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A novel channel access scheme for NOMA based IEEE 802.11 WLAN

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Abstract. In this letter, we propose a novel channel access scheme based on non-orthogonal multiple access (NOMA) for IEEE 802.11 to improve the throughput performance and connectivity of wireless local area network (WLAN). We consider a wireless network with NOMA at the physical layer and distributed coordination function (DCF) in the medium access control (MAC) layer. The proposed scheme allows the simultaneous transmission of multiple nodes using NOMA as well as reduces the number of contending nodes. In addition, we present a simple yet accurate analytical model for NOMA based IEEE 802.11 multi-rate WLAN. The analytical findings show that the aggregate throughput and connectivity are significantly improved compared with conventional IEEE 802.11 multi-rate WLANs. The analytical results are corroborated with extensive simulation studies.

Keyword. IEEE 802.11 WLAN; Internet of things; non-orthogonal multiple access.

1. Introduction

Nowadays, due to the wide popularity of Internet of things (IoT), applications such as E-Health, E-Learning, smart environment, high-resolution video streaming, etc. are gaining more attention. This leads to a drastic increase in the number of connected Internet users and Internet utilization. Such applications demand high data rate, high throughput, and massive connectivity [1]. IEEE 802.11 wireless local area network (WLAN) has emerged as a popular technology for supporting these applications due to its low cost, license-free spectrum, flexible deployment, and high data rate. The stringent requirements of high throughput and connectivity are the major technical challenges for the next-generation WLANs [2]. IEEE 802.11 defines physical (PHY) and medium access control (MAC) layer specifications [3]. The IEEE 802.11 PHY layer allows rate adaptation where the nodes can transfer the data using different modulation and coding schemes (MCSs) depending on channel conditions at various transmission rates [4]. IEEE 802.11 MAC layer uses a medium access mechanism known as distributed coordination function (DCF). Due to the limited radio resources, the resource allocation plays a key role in effective utilization of wireless spectrum [2, 5].

Multiple access techniques are crucial to employ the sharing of spectrum resources among several users. Recently, non-orthogonal multiple access (NOMA) has emerged as a potential candidate for next-generation wireless networks. The superiority of NOMA in contrast with orthogonal multiple access (OMA) techniques is that many users can simultaneously transmit in the same resource block (same time/frequency/code). Therefore, NOMA offers enhanced performance, spectrum efficiency, and massive connectivity [6]. Among different types of NOMA, power-domain NOMA is considered as a prominent scheme because of its high spectrum efficiency and compatibility [7]. In power-domain NOMA, the users can transmit with different power levels in the same resource block without causing any interference. In contrast with downlink NOMA, the transmit power of the users in uplink NOMA need not be different always. It depends on the channel conditions of each user, since each node's data will be received at the access point (AP) with different power levels based on its distance from the AP. The power-domain NOMA uses superposition coding (SC) at the transmitter and successive interference cancellation (SIC) at the receiver to serve multiple users based on the channel conditions.

With the traditional multiple access techniques in the PHY layer, the IEEE 802.11 WLAN is incapable of supporting dense networks within the limited radio spectrum [5]. Thus, novel channel access schemes are required to support data-intensive applications in dense networks within the limited wireless spectrum. NOMA can be an effective solution as it allows multiple nodes to transmit simultaneously, and thereby improves the performance of the network. A few works have been published to incorporate NOMA in WLAN [5, 8, 9]. Forkan Uddin [5] proposed NOMA in WLAN to improve the throughput and compared it with the traditional OMA techniques. Kheirkhah Sangdeh *et al* [8] built a prototype on a wireless test bed using NOMA, which improves the data rate of the weak user and weighted sum rate of WLAN compared with OMA techniques. Khorov *et al* [9]

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implemented a Wi-Fi prototype that supports NOMA over software-defined radio platform, which will benefit future Wi-Fi networks.

