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RESEARCH ARTICLE

Optimized MAC Protocol Using Fuzzy-Based Framework for Cognitive Radio AdHoc Networks

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ABSTRACT Cognitive radio networks (CRNs) have been widely used in various applications for effective radio spectrum utilization in recent years. It is essential to fend off the growing demand for this finite natural resource for next-generation communications. In CRNs, detecting the activity of the primary user requires opportunistic spectrum sensing for efficient usage of the available radio spectrum, which is a limited and exquisite resource. Thus, CRNs are the key component in solving the spectrum scarcity issue in the presence of primary user bands through secondary users. Cognitive radio AdHoc networks (CRAHNs) are a unique kind of CRNs where infrastructures less cognitive radio (CR) nodes are furnished. In CRAHN, the CR-MAC protocol works slightly differently from the traditional wireless network MAC protocols. Particularly, the proposed method includes a high traffic scenario under contention-based IEEE 802.11 DCF MAC protocol. Accordingly, it can be observed that both, throughput and delay, increase as the CW size and packet length of the 802.11 (DCF) MAC protocol for CRAHN varies. Therefore, this paper proposed a fuzzy-based optimization framework for the 802.11 (DCF) MAC protocol in CRAHNs. Furthermore, it optimized throughput and delay by training a database of input parameters, contention window, and packet length for the Mamdani and Sugeno fuzzy inference system (FIS) models of the 802.11 (DCF) protocol simultaneously. The experimental result of the proposed framework for CRAHN with FIS shows that altering the contention window increases throughput by 25% and reduces the delay by 38% compared to the IEEE802.11 (DCF) protocol for CRAHNs without FIS. Moreover, it is also revealed that the throughput is increased by and 7% and the delay is reduced by 40% to 50% due to altering the packet length.

INDEX TERMS Cognitive radio AdHoc networks (CRAHNs), MAC protocol, 802.11 (DCF), FIS-based optimization.

LIST OF ABBREVIATIONS

CRNs	Cognitive radio networks.
CRAHNs	CR-AdHoc network.
SU	Secondary user.
PU	Primary user.
CR-WLAN	Cognitive Radio wireless Local area network.
MAC	Medium access control.
CSMA/CA	K_{th} Carrier sense multiple access/collision avoidance.
RTS	Request to send.
CTS	Clear to send.
DCF	Distributed coordination function.
TDMA	Time division multiple access.
CDMA	Code division multiple access.
FDMA	Frequency division multiple access.
FIS	Fuzzy inference system.
DTMC	Discrete-Time Markov Chain.

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DIFS	Distributed interframe spacing.
SIFS	K_{th} Short Interframe Space.
PL	Packet length.
CW	Contention window.

I. INTRODUCTION

The potential technique known as Cognitive Radio (CR) addresses the spectrum scarcity issue by opportunistically utilizing vacant spectrum bands for transmission while safeguarding the licensed bands or primary users (PUs). There are two categories of spectrum users in these networks viz., primary users, who have more priority to access the spectrum, and secondary users (SUs), who find and exploit 'spectrum gaps' of the spectrum that the PUs are not using actively [1], [2], [3]. An excellent wireless MAC protocol must offer a simple method for wireless channel sharing, high bandwidth usage, and network fairness (i.e., parity in channel access). Subsequently, [4] mention that the main challenges to an ideal wireless network are low mean packet latency (minimum delay), high throughput, low packet drop ratio, and good fairness under heavy traffic loads. In this scenario, cognitive radio MAC protocol may be an efficient solution for the maximum utility of the radio spectrum. Since cognitive radio users utilize the PU user spectrum opportunistically by adding spectrum sensing techniques, the MAC protocol for the CR-AdHoc network (CRAHNs) is slightly different from conventional wireless AdHoc Networks [5]. Therefore, developing a successful medium access control (MAC) protocol is crucial for CRAHN i.e., SU must exploit the spectrum available from PU while ensuring good quality of service (QoS) (e.g., throughput, delay) [6].

Several ongoing standardization initiatives by the IEEE 802 community, including IEEE 802.22 [7], IEEE 802.11af [8], and IEEE 1900 [9], are focused on CRNs. The infrastructure-based CR network and CRAHNs are two categories into which CRNs can be subdivided based on the network architecture [10]. In the first type, the network is managed and supervised by a central body, such as an access point (identical to a cellular network) [11], [12]. Although the CRAHNs network does not have the backbone of any established infrastructure, it does have AdHoc communication amongst CR users [13]. Compared to infrastructure-based CRN, the CRAHNs are a better solution because of their reduced implementation costs, more straightforward system, and quicker alignment positioning. Due to the distributed nature of CRAHNs, these networks frequently use the distributed coordination function (DCF) as stated in IEEE 802.11. It is easier to combine IEEE 802.11 (DCF) with a cognitive radio network to develop a CR-MAC protocol because IEEE 802.11 (DCF) can use unlicensed CR spectrum bands, such as the 2.4 ISM band and TV whitespace band. Mainly, CR MAC protocols are divided into three categories such as random access (e.g., Aloha, CSMA/CA), Controlled access (e.g., Reservation, Poling), and channel access (e.g., FDMA, TDMA, CDMA). Our paper presents a CSMA/CA based 802.11 (DCF) random access protocol for CRAHNs; Its background and related studies are presented in the next section. The correlations of various MAC protocols for multichannel AdHoc CRNs are presented in [6], [14], and [15]. These studies indicate that no single MAC protocol always continues to perform well because it mainly depends on the number of channels, the number of nodes, the characteristics of the data traffic in the network, etc. Article [16] uses the Markov chain model to examine the effectiveness of multi-channel access protocols for CR-WLAN in terms of delay and throughput while altering the number of CR users, channels, and spectrum availability. It is essential to develop the MAC protocols adapted to the characteristics of given network circumstances. In other words, any wireless network must operate with high throughput and little access lag to perform at its optimum. Accordingly, our work proposes a fuzzy inference system (FIS) optimization-based strategy to address these issues for CRAHNs. The proposed method analyzes the network for different data traffic conditions and varying CSMA/CA wait for state parameters. The contribution and novelty of the present work can be described as follows:

- Analysis of an efficient sensing scheme for the proposed CRAHN in which periodic sensing and continuous sensing are used to PU ON and PU OFF states, respectively.
- Contention-based 802.11 DCF MAC protocol is adopted to proposed CRAHN, and delineated a flowchart with respect to its working procedure for the proposed framework.
- A FIS-based optimization framework is proposed for 802.11 DCF CSMA/CA MAC protocol in CRAHNs, outlining it for Mamdani and Sugeno FIS models.
- Analyze and optimize the throughput and delay simultaneously to improve the performance of the 802.11 for CRAHNs.

The rest of the paper is organized as follows. The related work of the proposed work is described in Section II. The proposed network access model and mac protocol for CRAHNs are presented in section III. The results are analyzed in Section IV and finally, the final findings are concluded in Section V.

