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CFFD-MAC: A Hybrid MAC for Collision Free Full-Duplex Communication in Wireless Ad-Hoc Networks

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ABSTRACT Infrastructure-less (sometimes known as ad-hoc) networking paradigm is very appealing and potentially shaping its future into almost all emerging networks (i.e., IoT, wireless sensor networks, vehicular ad-hoc networks, emergency, and tactical radio networks, etc.). However, when conventional networking protocols are used, such networks often perform poorly, mainly because of interference within the network and limited network throughput. Recent advancements in wireless communications have enabled full-duplex (FD) operation by suppressing self-interference, which can theoretically double the network throughput. However, conventional medium access control (MAC) protocols like carrier-sense multiple access with collision avoidance (CSMA/CA) favor half-duplex (HD) operation and fail to benefit from FD transmission opportunities. This article proposes a novel hybrid MAC protocol for full-duplex ad-hoc networks. The proposed MAC combines time division multiple access (TDMA) and IEEE 802.11 distributed coordination function (DCF) strengths in chains of time-slotted contention-based control frames and collision-free data frames. The aim is to fully utilize FD transmission opportunities to increase network throughput. The proposed protocol modifies request-to-send (RTS) and clear-to-send (CTS) frames in IEEE 802.11 DCF MAC to form FD-RTS/CTS frames. These frames are used to enable collision-free FD communications among neighbors. The proposed scheme mitigates conventional MAC issues like hidden-node problem (HNP) and exposed-node problem (ENP). It also allows concurrent FD data transmissions in a collision-free manner. The model is generic and can be applied to any ad-hoc wireless network. In this article, the design is applied to a single channel ad-hoc network with FD transceivers. We compared the proposed design with IEEE 802.11 CSMA/CA protocol with both HD and FD transceivers. The simulation results show a 30% gain in throughput, reduced latency, and fairness among participating wireless nodes.

INDEX TERMS Ad-hoc networks, collision-free, full-duplex, medium-access-control, RTS/CTS, wireless networks.

I. INTRODUCTION

The emerging requirement of pervasive wireless communications is resulting in the fast evolution of ad-hoc networks. Today, we witness ad-hoc networks shaping into the internet of things, wireless sensor networks, vehicular ad-hoc networks, emergency, tactical radio networks, etc. Increased data rate and reduced latency appear to be the desiderata of all such networks. Serious efforts are being made on both physical and data link layers to achieve these goals. Improvement in transceiver design is one such example. At present, most of the nodes use conventional half-duplex (HD) transceivers to either transmit or receive data. However, these transceivers have fundamental design constraints and reduce potential network throughput. The modern communication systems overcome HD shortcomings by employing full-duplex (FD) wireless transmission opportunities over a single channel [1], [2].

In FD wireless networks, the receiver can perform concomitant transmissions, including bi-directional, simultaneous, and relayed communication between nodes e.g. bi-directional: ($N_i \leftrightarrow N_j$), simultaneous: ($N_i \rightarrow N_j$),

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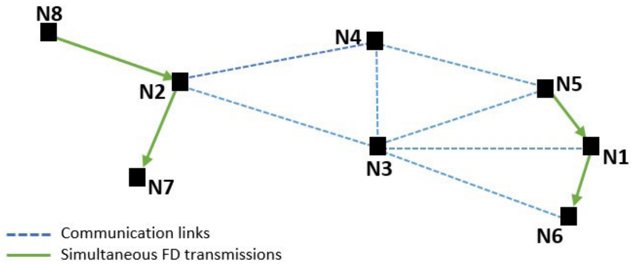

FIGURE 1. Full-duplex and simultaneous transmissions in a wireless ad-hoc network.

$(N_j \rightarrow N_k)$ and relayed: $(N_i \rightarrow N_j \rightarrow N_k)$ transmissions, where N_i, N_j and N_k are node Ids. However, these transmissions are only possible when communicating pairs have no neighbors transmitting at the same time. The relayed and simultaneous transmissions scenario is shown in Fig. 1 where node N_2 acts as a relay node for the data flow from source node N_8 to destination node N_7. In simultaneous transmission node N_5 sends data to node N_1, which can transmit its data to node N_6. The provision is possible only if nodes N_2 and N_1 operate as full-duplex nodes. These two communications can be performed simultaneously without causing a collision on any network node under the same interference domain because the receiving nodes can perform self-interference cancellation on the received signal. Likewise, if two nodes intend for bi-directional communication, then there can be a concurrent data transmission between the nodes with full-duplex transceivers. These transmissions are not possible when communicating nodes operate in half-duplex. The scenario in Fig. 2 shows collisions at nodes N_1, N_2, N_4 and N_6 when node N_3 sends data to node N_4. The collisions happen because suffering nodes overhear node N_3 transmission, which collides with their own pair nodes' transmission. In this case, no interference cancellation is performed by half-duplex nodes on the received signal, resulting in collisions. These collisions refer to the hidden-node problem (HNP), which frequently occurs in wireless ad-hoc networks.

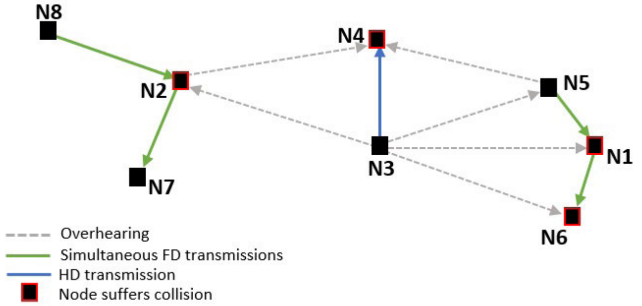

FIGURE 2. Collisions and transmission interference in a wireless ad-hoc network.

The integration of FD transmission with reducing the above highlighted collisions can provide many benefits such as reduced control overhead, spatial channel reuse, and faster throughput gain. Recent advancements in FD transceiver design unfold many communication possibilities. The signal processing based self-interference (SI) cancellation schemes have a significant contribution to canceling self-interference [3]–[6], caused by concurrent transmission and reception of the transceiver's own leaked transmission [7], [8]. The designs can provide 85dB cancellation but still leave considerable SI. The significant contribution in FD design is proposed to achieve 110dB of cancellation for 802.11 transceivers [9]. The main objective behind the advancement is to double the channel capacity, compared to HD communication [10]–[15]. This theoretical assumption is explored by many medium access control (MAC) protocols that have been critically investigated in favor of FD communication [16], [17]. The study opens many challenges including capacity gain, conventional HNP, and multiple access collisions.

Several MAC layer protocols use the combination of fixed or on-demand channel assignment protocols with random access techniques to deal with the above challenges. Hybrid time division multiple access (TDMA) and carrier sense multiple access (CSMA) based protocols make the schemes more robust to failures, variable channel conditions, and topology dynamics. Many TDMA based protocols [18], [19] are proposed but failed in addressing the modern network requirements. The schemes proposed by [20], [21] failed in providing an optimal solution and reduce reliability in terms of a higher number of collision and retransmission rate. However, the physical carrier sensing based designs such as CSMA make the channel access dynamic and provide immediate data transmission but decrease the system throughput due to collisions and longer backoff periods [22]–[24]. The problem further becomes complicated when nodes in close connectivity intend to participate in FD transmissions. The prevalence of multiple access collisions wastes channel capacity and reduces bandwidth utilization by missing many possible transmission opportunities.

This paper presents a novel collision-free full-duplex (CFFD) MAC protocol based on distributed coordination function (DCF). The design distinctively blends TDMA with the IEEE 802.11 channel access mechanism with modest changes to incorporate full-duplex operation. These changes include the segregation of contention-based control and reservation-based data slots. Control slots use modified RTS/CTS frames named FD-RTS/CTS (FD-request-to-send/clear-to-send). IEEE 802.11 RTS/CTS frames only deal with hidden-node problem, while sometimes causing exposed-node problem (ENP). Whereas, the designed FD-RTS/CTS frames also enable FD transmissions and perform guaranteed reservation of data slots. Changes in TDMA involve the use of the initial random backoff timer during control slots. Since the design applies collision avoidance before sending the packet on the channel, it considerably reduces the number of collisions that preserves channel capacity for data transmission. The retransmission limit keeps the contention window size small and adds fairness among nodes during channel access.

