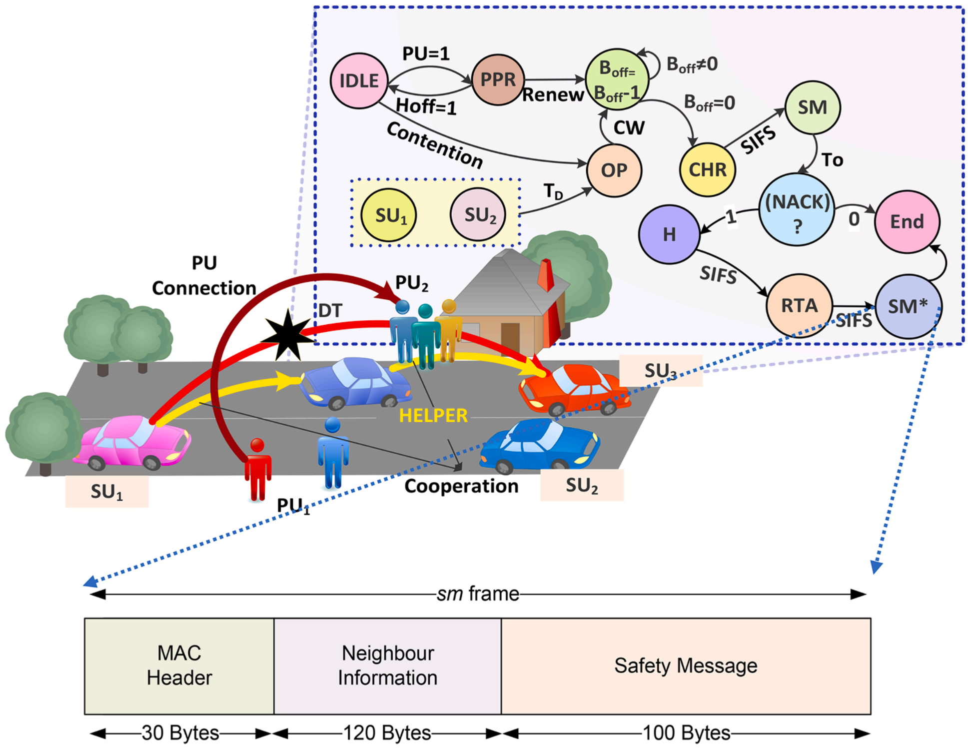
Fig. 1(a) and 1(b) demonstrates a fundamental CR-VANET scenario, with ACCRV- MAC's operation depicted as a finite state machine (FSM) and a basic frame structural model depicting the contention and transmission phases. For the sake of simplicity, we assume that two SUs, $SU1$ and $SU2$, desire to broadcast data in the network. When PU appears, ACCRV causes the SU to relinquish the licenced channel by executing a hand-off, which is indicated by *Hoff* in the diagram. After that, the SU transmits the PPR and resets the timer. If PU is not detected in the channel, the ideal CW size of nodes $SU1$ and $SU2$ is computed based on the traffic density, which is denoted by the abbreviation T_D in the diagram. This computation takes place in the state designated as OP, i.e., the Optimization Problem formulated in Section 4. The SU broadcasts in DT mode when the counter reaches zero. If DT fails, the protocol switches to CT mode via state H, depicting the presence of a helper node and rebroadcasts the *sm*, designated as SM* in the FSM.

4. Problem formulation

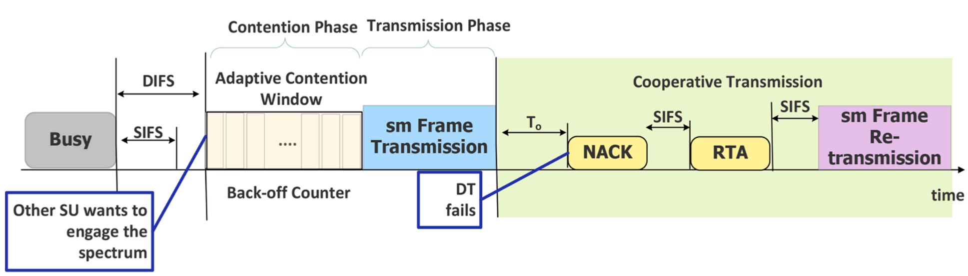
In a CR-VANET scenario, the presence of dynamic traffic results in backlogged packets; there is only a fraction of channel time, called the effective capacity ε, that is used for successful *sm* dissemination. The rest of the channel time is consumed by the backoff process or packet collisions. Hence, the bandwidth β_k allocated to an arbitrary node k is termed as a fraction μ_k of the effective capacity can be given as: $\beta_k = \mu_k\varepsilon$, such that, $\sum_{k=1}^{\eta}\mu_k = 1$, where η is the set of all transmitting nodes. Alternatively, $\beta_k = \tau_k/\xi_{ns}^k$, where τ_k is the transmission rate at the physical layer multiplied by the duration of successful transmission and ξ_{ns}^k is the value of the contention window, defined by a non-stationary (ns) backoff timer, assigned to node k [21]. Hence, we can state,

$$\mu_k = \frac{\tau_k/\xi_{ns}^k}{\sum_{n=1}^{\eta}\tau_n/\xi_{ns}^n}, \quad \xi_{ns}^k \gg 1 \ and \ \forall k \in \eta \tag{1}$$

This relation demonstrates the dependence of CW size and bandwidth allocation on each other.



(a) A basic system model, *sm* frame structure, and process flow FSM depicting the working of



(b). A fundamental frame structure model depicting the working of ACCRV-MAC.