II. BACKGROUND AND RELATED WORKS

For the particular application of the CR, pre-defined well-performing architectures of CR should be required. Subsequently, extensive analysis and recently proposed architectures for cognitive radio AdHoc networks with their strengths and limitations are described in [10]. The authors surveyed the spectrum management architecture for CRAHNs and highlighted the differences between CRAHNs and traditional AdHoc networks [17]. MAC protocols for the centralized network topology of CRNs are specified by the IEEE 802.22 [18], and IEEE 802.11af [8] standards. The IEEE 802.11 DCF protocol is a random-access protocol based on contention and is better suited for CRAHNs. In [19], [20], 2D DTMC is used to control the contention window of

IEEE 802.11 DCF protocol, i.e., Bianchi model, for better performance. Moreover, [21] investigate the throughput and delay of this CSMA/CA-based IEEE 802.11 (DCF) protocol under maximum load conditions using a 2D-DTMC model. The MAC protocol for cognitive radio networks requires control channels for spectrum sensing or observing primary user activity. This dedicated control channel-based dynamic open spectrum sharing (DOSS) protocol is proposed in the secondary network with two transceivers per node [22], [23], [24]. In further work, a decentralized MAC protocol is introduced in [25], where communication time and throughput performance improvement are accomplished by reducing the number of handshaking signals broadcast over a common control channel (CCC) between SUs. In [26], the point coordination function (PCF) of Wi-Fi networks is used to create a reliable and efficient control channel (CC) in Wi-Fi-based CRNs.

Fuzzy logic has been used in numerous types of research to improve the quality of service in wireless networks viz., the FLCMAC adaptive fuzzy logic cooperative MAC protocol is presented for efficient prioritized traffic management to achieve QoS. It has been shown that using the suggested approach, both single-hop and multi-hop wireless transmission has increased efficiency in terms of delay time and throughput [27]. Another fuzzy logic-based study offered a fuzzy expert system that increases VoIP (voice over internet protocol) user's connections even by 40% in AdHoc networks. It can also quickly modify packet size values to the current optimal level and has been enhanced with minimal delay, and tolerable packet loss [28]. A fuzzy logic-based approach was adopted to load balancing to the access point (AP) in IEEE 802.11 networks for improving the QoS exhibited by various wireless scenarios [29]. The congestion, a typical network issue, and barrier were addressed using fuzzy logic, and the resulting technique was known as fuzzy random early detection (FLRED) [30]. In order to train the neuron fuzzy models, a genetic algorithm and backpropagation learning algorithm were employed via adaptive traffic engineering solution for video surveillance systems over SDN based on type-2 fuzzy logic [31]. A fuzzy-based scheduler system is also developed for mobile AdHoc networks to prioritize packets using routing protocols by looking at packet-scheduling methods that enhance the performance of congested networks [32]. In addition, a fuzzy logic-based prioritized scheduler for MANET is suggested, employing the data rate, signal-to-noise ratio (SNR), and queue size as inputs. Moreover, [33] has presented a scheduler that outperformed the previous scheduler in terms of performance i.e., averaging improvements of 37% for the end-to-end delay, 56% for throughput, and 57% for the packet delivery ratio. Subsequently, [34] uses adaptive neuro-FIS to optimize the power control ratio in CRNs. Adaptive neuro-fuzzy inference systems, self-organizing maps, artificial immune systems, fuzzy logic and neural models, and hybrid models are among the prominent soft computing methodologies that WLAN researchers have been progressively incorporating. Furthermore, [35] improves the performance of the IEEE 802.11 MAC protocol performance for WLANs employing fuzzy logics and the ANOVA regression model [35].

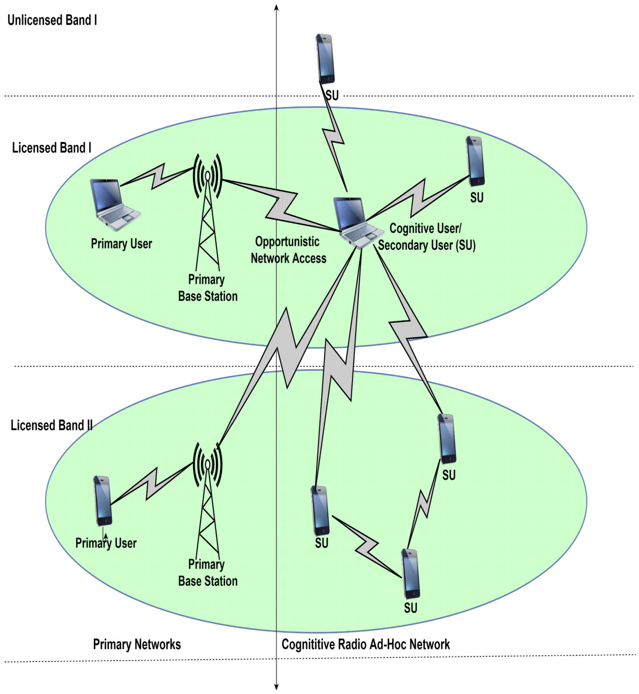


FIGURE 1. **Cognitive Radio AdHoc (CRAHNs) networks architecture.**

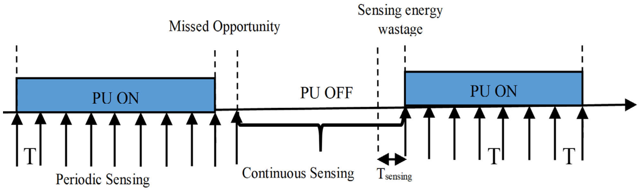
Therefore, to the best of the author's knowledge, the 802.11 (DCF) protocol for cognitive radio networks using FIS, which can improve throughput and delay, is not yet available in the literature. In light of the preceding discussions, we have developed a FIS-based strategy for IEEE 802.11 (DCF) based protocols in CRAHNs, which increases the throughput with reducing the delay simultaneously.

III. SYSTEM MODEL

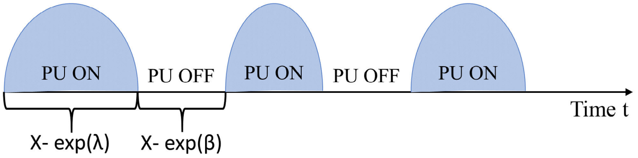
Consider a cognitive radio AdHoc network (CRAHN) that employs the IEEE 802.11 DCF protocol and is composed of single-hop communication as in Fig.1. In this network, the spectrum is licensed to the primary users and secondary users use the licensed bands opportunistically considering overlay mode. The CRAHNs do not offer an infrastructure system, and the network does not even depend on the pre-existing infrastructure. As is well known, the proposed 802.11 (DCF) protocol is a contention-based system where sensing is crucial for CRAHNs. Therefore, the two primary purposes of the cognitive radio MAC protocol are contention and spectrum sensing.

A. CONTENTION

The proposed CRAHN shows that the number of SUs utilized by the PUs spectrum and may vary according to the network requirement coverage Fig.1. The IEEE 802.11 (DCF) is the random access type of MAC protocol reported for wireless AdHoc networks [36], and CSMA/CA access is the foundation of this protocol. In this protocol, a random backoff mechanism follows every busy medium scenario. After completing the spectrum sensing in the CRAHNs, if any SU has a packet to broadcast, it must first "listen" to the channel, according to the CSMA/CA-based 802.11-based (DCF) approach. If another user is sending the data packet, wait for the DIFS time interval, which is the minimum time for that user to be inactive. After DIFS, if the medium is still available, the current user initiates transmission, otherwise, it waits for the previous user to finish transmitting the packets. After that, it will generate a random delay and wait for another DIFS time before broadcasting its packet, which refers to as the back-off procedure. This delay is randomly selected in the contention window (0, $CW - 1$). The SU sends its packet if no other transmissions occur before the expiration of this time frame. When other SU's are broadcasting during this time, the back-off counter is frozen until the end of each broadcast, and then the counting procedure is resumed after DIFS time. The SU sends its packet when its counter hits zero. The first transmission attempt is for the minimum size of the contention window CW_{min}, after which CW doubles to a maximum value after each retransmission brought on by a collision, i.e., $C_{max} = 2^m CW_{min}$, where m is the number of contention window sizes. Once the contention window is maximum, it resets the counter and again follows the back-off procedure reported in [37].



(a) PU ON-OFF Strategy.