A. RESEARCH CONTRIBUTIONS

Recent research demonstrates the efficient use of full-duplex radios in wireless networks, focuses on collision resolution methods, and uses a centralized approach to establish FD communication among nodes [22], [25]. The proposed work is first to consider initial channel access collisions and enable opportunistic FD transmissions in non-contention based data slots in ad-hoc wireless networks. The design yields significant research contributions. It provides:

1) Random medium access using contention over control slots and no contention in data slots for distributed environment.
2) The use of control frames (FD-RTS/CTS) reduces control messages overhead and enables FD transmissions in a collision-free manner, which results in increased network throughput.
3) Virtual carrier sensing using control frames that eliminates HNP and opportunistic transmission agreements in the control phase mitigate ENP using time-slotted communication.
4) Minimum number of collisions and helps to restrict the contention window to smaller values.

II. RELATED WORK

The potential benefits of FD radios are achieved through various MAC designs. Many protocols are proposed in recent years that explore FD transmissions over a single channel [26]. A MAC protocol is proposed by [27] to solve the problem of channel inefficiency in the FD environment. The scheme uses a secondary backoff mechanism to enable more transmissions depending on the difference in up-link and down-link transmission time. A method is proposed by [28], which modifies the MAC sub-layer of communication node protocols. The system allows nodes to communicate in FD mode over a single frequency. The timing of simultaneous transmissions, acknowledgments, and waiting periods are determined using network allocation vectors in association with RTS and CTS frames. An FD MAC protocol for single-hop networks is proposed by [29], which detects collisions in a network, prevents long timed channel occupancy, and provides FD transmission possibilities. The protocol uses CSMA/CA mechanism to contend for channel access and improves system throughput compared to conventional CSMA/CA protocol in HD networks. An analytical FD framework for IEEE 802.11 is proposed by [30], which explores various ways to reduce packet collisions and increases throughput in Wi-Fi systems. A distributed cooperative MAC design is proposed by [31] which is based on the statistical probability of the channel gains. Cooperative nodes relay the sender packets according to their cooperation capability. The method guarantees earlier channel access for nodes with higher cooperation capability and reduces collision probability.

Many hybrid approaches are also used to enable FD transmissions. A hybrid HD/FD-MAC is proposed by [32] in which a two-fold RTS/CTS contention resolution mechanism is used to exploit channel access opportunities provided by simultaneous downlink and uplink transmissions. The protocol involves an access point to decide the probability to construct FD transmissions and considers the spectrum efficiency in the process. An asymmetric (AFD-MAC) protocol is proposed by [33], which provides random backoff and carrier sensing. It uses two signals to exploit the FD capability of an access point and captures the difference in statistical properties of nodes and access point. AFD-MAC increases throughput and reduces head-of-the line delay compared to conventional 802.11 HD-MAC protocol. AMAC protocol for full-duplex radios is proposed by [34] in which FD downlink station uses acknowledgment frame to report its buffer status to access point. The protocol uses an access point to establish the FD link without contention. An optimal resource allocation scheme for vehicular networks is proposed in [35], which exploits spectral efficiency of FD communication to handle reliability constraints of vehicle-to-vehicle (V2V) links and high-capacity demand of vehicle-to-infrastructure (V2I) links. It also proposes a hybrid HD/FD scheme that provides high-performance gain.

Furthermore, recent work highlights the benefits of full-duplex communication in the domain of VANETs. An investigation to utilize long term evolution (LTE) technology for vehicle-to-vehicle communication is exploited in [36]. The study introduces a novel analytical framework that incorporates full-duplex radios and evaluates the reduction in occupancy of resources for the beaconing service using LTE. A study focused on vehicular visible light networks (VVLNs) is presented in [37], focuses on vehicular visible light networks (VVLNs) and proposed a MAC design to enable FD capabilities of LEDs at receiving nodes to send immediate response after message decoding. The proposed design shows less collisions and reliable delivery by adopting FD characteristics. The design implications of FD devices at upper-layer protocols of next generation vehicular networks are studied in [38], by considering the imperfect self-interference cancellation.

All schemes mentioned above emphasize getting FD transmissions. However, very few of the existing techniques succeed in achieving noticeable throughput gain without increasing the control overhead. In comparison, the proposed CFFD-MAC enables FD transmissions with minimum control overhead and succeeds in achieving evident throughput gains in a distributed manner. The designed scheme has no intervention of access points and gains effectual access over medium with collision-free contention approach, comprehensively discussed in the next section. Further, none of the existing approaches worked on the rational reservation of data slots for non-contention based full-duplex data transmissions.

The design uses no distinct signaling to enable FD transmissions and makes it possible for every node to transmit in HD and FD modes. It uses virtual carrier sensing, which mitigates the issue of decentralized data slot reservations and accomplishes primary FD MAC layer design considerations.

The qualitative comparison with recent research is enlisted in the results section further to clarify the value differences of the designed approach.

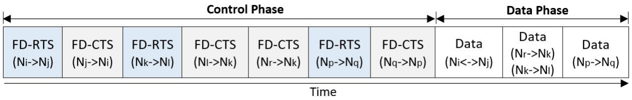

FIGURE 3. **TDMA frame for control and data messages.**

III. CFFD-MAC DESIGN METHODOLOGY

A. SYSTEM MODEL

The proposed hybrid MAC design uses TDMA and IEEE 802.11 DCF virtual carrier sensing mechanism with modified RTS/CTS frames. We consider the system is divided into two phases (i) control and (ii) data phase as shown in Fig. 3. Each phase operates over time slots of a fixed size TDMA frame in which each slot is of a few hundred microseconds (μs). The total time for a TDMA frame is defined in (1) where node i contends to send control frame C_i to access time slot(s) t_s in control phase and sends data message D_i in time slot t_s in the data phase. The control frame C_i can be either FD-RTS or FD-CTS frame, for which the duration of a control slot is DIFS_time + FD-RTS/CTS transmission time.

$$\sum_{i=1}^{C} C_i \times t_s + \sum_{d=1}^{D} D_d \times t_s \tag{1}$$

The nodes contend for the control slot using a virtual carrier sensing mechanism, making the access over time slots dynamic for nodes and restricting slot wastage. It is unlike static TDMA in which each node has a fixed slot to transmit its data.

For virtual carrier sensing and to find opportunistic FD transmissions, FD-RTS and FD-CTS frames are used. Formats of the frames are shown in Fig. 4, and description of frames fields and their size are listed in Table 1. FD-RTS frame is used to send request towards the destination and ask neighbors if anyone has data for the requesting node. In response to FD-RTS, the destination node sends FD-CTS with ‘0’ in its A/O[1] field, and neighbors send the frame with ‘1’ in A/O field if have data for the requesting node. These control frames help to find one-hop FD transmission possibilities and are used to decide data slots for pairing nodes to communicate. The frames also restrict neighbors from using conflicted data slots and decide the time slots of the data phase to send and receive data. The information regarding data slots is incorporated in FD-RTS/CTS frames, which overcomes collisions faced in FD and HD transmissions.

B. INITIAL RANDOM BACK-OFF TIME

For sending control frames, the system uses a random counter to restrict initial collisions, resulting in bandwidth wastage. At the initial step, each node chooses a waiting timer (known as “backoff timer”) for each control frame it has to send. The timer is chosen randomly in the interval [0,CW], where CW is the contention window and initially set to the minimum value: $CW = CW_{min} - 1$. This timer is decremented if the channel is found idle for distributed interframe space (DIFS) interval. When the counter reaches zero, after DIFS time the source sends FD-RTS frame towards the destination. The sender’s neighbors also hear and process FD-RTS message. Afterward, the source node waits for the FD-CTS frame from the destination node or any other neighbor(s). Upon receiving FD-RTS frame, destination transmits FD-CTS message after short inter-frame space (SIFS) interval as shown in Fig. 5. It is done to get immediate CTS after sending the request message. If the receiving node is not the destination but has data for the source node, then the node sets its FD-CTS timer to $RND\_time - DIFS\_time$ to prioritize other FD-RTS transmissions. The benefit of setting neighbor FD-CTS timer larger than SIFS_time is to avoid collision between destination and neighbor(s) FD-CTS messages. There is a possibility of having many FD-CTS messages from different neighbors against one FD-RTS packet. These messages contend for the time slot depending on the timer value. This timer value is less than the DIFS_time and is different from other neighbors due to the random timer selected upon message arrival in the node’s queue. If a node fails to contend for the current slot, it uses the remaining timer to contend for the next control slot. When the source node receives multiple FD-CTS frames over the control phase, it schedules slots for one FD communication, as discussed in section I.