Fig. 1. (a) A basic system model, *sm* frame structure, and process flow FSM depicting the working of ACCRV-MAC. (b). A fundamental frame structure model depicting the working of ACCRV-MAC.

Assumption 1. Each SU is assumed to have a utility function $\Psi_k(.)$ [22]. For CR-VANET, $\Psi_k(.)$ is an increasing, strictly concave and continuously differentiable function of bandwidth allocated to a SU.

Assumption 2. The maximum effective capacity allocated to the considered network is ε_m.

From the above assumptions, we can state the optimisation problem as follows,

$$\begin{cases} OP: \ \xi^{o}_{ns}(\Psi,\varepsilon) = \max\limits_{\varepsilon<\varepsilon_m}\left[\sum\limits_{k=1}^{\eta}\Psi_k\left(\dfrac{\tau_k/\xi^k_{ns}}{\sum_{n=1}^{\eta}\tau_n\Big/\xi^n_{ns}}\varepsilon\right)\right] \\ C1: \ \xi^n_{ns} > 0 \\ C2: \ \tau_k > 0 \end{cases} \tag{2}$$

The optimisation problem states that the SU does not have complete control over its transmission rate, which is determined by CW assignments at all nodes. The optimal CW size can be determined by maximising a concave and increasing the utility function of β_k. The constraints $C1$ and $C2$ state that the CW size, as well as the transmission rate at the physical layer, will always be non-zero and non-negative numbers.

5. Performance analysis

5.1. Adaptive contention control

The CW size is carefully optimised according to the number of contending nodes, maximising the network's throughput with lower broadcast delay. This CW value is achieved by the solution of the optimisation problem stated in (2). According to the KKT optimality condition [23], the unique solution to (2) is given by,

$$\begin{cases} \Psi'_k(\beta_k) = \mu_0, \ \mu_0 > 0, \ \forall k \in \eta \\ \sum\limits_{k=1}^{\eta}\beta_k = \varepsilon_m, \quad \forall k \in \eta \end{cases} \tag{3}$$

where $\Psi'_k(\beta_k) = \frac{\delta\Psi_k(\beta_k)}{\delta\beta_k}$ and μ_0 is the Lagrange multiplier [23]. With the condition that $\forall k$, $1 \le k \le \eta$ and $\mu_0 > 0$, From β_k and (1) the solution set of (2) can be given as,

$$\begin{cases} \Psi_k(\mu_k, \varepsilon_m) = \widetilde{\Psi'_k}\left(\dfrac{\tau_k/\xi_{ns}^k}{\sum_{n=1}^{\eta}\tau_n \Big/ \xi_{ns}^n}\right) = \mu_0 \\ \varepsilon = \varepsilon_m \\ \Psi_k(\beta_k) = \widetilde{\Psi_k}\left(\dfrac{\beta_k}{\varepsilon_m}\right) \\ \Psi'_k(\mu_k) = \dfrac{\delta\widetilde{\Psi'_k}(\mu_k)}{\delta\mu_k} \\ \mu_k \ge 0 \end{cases} \tag{4}$$

Where $\widetilde{\Psi'_k}$ is the derivative of $\widetilde{\Psi_k}$. Similar to $\Psi_k(.)$, $\widetilde{\Psi_k}$ is also an increasing, strictly concave and continuously differentiable function of bandwidth. For simplicity in the calculation, we have assigned a different symbol to $\widetilde{\Psi_k}$, a dummy variable that represents the same utility function as Ψ_k. Assuming that ρ is a constant positive factor and σ is the channel status as observed by the node, the derivative of the utility function of node k is higher than the cost function denoted by $F(\sigma)$, when the bandwidth is given to it is less than its fair proportion. In such instances, the CW size at Node k will be reduced to enhance bandwidth allotment. Consequently, if the considered node receives more bandwidth than it warrants, the utility function's derivative would be less than the cost function; this increases the CW of node k and, as a result, reduces the bandwidth provided to it. In other words, we can determine the cost function to adjust the CW size efficiently by using the utility criteria to assert a node's preference for the bandwidth required. Hence, the node adapts its CW size as follows,

$$\frac{d}{dt}\xi_{ns}^k(t) = -\rho\xi_{ns}^k(t)\left[\widetilde{\Psi'_k} - F(\sigma)\right] \tag{5}$$

Theorem 1. The solution set of (4) is denoted by ξ_{ns}^* and can be given as,

$$\xi_{ns}^* = \left\{\widetilde{\Psi'_k}\left(\frac{\tau_k/\xi_{ns}^k}{\sum_{n=1}^{\eta}\tau_n/\xi_{ns}^n}\right) = \widetilde{\Psi'_k}\left(\frac{\tau_\ell/\xi_{ns}^\ell}{\sum_{n=1}^{\eta}\tau_n/\xi_{ns}^\ell}\right)\right\},\ \forall\ k, \ell\ s.t.\ 1 \le (k, \ell) \le \eta,\ k \ne \ell \tag{6}$$

ξ_{ns}^* converges to a unique point $\widehat{\xi_{ns}}$, s.t., $\widehat{\xi_{ns}}\ \epsilon\ \xi_{ns}^*$.