Differently from the existing research works, in this letter, we propose a novel channel access mechanism based on NOMA for next-generation IEEE 802.11 WLANs. With the proposed scheme, multiple nodes during the uplink transmission can transfer the data to the AP simultaneously. To the best of authors' knowledge, this work is the first to propose a channel access scheme for NOMA based IEEE 802.11 multi-rate WLAN to improve the throughput and connectivity. The significant contributions of this letter are organized as follows. (1) We propose a novel channel access scheme based on NOMA for IEEE 802.11 multi-rate WLAN. (2) We present a simple yet accurate analytical model for NOMA based IEEE 802.11 multi-rate WLAN to evaluate the aggregate throughput of the network. (3) From the analytical and simulation results, we observe that the throughput performance and connectivity are significantly improved compared with conventional IEEE 802.11 multi-rate WLAN. (4) Finally, the analytical results are corroborated with simulation studies using ns-3.

2. NOMA based IEEE 802.11 multi-rate WLAN

In this section, we present a NOMA based channel access scheme for IEEE 802.11 multi-rate WLAN, where the AP is located at the centre of the coverage area as shown in figure 1. The entire coverage area is divided into Z regions based on the data rates. The network comprises N number of nodes, which are uniformly deployed and equally distributed over Z regions. The transmission rate of the nodes in region-z is indicated by $R_z | z \in [1, Z]$. The position of the node and its distance $d_z | z \in [1, Z]$ from the AP determine its transmission rate. Here, the nodes transmit at distinct data rates using rate adaptation. The nodes in the near region (region-1) use higher data rate, whereas the far region nodes support lower data rate based on the signal-to-noise ratio (SNR). For the proposed scheme we present a data rate based user-clustering algorithm based on [10], which is described as follows.

Algorithm 1 Data rate based user-clustering

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1. $N$ is the total number of nodes/users uniformly deployed and $Z$ is the number of regions.
2. Nodes in region-$z$ transmit at a data rate of $R_z | z \in [1, Z]$.
3. Select the number of user-clusters K= $\lceil \frac{N}{Z} \rceil$ based on number of regions.
4. Group the users into user-clusters for uplink NOMA.
$1^{st}$ user-cluster = $\{n_1, n_{K+1}, n_{2K+1}, ..., n_{(Z-1)K+1}\}$,
$2^{nd}$ user-cluster = $\{n_2, n_{K+2}, n_{2K+2}, ..., n_{(Z-1)K+2}\}$, ...,
$K^{th}$ user-cluster = $\{n_K, n_{2K}, n_{3K}, ..., n_{ZK}\}$.
5. Now, each user-cluster formed is of size $\lceil \frac{N}{K} \rceil$ that consists of one node from each region as depicted in figure 1.
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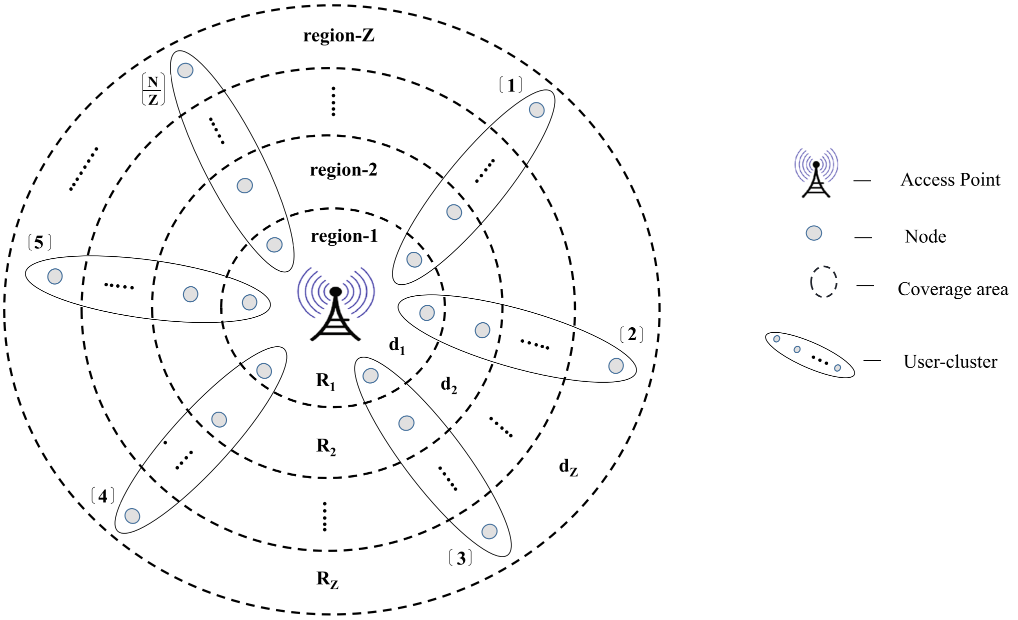