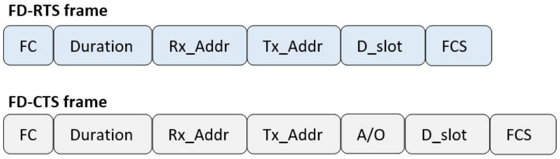

FIGURE 4. **CFFD-MAC control frames format.**

TABLE 1. **Description of control frame fields.**

Symbol	Parameters	Field Size (bytes)
FC	Frame control	2
Duration	Data frame transmission time	2
Tx_Addr	Address of transmitter	6
Rx_Addr	Address of receiver	6
A/O	Actual/ Opportunistic transmission	1 (bit)
D_slot	Data slot	1
FCS	Frame Check Sequence	4

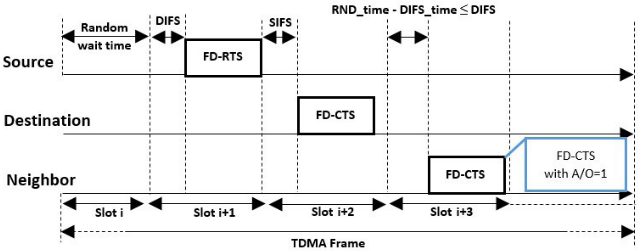

FIGURE 5. **Control frames transmission in CFFD-MAC design.**

[1] A/O =0/1 1-bit field for opportunistic transmission

In many cases, most FD-CTS frames get the chance to be transmitted after the destination's FD-CTS frame as these frames have a small random timer than the next FD-RTS frame. The number of FD-CTS frames does not affect the control slot's duration but depends on the available control slots, which are fixed in numbers in a TDMA frame.

However, after sending FD-RTS, a node may not receive FD-CTS from the receiver in response due to the collision. In this case, the contention window size gets doubled ($CW = [2 * CW_{min}]$) and the node participates for contention in the succeeding slot of the same TDMA frame. If the channel is idle, it waits for the $DIFS\_time + backofftime$ and retransmits the packet.

Conversely, for successful FD-RTS transmission, the source node keeps the current CW value and chooses a new timer upon new message arrival. The use of FD-RTS/CTS frames decreases control messages overhead as each node asks its neighbors in FD-RTS to acknowledge if they have data for it. The detailed discussion over decision of data slots for transmission using these control frames is discussed in the next section. The workflow of the proposed scheme is depicted in Fig. 6. The light blue colored dotted boxes show the modules which are part of conventional IEEE 802.11, whereas light gray colored boxes identify the modules use in CFFD-MAC design.

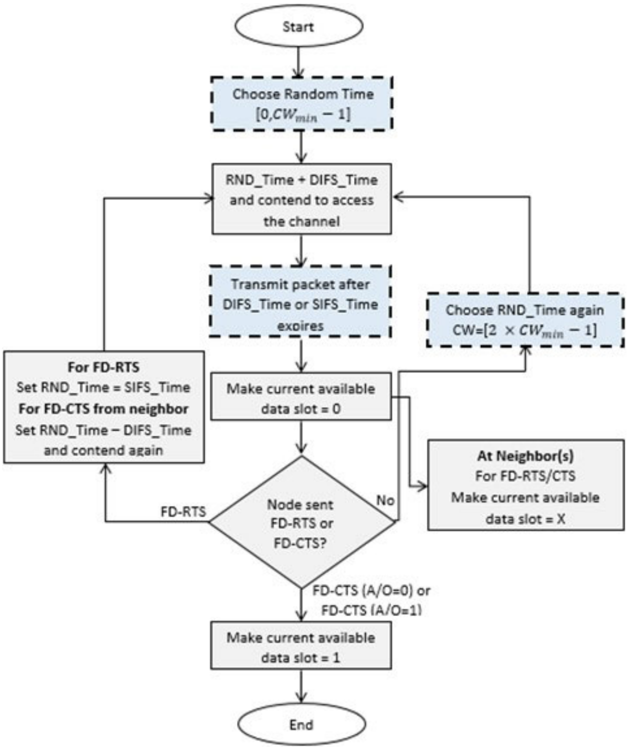

FIGURE 6. **Workflow of proposed CFFD-MAC design.**

The time slotting approach in the proposed technique makes the channel access better for nodes, especially in the data phase, and increases the network's goodput. The contention over slots usually adds up delays but makes the system dynamic. There are fewer control messages in our proposed design, which can provide more transmission opportunities and decrease contention delays by assigning a random time value to each sender packet. The contention-based slots agreements make the message exchange collision-free for multiple node pairs. The combination of time slotting and FD node discovery make the design stand out in terms of achieving higher capacity gain as compared to other CSMA based or hybrid MAC protocols.

The idea to assign random backoff time to every packet upon its arrival is to reduce the number of collisions, affecting system throughput. The random time is of few microseconds so, it merely adds delay on packet transmission time.

C. A FINITE STATE MACHINE FOR CONTROL PHASE OF CFFD-MAC DESIGN

To implement and precisely analyze the working of the proposed CFFD-MAC design for the control phase duration, we use a finite state machine (FSM). The MAC design defines the set of states, events, conditions, and actions required to operate FSM. The FSM is generally in WAIT STATE until an event is invoked to start the state transition process.

For FSM execution, we suppose that n number of nodes contend for a time slot at the start of the control phase to send FD-RTS frame. Fig. 7 shows that initially, the FSM is in WAIT STATE when a node has nothing in its queue. It transits to the CONTEND STATE upon arrival of the FD-RTS packet in the queue. Once the packet arrives in the node's queue, an event of *select_RND_time* occurs and the node selects a random time $r(t)$ for the FD-RTS packet and waits the time $w(t) = r(t) + DIFS\_time$. The node contends for the slot by waiting for the $w(t)$ to expire. Upon the expiration of $w(t)$, the FSM transits to the SEND STATE, where the node transmits the FD-RTS packet towards the receiver and marks its current available data slot as '1'. Upon successful transmission, the FSM goes into the RESPONSE WAIT STATE, where the node waits for the FD-CTS packet from the receiver or its neighbor(s) for opportunistic transmission (e.g., $A/O = 0$ or 1). When FSM performs the *Received_FD-CTS* event, it transits to the initial WAIT STATE, where the node may have an FD-RTS packet for any other node.

The FSM also deals with an event *collision_packet* and can transit to the COLLISION STATE from RESPONSE WAIT STATE when there is another transmission on the channel and collision occurs. This happens because the node has not received any FD-CTS from the receiver during the wait time. The random time $r'(t)$ (by increase in backoff stage) is selected at this state and the FSM transits to the CONTEND STATE. The same process is repeated for an FD-RTS packet till the retransmission limit. The rest of the state transition diagram can be interpreted in a similar manner.

1) CONTROL PACKET TRANSMISSION PROBABILITY

The control packet transmission probability for CFFD-MAC design is described using the model presented in [22]. Suppose $r(t)$ be the stochastic process and represents the random

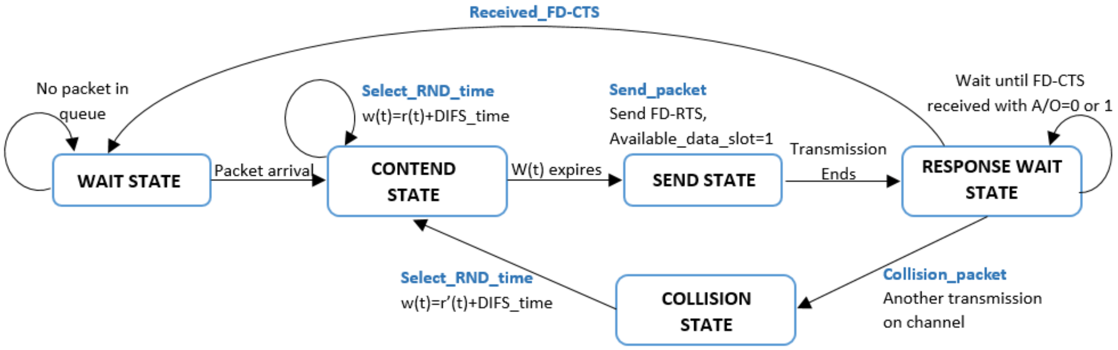

FIGURE 7. Finite state machine for the control packet transmission.

backoff timer for a given FD-RTS frame of a node. At each node, the value of random backoff timer depends on the preceding transmissions of the suffered frame except the first random backoff value independent of any transmission history and makes $r(t)$ non-markovian.