Proof. For ease in derivation, we translate ξ_{ns}^k into Ω_k as $\Omega_k = \frac{1}{\xi_{ns}^k}$. Therefore,

$$\frac{d\Omega_k}{dt} = \frac{1}{\left(\xi_{ns}^k\right)^2}\frac{\delta\xi_{ns}^k}{\delta t} = -\Omega_k^2\frac{\delta\xi_{ns}^k}{\delta t} \tag{7}$$

The above relation can be re-stated as,

$$\frac{d\Omega_k}{dt} = \sigma\Omega_k\left[\widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right) - F(\sigma)\right] \tag{8}$$

and,

$$\phi = \left\{\Omega : \widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right) = \widetilde{\Psi'_\ell}\left(\frac{\tau_\ell\Omega_\ell}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right),\ \forall\ k, \ell, s.t. 1 \le k, \ell \le \eta,\ k \ne \ell\right. \tag{9}$$

To prove that ϕ is an invariant set,

$$\frac{d}{dt}\widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right) = \sum_{\ell=1}^{\eta}\tau_n\Omega_n\frac{\delta}{\delta\Omega_\ell}\widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right)\frac{d\Omega_\ell}{dt} \tag{10}$$

$$\frac{d^2}{dt^2}\widetilde{\Psi_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right)\ \frac{\tau_k}{\left(\sum_{n=1}^{\eta}\tau_n\Omega_n\right)^2} \times \left[\sum_{\ell=1}^{\eta}\Omega_\ell\frac{d\Omega_k}{dt}\tau_\ell - \sum_{\ell=1}^{\eta}\Omega_k\frac{d\Omega_k}{dt}\tau_\ell\right] = 0,\ k \ne \ell \tag{11}$$

We know that inside ϕ, $\Omega_\ell\frac{d\Omega_k}{dt} = \Omega_k\frac{d\Omega_\ell}{dt}$. Therefore, $\widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right)\forall\ k$, s.t $\forall k$, $1 \le k \le \eta$, remains constant denoted by $\boldsymbol{\mu}_o^*$. Hence, ϕ is an invariant set. When the system state changes into ϕ, it stays in that state. We can say that ξ_{ns}^* asymptotically converges to ϕ using the La Salle Invariant Set Principle [24]. Therefore, $\widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{n=1}^{\eta}\tau_n\Omega_n}\right) = \widetilde{\Psi'_k}\left(\frac{\tau_k\Omega_k}{\sum_{k=1}^{\eta}\tau_k\Omega_k}\right) = \boldsymbol{\mu}_o^*$, *for*$\forall k$, $1 \le k \le \eta$, stating that Ω converges to $\widehat{\Omega}$, s.t. $\widehat{\Omega} \in \phi$ and proving *Theorem 1*.

Definition. Assuming $\mathcal{F}(.) = \{(\widetilde{\Psi'_k})^{-1}(.) : 1 \le k \le \eta\}$ we can define Ω as,

$$\Omega = \{\Omega_k\} = (\widetilde{\Psi'_k})^{-1}(\boldsymbol{\mu}_o^*)\left(\sum_{k=1}^{\eta}\tau_k\Omega_k\right)\frac{1}{\tau_k} = \left(\sum_{k=1}^{\eta}\tau_k\Omega_k\right)\{\mathcal{F}(\boldsymbol{\mu}_o^*)\}^{\gamma}\frac{1}{\boldsymbol{\tau}} \tag{12}$$

For ease in representation, we use $f(\Omega, \boldsymbol{\tau})$ to represent $f(\sigma(\Omega, \boldsymbol{\tau}))$.

Hence, $f(\Omega, \boldsymbol{\tau}) = f\left(\sum_{k=1}^{\eta}\tau_k\Omega_k[g(\boldsymbol{\mu}_o^*)]^{\gamma}\frac{1}{\boldsymbol{\tau}}, \boldsymbol{\tau}\right) = \boldsymbol{\mu}_o^*$. Given $f(\Omega, \boldsymbol{\tau})$ is strictly increasing with $\sum_{k=1}^{\eta}\tau_k\Omega_k$, $\widehat{\Omega}$ is unique. Hence, a unique equilibrium point in ϕ denoted by $\widehat{\Omega}$ can be stated as $\widehat{\Omega} = \sum_{n=1}^{\eta}\tau_n\widehat{\Omega}_n[g(\boldsymbol{\mu}_o^*)]^{\gamma}\frac{1}{\boldsymbol{\tau}}$. In terms of ξ_{ns}^*,

$$\widehat{\xi_{ns}} = \left[\sum_{n=1}^{\eta}\widetilde{\Psi'_n}^{-1}(\boldsymbol{\mu}_o^*) \Big/ \tau_n\right].\sum_{k=1}^{\eta}\tau_k\frac{1}{\xi_{ns}^k} \tag{13}$$

Hence, the optimal CW size according to elastic traffic for the proposed protocol is given by (13).

5.2. Markov chain model

To depict the contention phase of the vehicular nodes, an MCDM is employed. Fig. 2 depicts a model of a back-off counter of ACCRV-MAC where $\widehat{\xi_{ns}}$ is adaptable. The back-off timer counter, which can range from zero to $\widehat{\xi_{ns}} - 1$, is assumed to be a non-stationary random variable with a value of ψ_s at time t, indicated by $\psi_s(t)$ [25]. The zero value means the vehicular node has won the contention procedure, and *sm* may now be broadcast. The SU detects the channel when it competes and adjusts the back-off timer accordingly. Assuming that the present value of the timer is ψ_s, the possible outcomes for the next transition can be: (i) the value of the counter might decrement by unity if the channel is sensed vacant with a probability p_v, (ii) the value of the timer might remain unchanged when the channel is sensed busy with probability p_b, due to the presence of another SU, (iii) the vehicular node might switch the channel and resume broadcast (say, from the present channel i to a new channel j, s.t. $i \ne j$) after renewing the value of the counter if a licensed PU interferes with the probability p_l, and (iv) the counter might attain

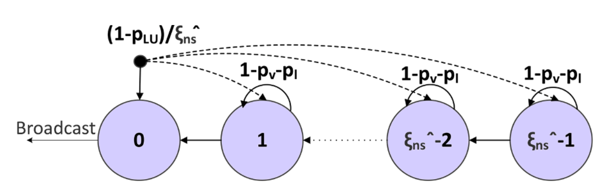


Fig. 2. MCDM of contention phase of ACCRV-MAC protocol.

zero, implying that the vehicle has won contention and *sm* can be broadcasted.