(b) PU ON-OFF distributions (stochastic process).

FIGURE 2. Spectrum sensing scheme.

B. SENSING

In CR networks, despite the cohabitation of SU and PU in the same spectrum band, both are typically unaware of each other. It is challenging to determine the ON/OFF state of a PU by using the carrier sensing approach when it lies from outside the carrier sensing range (CSR) of an SU. To prevent interference among them, we should take into account the spectrum sensing technology [10], [38], such as energy detection or cyclostationary feature detection, etc. Spectrum sensing is carried out by the MAC protocol at the physical layer and packet scheduling at the MAC layer, respectively [39]. A node continuously senses the channel in accordance with the IEEE 802.11 DCF standard [40], which causes the wastage of energy. This problem has been reformed by adopting an approach wherein SUs start periodic sensing during the ON condition and continuous sensing built on the DCF during the OFF condition of the PUs, respectively [41]. This process has been adopted in the proposed work. When the channel is discovered to be empty in a sensing start instantly while in periodic sensing mode, the CR changes to continuous sensing mode and adheres to the 802.11 DCF protocol.

The proposed methodology employs periodic sensing with periods of T when the PU is ON (the channel is not open to SUs), and the time period T can either have a constant, deterministic value or be randomly chosen from a suitable distribution [42], [43] Fig.2a. According to this adopted method, the length of the SU packet is limited by $T_{sensing}$ to prevent interference on the PU. Suppose that the channel is detected to be engaged in continuous sensing mode for a period longer than $T_{sensing}$. In this case, CR assumes that PU has occupied the channel and returns to the periodic sensing mode after the sensing period $T_{sensing}$ with periods T, as long as PU is sensed busy. Here, $1/\lambda$ and $1/\beta$ are the mean values for exponentially distributed PU ON and PU OFF duration, respectively. As long as the channel is considered busy, it remains in periodic sensing mode, otherwise, in ideal conditions, the SU uses it with continuous sensing. Now, from Fig.2a, energy spent for periodic sensing E_{PS} and continuous sensing E_{CS} can be formulated as follows [41]:

$$E_{PS} = \left[\frac{1}{\lambda T}\right] E_S, \tag{1}$$

$$E_{CS} = E\left[\frac{1}{\beta} + T_{sensing} - \frac{T}{2}\right], \tag{2}$$

where E_S represented as energy spent per sensing, the expected number of sensing is represented as $\left[\frac{1}{\lambda T}\right]$, E is the energy per unit time duration in continuous sensing configuration, $T_{sensing}$ is time units for continuous sensing before switching to periodic sensing mode on activation of PU. Moreover, it is visible in Fig.2b that in the OFF phase of the PU (continuous sensing), the $T/2$ time unit is often wasted to detect it. It indicates that starting from the moment PU turns off, the typical delay for transitioning from periodic sensing to continuous sensing is provided by the constant $T/2$. Furthermore, on the basis of (1) and (2), E_{total} i.e., (3), which is the average total energy consumed during an ON-OFF cycle, can be written as follows

$$E_{total} = E_{CS} + E_{PS}. \tag{3}$$

IV. PROPOSED SCHEME FOR 802.11 PROTOCOL FOR CRAHNS

A. 802.11 DCF PROTOCOL FOR CRAHNS

For proposed CRAHNs, this scheme includes the sensing function with the 802.11 (DCF) protocol that contains $M = 50$ contending SU's and defined simulation time to obtain the output results such as throughput and delay by varying the input parameters like packet length and contention window. Based on the literature, many types of MAC protocols

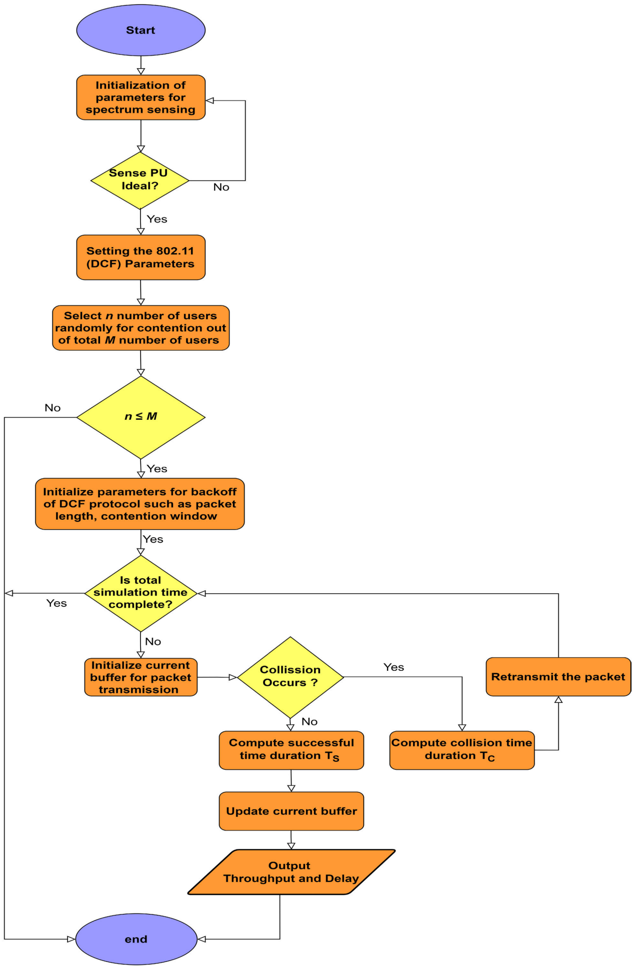


FIGURE 3. Flow chart of the simulation for the proposed scheme.

are reported, a Markov chain-based analytical model for the 802.11 (DCF) protocol is presented in [21] and [36], which are relevant in the context of the proposed work. The flow chart which describes the simulation for the proposed scheme is shown in Fig.3. First, the sensing functions are utilized to observe the PU activity, thereafter, DCF based back-off process will start and initialize its parameters. Here, the time counter will start from '0' to the total simulation time and calculate the successful time T_s (average time that the channel is occupied with a successful transmission of SU packet) i.e., equivalent to $T_{sensing}$ in this case, and the collision time T_c (average time the channel is occupied by colliding SU's). In this back-off process, if cognitive radio user packets collide with increment collision time T_c, these packets are re-transmitted with back-off counter resets to the back-off process. If there is no collision, i.e., successful transmission of the packet, then the successful time is incremented, and at the end, the outputs throughput and delay results are obtained from (4) and (6).

The main objective of the network MAC protocol is to maximize the throughput and minimize the access delay since throughput and access delay mainly depends on the traffic load and the design of the MAC protocol. Note that, the IEEE 802.11 DCF protocol is being used in the presented work, therefore, these parameters depend on factors associated with this protocol. The contention window size and packet length are two factors that this study takes into account to optimize throughput and access delay. The mathematical analysis for IEEE 802.11 (DCF) in detail is reported in [19], [20], and [21], [36] presented the detailed analysis of throughput and delay for both two-way (acknowledgment) and four-way access (RTS-CTS) methods of this MAC protocol at high traffic condition using a renewal process.