In the designed scheme, we consider the backoff time events from the arrival of new messages instead of after collisions. Therefore, each node gets a random backoff time for the FD-RTS frame upon its arrival at the node's queue from a range $[0, CW_{min} - 1]$. After random time selection, each node defers accessing the channel till the expiration of backoff time and further waits for DIFS_time before sending FD-RTS towards a destination. The nodes wait for the time before sending the FD-RTS frame in their contention state. The wait time is represented by $w(t)$, which is also a stochastic process and for initial backoff stage 0, it is described as $w_0(t)$ in (2). The DIFS_time is added at each backoff time and decreases at the beginning of the time slot.

$$w_0(t) = r(t) + DIFS\_time \tag{2}$$

The design embraces a similar random backoff mechanism of IEEE 802.11 with modified RTS/CTS frames to reduce the initial number of collisions. Therefore, we use the same packet transition probabilities presented in [22], with the changes to limit unsuccessful transmissions to maximum backoff stage s and assign random backoff time to FD-RTS frame on its arrival in the node's queue, identified as backoff stage 0. The state transition probability is defined in (3), where, $l\epsilon(0, CW_x - 2), x\epsilon(0, s)$. It accounts for the fact that the backoff time is decremented at the beginning of each time slot as long as the counter has not reached equal to zero.

$$p\{x, l|x, l+1\} = 1 \tag{3}$$

The transition of states for collisions of a frame are associated with conditional collision probability p and is defined in (4), where $l\epsilon(0, CW_0 - 1)$ and $x\epsilon(0, s)$.

$$p\{0, l|x, 0\} = (1-p)/CW_0 \tag{4}$$

A successful packet transmission starts with backoff stage 0, where the node already has FD-RTS in its queue upon waiting for the time, defined in (2). When an unsuccessful transmission occurs at the backoff stage $x - 1$, the backoff stage increases and the new backoff value is uniformly chosen in the range $[0, CW_x]$, as described in (5).

$$w_x(t) = r(t)' + DIFS\_time \tag{5}$$

The probability for the transmission is defined in (6), where $l\epsilon(0, CW_x - 1)$ and $x\epsilon(1, s)$. Once the backoff stage reaches to s (i.e., s = 3) it is not increased in subsequent packet transmission, defined in (7), where $l\epsilon(0, CW_s - 1)$.

$$p\{x, l|x-1, 0\} = p/CW_x \tag{6}$$

$$p\{s, l|s, 0\} = p/CW_s \tag{7}$$

In the proposed design, we set the CW to double the size of CW_{min} whenever an FD-RTS frame gets into a collision. The size of CW grows large exponentially with the number of collisions. However, the larger CW can reduce collisions but adds delays in data sending. To deal with this, we set the limit on the number of retransmissions (s = 3) to add fairness among node transmissions (suggested in IEEE Network RFC1042). After this, the message will be discarded or deleted from the node's queue and must be regenerated with a new random time chosen from the range $[0, CW_{min} - 1]$. The solution for the system along with its derivation, is already proven in [22] and hence not fused in this paper.

D. TRANSMISSION AGREEMENTS AND DATA SLOTS RESERVATION

In CFFD-MAC design, slot reservation for data sending is made in a distributed manner by keeping it fair and collision-free. The proposed design performs dynamic slot reservation using FD-RTS and FD-CTS control frames to which both sender and receiver agree. These control frames are exchanged during the control time slots of the TDMA frame. The technique makes different node pairs to communicate independently within the same data slot, provided they do not disturb or interfere with each other's or any other node's reception.

For protocol description, we consider a network of five nodes (N_1, N_2, N_3, N_4 and N_5). Each node has ten small control slots and five data slots for transmission agreements and data sending, respectively. Fig. 8 depicts the process in

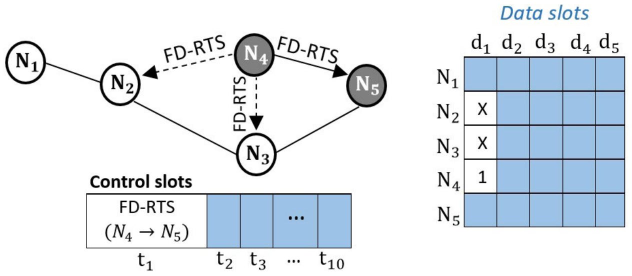

FIGURE 8. Transmission of FD-RTS and slot reservation at node N_4.

which node N_4 sends FD-RTS frame to node N_5 in time slot t_1 of control slots. The FD-RTS frame of node N_4 is overheard by its one hop neighbors N_2 and N_3. At the time of FD-RTS transmission, node N_4 marks its first available data slot d_1 to '1'[2]. The assumption is made here that the nodes which overhear FD-RTS message will mark their current available slot as 'X' [3] and on this slot, no neighbor can transmit and receive data. The FD-RTS frame is used to keep neighbors deferred in the data slot and asks them for an opportunistic transmission if any of the neighbors have data for the FD-RTS sender.

When node N_5 receives FD-RTS from node N_4, it also marks its current available data slot as '1' and sends FD-CTS frame with its reserved slot mentioned in it and asks node N_4 to mark the same data slot as '1'. This FD-CTS frame from node N_5 acknowledges the agreement and asks node N_4 to mark the same data slot. In this case, node N_4 marks the same slot as of N_5 and keeps the slot reservation unchanged, as shown in Fig. 9.

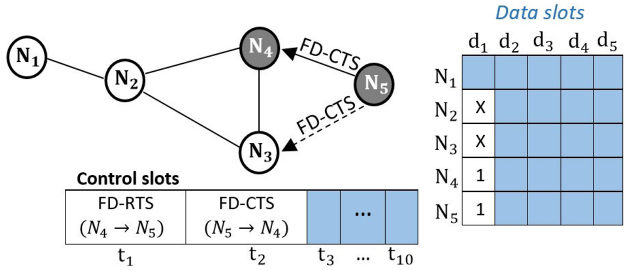

FIGURE 9. Transmission of FD-CTS and slot reservation at node N_4 and N_5.

The data slot information propagates in FD-CTS frame has more preference over FD-RTS. The slot information is not upright on all one-hop neighbors of transmitter and receiver because those who listen FD-RTS may not listen FD-CTS. Therefore, the scenario creates conventional MAC issues such as hidden and exposed node problems.

The data slot information in FD-CTS does not solve the problem completely. In first agreement, nodes N_2 and N_3 mark data slot d_1 as 'X' when N_4 sends FD-RTS frame to N_5. Now, at time slot t_3 node N_3 sends FD-RTS to node N_5 and marks its data slot d_2 to '1'. With FD-RTS transmission N_3 forces its neighbors N_4 and N_2 to mark their current unmarked slot d_2 as 'X'. When node N_4 overhears FD-RTS from N_3, it marks the data slot as 'X' but N_2 makes its data slot $d_2 =$ '0' because it has data for N_3, as shown in Fig. 10.

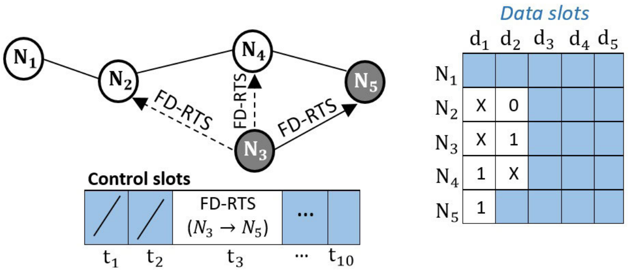

FIGURE 10. Transmission of FD-RTS and slot reservation at node N_3.

