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NOMA based RAW mechanism for performance enhancement of IEEE 802.11ah dense IoT networks

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Abstract. In this article, we propose non-orthogonal multiple access (NOMA) based restricted access window (RAW) mechanism for IEEE 802.11ah compliant dense Internet of Things networks. The proposed scheme utilizes the principles of NOMA at the physical layer and distributed coordination function with the RAW mechanism at the data link layer. Using an analytical model, we evaluate the throughput of IEEE 802.11ah wireless local area network (WLAN) under the proposed RAW-NOMA integrated mechanism. From the results, we establish that the throughput and scalability of IEEE 802.11ah WLAN are significantly improved under the proposed channel access scheme. Finally, analytical findings are corroborated with ns-3 simulations.

Keywords. IEEE 802.11ah; internet of things; non-orthogonal multiple access; restricted access window; WLAN.

1. Introduction

The proliferation of Internet of Things (IoT) has accelerated the Internet usage, as IoT interconnects myriads of devices by equipping them with the capability to collect, process, and communicate information without human intervention. With the rapid increase in the number of wireless devices, scalability and throughput are the critical concerns in IoT networks. Nevertheless, the scarcity of wireless spectrum is a significant challenge in overcoming these issues. This leads to the need for effective utilization of spectral resources to enhance the performance of dense IoT networks.

The non-orthogonal multiple access (NOMA) technique has recently received significant attention for LTE, 5G, and beyond systems. It is a promising radio access technology that can empower dense and heterogeneous IoT networks to overcome the limitations of spectral scarcity. In contrast to orthogonal multiple access radio technologies (TDMA, FDMA, etc.), NOMA has proven its capability to improve network connectivity, throughput, and fairness. On the other hand, IEEE 802.11ah, popularly known as Wi-Fi HaLow, is introduced as an amendment to the legacy IEEE 802.11 with a motive to provide broad coverage, large-scale deployment, high throughput, and low power consumption. One of the significant enhancements of IEEE 802.11ah is the restricted access window (RAW) mechanism. The RAW mechanism is a group-based contention mechanism that improves the network performance in dense networks by distributing the contention among the devices in various RAW slots [1]. The contention in a dense IoT network is reduced by grouping them and allowing the devices within a group to simultaneously contend for channel access during a RAW slot by adopting the distributed coordination function (DCF) protocol. On account of this, the RAW mechanism enhances the throughput and scalability of 802.11ah based dense IoT networks.

NOMA can be a potential candidate for wireless local area network (WLAN) because of its exceptional performance in dense heterogeneous environments with diverse channel conditions, which can be prone to extreme interference [2]. As NOMA facilitates multiple transmissions simultaneously, its inclusion in the 802.11ah brings forth the opportunity to utilize the spectrum efficiently, reduce channel contention, and improve the scalability of IoT networks. A few research works have been published to examine NOMA for WLANs. The authors in [3] used NOMA and proposed a smart antennae based beam allocation system to improve the average user throughput by serving two users simultaneously. Targeting the multi-

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channel ALOHA based WLANs, the authors in [4] proposed a NOMA-aware MAC protocol to improve the uplink throughput and scalability by exploiting different transmission power levels based on channel gains. Similarly, the authors in [5], and [6] enhanced the network utility of ALOHA and CSMA networks by using game theory and optimal user pairing.

Unlike state-of-the-art, this article proposes NOMA based WLAN to improve the scalability and throughput of Wi-Fi HaLow based dense IoT networks. To the best of the authors' knowledge, this work is the first to propose and analytically model for NOMA based RAW mechanism to enhance the performance of dense IoT networks.

2. NOMA based WLAN: Channel access procedure and throughput model

In this section, we present a simple yet accurate analytical model to assess the IEEE 802.11ah RAW mechanism with NOMA. Initially, we determine the achievable data rate by exploiting NOMA at the physical layer of Wi-Fi HaLow. Having estimated the achievable data rate, we use the RAW mechanism at the MAC layer to enhance the network performance in terms of throughput and scalability. The access point (AP) is at the centre of the coverage defined by radius R_c with N associated devices of limited mobility. Further, we assume that the network is free from hidden terminals and evaluate the up-link performance of NOMA based WLAN.