1) THROUGHPUT FOR IEEE 802.11 (DCF)

In one renewing interval among two subsequent transmissions, the normalized throughput [19], [20] is described as

$$S = \frac{\mathbb{E}[\text{successful packet payload transm. in a slot time}]}{\mathbb{E}[\text{ length between two subsequent transmissions}]}$$

It can be also elaborated as follows

$$S = \frac{\text{Average successful packet payload transmission}}{AID_{NT} + STD_{ST} + CD_{C}}$$

where

$$\begin{aligned} AID_{NT} &= \text{Average ideal duration with no transmission} \\ STD_{ST} &= \text{Successful transmission duration with successful} \\ &\quad\ \text{transmission} \\ CD_{C} &= \text{Collision duration with collision} \end{aligned}$$

Consequently, S can be written mathematically as

$$S = \frac{P_S\,\mathbb{E}[P^{av}]}{\mathbb{E}[Z] + P_S T_S + (1 - P_S) T_C}, \tag{4}$$

where (4) represents the saturation throughput for the IEEE 802.11 (DCF) protocol, P_S is the successful probability of transmission, $\mathbb{E}[P^{av}]$ is the average packet payload size for DCF protocol, $\mathbb{E}[Z]$ is the average number of consecutive ideal slots, T_S successful time duration (average time that the channel is occupied with a successful transmission of SU packet) and T_C collision time duration (average time the channel is occupied by colliding SU's) for SU's packet transmission that can be defined as below

$$\left.\begin{aligned} T_S &= H + \mathbb{E}[P^{av}] + SIFS + \tau + ACK + DIFS + \tau \\ T_C &= H + \mathbb{E}[P^{\max\_coll}] + DIFS + \tau \end{aligned}\right\}, \tag{5}$$

where $H = MAC\_header + PHY\_header$ is representing the packet header and τ is known as propagation delay, $\mathbb{E}[P^{av}]$ is the average packet payload size and $\mathbb{E}[P^{\max\_coll}]$ is the longest packet payload size at the collision, which can be calculated by the PDF of respective payload size and channel bit rate.

2) DELAY FOR IEEE 802.11 (DCF)

The period between the creation of a packet and its successful reception is known as a packet access delay. Let us assume that $\mathbb{E}[AD]$ is the mean value of the random variable AD

which represents the packet access delay. The relationship, as shown below, can be used to get the mean frame delay (6)

$$\begin{aligned}\mathbb{E}[AD] &= \text{Average delay due to total number of Collisions}\\ &\quad + \text{Average delay during the}\\ &\qquad \times \text{ successful transmission },\\ \mathbb{E}[AD] &= \mathbb{E}[N_{collisions}](\mathbb{E}[BOD] + T_C + T_W)\\ &\quad + (\mathbb{E}[BOD] + T_S), \end{aligned} \tag{6}$$

where T_W is DIFS, $\mathbb{E}[N_{collisions}]$ is the mean number of collisions up to the anticipation of successful transmission, and the mean back-off delay $\mathbb{E}[BOD]$ is the time when a station chooses to wait before entering a channel when it is congested. When a broadcast packet collides between two nodes, it must wait until T_W before sensing the channel once again. Different delays, to calculate the total access delay of the packet such as $\mathbb{E}[N_{collisions}]$, $\mathbb{E}[BOD]$ at a different situation, have been exhibited in [21], [36], [44].

B. PROPOSED FUZZY BASED OPTIMIZATION SCHEME

There are mainly three types of Fuzzy inference systems like Mamdani fuzzy model, Takagi-Sugeno fuzzy model, and Tsukamoto fuzzy model that are being used as a controller for optimization purposes. E. H. Mamdani is credited with developing the Mamdani fuzzy inference system [45], [46]. In this system, both the input and output membership functions take the form of linguistic variables, such that the Mamdani system requires human expert knowledge for fuzzification and fuzzy rule setting. Takagi, Sugeno, and Kang introduced the Sugeno fuzzy model [47], sometimes referred to as the TSK fuzzy model, in an aim to provide a methodical process for generating fuzzy rules from a given input and output data set [48]. In the Sugeno system, input membership functions also take the form of linguistic variables, and output should be linear or constant (Crisp value). Since each rule's output is a crisp value, the sum of all the outputs is determined as their weighting factor. This method is less difficult than the Mamdani model since defuzzification is not required because the output is a crisp value. In Tsukamoto Fuzzy Model [49], each fuzzy if-then rule's consequence is represented by a fuzzy set with a monotonic membership function. The Tsukamoto fuzzy model is not widely used because it is not as transparent as the Mamdani or Sugeno fuzzy models. The following steps have been followed to implement such a fuzzy model i.e., Mamdani or Sugeno fuzzy models, in the proposed strategy Fig. 4.

1) Crips inputs mean a statement is 'True' or 'Not' with proposed parameters (contention window and packet Length) of the proposed problem and membership functions are the method for solving practical problems employing experiences instead of knowledge.
2) In this step combined the Crips inputs and membership functions to fuzzification. Fuzzification is the process to convert the crisp data of proposed parameters to the fuzzy sets of the inputs in FIS.

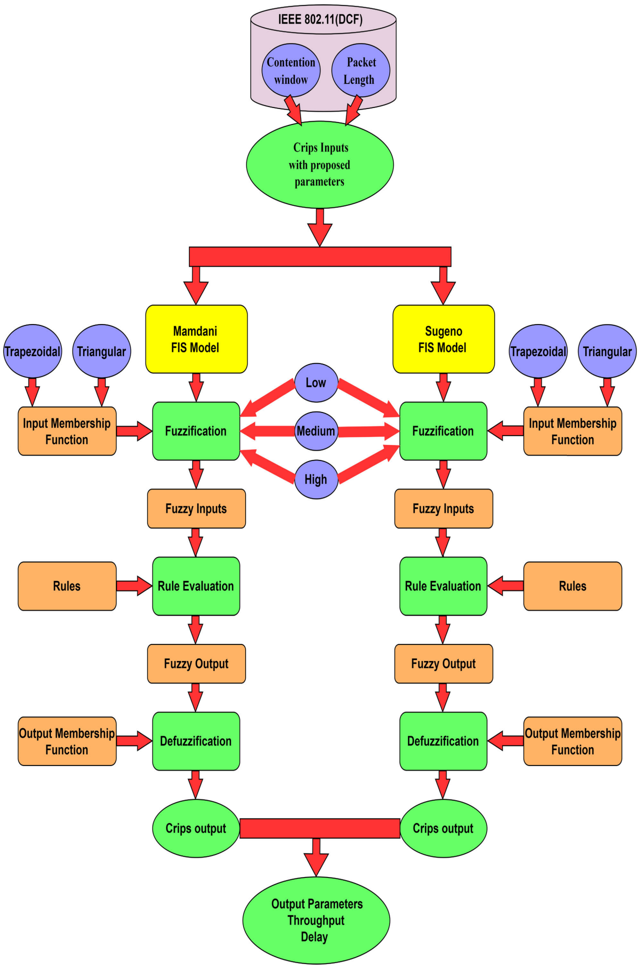


FIGURE 4. Proposed fuzzy inference based complete flow chart of a proposed solution.

3) Rule evaluation has been done on basis of experiences instead of knowledge with the help of Boolean algebra and fuzzy rules in FIS.
4) Fuzzy outputs are introduced from rule evaluation, and predefined membership functions for the parameters for proposed parameters are combined for defuzzification to get the crisp output.
5) An output distribution is created by calculating and combining the results of all the fuzzy rules.
6) In most applications, a sharp output is usually necessary. Defuzzification is the turning of ambiguous data (such as output distribution) into comprehensive information (single value or crisp data). Numerous techniques can be applied in this situation like the center of Mass, Mean of the Maximum, and other frequently used techniques.

Algorithms 1 and 2 exhibit the pseudocode of the Mamdani and Sugeno FIS models, which were used for optimization in the proposed work. The Mamdani model for defuzzification employs the centroid approach, while the Sugeno model employs the weight sum method.

