



Cooperative NOMA for Throughput Enhancement of IEEE 802.11 WLANs: Channel Access Design and Performance Analysis

Jomon K. Charly , and V. P. Harigovindan , *Senior Member, IEEE*

Abstract—In this research work, we propose cooperative non-orthogonal multiple access (CNOMA) based IEEE 802.11 wireless local area network (WLAN) and design a novel channel access scheme for CNOMA based WLAN. The proposed scheme integrates the resource efficiency of NOMA with cooperative relaying technique to enhance the throughput performance. In this scheme, stations (STAs) in the nearer regions act as the relay nodes for the STAs farther from the access point (AP). The novel channel access scheme forms clusters by selecting STAs from the various data rate regions and allows nearest region nodes (cluster heads) alone to take part in the contention. This scheme also includes a procedure to select helper nodes from the high data rate regions. Additionally, we present an accurate analytical model for calculating the throughput of CNOMA based WLANs. Analytical and simulation results demonstrate that the proposed approach can significantly enhance the throughput performance of NOMA based WLANs.

Link to graphical and video abstracts, and to code:
<https://latam.ieee9.org/index.php/transactions/article/view/10318>

Index Terms—Cooperative communication, NOMA, CNOMA, Wi-Fi, WLAN

I. INTRODUCTION

WLANs provide significant advantages over wired networks because of their flexibility and convenience. The most popular and widely deployed WLAN is Wi-Fi, which is standardised as IEEE 802.11. Wi-Fi is found in a wide range of devices, from smartphones to various consumer electronics. The number of devices in WLANs is increasing day by day. Wi-Fi uses the distributed coordination function (DCF), in which devices in the network can initiate transmission of a frame if the channel is idle. The DCF is based on carrier-sense multiple access with collision avoidance (CSMA/CA) [1]. In this channel access mechanism, each device will check the channel prior to transmission; if the channel is sensed busy, the node will wait, and if the channel is free, then the node will initiate transmission. To control repeated collisions, IEEE 802.11 uses a binary exponential backoff in which the contention window (CW_{\min}) doubles after each collision [2] up to the maximum backoff stage (m). If the number of retransmissions exceeds the retry limit (L), the packet is dropped. When the number of devices increases, the

throughput will decline, due to higher collisions among packet transmissions by nodes [3].

Wi-Fi works in the industrial, scientific, and medical (ISM) band and has limited spectrum resources. It has higher chances of interference due to this unlicensed band of operation, compared to its wired counterparts. In a Wi-Fi basic service set (BSS), nodes can receive interference from the nodes in other BSS or even from other wireless technologies which use the same frequency bands [4]. The radio waves transmitting in WLANs are subjected to propagation losses, which will reduce the received signal strength. The propagation loss experienced by the radio signal also increases with increase in distance from the AP [5]. The effects of radio signal degradation in WLANs will reduce the overall network throughput. Conventional WLANs employ multiple-input multiple-output (MIMO) systems to perform antenna beamforming, which helps to cancel interference and direct beams towards intended nodes. However, the added hardware complexity of MIMO is not always suitable for nodes in WLANs, particularly handheld and compact devices. Cooperative communication leverages transmitted signals overheard by neighboring nodes to enhance the network performance, allowing near nodes in the network to serve as a relay for nodes located farther from the AP [6]. This can significantly enhance the reliability performance of WLANs.

In a BSS, stations (STAs) near the AP can transmit at a higher data rate compared to STAs far from the access point due to the propagation losses of the radio signal. Based on the achievable data rate, each STA is adapted to different modulation and coding schemes (MCS). The nearby STAs receive higher MCS indices, allowing them to transmit at higher data rates, whereas the farther STAs receive lower MCS indices and therefore achieve lower data rates [7]. These low-rate STAs can significantly reduce the aggregate throughput performance of the network. This is due to the fact that slow stations will take more time to transmit a frame compared to high data rate stations near the AP [8]. Cooperative WLAN can resolve this performance anomaly present in conventional WLANs by utilizing high data rate STAs as relays to forward the data from low data rate STAs. In this way, data from a low data rate station can transmit at high data rates with an additional overhead [6].

Wireless networks use different multiple access techniques to share network resources among several nodes simultaneously. There are two major categories of multiple-access techniques: orthogonal multiple-access techniques (OMA)

The associate editor coordinating the review of this manuscript and approving it for publication was Roberto S. Murphy (*Corresponding author: V. P. Harigovindan*).

J. K. Charly, and V. P. Harigovindan are with the Department of ECE, National Institute of Technology Puducherry, Karaikal, India (e-mails: jomonkcharly1992@gmail.com, and hari@nitpy.ac.in).

and non-orthogonal multiple-access techniques (NOMA) [9]. OMA techniques use different resource blocks for each user, and the orthogonality principle is utilised to isolate each transmission efficiently. Orthogonal frequency division multiple access (OFDMA) is a representative example of OMA and has been widely adopted in IEEE 802.11 WLANs. It continues to serve as the multiple-access technique in the latest amendment, IEEE 802.11bn (Wi-Fi 8) [10]. Compared to OMA schemes, NOMA schemes provide efficient utilisation of spectral resources by supporting parallel transmissions of multiple users. There are mainly two types of NOMA: power domain NOMA and code domain NOMA. Power domain NOMA simultaneously supports the transmission of multiple users by differentiating them with different power levels. At the transmitter side, information signals from multiple stations can be superimposed and transmitted in a single radio channel. At the receiver, successive interference cancellation (SIC) can be utilised to separate the information received from multiple users [11], [12]. While our earlier work [13] studied NOMA-based channel access for WLANs, this work extends it by integrating cooperative relaying, resulting in further performance gains.

In contrast to earlier research, we present a CNOMA-based channel access mechanism for IEEE 802.11 WLANs. In this scheme, users located closer to the AP act as relays for distant users, thereby improving overall network performance. In a CNOMA-based WLAN, data transmission is carried out in two phases. In the first phase, far users identify suitable idle nodes located near the AP to serve as relays and forward their data to these helper nodes. This phase exhibits similarity to peer-to-peer (P2P) communication, as data is exchanged directly between far users and their helper nodes after successful channel sensing and appropriate control signaling [14]. However, unlike conventional P2P systems, the relay selection and transmission process in the proposed scheme is facilitated by the AP and is specifically designed to enable cooperative NOMA operation. In the second phase, relay nodes and near users simultaneously transmit their uplink data to the AP, where SIC is employed to decode the superimposed signals. The remainder of the paper is organized as follows. Section II summarizes the related literature. Section III describes the proposed CNOMA-enabled channel access procedure for IEEE 802.11 WLANs. Section IV develops the analytical model of the CNOMA-based WLAN. Section V presents and discusses the results. Finally, Section VI concludes the paper.

II. RELATED WORKS

In [3], the authors have analysed the saturation throughput performance of IEEE 802.11 WLANs. As the number of users increases, throughput decreases due to increased contention and collisions. NOMA can mitigate this performance limitation by enabling parallel transmissions among multiple devices in the network [11]. There are several works in the literature that utilise NOMA to improve the performance in wireless communication networks. In [15], the authors have proposed a NOMA-based multiple access scheme with SIC for cellular networks. When combined with proportional fair scheduling

and appropriate power allocation strategies, this approach has been shown to improve the overall system throughput compared to conventional multiple access methods. In [16], the authors introduced the NOMA framework for next-generation radio access in cellular networks and demonstrated that it can enhance both capacity and cell-edge user throughput, irrespective of whether frequency-selective channel quality indicator (CQI) information is available at the base station. Furthermore, when combined with MIMO techniques, the proposed scheme achieved additional capacity gains. A linear precoding strategy is employed in [17] to enhance security in MIMO-NOMA-based channel access, leading to higher secrecy rates compared to conventional approaches. Massive MIMO-NOMA with dynamic power allocation offers significant improvements in fairness and outage probability, even under imperfect SIC conditions [18]. In comparison with OMA, NOMA has the potential to enhance the performance metrics, including sum rate, fairness, and energy efficiency [19]. However, these studies primarily focus on the applicability of NOMA in cellular and other networks. The direct applicability of NOMA to contention-based WLANs remains limited due to differences in channel access mechanisms and synchronization requirements.