Hence, the transition probabilities can be given as,

$$
\begin{cases}
P^T|\psi_{s|i,s+1|i} = p_v + \dfrac{p_l}{\left[\sum_{n=1}^{\eta} \widetilde{\Psi_n^{,}}^{-1}(\boldsymbol{\mu}_o^*) \Big/ \tau_n\right] \cdot \sum_{k=1}^{\eta} \tau_k \frac{1}{\xi_{ns}^k}}, \ \psi_s \in [0, \ \widehat{\xi_{ns}}) \\
P^T|\psi_{s|i,s|i} = p_b - p_l \left(1 - \dfrac{1}{\left[\sum_{n=1}^{\eta} \widetilde{\Psi_n^{,}}^{-1}(\boldsymbol{\mu}_o^*) \Big/ \tau_n\right] \cdot \sum_{k=1}^{\eta} \tau_k \frac{1}{\xi_{ns}^k}}\right), \ \psi_s \in [0, \ \widehat{\xi_{ns}}) \\
P^T|\psi_{s|i,0|i} = \dfrac{1 - p_c}{\left[\sum_{n=1}^{\eta} \widetilde{\Psi_n^{,}}^{-1}(\boldsymbol{\mu}_o^*) \Big/ \tau_n\right] \cdot \sum_{k=1}^{\eta} \tau_k \frac{1}{\xi_{ns}^k}}, \ \psi_s \in [0, \ \widehat{\xi_{ns}}) \\
P^T|\psi_{s|i,r|j} = \dfrac{p_l}{\left[\sum_{n=1}^{\eta} \widetilde{\Psi_n^{,}}^{-1}(\boldsymbol{\mu}_o^*) \Big/ \tau_n\right] \cdot \sum_{k=1}^{\eta} \tau_k \frac{1}{\xi_{ns}^k}}, \ \psi_s, \psi_r \in [0, \ \widehat{\xi_{ns}}) \forall (\psi_s \neq \psi_r, \psi_r \neq 0)
\end{cases}
\tag{14}
$$

where p_c is the packet collision likelihood within the channel i and ψ_r is the reset value of the back-off timer after handoff.

As evident from the above discussion, the proposed protocol involves adaptable MCDM transition states. Hence, the number of equilibrium equations varies, highlighting that the vehicle density influences the Markov Chain's equilibrium.

Assumption. Let vector $\overrightarrow{S}$, with its magnitude ranging from zero to $\overrightarrow{S_{\widehat{\xi_{ns}}}}$ represent the stationary probability for $\widehat{\xi_{ns}}$ equilibrium equations and S_0 be the stationary probability when the MCDM is at zero state.

The equilibrium equations can be given as [7],

$$S_{\psi_r} = \sum S_{\psi_s} P^T|\psi_{s,r}, \ \ 0 \leq \psi_s, \psi_r \leq \widehat{\xi_{ns}} - 1 \tag{15}$$

At equilibrium, the MCDM meets the following condition [7],

$$\sum_{\psi_r=0}^{\widehat{\xi_{ns}}-1} S_{\psi_r} P^T \Big| \psi_{s,r} = \sum_{n=0}^{\widehat{\xi_{ns}}-1} S_{\psi_s} P^T \Big| \psi_{s,n} \tag{16}$$

where n is an arbitrary intermediate transition state. From (15) and (16), S_0 can be derived as

$$S_0 = p_v S_1 + \frac{\psi_0}{\widehat{\xi_{ns}}} + \frac{p_l}{\widehat{\xi_{ns}}} \left(S_1 + \sum_{\psi_r \neq 0,1} S_{\psi_r} \right) \tag{17}$$

where S_1 is the stationary probability when the backoff counter is unity. Hence, for the transitional state ψ_s,

$$S_{\psi_s} = \frac{S_0}{\widehat{\xi_{ns}}} + \left(p_b - p_l + \frac{p_l}{\widehat{\xi_{ns}}} \right) S_{\psi_r} + \left(p_v + \frac{p_l}{\widehat{\xi_{ns}}} \right) S_{\psi_{r+1}} \tag{18}$$

From (17) and (18), S_0 can be simplified with an assumption that $\widehat{\xi_{ns}} \gg 1$, as $S_0 \approx \frac{p_v + p_l}{p_v + p_l + \widehat{\xi_{ns}}}$. We know that the vehicular node commences broadcasting when the backoff counter is zero, hence $S_0 = \wp_t$, which represents the SU's transmission probability. Consequently, the likelihood that a packet is successfully transmitted, $\wp_s$, is influenced by the presence of PU in the vicinity, SU's transmission probability, and number of SU's in the CR-VANET scenario, such that,

$$\wp_s = \wp_t (1 - p_l) \eta \left\{ 1 - \wp_t (\eta - 1) + \frac{(\eta - 1)(\eta - 2) \wp_t^2}{2} \right\} \tag{19}$$