Algorithm 1 Pseudo Code for Mamdani Fuzzy-Model-Based Optimization of 801.11 (DCF) Protocol to CRAHN

```
Input  : Contention Window, Packet Length
         (antecedents)
Output: Throughput, Delay (consequents)
  1) Adopted the database from the proposed 802.11
     (DCF) protocol of antecedents and consequents
     for the FIS model
  2) Chose Mamdani fuzzy model
  3) Initilize the different methods for Mamdani FIS -
     AndMethod= min
     OrMethod= max
     ImpMethod= min
     AggMethod= max
     DefuzzMethod= centroid
  4) Defined the membership function for 1)
  5) Generate the fuzzy rule database for 1), 2), and 3)
  6) Compare the optimized result
  7) end
```

Algorithm 2 Pseudo Code for Sugeno Fuzzy-Model-Based Optimization of 801.11 (DCF) Protocol to CRAHN

```
Input  : Contention Window, Packet Length
         (antecedents)
Output: Throughput, Delay (consequents)
  1) Adopted the database from the proposed 802.11
     (DCF) protocol of antecedents and consequents for
     the FIS model
  2) Chose Sugeno Fuzzy model
  3) Initilize the different methods for Sugeno FIS -
     AndMethod= min
     OrMethod= max
     ImpMethod= prod
     AggMethod= sum
     DefuzzMethod= wtsum
  4) Defined the membership function for 1)
  5) Generate the fuzzy rule database for 1), 2), and 3)
  6) Compare the optimized result
  7) end
```

V. RESULTS AND DISCUSSION

A fuzzy inference model's membership function (MF) encapsulates all its characteristics. Most fuzzy inference model applications use membership functions, which are straightforward composites of linear functions and more controllable than Gaussian functions [50]. In the proposed work, triangular and trapezoidal membership functions are used for input and output parameters for Mamdani FIS, whereas, in the Sugeno model, consequents exhibited the content linear membership function. The mathematical modeling of different types of membership [49] is defined as follows

TABLE 1. Fuzzy sets for Mamdani FIS.

Linguistic Variables x	Linguistic values	Membership function	Parameters $[a_1, a_2, a_3, a_4]$
Contention Window	Low	trapezoidal	[0 0 16 32]
	Medium	triangular	[16 32 48]
	High	trapezoidal	[32 48 64 64]
Packet length	Low	trapezoidal	[0 0 0 25]
	Medium	triangular	[0 25 50]
	High	trapezoidal	[25 50 50 50]
Throughput	Low	trapezoidal	[0 0 0 0.5]
	Medium	triangular	[0 0.5 1]
	High	trapezoidal	[0.5 1 1 1]
Delay	Low	trapezoidal	[0 0 0 0.05]
	Medium	triangular	[0 0.05 0.1]
	High	trapezoidal	[0.05 0.1 0.1 0.1]

1. Three parameters, a_1, a_2 and a_3, are used to specify a triangular MF as follows:

$$triangle(x; a_1, a_2, a_3) = \begin{cases} 0 & x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & a_1 \leq x \leq a_2 \\ \dfrac{a_3 - x}{a_3 - a_2} & a_2 \leq x \leq a_3 \\ 0 & a_3 \leq x \end{cases}, \quad (7)$$

Alternatively, this MF can also be expressed as below by using min and max

$$triangle(x; a_1, a_2, a_3, a_4) = \max\left(\min\left(\frac{x - a_1}{a_2 - a_1}, \frac{a_3 - x}{a_3 - a_2}\right), 0\right). \quad (8)$$

2. Three parameters, a_1,a_2,a_3 and a_4 are used to specify a trapezoidal MF as follows:

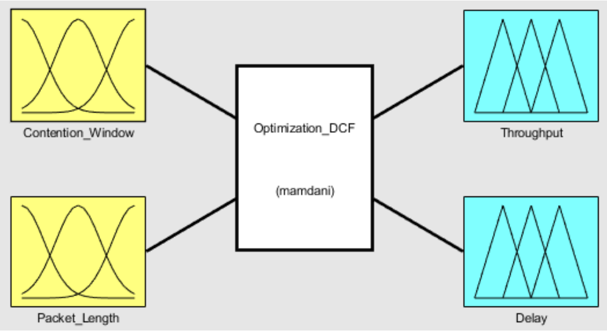
$$trapezoid(x; a_1, a_2, a_3, a_4) = \begin{cases} 0 & x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & a_1 \leq x \leq a_2 \\ 1 & a_2 \leq x \leq a_3 \\ \dfrac{a_4 - x}{a_4 - a_3} & a_3 \leq x \leq a_4 \\ 0 & a_3 \leq x \end{cases} \quad (9)$$

Similarly, MF can also be written as

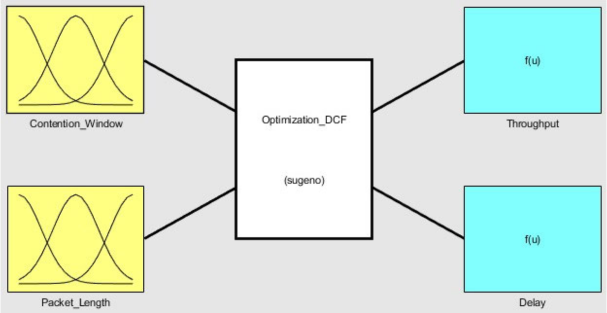
$$trapezoid(x; a_1, a_2, a_3, a_4) = \max\left(\min\left(\frac{x - a_1}{a_2 - a_1}, 1, \frac{a_4 - x}{a_4 - a_3}\right), 0\right). \quad (10)$$

The proposed Mamdani model is depicted in Fig. 5a, and the Sugeno fuzzy model is illustrated in Fig. 5b. Table 1 shows the proposed fuzzy sets for input and output parameters for Mamdani FIS, and their linguistic values are considered 'Low,' 'Medium,' and 'High.' The trapezoidal type membership function is evaluated for 'Low,' 'High,' and the triangular type membership function is considered for the 'Medium' linguistic values, shown in Fig. 6. Similarly, Table 2 shows the fuzzy sets for the Sugeno model.

Fig.7a attains the proposed 9 (3^2) rules with two input variables and three linguistic levels for the Mamdani technique



(a) Proposed Mamdani Model.

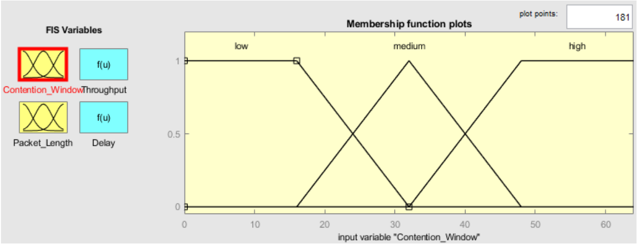


(b) Proposed Sugeno Model.