Several studies in the literature have explored the use of NOMA in WLANs to improve throughput performance. A NOMA-based channel access scheme can be used in IEEE 802.11 WLANs to enhance throughput performance by efficiently utilising frequency resources through user clustering and SIC [13]. The work in [20] presented a NOMA-based restricted access window (RAW) mechanism designed to improve throughput and scalability in IEEE 802.11ah-compliant dense IoT networks. In [21], the authors presented the first prototype of a Wi-Fi device with NOMA, implemented on a software-defined radio platform, while maintaining compatibility with previous versions of the Wi-Fi standard. In [22], the authors proposed a practical downlink NOMA scheme and implemented the proposed system in a wireless testbed. On the transmitter side, there is a precoder, and it is implemented based on an optimisation problem. They also introduced a user clustering method to guarantee effective SIC operation at the receiver side. At the receiver, a novel SIC technique is introduced which eliminates the need for channel estimation during signal decoding. In [23], the authors proposed a method to combine a smart antenna-based beam allocation system with NOMA to enhance WLAN throughput performance in dense network scenarios. A joint scheduling and power allocation scheme can be employed to address the high computational complexity of this integrated system. This approach enabled practical implementation while ensuring high average user throughput in dense networks. In [13], it is observed that far users in NOMA-based WLAN implementations degrade overall system performance due to their lower transmission rates, which lead to longer transmission duration compared to near users. Consequently, uplink synchronisation becomes challenging, further deteriorating the network performance. Even though these studies demonstrate that NOMA can enhance channel access in WLANs, its applicability in multirate WLANs with heterogeneous user data rates has not been

adequately addressed.

The problems arising from slow stations in a multirate WLAN can be addressed through cooperative communication. Cooperative communications are popular in wireless networks due to their ability to reduce fading and eliminate the need for multiple antennas on small terminals. Cooperative communications involve relay nodes assisting a source in transmitting information to specific destinations [24]. In [25], the authors have proposed a cooperative MAC protocol for distributed wireless networks that employs a grouping mechanism aimed at effective helper node selection. Additionally, a greedy algorithm is introduced to refine the protocol. The proposed approach enhances throughput performance by selecting optimal helper nodes within the network.

Integrating cooperative communications with NOMA can increase system efficiency, capacity, and reliability. In NOMA, the data of other users obtained during the SIC decoding step can be exploited in CNOMA to enable effective relaying [26]. In this method, users with better channel conditions function as relays for users with poor channel conditions [12]. Compared to conventional NOMA, CNOMA can guarantee better performance under practical conditions such as imperfect SIC, imperfect channel state information (CSI), and hardware impairments [27]. CNOMA, when combined with space-time codes such as Alamouti coding, can significantly improve the robustness of poor-quality links by providing space diversity gain [28]. A NOMA-based cooperative relaying strategy (NOMA-CRS) is proposed in underwater acoustic sensor networks (UASNs) to enhance ergodic rate, reduce outage probability, and improve energy efficiency [29]. CNOMA with optimal relay selection and deep learning-based power allocation can enhance the energy efficiency of data transmission [30]. Despite these advances, the integration of cooperative NOMA into IEEE 802.11 WLANs particularly at the MAC layer with contention based channel access has received limited attention in the existing literature. Motivated by this gap, this work investigates a cooperative NOMA-based channel access scheme for WLANs to improve throughput, connectivity, and far-user performance.

III. PROPOSED CHANNEL ACCESS SCHEME FOR IEEE 802.11 WLAN

In this section, we consider a multi-rate IEEE 802.11 WLAN and propose a CNOMA-based channel access scheme for this network. The network consists of N STAs along with an AP at the centre, as shown in Fig.1. The coverage area of AP is divided into M regions, with N nodes uniformly distributed across these M regions. Let the number of STAs in the r^{th} region be c_r and let the transmission rate of a node in the r^{th} region that is located at an average distance of d_r from the AP be R_r . Here, R_1 represents the transmission rate of the nearest user located at distance d_1 from the AP, whereas R_M denotes the transmission rate of the farthest user located at distance d_M . The proposed channel access scheme for the CNOMA is described in Algorithm 1. Initially, STAs are clustered into $U = \frac{N}{M}$ user clusters by selecting one node from each of the regions [13].

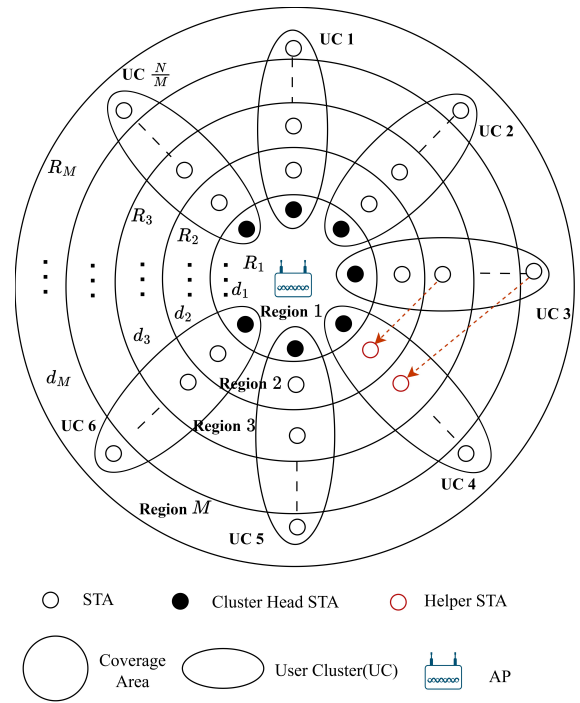


Fig. 1. System model of the proposed CNOMA-based IEEE 802.11 WLAN, where the AP is located at the center of the coverage area and the STAs are clustered based on their achievable data rates.

In the proposed scheme, the near-users act as cluster head STAs, and these cluster heads are only permitted to contend for channel access. After sensing the channel idle for a distributed inter-frame space (DIFS) duration, each cluster head initiates a random backoff procedure. When a cluster head STA (nearby user 1) from a specific cluster wins the contention, then that node will send a request to send (RTS) frame to the AP, and this RTS frame will be received by all the far users of the cluster. Upon receiving the RTS frame, all far users will find a potential helper node outside the cluster using the helper table as depicted in Table I. Then, all far users will send a cooperative RTS (CRTS) frame to the helper nodes separated by a short inter frame spacing (SIFS) duration. If the helper STA is ready to relay the data, it will send a helper ready to send (HTS) frame to both the AP and sending STA [6]. Since nodes outside the cluster remain free when a particular cluster gains channel access and can act as helper nodes, hence far-users are always ensured of helper node availability. The clear-to-send (CTS) response frame from the AP contains the address of the near region node that won the channel access, and this CTS frame will be received by all devices in the network. The control frame transmission is pictorially represented in Fig. 2. Then, the far region nodes will transmit their data to the corresponding helper nodes separated by the SIFS duration. The transmission power of helper stations is adjusted to ensure proper SIC operation as shown in Algorithm 1. For each helper node located in the i^{th} near region and each source node located in the j^{th} far region, the transmission power of the helper node is determined as,

$$P_{i,j} = \alpha_{i,j} P, \quad i = 1, 2, \dots, N_h, \quad j = 1, 2, \dots, N_f \quad (1)$$