Figure 1. NOMA based IEEE 802.11 multi-rate WLAN.

2.1 *Proposed channel access scheme for NOMA based WLAN*

The proposed channel access scheme for the NOMA based WLAN is described as follows. (1) Initially, user-clusters are formed based on the data rate based user-clustering algorithm as given earlier. Each user-cluster consists of nodes, one each from the Z regions. (2) In the proposed scheme, the nodes in the near region alone will contend for medium access. Thus the number of contending nodes for channel access is $\lceil \frac{N}{Z} \rceil$ instead of N nodes. (3) When the near region node obtains the channel access after the distributed inter-frame space (DIFS) duration, it waits for transmission. (4) After this, the node in near region will send a request-to-send (RTS) control frame to the AP. Then the AP responds with clear-to-send (CTS) frame, which consists of the address of near region node that won the channel access in the destination address field. This CTS frame is received by all the nodes in the network. (5) The nodes in the corresponding user-cluster are now aware that their paired near region node won the channel access from the received CTS frame. (6) All the nodes in the corresponding user-cluster will concurrently transmit using power-domain NOMA. (7) Superimposed data of near and far region nodes received at the AP is decoded using SIC technique.

3. System model

In this section, we present a simple yet accurate analytical model to compute the aggregate throughput of conventional IEEE 802.11 multi-rate WLAN and the proposed NOMA based IEEE 802.11 multi-rate WLAN. Here we assume that each node always has a frame ready for transmission, i.e. saturated condition. We also assume that there are no hidden and exposed nodes in the network. The nodes contend for channel access using DCF [3], which is based on carrier sense multiple access with collision avoidance (CSMA-CA) and adapts exponential back-off (BO). Initially, the nodes in the network sense the channel. If the channel is idle, then it waits for DIFS duration and initiates the transmission. In case the channel is sensed busy then every node commences a random BO process and chooses the initial BO in the range $[0, W_0 - 1]$, where W_0 represents the minimum contention window (CW). The counter decrements by one during the BO process when the channel is sensed to be idle and freezes if the channel is busy. For every unsuccessful transmission/collision the BO stage doubles till the maximum CW of $W_m = 2^m W_0$, where m is the maximum BO stage. Once the BO stage approaches maximum CW, it stays there until the number of retransmission attempts reaches the retry limit (L). During the BO process, the nodes are allowed for transmission when the BO counter approaches zero regardless of their BO stage. The conditional transmission probability [3, 11] of a node in region-z with data rate $R_z \,|z \in [1, Z]$ transmits in the randomly chosen slot time is given by,

$$\tau_z^{(R_z)} = \frac{2\left(1 - 2P_{c,z}^{(R_z)}\right)\left(1 - (P_{c,z}^{(R_z)})^{L+1}\right)}{\left(\begin{array}{c} W_0\left(1 - (2P_{c,z}^{(R_z)})^{m+1}\right)\left(1 - P_{c,z}^{(R_z)}\right) + \left(1 - 2P_{c,z}^{(R_z)}\right) \\ \times\left(\left(1 - (P_{c,z}^{(R_z)})^{L+1}\right) + 2^m W_0 (P_{c,z}^{(R_z)})^{m+1}\left(1 - (P_{c,z}^{(R_z)})^{L-m}\right)\right)\end{array}\right)}, \tag{1}$$

where $P_{c,z}^{(R_z)}$ is the probability that the node belonging to region-z with data rate $R_z|z \in [1, Z]$ encounters a collision.