Now, two nodes N_2 and N_5 have FD-CTS to send towards node N_3 for opportunistic and actual (A/O) data transmissions respectively. For control slot t_4 both nodes will contend as we assume that each node sends FD-CTS frame right after the reception of FD-RTS, and its defer time to access the channel is just SIFS_time which is less than DIFS_time. Whereas, for opportunistic transmissions, the defer time for node N_2 has come down from random backoff time $r(t)$ to $r(t) - DIFS\_time$. We use the approach as node N_2 did not have to send FD-RTS and should get time slot right after the actual FD-CTS of node N_5 in order to achieve simultaneous transmissions. So, in control slot t_4, node N_5 gets the chance to send FD-CTS towards N_3, as shown in Fig. 11. It confirms data slot d_2 for data reception and makes its neighbor N_4 to mark data slot d_2 as 'X' which is already marked because N_4 is common neighbor of nodes N_3 and N_5.

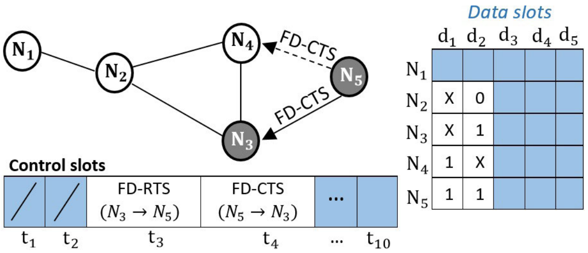

FIGURE 11. FD-CTS transmission of N_5 and slot reservation.

Afterwards, at data slot d_5 node N_2 sends FD-CTS with A/O = '1' in the frame field and makes its data slot d_2 from '0' to '1', which results in FD transmissions $(N_2 \rightarrow N_3), (N_3 \rightarrow N_5)$, as shown in Fig. 12. The transmission makes the first available data slot $d_1 =$ 'X' at node N_1 which is neighbor of N_2.

As we discussed above, slot reservation made in FD-CTS has priority over slot reservation made during FD-RTS. Suppose another node N_6 is the neighbor of only node N_1 and did not mark any of its data slot yet. Let us suppose that node N_1 has data for node N_6 and sends FD-RTS at time slot t_6

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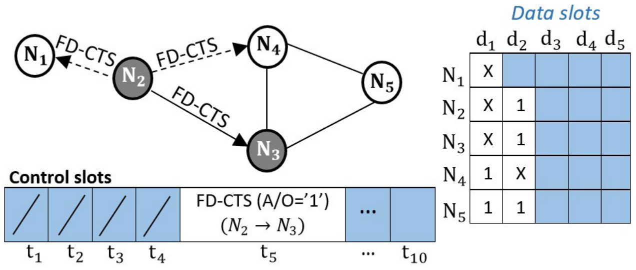
[2] 1= Reserved

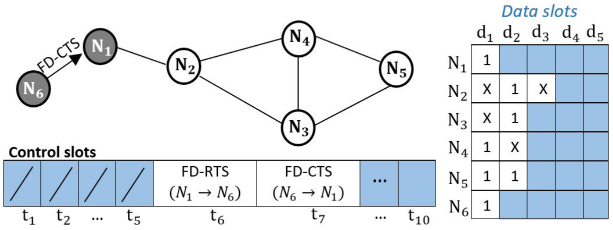
[3] X= N/A (Not Available)



	d1	d2	d3	d4	d5
N1	X				
N2	X	1			
N3	X	1			
N4	1	X			
N5	1	1			

FIGURE 12. FD-CTS of N_2 for opportunistic FD transmission and slot reservation.

towards it and asks node N_2 to make its slot unavailable for any transmission, which is d_3. Node N_6 replies with FD-CTS and informs N_1 about its selected data slot d_1. In this case, N_1 will change status of data slot d_1 from 'X' to '1', as shown in Fig. 13. Now, at data slot d_1, ($N_1 \rightarrow N_6$) and ($N_4 \rightarrow N_5$) transmissions can occur simultaneously without disrupting each other's transmissions. The transmission ($N_1 \rightarrow N_6$) can also be performed in data slot d_2. Therefore, the design restricts schedules most possible transmissions in fewer data slots, which positively impacts the network throughput.



	d1	d2	d3	d4	d5
N1	1				
N2	X	1	X		
N3	X	1			
N4	1	X			
N5	1	1			
N6	1				

FIGURE 13. FD-CTS transmission of N_6 and slot reservation.

There is another case with agreed nodes pair if a neighbor asks a node to change its data slot from '1' to 'X', the node will not change the status of the data slot as it has agreed with other node on this slot. There is no possibility to inform the node of the change except by sending one more message or cancel the agreement. Algorithm 1 explains the backoff mechanism and process of slot reservation in CFFD-MAC design.

The CFFD-MAC design provides many FD communication possibilities, increases network throughput, and overcomes contention delays, which are already less than contention periods of conventional MAC designs. The design can also handle HD communication smoothly in the data phase by assigning the same slots to multiple node pairs having no collision in them. However, for only HD transceivers, the design will need more contention slots as each node will send control frames for each message, which are less in number when using for FD transmissions.

Algorithm 1 CFFD-MAC Protocol

```
Notation:
1. Node $N_i$ has $k$ neighbors where $(N_i, N_j) \epsilon L$
2. Nodes start contending over $\tau_{ctrl\_slots}$
3. On packet arrival, node gets random time $R_i$ from range $[0, CW_{min} - 1]$
4. $N_i$ = Source, $N_j$ = Destination, $N_k$ = Neighbor
procedure Control Phase
    for each integer $i$ in $N$ do
        if $Ni$ has Packet then
            $wait\_time \leftarrow R(i) + DIFS\_time$
            After $wait\_time$ Send
            $FD - RTS(N_i \rightarrow N_j)$ or $FD - CTS\ (N_j \rightarrow N_i) \parallel FD - CTS\ (N_k \rightarrow N_i)$
        end if
        if there is collision then
            $CW = 2 * CW\_min$
            $N_i$ gets random back-off value
            $wait\_time = RND[0, CW - 1]$
        else
            Complete transmission
        end if
        if $N_j$ receives $FD - RTS(N_i \rightarrow N_j)$ then
            $Available\_data\_slot \leftarrow 1$
            Send $FD - CTS(N_j \rightarrow N_i)$
            with $(A/O = 0, Reserved\_data\_slot)$
        end if
        if $N_k$ receives $FD - RTS(N_i \rightarrow N_j$ then
            Make $current\_available\_data\_slot \leftarrow X$
        end if
        if $(N_i$ receives $FD - CTS(N_j||N_k \rightarrow N_i)$ then
            $data\_slot(FD - CTS(Available\_slot) \leftarrow 1)$
        else
            leave the slot empty
        end if
    end for
end procedure
// End of control phase
procedure Data Phase
    for each integer $i$ in data_slot do
        if $\tau data\_slot(i) == 1$ then
            Ready to TX or RX
        end if
        if $\tau data\_slot(i) == 0 \parallel \tau data\_slot(i) == X$ then
            Remain Silent or no TX/RX
        end if
    end for
end procedure
```

IV. RESULTS AND DISCUSSION

In this section, the CFFD-MAC design performance is tested over different sets of topologies for which nodes are deployed randomly. The experimental analysis of the initial random backoff mechanism and extensive simulations for the proposed design is performed in OMNET++5.4.1 with INET framework 4.6.0 to analyze the designed protocol's behavior for different performance metrics in ideal channel conditions.

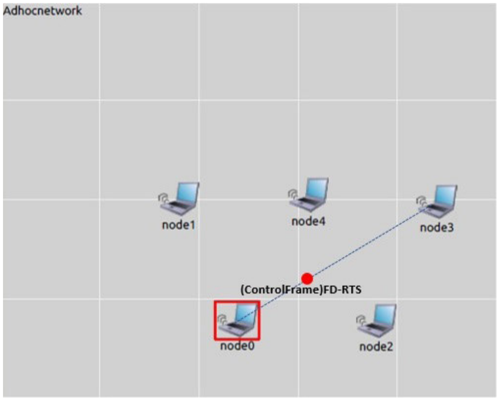


FIGURE 14. FD-RTS transmission from node0 to node3.