Algorithm 1 Proposed Cooperative NOMA-Based Channel Access Scheme

- 1: **User Clustering:** Partition N STAs into $U = \frac{N}{M}$ clusters by selecting one node from each region:
 Cluster 1: $\{D_1, D_{U+1}, \dots, D_{(M-1)U+1}\}$
 Cluster 2: $\{D_2, D_{U+2}, \dots, D_{(M-1)U+2}\}$
 \vdots
 Cluster U : $\{D_U, D_{2U}, \dots, D_{MU}\}$
 - 2: **RTS Transmission:** The winning cluster head sends an RTS to the AP, overheard by far-users.
 - 3: **Helper Selection:**
 - 4: **for** each far-user **do**
 - 5: **for** each helper in the table **do**
 - 6: Compute $t_h = \frac{1}{R_{fh}} + \frac{1}{R_{hd}}$
 - 7: **end for**
 - 8: Select helper with minimum t_h ; if equal, choose the one with lesser transmission failures.
 - 9: **end for**
 - 10: **CRTS Transmission:**
 - 11: **for** each far-user **do**
 - 12: **if** $t_h < \frac{1}{R_{fd}}$ **then**
 - 13: Send CRTS to the chosen helper (after SIFS).
 - 14: **else**
 - 15: Wait for CTS from the AP.
 - 16: **end if**
 - 17: **end for**
 - 18: **Helper Readiness:** Helpers reply with HTS to both AP and STA if ready.
 - 19: **CTS Response:** AP broadcasts CTS indicating the winning cluster head.
 - 20: **Far-User Data:** Far-users transmit data to their selected helpers, separated by SIFS intervals.
 - 21: **Helper Power Adjustment:**
 - 22: **for** All helper nodes in a i^{th} near regions **do**
 - 23: **for** All source nodes in a j^{th} far regions **do**
 - 24: $P_{i,j} = \alpha_{i,j}P$
 - 25: **end for**
 - 26: **end for**
 - 27: **NOMA Transmission:** Near-users and helpers transmit simultaneously to the AP using power-domain NOMA.
 - 28: **Decoding:** The AP applies SIC to decode the concurrent transmissions.
-

where $\alpha_{i,j}$ represents the power-control constant corresponding to the helper–source pair (i, j) . Here, N_h denotes the number of near regions whose nodes can act as helper nodes for far regions, and N_f denotes the number of far regions. The power control constants $\alpha_{i,j}$ are selected based on the principle that,

$$\alpha_{i,j} > \alpha_{i,j+1}, \quad \forall j, \quad (2)$$

to ensure distinguishable received signal levels at the AP for effective SIC in the NOMA framework. In this work, a total of four regions are considered. The nodes located in the first and second regions function as helper nodes for the source nodes in the third and fourth regions. Additionally, nodes in the first three regions can serve as helper nodes for source nodes located in the fourth region. The corresponding power control terms for various helper–source pairs are defined as follows:

- $\alpha_{1,3}$: power control term for a first-region helper forwarding data from a third-region source node,
- $\alpha_{1,4}$: power control term for a first-region helper forwarding data from a fourth-region source node,
- $\alpha_{2,3}$: power control term for a second-region helper forwarding data from a third-region source node,
- $\alpha_{2,4}$: power control term for a second-region helper forwarding data from a fourth-region source node,
- $\alpha_{3,4}$: power control term for a third-region helper forwarding data from a fourth-region source node.

Then all near users in the cluster and helper nodes will initiate data transmission to AP simultaneously using the power domain NOMA as shown in Fig.3. The receiver then decodes

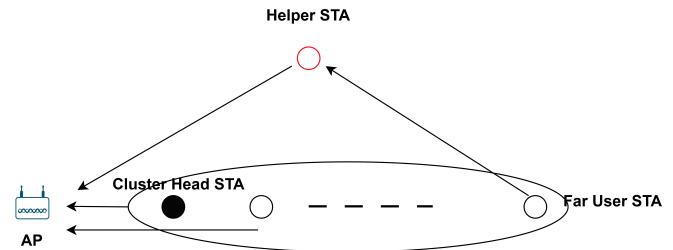


Fig. 3. Data frame transmission procedure in the proposed CNOMA-based WLAN for the contention-winning cluster after receiving the CTS message.

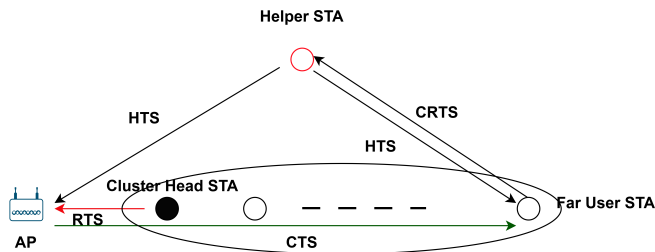


Fig. 2. Control frame transmission procedure in the proposed CNOMA-based WLAN when the cluster head wins the channel contention.

these concurrent transmissions using the SIC technique. After successfully receiving data from all STAs, the AP will respond with an acknowledgement (ACK) frame. Fig. 4 illustrates the timing diagram of CNOMA-based channel access in a WLAN with four regions. Then, the number of contenting users in the network will be $\frac{N}{M}$ instead of N .

In CNOMA-based channel access, once a near-user obtains channel access, the far-users transmit their data to the AP through helper nodes located outside their respective clusters. Each far user must find a helper node to relay their data to the AP successfully. In a CNOMA-based network, every node must maintain a helper table to find the optimal helper node. This helper table is updated by the node by sensing the transmission in the network. Let the far users of the cluster be denoted as n_f and the corresponding helper node be denoted