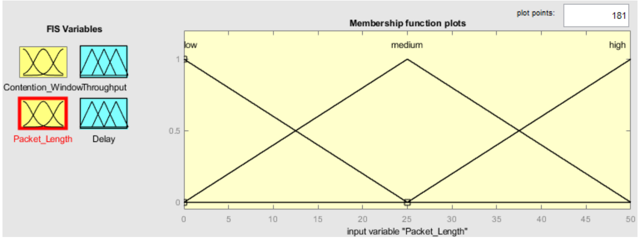
FIGURE 5. **Antecedent and consequent in fuzzy logic.**

TABLE 2. **Fuzzy sets for Sugeno FIS.**

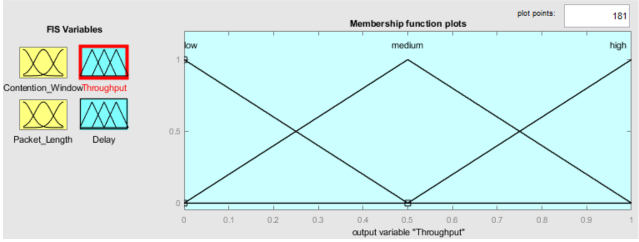
Linguistic Variables x	**Linguistic values**	**Membership function**	**Parameters** $[a_1, a_2, a_3, a_4]$
Contention Window	Low Medium High	trapezoidal triangular trapezoidal	[0 0 16 32] [16 32 48] [32 48 64 64]
Packet length	Low Medium High	trapezoidal triangular trapezoidal	[0 0 0 25] [0 25 50] [25 50 50 50]
Throughput	Low Medium High	Linear Linear Linear	[0 0 0.1633] [0 0 0.5] [0 0 0.8366]
Delay	Low Medium High	Linear Linear Linear	[0 0 0.01633] [0 0 0.05] [0 0 0.08366]



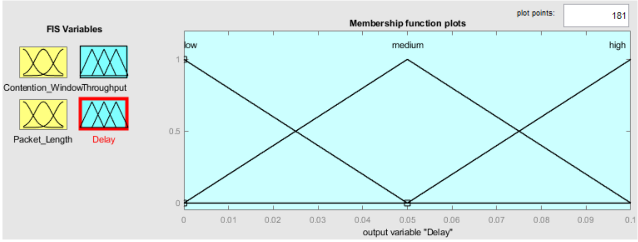
(a) Membership for Contention Window.



(b) Membership for Packet Length.



(c) Membership for Throughput.

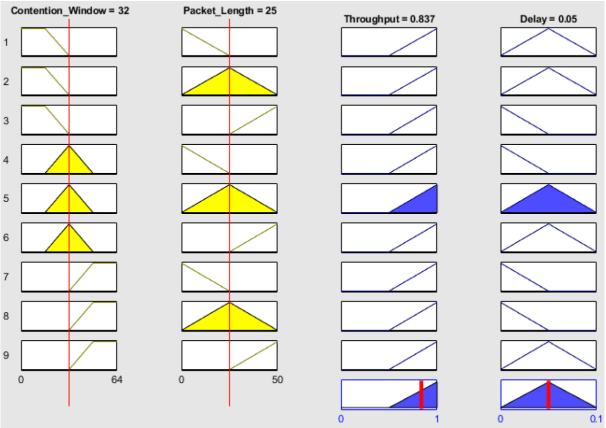


(d) Membership for Delay.

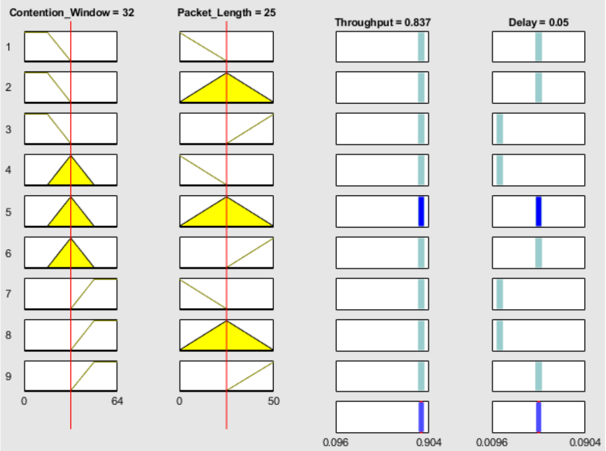
FIGURE 6. **Membership for antecedent and consequent.**

employing max(maximum), and min(minimize) approaches for constructing rules. In this approach, the fuzzy sets produced as the result of obtaining the most significant value of a rule are then used to change the fuzzy region and applied to the output using the OR operator (Union) to maximize the output variable throughput. Similarly, to minimize the output variable delay employed by the min(minimize) approach, which fuzzy set produced as the result of obtaining the minimum value of a rule is then used to change the fuzzy region and applied to the output using the 'AND' operator (intersection or conjunction). The first column shows the degree of membership of the antecedent, i.e., contention window $(X1) = 32$, followed by the remaining antecedent's packet length $(X2) = 25$ for the second column, and the consequent throughput is displayed in the third column. In contrast, the delay is provided in the fourth column for these conditions. From the first to the fifth, each column indicates the collective area of each fuzzy rule, which are the consequence of the fuzzy rule's structure. The centroid defuzzification methodology was the one that was employed with the Sugeno FIS model and results are displayed in Fig.7b. With a similar procedure, we can use defuzzification with Mamdani FIS except for the type of method i.e., in this case, a weighted sum approach is applied to the defuzzification in which consequents are represented as constant linear equations.

Fig. 8a and 8b show the surface results for Mamdani FIS for proposed antecedents and consequents under different rule-base conditions. Fig. 8a shows as the consequent parameter throughput goes to the greatest upward region and in Fig. 8b consequent parameter delay goes to the downward region. Similar findings are shown in Fig. 9a and 9b for Sugeno FIS for proposed antecedents and consequences under various rule-base conditions. Fig. 9a illustrates how the subsequent parameter throughput moves to the largest upward zone, whereas Fig. 9b illustrates how the subsequent parameter



(a) Fuzzy rule base for Mamdani FIS.

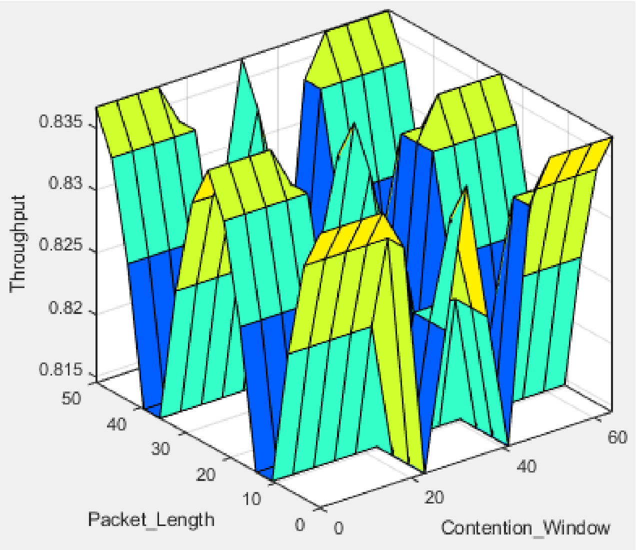


(b) Fuzzy rule base for Sugeno FIS.

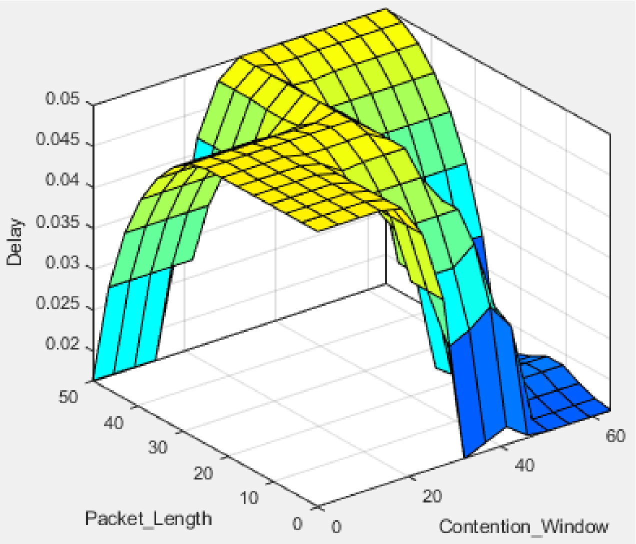
FIGURE 7. **Fuzzy rule base for antecedent and consequent.**

TABLE 3. **Simulation values.**

Parameters	Value
Number of Secondary users (N)	[1 5 10 15.....50]
Packet payload size	8184 $bits$
MAC header	272 $bits$
PHY header	128 $bits$
ACK	112 $bits + PHY header$
SIFS	10 μs
DIFS	50 μs
Slot Duration	20 μs
Channel bit rate	1 $Mbps$
Propagation delay	1 μs
PU ON time Exp($1/\lambda$)	50 ms
PU OFF time Exp($1/\beta$)	50 ms



(a) Surface results of throughput for the Mamdani model.