Similarly, the absence of an active (i.e., transmitting) vehicular node or a PU improves the probability of the channel being vacant, such that,

$$p_v = (1 - p_l) \left\{ 1 - \eta \wp_t + \frac{\eta(\eta - 1) \wp_t^2}{2} \right\} \tag{20}$$

Therefore, $\wp_t$ can be redefined as,

$$\wp_t = 1 - \frac{\widehat{\xi_{ns}}}{\widehat{\xi_{ns}} + \left\{ \eta \psi_0 p_l + \left(1 - \frac{(\eta-1)}{2} \psi_0 \right) + (1 - \psi_0)^{\eta} \right\}} \tag{21}$$

When multiple SUs try to access the spectrum simultaneously, packet collision might occur with a likelihood of p_c, such that,

$$p_c = (1 - p_l) \eta \wp_t \left\{ 1 - \frac{\wp_t (\eta - 1)}{2} + (1 - \wp_t)^{\eta - 1} \right\} \tag{22}$$

5.3. Cooperative data transmission

In the event, DT between vehicular nodes has failed due to collisions, and that $\mathscr{h}$ potential helper nodes are available among $\mathscr{V}$ vehicles, s.t., $0 \leq \mathscr{h} \leq \mathscr{V} - 2$, the probability that the proposed protocol relies on cooperative communication may be expressed as,

$$P_{CT} = \frac{\mathscr{h}}{\mathscr{V}} (1 - p_l) \eta \wp_t \left\{ 1 - \frac{\wp_t (\eta - 1)}{2} + (1 - \wp_t)^{\eta - 1} \right\} \tag{23}$$

Assuming that a packet of length l_p with a header of length l_h is broadcast with a rate b_t facing a propagation delay of Δ_{pr} seconds, then the average duration of a successful DT broadcast can be given as,

$$T_{dt} = \frac{t_{neg} b_t + l_h + l_p + \Delta_{pr} b_t}{b_t} + DIFS \tag{24}$$

where t_{neg} is the duration of channel negotiation, and DIFS denotes the distributed inter-frame spacing duration. In CT mode, assuming that $l_h^{'}$ is the length of the header the CT packet and T_{sg} is the time required for cooperative signalling, i.e., the time required for the reception of NACK and RTA signals, the duration of a successful cooperative broadcast can be expressed as,

$$T_{ct} = \frac{t_{neg} b_t + l_h + 2 l_p + l_h^{'} + \Delta_{pr} b_t}{b_t} + T_{sg} + 2SIFS + DIFS \tag{25}$$

The time taken by a SU to yield the spectrum in the event of a legacy

Table 2
Pseudocode 1: DT mode.

Input Parameters: η, ξ_{ns}^{k}, $\widetilde{\Psi_k}$, $F(\sigma)$ and p_l.		
Input Information: Channel Status		
Initialization: $flag_N$=0, $flag_{PU}$=0.		
1:	Channel Scan (); //Returns ch_{busy}	
2:	**if**	(ch_{busy} = =0)
3:		CHR ← channel //Reserve the current
4:		DT () //Initiate Direct Transmission
5:		$DIFS \leftarrow T_o$
6:	**if**	($flag_N$ = =0) //indicates NACK is absent
7:		*sm* broadcast → successful
8:	**else**	
9:		*call* CT () //Cooperative transmission
10:	**end if**	
11:	**else**	
12:	**if**	($flag_{PU}$ = =1) //PU is sensed
13:		broadcast ← PPR () //PU presence report
14:		hand-off () //Channel is switched
15:		$Boff_j \leftarrow Boff_i$ //Reset counter from *i* to *j*
16:		Go to: **2**
17:	**else**	**if** ($\widetilde{\Psi_k} > F(\sigma)$) //check utility and cost function
18:		ξ_{ns}^{k} ← reduced //CW size reduced
19:		**else**
20:		ξ_{ns}^{k} ← increased //CW size increased
21:		**end if**
22:		$Boff_i = Boff_i - 1$ //Continue contention
23:		Go to: **2**
24:	**end if**	
25:	**end if**	

Table 3
Pseudocode 2: CT mode.

Initialization: Channel condition			
1:	**if**	($flag_N$ = =1) && ($p_h > 0$)	
2:		**for** $k = 0$: η − 2 //using loop statement	
3:		**if**	*Channel condition (P)> Channel condition(S&R)*
4:			$h \leftarrow k$ //node p is identified as a helper
5:	**end for**		
6:			rebroadcast
7:		**else** CT = 0 //cooperation is not feasible	
8:		**end if**	
9:	**else**	CT=0 //cooperation is not feasible	
10:	**end if**		

user arrival or misdetection can be stated as,

$$T_{PU} = R_{avg}\left(\frac{l_h + l_p}{b_t}\right) + t_{hand-off}, \;\; R_{avg} \in [0, 1] \tag{26}$$

where R_{avg} is the average rate of PU arrival in a given broadcast range and $t_{hand-off}$ is the average time required in the case of spectrum hand-off. Similarly, let T_{col} be the amount of time consumed in the case of a packet collision, such that,

$$T_{col} = \left(\frac{l_h + l_p}{b_t}\right) + \Delta_{pr} + DIFS \tag{27}$$

Let the estimated duration SU spends on each Markov transition state in the case of DT and CT be $\langle E_D \rangle$ and $\langle E_C \rangle$ respectively, such that,

$$\langle E_D \rangle = p_v T_{slot} + p_b T_{d}\rho_s + p_b T_{col}(1 - \rho_s) + T_{PU} p_l \tag{28}$$

$$\langle E_C \rangle = p_v T_{slot} + p_b [p_c (1 - \rho_s) p_h \rho_s] T_{ct} + T_{col} p_b [1 - p_c (1 - \rho_s) p_h \rho_s] + T_{PU} p_l \tag{29}$$

where p_h is the likelihood of cooperative decision, such that $p_h = p_c \frac{h}{\mathcal{V}}$.