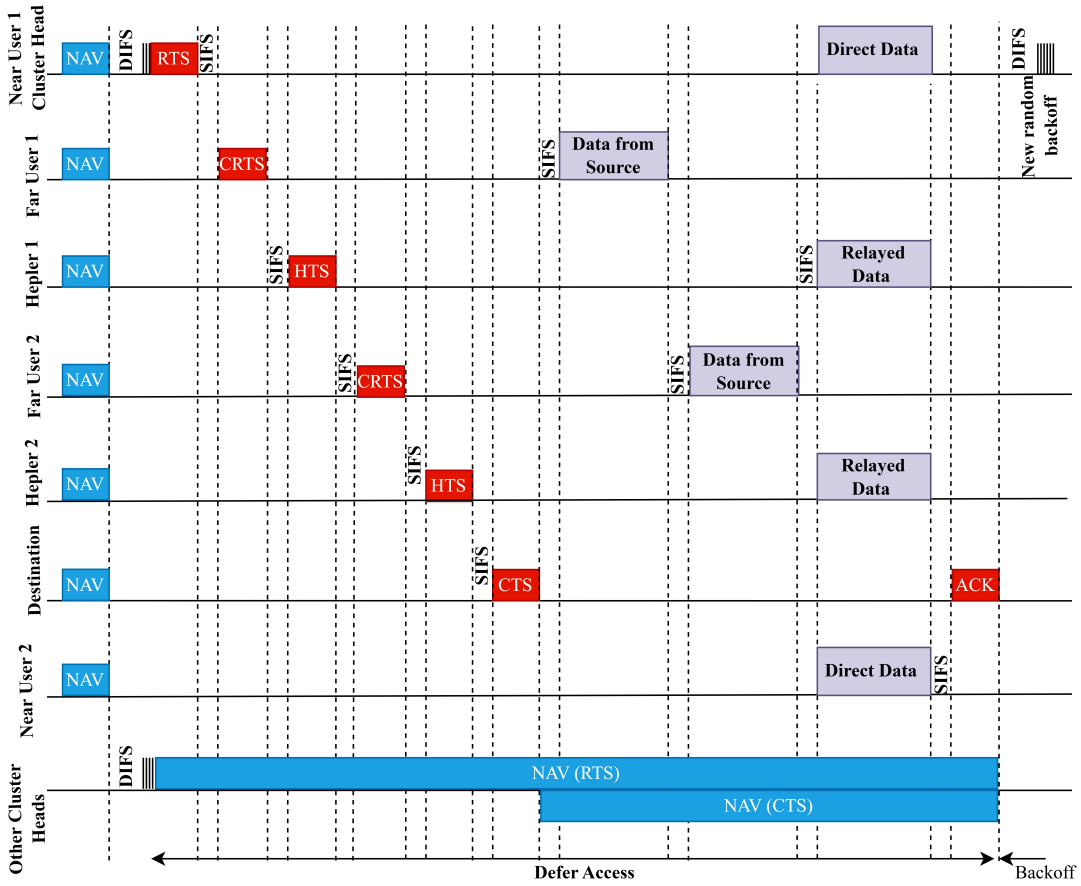


Fig. 4. Timing diagram of the proposed CNOMA-based WLAN illustrating transmission within a cluster, including control frame exchange, relayed data transmission from outside-cluster helper nodes, and simultaneous transmission based on the NOMA principle.

as n_h . Let the transmission rate between the n_f and n_h be R_{fh} . The transmission rate between the AP and n_h , denoted as R_{hd} , can be estimated by the n_f by decoding information in the physical layer convergence procedure (PLCP) header. Suppose the direct transmission rate between AP and n_f is referred to as R_{fd} . A far node creates an entry for a helper if the transmission time from the far node to the AP exceeds the sum of the transmission times from the far node to the helper and from the helper to the destination. The format for the helper table is depicted in Table I. The last column of the table records the total number of consecutive transmission failures. Due to memory constraints, when a helper exceeds a predefined number of transmission attempts, its corresponding entry in the table is removed. Additionally, if a far user identifies a potential helper outside its current cluster, the corresponding table entry is updated accordingly.

Far users in the contention won cluster examine the helper table and calculate the time for transmission of unit information $t_h = \frac{1}{R_{fh}} + \frac{1}{R_{hd}}$ for each helper, and they will choose the helper with the minimum value of t_h . If a user finds two helpers with precisely the same transmission time, it will take the helper with the minimum number of transmission failures in the past. If the time t_h is less than the time for direct transmission, the far user will send a CRTS frame with the frame format shown in Fig. 5. When a helper node

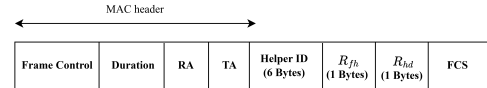


Fig. 5. Frame format of the proposed CRTS frame in the CNOMA-based WLAN.

receives a CRTS frame, it responds by transmitting an HTS frame. The HTS frame will have the same format and length as the CTS frame. If the HTS frame is not received by the AP and the far user within a predefined time period, the far user retransmits a CRTS frame to the next helper node with a lower transmission time. We consider a quasi-static block-fading channel in which the channel remains constant over the duration of a data transmission. We assume that perfect channel state information (CSI) and perfect SIC. Based on the CNOMA principle, four simultaneous transmissions are supported from each region. All devices, including the access point (AP) and stations (STAs), are equipped with a single antenna. The proposed scheme relies on coordination among the source, helper nodes, and the AP while restricting channel contention to cluster heads; the performance degradation due to retransmissions caused by coordination failures is not explicitly modeled. This analysis will be considered in the future extensions.

TABLE I

FORMAT OF THE HELPER TABLE FOR H HELPER NODES, CONTAINING THE MAC ADDRESSES, TWO-HOP DATA RATES, AND NUMBER OF FAILED TRANSMISSION ATTEMPTS

MAC Address	R_{fh}	R_{hd}	Number of Attempts
MAC address of helper 1	Transmission rate between far user and helper 1	Transmission rate between helper 1 and destination	Number of transmission failures of helper 1
\vdots	\vdots	\vdots	\vdots
MAC address of helper H	Transmission rate between far user and helper H	Transmission rate between helper H and destination	Number of transmission failures of helper H

IV. ANALYTICAL MODEL OF CNOMA-BASED WLAN

In this section, we discuss the analytical model of CNOMA-based WLAN and derive the closed-form expressions for saturation throughput. The system parameters are chosen in accordance with the IEEE 802.11b standard [6]. This analysis can be extended to any future amendments to IEEE 802.11 WLAN. We consider a CNOMA-based multi-rate WLAN with four regions with data rates 11 Mbps, 5.5 Mbps, 2 Mbps and 1 Mbps. The radius of the coverage of these four areas is r_{11}, r_5, r_2 and r_1 respectively. When a cluster head attains channel access, nodes with transmission rates of 2 Mbps and 1 Mbps in that cluster will only perform cooperative communication. The users in the near region transmit to the AP through the direct mode. In order to find the saturation throughput of CNOMA-based WLAN, the probability that a relay node exists for far users must be calculated.

The area of intersection between two circles with radii r_u and r_v , and a center-to-center distance d , is given by,

$$A_{r_u, r_v}(d) = r_u^2 \arcsin \frac{h}{r_u} + r_v^2 \arcsin \frac{h}{r_v} - hd, \quad (3)$$

where,

$$h = \frac{\sqrt{2r_u^2 r_v^2 + 2(r_u^2 + r_v^2)d^2 - (r_u^4 + r_v^4) - d^4}}{2d}. \quad (4)$$

The area of intersection between the coverage circles of the AP and n_f is illustrated in Fig. 6. If a helper exists in the region $a_{u,v}$, then the far user can transmit its data at u Mbps and the helper can forward it at v Mbps [6]. The probability

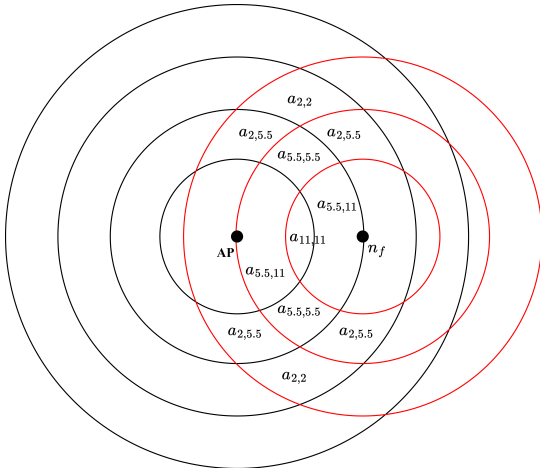


Fig. 6. Coverage area intersections illustrating cooperative regions.

that there exists a helper node in these area are given by the following equations

$$p_{11,11}(r) = \frac{A_{r_{11}, r_{11}}(r)}{\pi r_1^2}, \quad (5)$$

$$p_{5.5,11}(r) = \frac{2(A_{r_{5.5}, r_{11}}(r) - A_{r_{11}, r_{11}}(r))}{\pi r_1^2}, \quad (6)$$

$$p_{5.5,5.5}(r) = \frac{A_{r_{5.5}, r_{5.5}}(r) + A_{r_{11}, r_{11}}(r) - 2A_{r_{5.5}, r_{11}}(r)}{\pi r_1^2}, \quad (7)$$

$$p_{2,11}(r) = \frac{2(A_{r_2, r_{11}}(r) - A_{r_{5.5}, r_{11}}(r))}{\pi r_1^2}, \quad (8)$$

$$p_{2,5.5}(r) = \frac{2(A_{r_2, r_{5.5}}(r) + A_{r_{5.5}, r_{11}}(r))}{\pi r_1^2} - \frac{2(A_{r_2, r_{11}}(r) + A_{r_{5.5}, r_{5.5}}(r))}{\pi r_1^2}, \quad (9)$$

$$p_{2,2}(r) = \frac{A_{r_2, r_2}(r) + A_{r_{5.5}, r_{5.5}}(r) - 2A_{r_2, r_{5.5}}(r)}{\pi r_1^2}. \quad (10)$$