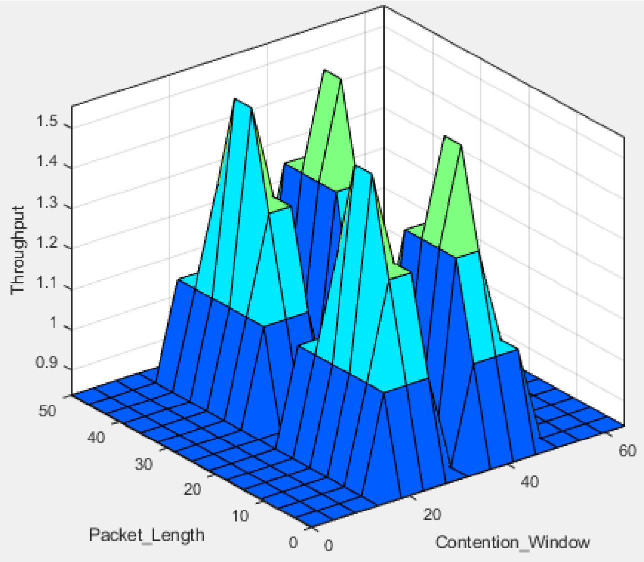


(b) Surface results of delay for the Mamdani model.

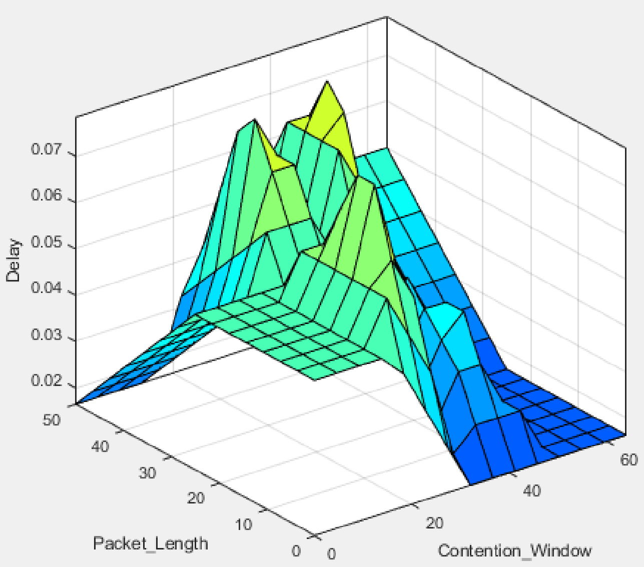
FIGURE 8. **Antecedent and consequent surface results for the Mamdani model.**

delay moves to the downward region. Here, the range of variation of CW (0, 64) slots, APL (0, 50) slots, throughput is (0, 1) and delay (0, 0.1) seconds.

To optimize the 802.11 (DCF) MAC protocol performance (simulation values are shown in Table 3) in CRAHNs, it should be required to consider the key parameters such as throughput and delay. For these parameters, the 802.11 random access type MAC protocol is already analyzed for conventional and small-scale wireless AdHoc wireless LANs in [21], [36]. It is widely known that contention window and packet length have a significant impact on the throughput and delay of any MAC protocol. Assuming the network system is stable, it is assumed that the anticipated network traffic is at its peak load and in saturation. We take into account the 802.11 (DCF) protocol and add it to our suggested CRAHN to assess the experiment's performance on MATLAB. Fig.10a shows the throughput-versus-CR-user relationship for various values of the contention window size. As per Fig.10a, if the number of CR users increases, throughput falls, however, as the contention window size expands, throughput rises. A fuzzy inference system is a tremendous tool for maximizing throughput, as evidenced by the FIS optimization results in Fig.10a, which are better compared to those obtained without the FIS at the same contention window size and which fluctuate between 0.35 and 0.75.

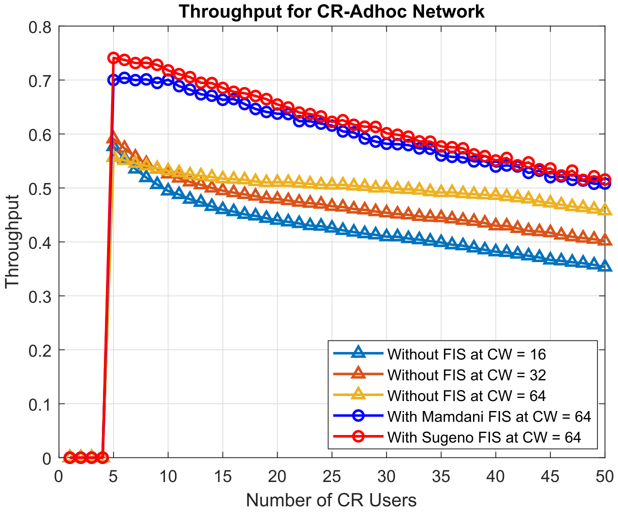


(a) Surface results of throughput for the Sugeno model.

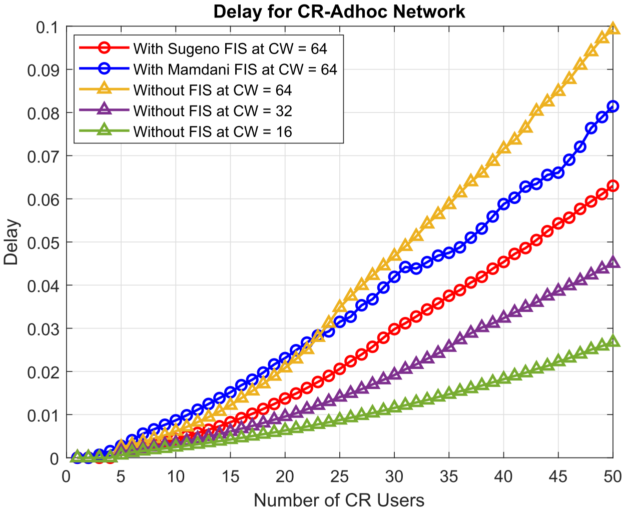


(b) Surface results of delay for the Sugeno model.

FIGURE 9. **Antecedent and consequent surface results for the Sugeno model.**



(a) Throughput on altering contention window.



(b) Delay on altering the contention window.

FIGURE 10. **Throughput and delay optimization on altering contention window.**

Since it is known that the delay should be as minimal as possible, we will turn our attention to its performance. Moreover, the delay which is also affected by the contention window and packet length depends on the total number of collisions and the successful time period. To do this, we will first incorporate the varying contention window, delay is constantly fluctuating between 0 and 0.1. Fig.10b demonstrates that it also increases in proportion to the expansion of the contention window. However, for promising wireless communication, it should be the minimum. This has been beneficially changed by training with the FIS on the contention window and packet length parameters of the chosen 802.11 (DCF) protocol. Fig.10 demonstrated that the delay has been decreased to 18 milliseconds (approximate) for the Mamdani model and to 38 milliseconds (approximate) for the Sugeno model at the contention window value 64. Moreover, with the throughput being maximized, it is seen that the delay is reduced at the same contention window value.