The network scenario envisaged in this article is shown in figure 1. We set a threshold ζ to differentiate the coverage of the AP into two regions. Let $r_1 \in (0, \zeta R_c)$ and $r_2 \in (\zeta R_c, R_c)$ be the continuous random variables that represent the distance from the AP to the edge of region-1 (near region) and from the edge of region-1 to region-2 (far region) respectively. Therefore, the probability density function of the near and the far devices being at a distance

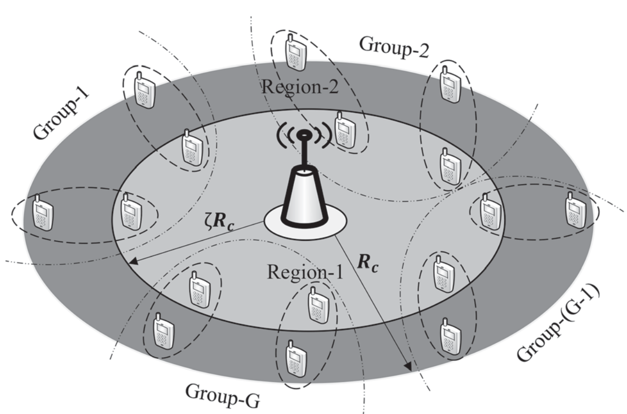

Figure 1. Network scenario.

r_1 and r_2 from the AP is given by $f_{r_1}(r_1) = \frac{2r_1}{(\zeta R_c)^2}$ and $f_{r_2}(r_2) = \frac{2r_2}{R_c^2 - (\zeta R_c)^2}$ respectively. In this article, we consider $\zeta = 0.707$, as a result, each region consists of $\frac{N}{2}$ devices. Let R_1 and R_2 be the data rates of devices present in the near and the far regions, where $R_1 > R_2$. respectively.

The duration of the beacon interval is divided into multiple RAW periods, each of duration T_{RAW}. Each RAW period is subdivided into G RAW slots, each of duration T_{slot} such that $G \times T_{slot} = T_{RAW}$. Here, the number of groups and the RAW slots are same. A holding period $T_h = \theta(R_2) + t_d + t_g - t_m$ is set at the end of each RAW slot such that transmission within a given RAW slot do not cross the RAW slot boundary. Here $\theta(R_2)$ is the transmission duration of the far devices with data rate R_2, t_d is the DCF interframe space (DIFS) duration, t_g is the guard interval and t_m is the mini-slot (channel time is considered as discrete mini-slots) duration . Assuming that the payload and control frames are transmitted at the same data rate (R_i), the transmission time of the near and the far devices with data rates R_1 and R_2 are given by,

$$\theta(R_i) = \frac{Header + \vartheta E[P]}{R_1} + 3t_s + 3t_p + \delta, \ \forall \ near\ devices, \tag{1}$$

$$= \frac{Header + E[P]}{R_2} + 3t_s + 3t_p, \ \forall \ far\ devices. \tag{2}$$

where $Header = RTS + CTS + H + ACK$, $\vartheta = \lceil \frac{\mathcal{M}_\theta^{(R_1)}}{\mathcal{M}_\theta^{(R_2)}} \rceil$ is the transmission opportunity (TXOP) of the near devices and $\mathcal{M}_\theta^{(R_i)} = \lfloor \frac{T'_{slot}}{\theta(R_i) + t_d + t_m} \rfloor$ is the maximum number of transmissions by a device with data rate R_i, in the effective duration of the RAW slot available for channel access ($T'_{slot} = T_{slot} - T_h$). In Eq. (1), RTS, CTS, H, $E[P]$ and ACK are the request-to-send, clear-to-send, header, average payload, and acknowledgement (ACK) frames respectively and t_s, and t_p and δ are the short interframe space (SIFS) duration, propagation delay respectively and the difference between the transmission durations of near and far devices.