Then the probability that a node in the farthest region with a direct transmission rate of 1 Mbps has a two-hop transmission is given by the following equations

$$P_{11,11}^{(1)} = 1 - \int_{r_2}^{r_1} \frac{2r(1 - p_{11,11}(r))^{N'}}{(r_1^2 - r_2^2)} dr, \quad (11)$$

$$P_{5.5,11}^{(1)} = 1 - P_{11,11}^{(1)} - \int_{r_2}^{r_1} \frac{2r}{r_1^2 - r_2^2} (1 - p_{11,11}(r) - p_{5.5,11}(r))^{N'} dr, \quad (12)$$

$$P_{5.5,5.5}^{(1)} = 1 - P_{11,11}^{(1)} - P_{5.5,11}^{(1)} - \int_{r_2}^{r_1} \frac{2r}{r_1^2 - r_2^2} (1 - p_{11,11}(r) - p_{5.5,11}(r) - p_{5.5,5.5}(r))^{N'} dr, \quad (13)$$

$$P_{2,11}^{(1)} = 1 - P_{11,11}^{(1)} - P_{5.5,11}^{(1)} - P_{5.5,5.5}^{(1)} - \int_{r_2}^{r_1} \frac{2r}{(r_1^2 - r_2^2)} (1 - p_{11,11}(r) - p_{5.5,11}(r) - p_{5.5,5.5}(r) - p_{2,11}(r))^{N'} dr, \quad (14)$$

$$P_{2,5.5}^{(1)} = 1 - P_{11,11}^{(1)} - P_{5.5,11}^{(1)} - P_{5.5,5.5}^{(1)} - P_{2,11}^{(1)} - \int_{r_2}^{r_1} \frac{2r}{(r_1^2 - r_2^2)} (1 - p_{11,11}(r) - p_{5.5,11}(r) - p_{5.5,5.5}(r) - p_{2,11}(r) - p_{2,5.5}(r))^{N'} dr, \quad (15)$$

$$P_{2,2}^{(1)} = 1 - P_{11,11}^{(1)} - P_{5.5,11}^{(1)} - P_{5.5,5.5}^{(1)} - P_{2,11}^{(1)} - P_{2,5.5}^{(1)} - \int_{r_2}^{r_1} \frac{2r}{r_1^2 - r_2^2} (1 - p_{11,11}(r) - p_{5.5,11}(r) - p_{5.5,5.5}(r) - p_{2,11}(r) - p_{2,5.5}(r) - p_{2,2}(r))^{N'} dr. \quad (16)$$

here N' represents the total number of users in the network, excluding the nodes in the contention-won cluster. For the nodes with direction transmission rate of 2 Mbps is given by,

$$P_{11,11}^{(2)} = 1 - \int_{r_{5.5}}^{r_2} \frac{2r (1 - p_{11,11}(r))^{N'}}{(r_1^2 - r_2^2)} dr, \quad (17)$$

$$P_{5.5,11}^{(2)} = 1 - P_{11,11}^{(2)} - \int_{r_{5.5}}^{r_2} \frac{2r}{r_1^2 - r_2^2} (1 - p_{11,11}(r) - p_{5.5,11}(r))^{N'} dr, \quad (18)$$

$$P_{5.5,5.5}^{(2)} = 1 - P_{11,11}^{(2)} - P_{5.5,11}^{(2)} - \int_{r_{5.5}}^{r_2} \frac{2r}{r_1^2 - r_2^2} (1 - p_{11,11}(r) - p_{5.5,11}(r) - p_{5.5,5.5}(r))^{N'} dr. \quad (19)$$

The transmission time of the farthest nodes with direct transmission rate 1 Mbps for $E[P]$ bits of data, and it is taking help from helper nodes with transmission rates 11 Mbps, 5.5 Mbps and 2 Mbps, is given by,

$$T_4 = (P_{11,11}^{(1)} + P_{5.5,11}^{(1)} + P_{5.5,5.5}^{(1)} + P_{2,11}^{(1)} + P_{2,5.5}^{(1)} + P_{2,2}^{(1)})T_{CNOH} + T_{SH1} + T_{HD1} + T_{SH2} + (1 - P_{11,11}^{(1)} - P_{5.5,11}^{(1)} - P_{5.5,5.5}^{(1)} - P_{2,11}^{(1)} - P_{2,5.5}^{(1)} - P_{2,2}^{(1)}) \left(T_{DOH} + \frac{E[P]}{R_1} \right) + 7\delta, \quad (20)$$

here, $T_{DOH} = PLCP + DIFS + 3SIFS + RTS + CTS + ACK$ is the overhead time required for direct communication, and $PLCP$ is the time required for transmitting physical layer convergence. R_x is the transmission rate of the station with x Mbps and δ is the propagation delay. The overhead time required for CNOMA communication is given by $T_{CNOH} = 2PLCP + DIFS + 9SIFS + RTS + 2CRTS + CTS + 2HTS + ACK$. The $CRTS$ and HTS are the time durations for additional control frames. $DIFS$, $SIFS$, RTS , CTS and ACK have the same meaning in [3]. T_{SH1} and T_{SH2} represent the average time required for data transmission from the source to the helper for nodes with direct transmission rates of 1 Mbps and 2 Mbps, respectively, and are derived in (21) and (22).

T_{HD1} and T_{HD2} represent the average time required for data transmission from the helper to the destination for nodes with direct transmission rates of 1 Mbps and 2 Mbps, respectively, and are derived in (23) and (24).

$$T_{SH1} = 8E[P] \left(\frac{P_{11,11}^{(1)} + P_{2,11}^{(1)}}{R_{11}} + \frac{P_{5.5,11}^{(1)} + P_{5.5,5.5}^{(1)}}{R_{5.5}} + \frac{P_{2,2}^{(1)} + P_{2,5.5}^{(1)}}{R_2} \right) \quad (21)$$

$$T_{SH2} = 8E[P] \left(\frac{P_{11,11}^{(2)}}{R_{11}} + \frac{P_{5.5,11}^{(2)} + P_{5.5,5.5}^{(2)}}{R_{5.5}} \right) \quad (22)$$

$$T_{HD1} = 8E[P] \left(\frac{P_{11,11}^{(1)} + P_{5.5,11}^{(1)}}{R_{11}} + \frac{P_{5.5,5.5}^{(1)} + P_{2,5.5}^{(1)}}{R_{5.5}} + \frac{P_{2,11}^{(1)} + P_{2,2}^{(1)}}{R_2} \right) \quad (23)$$

$$T_{HD2} = 8E[P] \left(\frac{P_{11,11}^{(2)} + P_{5.5,11}^{(2)}}{R_{11}} + \frac{P_{5.5,5.5}^{(2)}}{R_{5.5}} \right) \quad (24)$$

The transmission time of third region nodes with direct transmission rate 2 Mbps for $E[P]$ bits of data, and it is taking help from helper nodes with transmission rate 11 Mbps and 5.5 Mbps, is given by,

$$T_3 = (P_{11,11}^{(2)} + P_{5.5,11}^{(2)} + P_{5.5,5.5}^{(2)})T_{CNOH} + T_{SH2} + T_{HD2} + T_{SH1} + (1 - P_{11,11}^{(2)} - P_{5.5,11}^{(2)} - P_{5.5,5.5}^{(2)}) \left(T_{DOH} + \frac{E[P]}{R_2} \right) + 7\delta \quad (25)$$