A. DESIGN FEASIBILITY

To prove the design feasibility, we consider a network scenario, consisting of five (05) nodes (node0; node1; node2; node3 and node4). For instance, in Fig. 14, node0 wants to send data to node3 and sends FD-RTS frame. The transmission of control frames is overheard by its neighbors, restricting them from transmitting in their corresponding data slot. In return, node3 reserves its current available data slot and sends FD-CTS towards node0 ascertaining the actual transmission by A/O = '0', shown in Fig. 15.

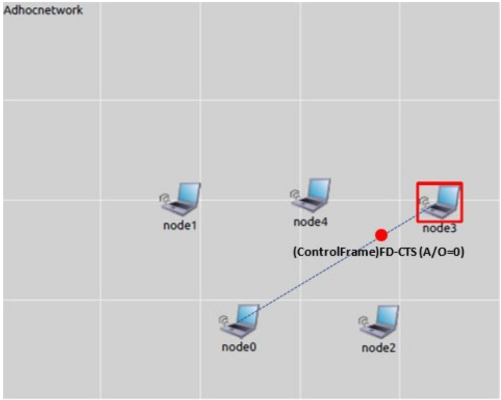


FIGURE 15. FD-CTS for actual transmission from node3 to node0.

After few control slots, node2 makes an agreement with another node and is overheard by node3. Let us suppose node3 has data for node2, and to schedule its opportunistic data transmission, it sends FD-CTS to node2 with A/O = '1', which is shown in Fig. 16. Likewise, in many scenarios with larger number of nodes, opportunistic transmission possibilities reduce control overhead, and overall time necessary for communicating data decreases.

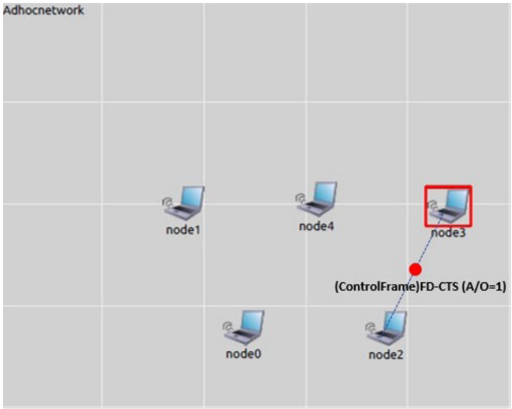


FIGURE 16. FD-CTS for opportunistic transmission from node3 to node2.

TABLE 2. Data slots reservation of N = 10 for HD and FD transmissions.

Node ID	d_1	d_2	d_3	d_4	d_5
node1	X	X	X	0	0
node2	0	X	X	0	0
node3	X	X	X	0	0
node4	1	X	1	X	0
node5	1	X	0	X	0
node6	X	1	X	X	0
node7	X	1	X	1	0
node8	0	1	X	0	0
node9	1	1	X	0	0
node10	X	X	1	1	0

$$d_1 = 5 \rightarrow 9, 9 \rightarrow 4$$
$$d_2 = 8 \rightarrow 7, 6 \rightarrow 9$$

The CFFD-MAC design ensures no collision within data slots and provides both HD and FD transmission opportunities. To analyze that, we simulated the protocol for 10 and 15 node networks and found FD and HD transmissions over a single data slot. It is shown in Table 2 where node5 can send data to node9, which can transmit to node4 simultaneously in data slot d_1. There is also HD communication in data slot d_2 where both pairs (node8,node7), (node6,node9) can communicate without having collision between them. While in Table 3, at data slot d_2, node5 and node13 both can transmit data to each other in FD mode by agreeing within same contention slot, which is not possible in CSMA/CA technique with HD transceivers.

TABLE 3. Data slots reservation of N = 15 for HD and FD transmissions.

Node ID	d_1	d_2	d_3	d_4	d_5
node1	X	X	X	X	X
node2	1	0	0	0	0
node3	X	X	0	0	0
node4	X	X	X	1	0
node5	X	1	X	0	0
node6	1	1	1	X	0
node7	X	X	X	X	0
node8	1	0	0	0	0
node9	1	X	X	0	0
node10	X	X	X	0	0
node11	X	1	X	X	0
node12	X	X	X	X	0
node13	X	1	X	0	0
node14	X	X	X	1	0
node15	0	0	0	0	0

$$d_1 = 9 \rightarrow 6, 8 \rightarrow 2$$
$$d_2 = 11 \rightarrow 6, 5 \iff 13$$

The results show that multiple collision-free data transmissions over single data slot increase throughput and slot utilization, which can be further improved when two disjoint nodes send FD-RTS/CTS in the same time slot of the control phase.

TABLE 4. Qualitative comparison of CFFD-MAC with other FD-MAC protocols.

Protocols with References	Application Area	Comments
A new collision resolution approach using full-duplex radios [2]	Wireless LAN	The design uses collision decoding to decode another transmitter's frame by canceling self-interference. The Station tells AP about the transmission of other stations in its data packet. AP offers transmission opportunity to that station by sending CTS. This way, the protocol reduces control messages overhead and collisions. It demands two stations not to be hidden from each other to detect collisions. CFFD-MAC design uses a pure distributed approach and does not depend on the decoding of collided packets, which may not be received by a node due to HNP or ENP, frequently occur in wireless networks. The proposed scheme can schedule multiple transmissions against a FD-RTS frame without transmitting any added information in control frames.
Opportunistic MAC for FD communication [27]	Wireless LAN	The scheme proposed minimal changes in IEEE 802.11 control frames (RTS/modified CTS). It uses secondary back off mechanism to enable transmission using transmission times. It relies on a central node to handle FD transmissions. Whereas in CFFD-MAC, nodes schedule their transmissions in distributed manner without having any central coordination among nodes. Also, our design uses initial random back-off time which reduces collision probability.
Full-duplex MAC using RTS signaling [28]	Wireless communication networks	The system modifies MAC sub-layer protocol for FD mode and supports HD communication. It uses RTS/CTS frames to coordinate data transmissions and ACKs. Interframe spaces are used to control channel access while ignores initial collisions when all nodes start sending RTS at once after DIFS time. Whereas in CFFD-MAC design, we use initial random backoff time and IEEE 802.11 DCF mechanism to avoid collisions. It also uses time slotting to transmit data as well as control signals.
Full-duplex MAC protocol based on CSMA/CA [29]	Single-hop wireless networks	The design detects collisions in network, prevents long timed channel occupancy using a cut-through mechanism, and provides FD transmission possibilities. It uses CSMA/CA mechanism to contend for channel access, which involves initial transmission that delays arises due to collisions and reduced in CFFD-MAC design that favors both FD and HD transmissions.
Distributed cooperative MAC with relay collision avoidance [31]	Wireless ad-hoc networks	The design is based on statistical probability of the channel gains, and cooperative nodes relay the sender's packets according to their cooperative capability. These cooperative nodes are selected through a selection phase, which increases protocol execution time. The design calculates access waiting time by using statistical distribution probability based on channel gains. The CFFD-MAC focuses on reducing initial collisions hence does not have to perform extensive statistical probability calculations.
Hybrid scheduling in heterogeneous HD and FD networks [39]	Infrastructure based Wireless Networks	The paper focuses on the design of scheduling algorithm for heterogeneous HD and FD users. It uses a greedy scheduling algorithm and combines it with a queue based random access mechanism. The design achieves better delay performance and improves fairness between HD and FD users. In the comparison of it, our CFFD-MAC design provides a full featured MAC design that schedules both HD and FD transmissions without using any heuristic-based approach and performs non-contention based data transmission.

B. COMPARISON OF CFFD-MAC WITH OTHER FD-MAC PROTOCOLS

1) QUALITATIVE COMPARISON

The FD-MAC designs presented in the literature are mostly based on CSMA/CA or IEEE 802.11 DCF mechanism. Most of them exchange too much information specified in RTS/CTS frames, which increases the control overhead. The collision avoidance mechanism to control initial collisions remains ignored, and the dependence is on inter-frame spaces (IFS). Table 4 provides a qualitative comparison of CFFD-MAC with other state of the art MAC protocols over a set of parameters such as control overhead, collision avoidance mechanism, and dynamic slot scheduling.