The pseudocodes of ACCRV-MAC DT and CT are given in Tables 2 and 3, respectively. Pseudocode 1 may be viewed as an outline of the main function, using subfunctions such as Channel Scan (.), CT(.), and PPR(.) to scan for available spectrum, activate CT mode, and broadcast PPR to signal PU existence to other network nodes. The utility and cost functions are also used to determine the CW size. The use of flags in decision statements to control the backoff counter and activate the CT(.) function is covered in Pseudocode 2. By identifying potential helpers, the CT(.) subfunction assesses whether cooperation is possible and executes sm retransmission. As described in Section 3.2, the timer is initialised with T_o to wait for the NACK signal for the DIFS schedule after the channel has been sensed in lines 1 to 5 of Table 2. If the channel is unoccupied, it is then reserved and the direct transmission is initiated. The broadcast is deemed successful if the NACK is not found; otherwise, the cooperative transmission described in Table 3 is initiated. The SU attempts to determine if a PU or another SU is using the spectrum if the results of the first channel sensing are affirmative, or if $ch_{busy} = 1$. If the PU is present, the SU transmits PPR and conducts hand-off to compete for another channel by resetting its back-off counter from initial value *i* to *j* and starting channel sense once more. The SU engages in contention with the current user if the channel is occupied by another SU and the PU was not sensed, as shown in lines 12 to 16 in Table 2. Following the resolution of optimization problem (2), the cost and utility functions are examined as mentioned in Section 5.1, and the CW size is modified correspondingly, as shown in lines 17 to 21 in Table 2. The back-off counter is decremented following the contention outcome following the determination of CW size. In pseudocode 2, the helper is recognised in the CT mode by continually monitoring the channel conditions of the users engaged using the loop statement, per Table 3 if NACK is detected and the likelihood of the helper's presence is not zero. The sm is rebroadcast once the helper is recognised as *h*, as shown in lines 2 to 4 in Table 3; if the optimal helper is not found, the CT is judged unfeasible; it is also deemed unfeasible if the p_h is zero or NACK is absent.

5.4. Performance parameters

The overall throughput of a CR-VANET scenario with numerous channels is calculated by adding the individual throughput of each channel. The following equations may be used to calculate the throughput, S_i, for the i^{th} channel in both DT and CT modes,

$$S_i^{DT} = \frac{p_b l_p \rho_s}{p_v T_{slot} + p_b T_{d}\rho_s + p_b T_{col}(1 - \rho_s) + T_{PU} p_l} \tag{30}$$

$$S_i^{CT} = \frac{p_c (1 - \rho_s) p_h \rho_s p_b l_p . (1/p_h)}{[p_v T_{slot} + p_b [p_c (1 - \rho_s) p_h \rho_s] T_{ct} + T_{col} p_b [1 - p_c (1 - \rho_s) p_h \rho_s] + T_{PU} p_l]} \tag{31}$$

The probability of a successful transmission is determined by the PDR of direct transmission, PDR_{DT}, hence $PDR_{DT} = \rho_s$. If DT fails, the proposed protocol tries to enter cooperative mode. As a consequence, the PDR of cooperative data transmission may be calculated using PDR_{CT}, which can be defined as, $PDR_{CT} = p_c (1 - \rho_s) p_h \rho_s$. Moreover, the average delay is the amount of time it takes for each packet to travel from the moment it is prepared in the transmitter's MAC queue until it is received. A delay of less than 100ms is suggested for successful *sm* broadcasting [6]. The average delay in ACCRV-MAC can be stated as follows,

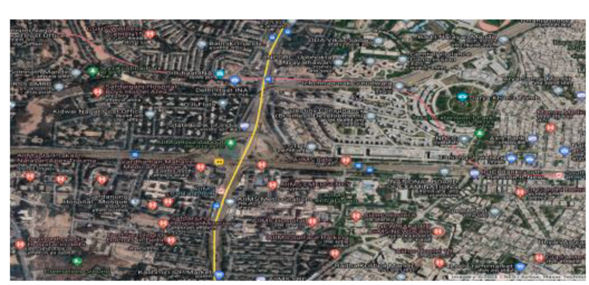


Fig. 3. Satellite view of area under simulation [28].

Table 4
Simulation parameters.

Parameters	Values
Simulation Area	4 km × 4 km
Simulation Time	150 s
Vehicle speed	10-130 km/hr
Transmission range	500 m
No. of vehicles	20-140
Lanes	2
CW size (ACCRV), CW (reference protocol CCRV)	16-1024, 32
Slot duration	20 µs
sm size	250 bytes
Propagation delay	1 µs
PU Connections	0-40 (in pairs)
Inter-vehicle distance	12 m
Propagation model	Nakagami
SIFS, DIFS	10 µs, 50 µs
NACK, ATA	20 µs, 26 µs

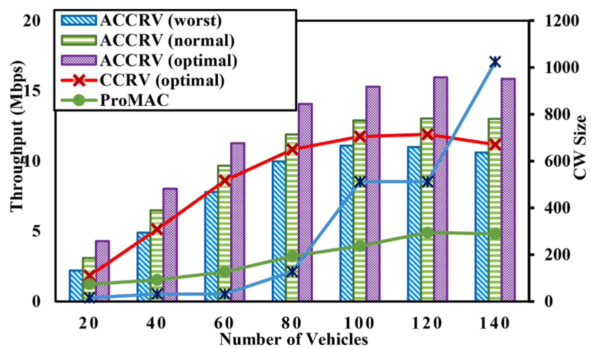


Fig. 4. Throughput (in Mbps) (Y1-axis) and CW size (Y2-axis) against the number of vehicles with ACCRV-MAC protocol, for normal ($p_h = 0.5, p_l = 0.5$), worse ($p_h \leq 0.2, p_l \geq 0.8$) and optimal conditions ($p_h \geq 0.8, p_l \leq 0.2$); and CCRV-MAC protocol in CR-VANET scenario.