In CNOMA-based channel access, before the transmission from the helper to the destination can occur, all transmissions from source nodes to helper nodes must be completed. Therefore, there is an additional waiting time: T_{SH2} is included in T_4 , and T_{SH1} is included in T_3 . As a result, the direct-transmission station must also wait for the completion of the source-to-helper transmissions, and the corresponding transmission time for a near-region node with direct transmission at 11 Mbps and 5.5 Mbps is given by,

$$T_1 = T_{SH1} + T_{SH2} + T_{DOH} + \frac{E[P]}{R_{11}} + 4\delta \quad (26)$$

$$T_2 = T_{SH1} + T_{SH2} + T_{DOH} + \frac{E[P]}{R_{5.5}} + 4\delta, \quad (27)$$

The collision time is given by,

$$T_C = RTS + DIFS + \delta \quad (28)$$

The transmission probability of a node in the r^{th} region with c_r devices in a multi-rate WLAN is given by

$$\tau_r = \frac{2(1 - 2p_r)}{(1 - 2p_r)(CW_{\min} + 1) + p_r CW_{\min}(1 - (2p_r)^m)}, \quad (29)$$

here, m is the maximum number of backoff stages, and p_r is the collision probability for a multi-rate WLAN, which is derived as given in [31], [32].

$$p_r = 1 - (1 - \tau_r)^{c_r - 1} \prod_{y=1, y \neq r}^4 (1 - \tau_y)^{c_y} \quad (30)$$

In the proposed scheme, only cluster heads participate in the contention process; therefore, the collision probability is given by

$$p_1 = 1 - (1 - \tau_1)^{c_1 - 1}. \quad (31)$$

The transmission probability of a node in the first region is given by

$$\tau_1 = \frac{2(1 - 2p_1)}{(1 - 2p_1)(CW_{\min} + 1) + p_1 CW_{\min}(1 - (2p_1)^m)}. \quad (32)$$

The probability that there is at least one transmission in the considered slot time for the first region ($P_{Tr}^{(1)}$) and the probability of an empty backoff slot ($P_e^{(1)}$) are given by,

$$P_{Tr}^{(1)} = 1 - (1 - \tau_1)^{c_1} \quad (33)$$

$$P_e^{(1)} = 1 - P_{Tr}^{(1)} \quad (34)$$

The probability of successful transmission ($P_S^{(r)}$) of a multi rate WLAN is the probability that only one STA in the r^{th} region transmits and all other STAs in the same region, as well as STAs in the other three regions, don't transmit at the same time, and it derived as follows [31], [32],

$$P_S^{(r)} = c_r \tau_r (1 - \tau_r)^{c_r - 1} \prod_{y=1, y \neq r}^4 (1 - \tau_y)^{c_y} \quad (35)$$

In the proposed scheme, the probability of successful transmission in the first region is given by

$$P_S^{(1)} = c_1 \tau_1 (1 - \tau_1)^{c_1 - 1}. \quad (36)$$

The probability of backoff slot containing a collision ($P_C^{(1)}$) in the first region is given by ,

$$P_C^{(1)} = 1 - P_S^{(1)} - P_e^{(1)} \quad (37)$$

The fixed-point equations (31) and (32) can be solved iteratively to get the values of τ_1 , to find $P_S^{(1)}$, $P_{Tr}^{(1)}$, $P_e^{(1)}$ and $P_C^{(1)}$. In a CNOMA-based WLAN, only near users can perform channel contention. Then, the throughput of the near user for the transmission of $E[P]$ bits of data is expressed as follows:

$$S_1 = \frac{P_S^{(1)} E[P]}{E[T_{slot}]}, \quad (38)$$

here $E[T_{slot}]$ is the average slot time of the near user and it is given by,

$$E[T_{slot}] = \sigma P_e^{(1)} + P_S^{(1)} \max(T_1, T_2, T_3, T_4) + P_C^{(1)} T_C^{(1)} \quad (39)$$

In CNOMA-based channel access, near-region nodes transmit directly, while far-region nodes transmit with the help of

near region helper nodes. Since these two types of transmissions occur simultaneously within a given user cluster, the average slot time $E[T_{slot}]$ remains the same for all transmissions in that cluster. Consequently, the aggregate throughput (S_{CNOMA}) of the four regions can be calculated as follows:

$$S_{CNOMA} = \sum_{r=1}^4 \frac{P_S^{(r)} E[P]}{E[T_{slot}]} \quad (40)$$

V. RESULTS AND DISCUSSION

In this research work, analytical results are generated using MATLAB R2024b and simulation results are generated using ns 3.44. The STA transmit power is set to 12 dBm. A log-distance path loss model with a path loss exponent of three is adopted as the channel propagation model, and a noise figure of 7 dB is used. We consider a multi-rate WLAN with four regions, each having transmission rates of 11 Mbps, 5.5 Mbps, 2 Mbps, and 1 Mbps, and the number of nodes in the network varies from 120 to 240. The corresponding coverage ranges for these data rate regions are 25 m, 50 m, 75 m, and 100 m, respectively. Once a cluster head wins contention, the nodes with 11 Mbps and 5.5 Mbps in that cluster perform direct transmission. Since nodes outside that cluster are idle, these nodes can act as helper nodes for nodes with transmission rates of 2 Mbps and 1 Mbps. The values of $\alpha_{1,3}$, $\alpha_{2,3}$, and $\alpha_{3,4}$ are taken as 0.8, while the values of $\alpha_{1,4}$ and $\alpha_{2,4}$ are taken as 0.7. These values are chosen by considering the propagation loss differences between the helper nodes and the AP. The system parameters used for analytical and simulation studies are provided in Table II. The

TABLE II
SYSTEM PARAMETERS FOR ANALYTICAL MODELING AND SIMULATION

Parameter	Value	Parameter	Value
SIFS	10 μs	PHY header	24 Bytes
DIFS	50 μs	MAC header	34 Bytes
Slot Time	20 μs	ACK	38 Bytes
CW_{min}	31	RTS	44 Bytes
m	5	CTS	38 Bytes
CW_{max}	1023	Packet Length	1024 Bytes

simulation results reported here are averages of multiple 100 s simulations. For the ns-3 simulations, we considered the IEEE 802.11b HR-DSSS PHY operating over a 20 MHz channel in the 2.4 GHz band. The MAC parameters, such as CW_{min} and CW_{max} , are taken as per Table II. The short and long retry limits are set to 6 and 4, respectively, in the ns-3 simulations. User datagram protocol (UDP) with a transmission interval of 0.01 s is considered for the ns-3 simulations [33]. The aggregate throughput of CNOMA-based WLAN is calculated both analytically and through ns-3 simulations. The saturation throughput of the conventional and NOMA-based WLANs is evaluated using the analytical expressions reported in [13], while the throughput of the cooperative WLAN is computed using the analytical expressions provided in [6].