3.1 *Analysis of conventional IEEE 802.11 multi-rate WLAN*

A node transmitting at data rate R_z in region-z will encounter a collision even if one of the similar data rate nodes among $(n^{(R_z)} - 1)$ or any of the nodes among the other regions $n^{(R_x)}|x \in [1, Z], x \neq z$ transmit at the same time, which is given by [11]

$$P_{c,z}^{(R_z)} = \left(1 - (1 - \tau_z^{(R_z)})^{n^{(R_z)}-1}\right)\left(\prod_{x=1, x\neq z}^{Z} (1 - \tau_x^{(R_x)})^{n^{(R_x)}}\right). \tag{2}$$

Equations (1) and (2) form a set of non-linear equations that are solved by numerical methods. The success probability is, if exactly one node transmits in $n^{(R_z)}$ of region-z in the randomly chosen slot time and if none of the nodes among $(n^{(R_z)} - 1)$ and $n^{(R_x)}|x \in [1, Z], x \neq z$ of the other regions transmit at the same time, conditioned such that there is at least one transmission in region-z, $z \in [1, Z]$, is given by [11]

$$P_{s,z}^{(R_z)} = \frac{\left(n^{(R_z)}\tau_z^{(R_z)}(1 - \tau_z^{(R_z)})^{n^{(R_z)}-1}\right)\left(\prod_{x=1,x\neq z}^{Z} (1 - \tau_x^{(R_x)})^{n^{(R_x)}}\right)}{P_{tr,z}^{(R_z)}}, \tag{3}$$

where the probability of transmitting at least one node at data rate $R_z|z \in [1, Z]$ is $P_{tr,z}^{(R_z)} = 1 - (1 - \tau_z^{(R_z)})^{n^{(R_z)}}$. Further, the throughput of region-z with data rate $R_z|z \in [1, Z]$ is given by

$$S_w^{(R_z)} = P_{tr,z}^{(R_z)}\ P_{s,z}^{(R_z)}\ E[P](E[T_{slot}])^{-1}, \tag{4}$$

where $E[P]$ is average payload and $E[T_{slot}]$ is the average length of the slot time [11]. Let the empty slot duration be σ; the successful and collision slots duration are given by [3],

$$\begin{aligned} T_{sw}^{(R_z)} &= DIFS + T_{RTS} + T_{CTS} + T_H^{(R_z)} + T_{E[P]}^{(R_z)} + 3SIFS \\ &\quad + T_{ACK} + 4\delta, \\ T_{cw}^{(R_z)} &= DIFS + T_{RTS} + \delta, \end{aligned}$$

where δ is the propagation delay; $DIFS$, T_{RTS}, T_{CTS}, $T_H^{(R_z)}$, $T_{E[P]}^{(R_z)}$, $SIFS$, and T_{ACK} represent the duration of DIFS, RTS, CTS, header, payload, SIFS, and acknowledgement (ACK) frame, respectively. The aggregate throughput of the conventional IEEE 802.11 multi-rate WLAN [11] is given by, $S_w = \sum_{z=1}^{Z} S_w^{(R_z)}$.