The 802.11 (DCF) protocol's throughput is depicted in Fig.11a, where throughput rises as packet length increases because more information is transmitted. But the packet length can only be increased to a certain limit, so the use of FIS is a great solution to maximize this further. The findings demonstrate that the throughput is raised about to 0. 05 bits per second with FIS. It also turns out that the Sugeno model produces better results that are consistent with fuzzy theories. Fig.11b demonstrates that it also increases in proportion to the expansion of the packet length (in slots). Here, the delay is reduced to the minimum length of the packet, which is achieved by comparing the same value without FIS. Additionally, Fig.11 reveals that the delay is decreased to

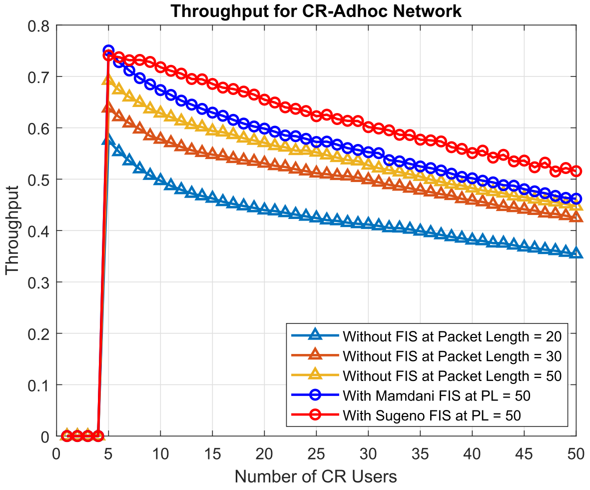
TABLE 4. Comparison to similar works.

Ref.	N/W type, Protocol & Technique Used	Connectivity	Comparision Parameters	Throughput Max. - Min.	Delay (in ms) Min.- Max.
[20]	WLAN, 802.11 (DCF) with Markov Chain Analysis	0 to 50 users were considered to be in contention	Varying CW 32 128	0.82 - 0.55 0.82 - 0.75	-
[21]	AdHoc N/W, 802.11 (DCF) with Markov Chain Analysis	0 to 50 users were considered to be in contention	Varying CW 64 32 16	0.82 - 0.68 0.80 - 0.63 0.75 - 0.58	80 - 1000 90 - 640 88 - 400
[34]	WLAN, 802.11 (DCF) with Fuzzy based ANOVA regression model	10 nodes are positioned symmetrically	Threshold Values 512 700 1024	776778 - 273626 (bps) 745790 - 274573 (bps) 728669 - 257925 (bps)	1.53 - 2.95 1.28 -2.79 1.5 - 2.5
Proposed Work	CRAHN 802.11 (DCF) with FIS based Mamdani and Sugeno Model	0 to 50 users were considered to be in contention	Varying CW Sugeno FIS 64 Mamdani FIS 64	0.75 - 0.50 0.70 - 0.50	0.002 - 0.08 0.002 - 0.064
			Varying CW 802.11 (DCF) 64 802.11 (DCF) 32 802.11 (DCF) 16	0.59 - 0.46 0.60 - 0.40 0.58 - 0.35	0.003 - 0.1 0.002 - 0.045 0.002 - 0.028
			Varying PL Sugeno FIS 50 Mamdani FIS 50	0.75 - 0.61 0.75 - 0.50	0.002 - 0.065 0.002 - 0.046
			Varying PL 802.11 (DCF) 50 802.11 (DCF) 30 802.11 (DCF) 20	0.70 - 0.49 0.65 - 0.45 0.58 - 0.35	0.003 - 0.1 0.002 - 0.036 0.002 - 0.029

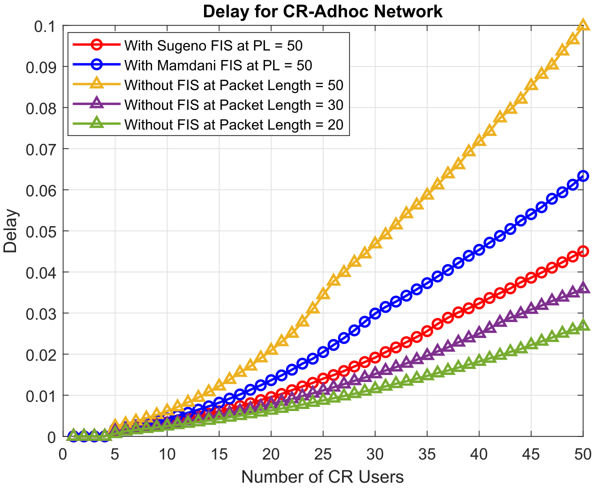
35 milliseconds (approximate) for the Mamdani model and to 54 milliseconds (approximate) for the Sugelo model at the packet length value 50. Additionally, with throughput being maximized, it is seen that the delay is reduced at the same packet length value.

Furthermore, for completeness, we provide a separate Table 4 containing the different network scenarios. Particularly, [20] has been focused on the throughput performance whereas [21] focused on both throughput and delay as shown in Table 4. These research works consider IEEE 802.11(DCF) as the primary MAC protocol for conventional wireless LAN and AdHoc networks with fifty contending users. Table 4 shows that [20] provides throughput analysis, varying from 0.55 (minimum value) to 0.82 (maximum value) for contention window sizes 32 and 128. In contrast, [21] provides throughput and delay analysis for contention window sizes (i.e., 16, 32, and 64), where throughput fluctuates from 0.58 to 0.82 and delay fluctuates from 88 to 1000 ms. Moreover, [35] enhances the performance of IEEE 802.11 (DCF) protocol by accomplishing fuzzy-based analysis with an ANOVA regression model for similar traditional protocol and network scenarios with ten contending nodes, as shown in Table 4. However, as per Table 4, the proposed CRAHN scenario with fifty CR contending users reveals that throughput has been reduced, whereas the delay is improved, as compared to [21]. Specifically, the throughput fluctuates from 0.35 to 0.59 with CW 16, 32, and 64, whereas with the variation of packet length 20, 30, and 50 slots, it fluctuates from 0.35 to 0.70. Note that delay performance has been improved and varies between 0.002 and 0.1 ms. Subsequently, the Mamdani and Sugeno FIS models are applied with CRAHN. As shown in Table 4 the proposed modification improved the throughput by 25% and reduced the delay by 38% for different contention window sizes. Moreover, by altering packet length, throughput is increased by 7%, and the delay is reduced by 40% to 50% as compared to the IEEE802.11 (DCF) for CRAHNs without FIS.

Conclusively, the proposed framework has improved the performance and delay of the CRAHN as compared to the existing networks.



(a) Throughput on altering the packet size.



(b) Delay on altering the packet size.

FIGURE 11. Throughput and delay optimization in altering packet size.

VI. CONCLUSION AND FUTURE SCOPE

Cognitive radios can play a vital role in future wireless communication, as well as in the efficient use of the available spectrum. However, cognitive radio wireless communication differs from ordinary wireless communication, where the trade-off increases the CW size and packet length of the 802.11 (DCF) MAC protocol for CRAHN which increases both throughput and delay. This work has improved the performance of the 802.11 protocol for CRAHNs using a fuzzy-based approach as revealed by the proposed algorithm. Specifically, altering the contention window increases throughput by 25% and reduces the contention window by 38%. Additionally, as a result of altering the packet length, the throughput has improved by 7% and the delay has been reduced by 40% to 50%. In future work, the performance of physical layer spectrum sensing, and machine learning applications can be used with the same parameters of this protocol, and the QoS of the 802.11 protocol can be further improved.

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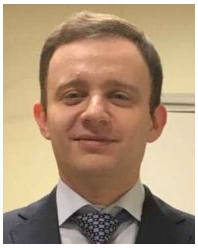

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