Furthermore, extensive simulations have been performed to verify the analytical findings. The number of users versus

aggregate throughput for CNOMA-based multi-rate WLAN, cooperative WLAN, NOMA-based WLAN and conventional multi-rate WLAN is shown in Fig.7. There is a substantial

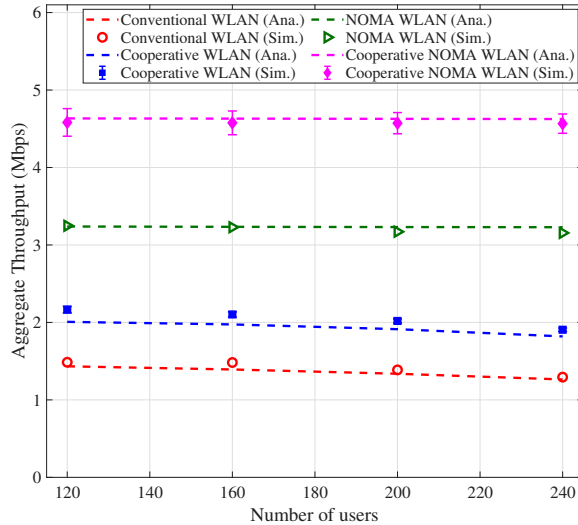


Fig. 7. Aggregate throughput comparison of the proposed CNOMA-based WLAN with NOMA-based WLAN, cooperative WLAN, and conventional WLAN.

enhancement in aggregate throughput for the CNOMA-based multi-rate WLAN compared to the conventional WLAN, owing to the combined use of cooperative communication and NOMA-based channel access. In the low user-density scenario with a total of 40 users, the CNOMA-based WLAN achieves an aggregate throughput improvement of 185% compared to the conventional WLAN. Throughput improvements of 223%, 234%, 249%, and 271% are observed for networks with 120, 160, 200, and 240 users, respectively, compared to the conventional channel access scheme. It is evident that the percentage improvement in throughput generally increases as the number of users increases, since far devices have a higher likelihood of obtaining helper nodes when more nearby users are present. However, a minor decrement in aggregate throughput is observed as the number of users continues to increase, due to the increased collision probability, which outweighs the throughput gains achieved by CNOMA from the higher likelihood of obtaining helper nodes. The additional control signaling overhead is explicitly incorporated into the throughput analysis through the overhead terms in (20) and (25). Although these equations account for the extra signaling required for CNOMA operation, the reduced effective transmission time enabled by simultaneous user transmission offsets this overhead, resulting in a net increase in the aggregate throughput.

In this work, perfect SIC and perfect time synchronization among STAs are assumed for analytical tractability. In practical implementations, imperfect SIC degrades performance by reducing the achievable signal-to-interference-plus-noise ratio (SINR) of the decoded signals, particularly for STAs with weaker channel conditions [34]. However, the proposed CNOMA framework can mitigate this effect to some extent, as cooperative relaying improves the received signal strength of far users. It may also be noted that with enhancement in hardware technology the SIC inefficiency factor is expected

to be very low in the order of 0.001 to 0.01 [35], [36]. Time synchronization errors may lead to misaligned transmissions, which reduce decoding efficiency and increase residual interference [37]. The proposed CNOMA-based WLAN introduces additional computational complexity due to SIC; however, this complexity is primarily incurred at the access point (AP). In the proposed scheme nearby devices act as helper nodes for cooperative transmission and this may increase their energy consumption. However, this increase in energy consumption is efficiently compensated by the significant improvement in throughput performance and by reducing the channel time wastage caused by unfair resource allocation. By leveraging existing nearby devices for cooperation, the proposed scheme also eliminates the need for deploying dedicated repeaters, thereby lowering both energy consumption and deployment cost.

VI. CONCLUSION

In this paper, we have proposed CNOMA for IEEE 802.11 WLAN and designed a novel channel access scheme for CNOMA based WLANs. In this proposed scheme, NOMA is used to support concurrent transmissions and cooperative communication enhances the throughput further by allowing nearer region nodes to act as relay for farther region nodes. We have analytically modeled the IEEE 802.11 multi-rate WLANs with CNOMA-based channel access. The proposed scheme outperforms conventional WLAN, cooperative WLAN, and NOMA-based WLAN in terms of throughput by reducing the number of contending users for channel access, enabling simultaneous transmissions using NOMA and leveraging cooperative communication to minimize the overall transmission time. The analytical results are validated through extensive ns-3 simulations. The proposed CNOMA-based channel access scheme can be applied to different amendments of the IEEE 802.11 WLAN family, particularly recent standards operating at higher frequency bands that experience greater propagation losses than the 2.4 GHz band; extending the proposed scheme to such scenarios is part of our future work.

REFERENCES

- [1] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 Wireless Local Area Networks," *IEEE Commun. Mag.*, vol. 35, no. 9, pp. 116–126, Sep. 1997, doi: 10.1109/35.620533.
- [2] R. O. LaMaire, A. Krishna, P. Bhagwat, and J. Panian, "Wireless LANs and Mobile Networking: Standards and Future Directions," *IEEE Commun. Mag.*, vol. 34, no. 8, pp. 86–94, Aug. 1996, doi: 10.1109/35.533925.
- [3] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000, doi: 10.1109/49.840210.
- [4] Y. Song, K. W. Sung, and Y. Han, "Coexistence of Wi-Fi and Cellular With Listen-Before-Talk in Unlicensed Spectrum," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 161–164, Jan. 2016, doi: 10.1109/LCOMM.2015.2504509.
- [5] S. V. Rakhmanov and D. A. Loktev, "Wi-Fi Signal Propagation Modeling," in *Proc. 7th Int. Youth Conf. Radio Electron., Electr. Power Eng. (REEPE)*, Moscow, Russia, 2025, pp. 1–6, doi: 10.1109/REEPE63962.2025.10971051.
- [6] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: A Cooperative MAC for Wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007, doi: 10.1109/JSAC.2007.070210.