3.2 *Analysis of NOMA based IEEE 802.11 multi-rate WLAN*

The significant feature of the proposed scheme is that the nodes in the near region ($z = 1$) alone are engaged in the process of contention. Thus, the collision probability and the success probability with data rate R_1 in the randomly chosen slot time, respectively, are given by [3]

$$P_{c,1}^{(R_1)} = 1 - (1 - \tau_1^{(R_1)})^{n^{(R_1)}-1}. \tag{5}$$

$$P_{s,1}^{(R_1)} = (n^{(R_1)}\tau_1^{(R_1)}(1 - \tau_1^{(R_1)})^{n^{(R_1)}-1})(P_{tr,1}^{(R_1)})^{-1}. \tag{6}$$

Here, the probability of transmitting at least one node at data rate R_1 is given by $P_{tr,1}^{(R_1)} = 1 - (1 - \tau_1^{(R_1)})^{n^{(R_1)}}$. We can find the transmission and collision probabilities using numerical methods from equations (1) and (5). The throughput of near region (region-1) with data rate R_1 is given by [3]

$$S_{nw}^{(R_1)} = \ P_{tr,1}^{(R_1)}\ P_{s,1}^{(R_1)}\ E[P](E[T_{nslot}])^{-1}. \tag{7}$$

The average length of slot time $E[T_{nslot}]$ is given by [11]

$$\begin{aligned} E[T_{nslot}] =& (1 - P_{tr,1})\sigma + P_{tr,1}^{(R_1)} P_{s,1}^{(R_1)} \\ & \times \max(T_{sw}^{(R_1)}, T_{sw}^{(R_2)}, \ldots, T_{sw}^{(R_Z)}) \\ & + P_{tr,1}^{(R_1)}(1 - P_{s,1}^{(R_1)})T_{cw}^{(R_1)}. \end{aligned} \tag{8}$$

In equation (8), the first term represents the mean duration of an idle slot. The second term accounts for the mean successful slot duration when the successful transmission is by user-cluster nodes of data rate R_1, R_2, ..., $R_{(Z-1)}$, R_Z. Here, the maximum successful duration is determined based on the far region nodes of lowest data rate R_Z since the nodes in the user-cluster transmit non-orthogonally in the allowed maximum duration. The third term signifies average duration of collision slot when the region-1 nodes that participate in the contention process may collide. When the node in region-1 obtains the channel access, the respective user-cluster nodes are allowed to concurrently transmit based on NOMA. Thus the aggregate throughput is the sum of the throughput of the user-cluster nodes of different regions of NOMA based IEEE 802.11 multi-rate WLAN, which is given by [3, 10, 11]

$$S_{nw} = \sum_{z=1}^{Z} \frac{P_{tr,z}^{(R_z)}\ P_{s,z}^{(R_z)}\ E[P]}{E[T_{nslot}]}. \tag{9}$$

4. Results and discussion

In this section, we present the analytical results obtained using MATLAB and validated with the extensive simulation works using ns-3 [12]. Here we consider NOMA based IEEE 802.11 multi-rate WLAN, which consists of an AP at the centre of the coverage area and 240 number of nodes. The uplink communication between the AP and the nodes is performed with the RTS/CTS mechanism. For simplicity, we consider an equal number of nodes in each region and form the user-clusters as depicted in figure 1. We selected the system parameters based on IEEE 802.11b standard to obtain the results as shown in table 1. Nevertheless, the model also applies to other amendments of IEEE 802.11 WLANs. The entire network is divided into four circular regions whose region lengths and data rates (1, 2, 5.5, and 11 Mbps) are reported in [11] according to the IEEE 802.11b standard. Here the region-1 nodes support the highest data rate of 11 Mbps, whereas, region-4 nodes exhibit the lowest data rate of 1 Mbps. Further, the simulations are conducted for 100 seconds 30 times with a confidence interval of 95% and are averaged to evaluate the throughput.

Figure 2 shows aggregate throughput of proposed NOMA based IEEE 802.11 multi-rate WLAN using the RTS/CTS mechanism. We compare the results with the conventional IEEE 802.11b multi-rate WLAN. Throughput performance in both the schemes reduces on increasing the number of nodes. This is because of the increase in contention among the nodes and collisions. Additionally, we notice substantial increase in the aggregate throughput using the proposed scheme. This is because the proposed scheme allows transmission of multiple user-cluster nodes in the same resource block

Table 1. Analytical and simulation parameters.