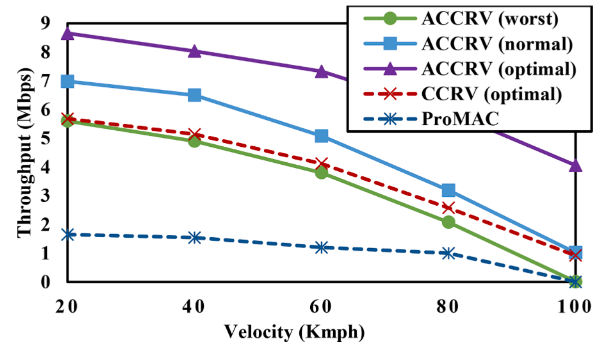


Fig. 5. Throughput (in Mbps) vs average speed of vehicles (in km/hr) for 40 vehicular nodes with ACCRV and CCRV MAC protocols.

increases packet collision in the network, and there is no way to rebroadcast rejected broadcast packets, resulting in a decrease in system throughput aligned by the paucity of helpers in the vicinity; (b) an increased performance is observed when the *sm* dissemination's dependability improves in tandem with the possibility of acquiring a helper at $p_h = 0.5$ and $p_l = 0.5$, which we refer to as the 'normal' case for ACCRV-MAC; and (c) when $p_h > 0.8$ and $p_l < 0.2$, we notice an improvement in performance because the broadcast reliability improves with the likelihood of acquiring helper and easily accessible licenced channels.

As traffic density increases, throughput rises to a point, saturates, and then gradually declines in all three instances, increasing packet collisions inside the network. The adaptive CW size of the proposed protocol outperforms CCRV-MAC (under optimal conditions) because the probability of each node selecting the same time slot to transmit messages lowers as the CW size of the node increases, and the throughput improves, reducing the risk of data collision in the proposed protocol. In the case of CCRV, however, if a data collision happens, the nodes will have to contend for the window afresh, resulting in a significant reduction in system performance. The CW size of ACCRV-MAC is depicted on the secondary axis in Fig. 4 at distinct periods. It is observed that the proposed protocol outperforms CCRV-MAC in terms of

$$\langle \Delta_{avg} \rangle = (1-p_l)\left[p_v T_{slot} + p_b[p_c(1-\wp_s)p_h\wp_s]T_{ct} + T_{col}p_b[1-p_c(1-\wp_s)p_h\wp_s] + T_{PU}p_l\left\{\eta - 1 + \left(\frac{\widehat{\xi_{ns}}+1}{2} - \frac{p_c}{1-p_c}\left(\frac{\widehat{\xi_{ns}}+1}{2}\right)\right)\right\} + \Delta_{pr}\right] \tag{32}$$

average throughput by 38.3%.

In the next section, the proposed protocol is analysed for throughput, packet delivery ratio, average delay, and CW size, and the results are compared with CCRV-MAC [7] and ProMAC [20] protocols.

6. Numerical analysis

The simulations of ACCRV-MAC are carried out using NS-2 version 2.34 [26] with OpenStreetMap [27] and Simulator for Urban Mobility (SUMO) [28] to create the traffic situation. Fig. 3 depicts an aerial view of the two-lane highway under consideration for simulation; for clarity, the image was obtained from reference [29]. Table 4 lists the simulation parameters [7].

As the number of vehicles moving at a speed of 40 km/h in the considered CR-VANET rises, Fig. 4 indicates an increasing pattern of system throughput. The results are interpreted in three ways: (a) in the worst-case scenario, when $p_h < 0.2$ and $p_l > 0.8$, the protocol struggles to demonstrate cooperative behaviour. The throughput is limited owing to the lack of potential helpers and the increasing prevalence of PUs in close proximity, with the growing number of vehicular nodes contributing to this deterioration. The existence of ignored NACK signals

For Forty SUs, Fig. 5 demonstrates the impact of increasing average vehicle velocity. Although extremely dynamic topologies result in unstable connectivity among vehicle nodes, ACCRV under normal and optimal conditions substantially outperforms the CCRV-MAC protocol under optimal conditions in terms of broadcast throughput. The proposed protocol is also compared to its contemporaneous ProMAC [20] in

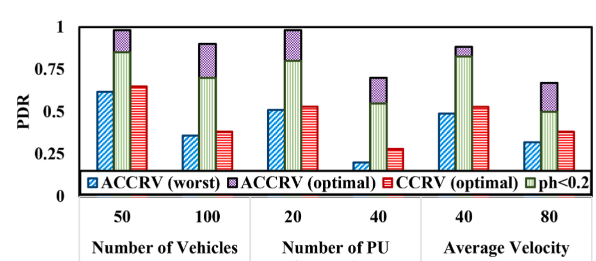


Fig. 6. PDR vs number of vehicles, number of PU connections and average velocity at different p_h for ACCRV and CCRV MAC protocols.