- [7] Q. Xia and M. Hamdi, "Smart Sender: A Practical Rate Adaptation Algorithm for Multirate IEEE 802.11 WLANS," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1764–1775, May 2008, doi: 10.1109/TWC.2008.061047.
- [8] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance Anomaly of 802.11b," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, 2003, vol. 2, pp. 836–843, doi: 10.1109/INF-COM.2003.1208921.
- [9] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Dresden, Germany, 2013, pp. 1–5, doi: 10.1109/VTC-Spring.2013.6692652.
- [10] L. Galati-Giordano, G. Geraci, M. Carrascosa, and B. Bellalta, "What Will Wi-Fi 8 Be? A Primer on IEEE 802.11bn Ultra High Reliability," *IEEE Commun. Mag.*, vol. 62, no. 8, pp. 126–132, Aug. 2024, doi: 10.1109/MCOM.001.2300728.
- [11] Y. Liu *et al.*, "Nonorthogonal Multiple Access for 5G and Beyond," *Proc. IEEE*, vol. 105, no. 12, pp. 2347–2381, Dec. 2017, doi: 10.1109/JPROC.2017.2768666.
- [12] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-S. Kwak, "Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges," *IEEE Commun. Surv. Tuts.*, vol. 19, no. 2, pp. 721–742, 2nd Quart. 2017, doi: 10.1109/COMST.2016.2621116.
- [13] B. S. Pavan and V. P. Harigovindan, "A Novel Channel Access Scheme for NOMA Based IEEE 802.11 WLAN," *Sādhanā*, vol. 46, no. 144, 2021, doi: 10.1007/s12046-021-01669-2.
- [14] A. P. Buchmann, K. Böhm, and P. Triantafyllou, Eds., *Peer-to-Peer Systems and Applications*, Berlin, Germany: Springer, 2005.
- [15] N. Otao, Y. Kishiyama, and K. Higuchi, "Performance of Non-Orthogonal Access With SIC in Cellular Downlink Using Proportional Fair-Based Resource Allocation," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Paris, France, 2012, pp. 476–480, doi: 10.1109/ISWCS.2012.6328413.
- [16] Y. Saito *et al.*, "Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Dresden, Germany, Jun. 2013, pp. 1–5, doi: 10.1109/VTC-Spring.2013.6692652.
- [17] Y. Qi and M. Vaezi, "Secure Transmission in MIMO-NOMA Networks," *IEEE Commun. Lett.*, vol. 24, no. 12, pp. 2696–2700, Dec. 2020, doi: 10.1109/LCOMM.2020.3016999.
- [18] A. S. de Sena *et al.*, "Massive MIMO-NOMA Networks With Imperfect SIC: Design and Fairness Enhancement," *IEEE Trans. Wireless Commun.*, vol. 19, no. 9, pp. 6100–6115, Sep. 2020, doi: 10.1109/TWC.2020.3000192.
- [19] P. Jain *et al.*, "Performance Evaluation of Cooperative OMA and NOMA Systems in 6G Deployment Scenarios," *Sensors*, vol. 22, no. 11, 3986, 2022, doi: 10.3390/s22113986.
- [20] M. Miriyala *et al.*, "NOMA-Based RAW Mechanism for Performance Enhancement of IEEE 802.11ah Dense IoT Networks," *Sādhanā*, vol. 47, no. 196, 2022, doi: 10.1007/s12046-022-01915-1.
- [21] E. Khorov, A. Kureev, I. Levitsky, and I. F. Akyildiz, "Prototyping and Experimental Study of Non-Orthogonal Multiple Access in Wi-Fi Networks," *IEEE Netw.*, vol. 34, no. 4, pp. 210–217, Jul./Aug. 2020, doi: 10.1109/MNET.011.1900498.
- [22] P. K. Sangdeh *et al.*, "A Practical Downlink NOMA Scheme for Wireless LANs," *IEEE Trans. Commun.*, vol. 68, no. 4, pp. 2236–2250, Apr. 2020, doi: 10.1109/TCOMM.2020.2965951.
- [23] K.-S. Shin and O. Jo, "Joint Scheduling and Power Allocation Using NOMA in Directional Beam-Based WLAN Systems," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 482–485, Aug. 2017, doi: 10.1109/LWC.2017.2707087.
- [24] H. R. Shamna, N. L. Appari, and L. Jacob, "Cooperative MAC Protocol: Performance Modeling and Analysis," in *Proc. IEEE Recent Adv. Intell. Comput. Syst. (RAICS)*, Trivandrum, India, 2013, pp. 233–238, doi: 10.1109/RAICS.2013.6745479.
- [25] H. Shan, H. T. Cheng, and W. Zhuang, "Cross-Layer Cooperative MAC Protocol in Distributed Wireless Networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2603–2615, Aug. 2011, doi: 10.1109/TWC.2011.060811.101196.
- [26] Z. Elsaraf *et al.*, "Cooperative Non-Orthogonal Multiple Access for Wireless Communication Networks by Exploiting the EXIT Chart Analysis," *EURASIP J. Wireless Commun. Netw.*, vol. 2021, no. 79, pp. 1–15, 2021, doi: 10.1186/s13638-021-01961-z.
- [27] S. Beddiaf *et al.*, "A Unified Performance Analysis of Cooperative NOMA with Practical Constraints," *IEEE Access*, vol. 10, pp. 132931–132948, 2022, doi: 10.1109/ACCESS.2022.3230650.
- [28] C. Zhai *et al.*, "Wireless Powered Cooperative NOMA With Alamouti Coding and Selection Relaying," *IEEE Trans. Mobile Comput.*, vol. 23, no. 2, pp. 1366–1381, Feb. 2024, doi: 10.1109/TMC.2023.3235394.
- [29] V. Goutham and V. P. Harigovindan, "NOMA-Based Cooperative Relaying Strategy for Underwater Acoustic Sensor Networks Under Imperfect SIC and CSI," *IEEE Access*, vol. 9, pp. 32857–32872, 2021, doi: 10.1109/ACCESS.2021.3060784.
- [30] M. K. Beuria and S. S. Singh, "Performance Analysis of Cooperative NOMA with Optimized Power Allocation Using Deep Learning Approach," *Wireless Netw.*, vol. 30, pp. 819–834, 2024, doi: 10.1007/s11276-023-03522-2.
- [31] V. P. Harigovindan, A. V. Babu, and L. Jacob, "Proportional Fair Resource Allocation in Vehicle-to-Infrastructure Networks for Drive-Thru Internet Applications," *Comput. Commun.*, vol. 40, pp. 33–50, 2014, doi: 10.1016/j.comcom.2013.12.001.
- [32] A. V. Babu and L. Jacob, "Fairness Analysis of IEEE 802.11 Multirate Wireless LANs," *IEEE Trans. Veh. Technol.*, vol. 56, no. 5, pp. 3073–3088, Sep. 2007, doi: 10.1109/TVT.2007.898397.
- [33] The ns-3 Project, "Wi-Fi Module – Design Documentation," *ns-3 Model Library Documentation*, version 3.44, Jun. 2025. [Online]. Available: <https://www.nsnam.org/docs/models/html/wifi.html>
- [34] V. Özduran, M. Mohammadi, N. Nomikos, I. S. Ansari and P. Trakadas, "On the performance of uplink power-domain NOMA with imperfect CSI and SIC in 6G networks," *Journal of Communications and Networks*, vol. 26, no. 4, pp. 445–460, Aug. 2024, doi: 10.23919/JCN.2024.000039.
- [35] V. Ozduran, M. Mohammadi, I. S. Ansari and N. Nomikos, "Performance Analysis of Uplink Non-Orthogonal Multiple Access in the Presence of Co-Channel Interference," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 9, pp. 11590–11602, Sept. 2023, doi: 10.1109/TVT.2023.3265190.
- [36] Y. Ren, L. Han, X. Zhang, J. Jiang, G. Lu and T. Lv, "Secure Communications for Wireless-Powered Cooperative NOMA Systems Under Imperfect CSI and Imperfect SIC," *IEEE Sensors Journal*, vol. 25, no. 22, pp. 42277–42291, Nov. 2025, doi: 10.1109/JSEN.2025.3615285.
- [37] M. W. Akhtar, S. A. Hassan, S. Saleem and H. Jung, "STBC-Aided Cooperative NOMA With Timing Offsets, Imperfect Successive Interference Cancellation, and Imperfect Channel State Information," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 10, pp. 11712–11727, Oct. 2020, doi: 10.1109/TVT.2020.3017249.

Jomon K. Charly received the B.Tech. degree in Electronics and Communication Engineering and the M.Tech. degree in Communication Systems from the University of Calicut, Kerala, India, in 2013 and 2015, respectively. He is currently pursuing the Ph.D. degree in the Department of Electronics and Communication, National Institute of Technology Puducherry, India. His research focuses on Wireless Local Area Networks, NOMA and Compressed sensing. (e-mail: jomonkcharly1992@gmail.com)



Harigovindan V. P. (Senior Member, IEEE) received the Bachelor of Technology degree in Electronics and Communication Engineering from University of Calicut, the Master of Technology degree in Digital Electronics and Communication Systems from Visvesvaraya Technological University (with first rank), and the Ph.D. degree from the National Institute of Technology Calicut, in 2013. He is currently working as Professor with the Department of Electronics and Communication Engineering, and Dean (Planning and Development) at National Institute of Technology Puducherry (under the Ministry of Education, Government of India). He has more than 75 international publications to his credit. He served as the Principal Investigator for three funded projects, each from the Department of Science and Technology, Government of India, Science and Engineering Research Board and Microsoft AI for Earth. Presently he is serving as the PI of a project funded by DST- Science for Equity, Empowerment and Development, Govt. of India. He has 7 patents granted to his credit. His research interests include wireless networks, artificial intelligence, Internet of things and wireless communications. (e-mail: hari@nitpy.ac.in)