2) QUANTITATIVE COMPARISON

We performed simulation of CFFD-MAC design for 5, 10, 15, 30, and 50 nodes with simulation parameters, listed in Table 5. The results and analysis show that the proposed design gets better throughput gain on all network topologies in finding FD communication possibilities and transmitting data in a collision-free manner. The reservation of data slots during contention in the control phase allows simultaneous transmissions within the same data slot. Although the control phase puts little overhead on the network, time slotting and chaining control/data phases reduce it.

TABLE 5. Simulation parameters for CFFD-MAC protocol.

Parameters	Value
Number of nodes	5, 10, 15, 30, 50
Network area	400 X 400 meter
Transmission range	200 meter
Traffic direction	Bidirectional
Packet length	1000 Bytes
Frame length	2 ms
Number of slots	10 (Control), 5 (Data)
CW_{min}	15 μs
Data rate	11 Mbps
Slot time	15 μs (control), 727 μs (Data)
DIFS_time	0.1 μs
SIFS_time	0.05 μs
Retransmission limit	3

Following performance parameters are measured to see the effectiveness of the proposed scheme. CSMA/CA MAC protocol with both HD and FD transceivers is used as a benchmark solution. In the case of HD transceivers, we consider the classical CSMA/CA with DCF mechanism

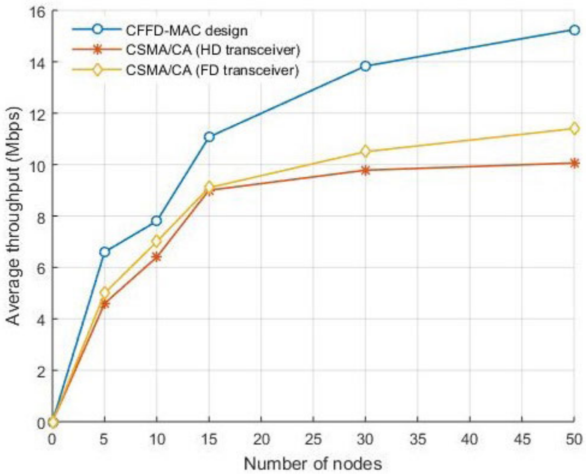


FIGURE 17. **Average throughput compared with CSMA/CA (HD and FD transceiver).**

in which each transmission agreement consumes two control slots in the control phase. Whereas CSMA/CA design with FD transceivers works the same as it works with HD transceiver. The difference is that a node can send an RTS frame and receive corresponding CTS message of previous RTS within the same slot, provided no collision occurs in both transmissions. There is no such assumption made like opportunistic CTS transmissions, and each transmitter expects the CTS of its own RTS message from the receiver of every intended communication.

3) THROUGHPUT

The scheme achieves a throughput of 6.5Mbps, 7.8Mbps, 11Mbps, 13.9Mbps, and 15Mbps for networks comprising 5, 10, 15, 30, and 50 nodes, respectively in comparison with CSMA/CA (HD and FD transceivers) as shown in Fig. 17. It provides a 30% gain when having more FD transmissions. In CSMA/CA, the throughput gain is always less due to initial collisions and long backoff delays. However, CFFD-MAC controls initial collisions and set retransmission limits in order to add fairness among transmitters.

In a fewer number of nodes, the collisions are restricted. Hence throughput starts increasing with an increase in the number of nodes and retains to a fixed value, after reaching certain number of contending nodes/data rate. It sometimes even decreases due to packet retransmissions. In CSMA/CA (HD transceiver), the throughput curve starts flattening when the network size reaches beyond 30 nodes. Fig. 17 shows the saturation point of CSMA/CA occurs much earlier than the CFFD-MAC and is susceptible to a decrease in throughput with an increase in the number of nodes due to packet collisions. Further, the rise in throughput is proportional to the increase in packet size due to reduced normalized control overhead [40]. For performance comparison, we considered the same packet size in CFFD-MAC and CSMA/CA (HD and FD transceivers); hence the change in packet size will have the same impact on throughput for all protocols. As shown in Fig. 17, the throughput of the designed scheme is about to converge to a certain point, after which it may start decreasing with an increase in the number of nodes.

Usually, in HD communication, the use of FD-RTS for opportunistic transmissions has no significance because each node can either transmit or receive and needs more control slots to get data slots, which increases delay so do the control and data cycles.

The analysis over throughput gain shows that the theoretical claim of doubling the throughput in FD communication is not possible in real-time networks due to interference, collisions, and contention delays. However, FD MAC protocols can still yield much higher throughput than conventional CSMA/CA.

4) TIME SLOTS AND CHANNEL UTILIZATION

Firstly, we compute the utilization in terms of time slots, which defines the number of time slots (Control + data) consumed by design to send control frames and data packets. To evaluate the use of time slots, we compare the design with time-slotted CSMA/CA with both HD and FD transceivers. The three curves in Fig. 18 show the consumption of time slots by CFFD-MAC and slotted CSMA/CA (HD and FD transceivers) protocols. The time slot utilization in all three fluctuates due to the number of TDMA frames required to incorporate all network transmissions. For example, in a network of 10 and 15 nodes, three (03) TDMA frames were required to complete all agreements included data transmissions. On the other hand, CSMA/CA (with HD transceiver) used only two (02) TDMA frames and almost all data slots for data transmissions. It happened because in CFFD-MAC, we incorporated opportunistic transmissions by sending only FD-CTS frames that do not require FD-RTS. Hence the control slots serve not only FD-RTS/CTS frames but also the FD-CTS for opportunistic transmissions, accommodate many data transmissions within few data slots.

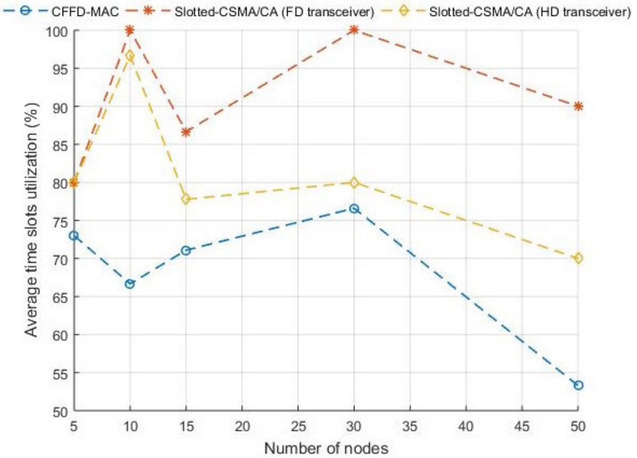


FIGURE 18. **Average time slot utilization in CFFD-MAC compares with CSMA/CA.**

In consideration of slots utilization, CSMA/CA consumes more time slots than CFFD-MAC because we consider that for HD transceivers, two (02) time slots are required to send RTS/CTS frames. With FD transceivers, no polling in RTS for opportunistic transmissions is considered. Irrespective of this consideration, CSMA/CA with FD transceiver still uses less control slots than HD transceivers due to the simultaneous transmissions scheduled in single data slots. Therefore, the analysis proves that our proposed design consumes few control slots for more data transmissions. The TDMA frame size of 15 time slots (control slots = 10, data slots = 5) can manage the collisions if few time slots are wasted, or in case of no collisions, a small TDMA frame size can accommodate more transmissions.

The channel utilization of the CFFD-MAC design is much better than CSMA/CA, as nodes can send multiple messages over a single data slot. The contention over slots allows improving performance when the offered load differs. The proposed technique may get underutilized if there are few successful contentions on the control slot or due to the size of the contention window. There might be a possibility of having idle slots, or two nodes could start transmitting at the same time and repeatedly collide, which is the ideal case as suffered nodes doubles their contention window on every collision.

5) CONTROL OVERHEAD

CFFD-MAC design consumes few control frames to schedule more data transmissions. To analyze the control overhead of the proposed scheme, we calculate the number of frames/bits sent to enable single data transmission and compare it with the CSMA/CA protocol. Fig. 19 shows the number of frames required for FD transmissions in a single time slot. We assume bi-directional or relayed FD transmissions to evaluate the control overhead for 1 to 5 FD transmissions schedule in a single time slot.