Parameter	Value	Parameter	Value
Payload $E[P]$	1023 bytes	Slot time σ	20 μs
MAC header	28 bytes	RTS frame	20 bytes+PHY header
PHY header	24 bytes	CTS frame	14 bytes+PHY header
DIFS, SIFS	50 μs, 10 μs	ACK frame	14 bytes+PHY header
Propagation delay δ	1 μs	m, L	5, 6
Minimum CW W_0	32	UDP interval	0.01

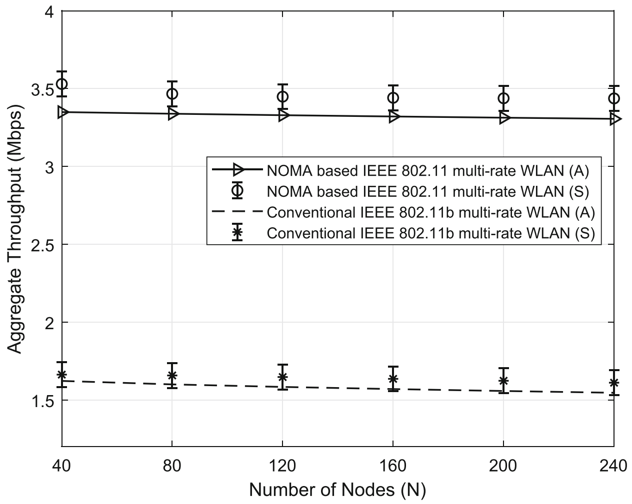

Figure 2. Aggregate throughput of proposed scheme.

using NOMA, thereby utilizing the available spectrum resources efficiently. The performance enhancement is also due to the reduction in the number of collisions as near region nodes alone participate in the contention for channel access. Thus, the proposed NOMA based WLAN provides improved throughput performance as well as throughput gain of 209.4% for $N = 100$ nodes compared with conventional multi-rate WLAN [5]. Table 2 provides the NOMA based IEEE 802.11 multi-rate WLAN's connectivity and aggregate throughput analysis for the network size of $N \in \{100, 200, 300, 400\}$. The aggregate throughput of NOMA based IEEE 802.11 multi-rate WLAN obtained for $N = 400$ is greatly improved compared with conventional IEEE 802.11b multi-rate WLAN because of the simultaneous transmissions of multiple users using NOMA. It clearly demonstrates the enhanced connectivity in NOMA based IEEE 802.11 multi-rate WLAN. It is evident from the results that the proposed scheme outperforms the conventional IEEE 802.11 multi-rate WLAN in terms of throughput and connectivity.

5. Conclusion

In this research work we have designed a novel channel access scheme for next-generation WLAN, by considering non-orthogonal multiple access (NOMA) at the physical layer and distributed coordination function (DCF) at the MAC layer. The proposed scheme allows simultaneous transmissions by user-cluster nodes in the same resource block using NOMA as well as reduces the number of contending nodes. We have presented an analytical model to evaluate the aggregate throughput of the proposed NOMA based IEEE 802.11 multi-rate WLAN. From the analytical and simulation results, it is evident that aggregate throughput and connectivity of the network can be significantly improved using the proposed scheme when

Table 2. Connectivity and aggregate throughput performance.

	Aggregate throughput (Mbps)			
	NOMA based IEEE 802.11 multi-rate WLAN		Conventional IEEE 802.11 multi-rate WLAN	
Network size (N)	Analytical (A)	Simulation (S)	Analytical (A)	Simulation (S)
100	3.3339	3.5069	1.5920	1.6517
200	3.3133	3.4567	1.5583	1.6201
300	3.2956	3.4432	1.5303	1.5882
400	3.2789	3.4385	1.5021	1.5588

compared with the conventional IEEE 802.11 multi-rate WLAN.

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