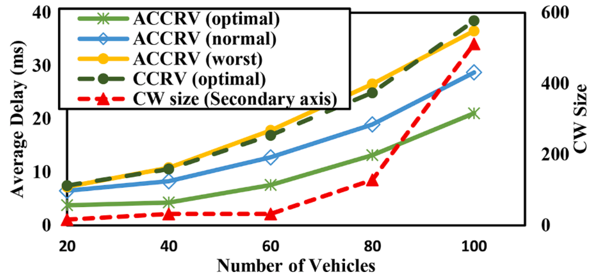


Fig. 7. Average Delay (Y1-axis), in milliseconds, and CW size (Y2-axis) versus number of vehicles for ACCRV (under all three scenarios) and CCRV (under optimal conditions) MAC protocols.

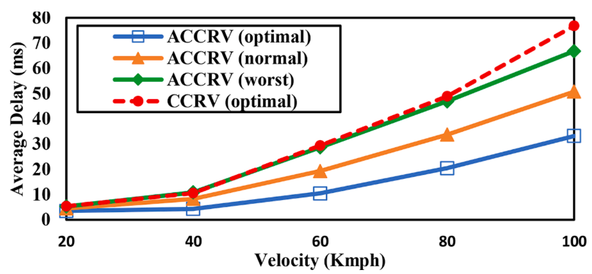


Fig. 8. Average Delay (in milliseconds) against average speed (in km/hr) for 40 vehicles with ACCRV and CCRV MAC protocols.

both Figs. 4 and 5, to illustrate that ACCRV performs approximately five times better. Under these conditions, the ideal CW size estimated by ACCRV is 32, and the methodology is developed so that it is unaffected by changes in velocity.

For a varying number of vehicles, PU connections, and average SU velocity, the system responses in terms of PDR are shown in Fig. 6. The proposed protocol surpasses the CCRV MAC protocol under optimal conditions, even when helper nodes are sparse, i.e., $p_h < 0.2$, since it uses an adjustable CW size to lower packet collision rate while optimising it to keep delay in check according to elastic traffic density. The ACCRV-MAC shows 85% and 61.2% more PDR when compared to the CCRV protocol for $p_h > 0.8$ and $p_h < 0.2$, respectively.

Figs. 7 and 8 depict the variation in average delay in broadcasting *sm* across the CR-VANET concerning the number of vehicles and their average velocities, respectively, for various PU appearance and helper node availability likelihood. As the broadcast frequency grows with the traffic, the latency increases due to the increased collision rate. Also, when the probability of PU appearance is large, the rate at which the average delay rises is increased because leaving the present spectrum and performing channel switching contributes to the latency suffered by a vehicular node. Furthermore, the paucity of helpers exacerbates the situation. When comparing the proposed protocol to CCRV MAC, it is estimated that in optimal conditions, the per cent decrease in average latency for all nodes is 49%. Due to its adaptability, ACCRV not only provides rapid packet dissemination but also satisfies the 100ms delay restriction for *sm* broadcast. On the secondary axis, the CW size variations are depicted. The average delay against rising vehicle velocity is depicted in Fig. 8. As a result of the dynamic topology, which causes frequent connection breakage and collisions among *sm* packets, the delay rises substantially. Compared to CCRV-MAC, the suggested protocol outperforms it due to the optimal CW size. CCRV-MAC's rigid CW structure fails to outperform ACCRV because in CCRV when the window size is more significant than necessary for contention, the nodes wait longer for transmitting slots, increasing the network's total latency. When the CW size is small, each node has fewer time slots from which to send data, and the chance of accessing the same time slot is higher, resulting in more data collisions and CT, increasing the overall network latency. As a result, adaptive CW size is advantageous since it reduces network delay while maintaining CR-VANET's throughput.

Although using the ACCRV-MAC protocol in CR-VANETs has numerous advantages, there are some drawbacks as well. These problems can be resolved as part of this study's future research. The basis for the receiver receiving the NACK signal is the presumption that the receiver has at least the initial broadcast frame, which may not always be feasible in real-world scenarios. Furthermore, there may be significant security vulnerabilities associated with NACK signals. SUMO simulations, which are capable of estimating real-time traffic, are used in this study to calculate the traffic. However, employing a variety of hardware elements, such as proximity sensors, it would be able to calculate the total number of nodes along a finite road length in real-world circumstances. Roadside units can also be used to count the number of cars within a particular range. Additionally, complex and arduous calculations for the utility and cost functions and determination of CW size can be tedious and overwhelming to the system when the traffic density is high.

7. Conclusion

In this paper, we present a systematic way for creating stable CW management algorithms that may be utilised to achieve optimal channel allocation based on traffic density in response to the constraints of existing approaches. To describe and solve the CW optimisation issue, we analyse the criteria for throughput and delay efficiency to select appropriate utility and cost functions. To choose suitable transmission modes and permit a cooperative makeup strategy to rebroadcast failed transmissions, the adaptive CW is combined with additional control signals. For real-time traffic, the proposed protocol is evaluated for throughput, PDR, and average delay. This work, on the other hand, is the first step toward a comprehensive solution for the CR-VANET CW control mechanism. Many unresolved concerns must be addressed in the future. The first issue is the disparity between mathematical modelling and real-world systems. We should consider the existence of multiple heterogeneous CR-VANETs to bring the model closer to being implemented in real-time scenarios. As a result, a significant focus of our future research will be on determining how to allocate bandwidth across co-existing and diverse network topologies fairly and efficiently.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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