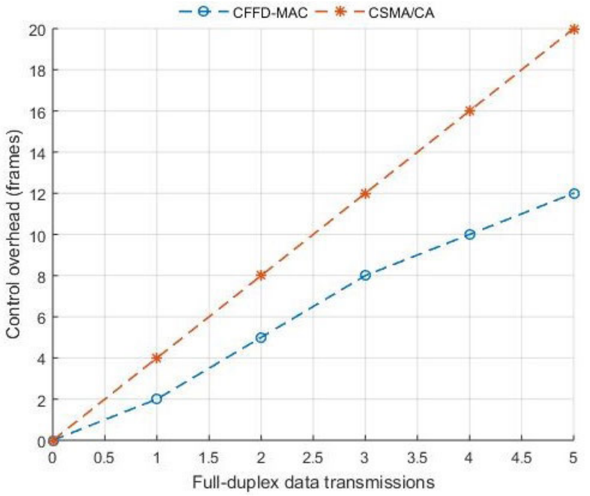


FIGURE 19. Control overhead as a function of FD transmissions compares with CSMA/CA.

The analysis shows that the proposed design uses fewer control frames to schedule FD transmission as compared to CSMA/CA because in CFFD-MAC, the number of FD-RTS frames are equal to the total FD transmissions in a slot, whereas FD-CTS depends on the FD transmission possibility. For instance, in bi-directional transmission, one FD-RTS and one FD-CTS frame are needed but for relayed transmission, one FD-RTS and two FD-CTS frames are required. In comparison, CSMA/CA consumes more control frames than the proposed scheme and the curves show the linear behavior where with an increase in transmissions control frames also increase. It happens because each data transmission schedules by using two control frames, RTS and CTS.

The above analysis represents transmissions for only a single time slot, but if we consider transmissions in all data slots, the control overhead will reduce more. The size of control frames FD-RTS and FD-CTS also play a significant role in deciding the duration of a time slot. These frames use limited control information, unlike other protocols, which usually incorporate data slots and other statistical information [28], [30].

6) LATENCY

The proposed CFFD-MAC design has low latency compared to CSMA/CA, as shown in Fig. 20. It happens for two reasons. First, in conventional CSMA/CA protocol, every data transmission follows a sequence of backoff, RTS/CTS, and actual data transmission. Backoff timers add significant delays to data transmissions, increasing exponentially with collisions. FD-RTS frame in CFFD-MAC eliminates the need for backoff and RTS transmission for many data packets. This not only results in smaller end-to-end delays but also minimizes collisions. Second, FD transmissions in the data phase enable sending more data packets in a smaller number of data slots. As a result, CFFD-MAC offers noticeably reduced latency to the participating nodes.

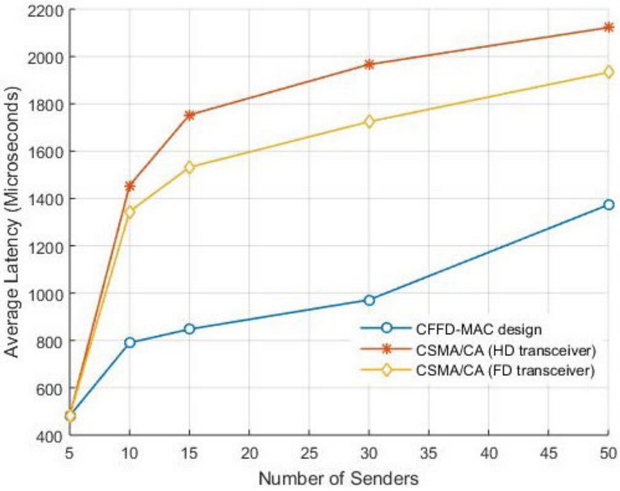


FIGURE 20. Average latency in CFFD-MAC as compared to CSMA/CA.

The results show marginally low average latency than CSMA/CA due to the transmission opportunities in a control phase. This improvement in latency reduction is experienced more when there is an increase in the number of nodes that utilize opportunistic transmissions using FD-CTS control frames. Hence, few control frames schedule more transmissions, which significantly impacts delay in data transmissions.

In performance comparison for dense networks such as urban VANETs, eradicating the RTS/CTS mechanism from CSMA/CA can reduce the latency for some transmissions. However, it increases the number of collisions as the network will face conventional MAC issues and start behaving like aloha [41], [42]. In multi-hop ad-hoc networks, packets usually traverse multiple hops to reach their intended destinations, which further proliferates collision probability. These collisions not only result in increased contention window size but also triggers retransmissions. As a result, average latency further increases for dense networks.

7) FAIRNESS

The technique fulfills the expectation of having fairness among nodes in terms of sending messages. We computed fairness in terms of latency for how long a node must wait for the reply of the request message. The latency values also show that each node gets an equal opportunity to transmit control messages. Most of the nodes transmit messages with an average latency of 1373μsec and a standard deviation of 853.43μsec, which is less than 1074.35μsec in CSMA/CA, shown in Fig. 21. However, nodes using an opportunistic FD transmission option occasionally get priority, but the initial random timer and contention over control slots keep the fairness intact. Each sender can send a message thrice upon collision and allows new or other nodes to contend. If we use the proposed design for only HD transmissions, the fairness will be the same as CSMA as each node gets an immediate reply to the request, but the focus is more on FD transmissions. The design fulfills the fairness criteria required for any MAC protocol design.

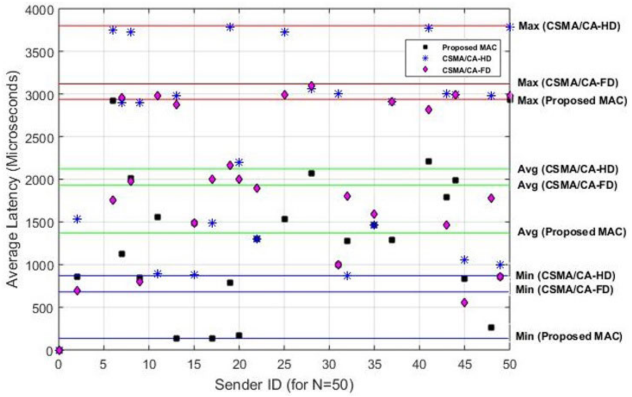


FIGURE 21. Fairness among nodes in terms of average latency for N = 50.

The technique also fulfills the criteria of getting FD-CTS immediately after sending FD-RTS frame within 0.05μs (SIFS_time). On average every FD-RTS gets its FD-CTS within zero slot duration while FD-CTS of opportunistic transmission in one slot. The backoff time and inter-frame delays are somehow affect the system performance, but multiple cycles of control and data phases reduce them.

The packet delivery ratio for the system is closed to 100% because the network load and throughput are almost equal. The proposed design considers no interference and propagation delays, affecting the delivery ratio and results in packet retransmission. The retransmission is only considered in case of collisions. There is a possibility that control or data slots get wasted when there is more than one collision or no node wins the contention for the data slot.

The proposed CFFD-MAC protocol's strength lies in enabling conflict-free FD transmissions. It results in noticeable throughput gain, cutback in average latency requirement for transmitting the same amount of data, and reduction in normalized control overhead needed to transmit the same amount of data as conventional CSMA/CA-based networks. As a result, a larger node density with relatively higher data needs can be supported by the proposed protocol. Moreover, the proposed design is generic and can be tuned for any network specification.

V. CONCLUSION AND FUTURE WORK

A. CONCLUSION

The main objective of the proposed CFFD-MAC design is to improve network throughput by discovering full-duplex transmission opportunities in modern wireless networks. To do so, we proposed a time-slotted contention-based MAC design in which nodes randomly access the medium with low control overhead. Upon agreements, nodes transmit data within non-contention based data slots in a collision-free manner. The design used virtual carrier sensing to discover FD nodes and make decisions on data slots. The results showed significant performance improvement compared to IEEE 802.11 CSMA/CA enabled for HD and FD capabilities. We simulated the design on generalized ad-hoc networks for proof of concept and achieved a 30% gain in throughput, reduced latency, and fairness among participating wireless nodes.

B. FUTURE WORK AND RECOMMENDATIONS

The significant design optimization can extend the design for multi-channel networks. Few techniques have been proposed to exploit full-duplex multi-channel communication [43]–[45]. The proposed technique eliminates the control channel to improve spectral efficiency, lacks in focusing channel access method. Most of the work is limited to channel hopping, which is important in a multi-channel environment but lacks in discovering FD transmission opportunities with dynamic channel access.

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