2.1 *Proposed NOMA based RAW mechanism for IoT networks*

In this subsection, we propose NOMA based RAW mechanism for Wi-Fi HaLow based dense IoT networks. The AP periodically broadcasts the beacon frames with several information elements. Having received the beacon, all the devices in the network try to associate with the AP. Based on the measured signal-to-noise ratio (SNR), each device sets its data rate and communicates the same to the AP with the physical layer header during the association procedure. The signalling (SIG) field in physical layer convergence protocol (PLCP) data unit (PPDU) is used by the AP to decode the transmission parameters of devices. The SIG field consists of two bits to select the appropriate bandwidth as well as four bits to choose the modulation and coding schemes. The AP uses decoded information to segregate the devices into near and far regions. The proposed scheme comprises three phases.

1. The AP forms the network into $\frac{N}{2}$ pairs by using the Hungarian pairing scheme [7], where each pair consists of a near device from region-1 and a far device from region-2. However, multiple users can simultaneously transmit with distinct power at the cost of the increased complexity of the AP. Hence, we consider two devices per pair to simplify the analysis.
2. Using the RAW mechanism, the AP uniformly divides the $\frac{N}{2}$ pairs into G groups such that each group consists of an equal number of devices from region-1 and region-2. Hence, the total number of contending devices in an i^{th} group are $\frac{g_i}{2}$ instead of g_i devices, where $g_i = \frac{N}{G}$.
3. Finally, the AP allocates each group with a RAW slot in which the near region devices of a group alone contend for the channel access in the allocated RAW slot.

Having completed the three phases, the AP assigns a unique association identifier (AID) to each device and broadcasts the RAW parameter set information elements (RPS-IE) which consist of parameters to configure the RAW mechanism. Then all the devices communicate with the AP by using the Algorithm 1. The algorithm is as follows: The near device senses the channel for DIFS duration and initializes the back-off counter from $[0, W_0 - 1]$ in a RAW slot, where W_0 is the minimum contention window. Having obtained the channel access, the near device sends an RTS packet with its source address to the AP. Then, the AP responds with a CTS packet with the destination address of the near device. If the source and destination address in the RTS/CTS packet matches with the address of the paired device, the far device simultaneously transmits the data packets along with the near device. The superposition coding enables the simultaneous transmission in the proposed channel access, whereas the conventional WLAN treats it as a collision. After the successful reception of the data packets, the AP sends the ACK frame. In this scheme, the high data rate (near) devices will be transmitting more packets compared to the low data rate (far) devices to maintain equal transmission time and to improve the channel utilization.

Algorithm 1 Channel access scheme for RAW-NOMA

```
AP segregates all the devices into near and far region devices;
for each device do
    if Near region device then
        starts contending for the channel;
        sends RTS packet;
        transmits data packet (DATA1) after receiving CTS from the AP;
    else if Far region device then
        waits till the reception of RTS and CTS packet from the device and the AP;
        if address in CTS = address of paired device then
            starts transmitting the data packet (DATA2);
        end if
    end if
end for
```

2.2 *Data rate analysis*

In this subsection, we assess the achievable data rate by considering a path loss model given by $PL(r) = 10^{0.8+\log_{10} E[r]^{\alpha}}$, where α is the path loss exponent. The transmission power is varied according to the distance between the AP and the device by adopting the fractional power control (FPC) scheme. Thus, the transmitted power is expressed as $P_i = P_t E[r_i]^{\beta\alpha}$, where $\beta \in [0, 1]$ is a FPC parameter, and P_t is transmission power without FPC scheme. If $\beta = 0$, all the devices transmit with the same power without FPC. If $\beta = 1$, the total path loss is fully compensated for all the devices so that all the devices should have the same target received power level at the AP.

At the AP, the message frame from the near device is received with higher power than that of the far device. Accordingly, the AP initially decodes the message corresponding to the near device by treating the signal from the far device as interference. After that, the decoded message of the near device is subtracted from the composite received signal by using the successive interference cancellation (SIC) technique to retrieve the message corresponding to the far device. Therefore, the signal-to-interference-plus-noise ratio at the AP corresponding to the decoding of messages of the near and the far devices (γ_1 and γ_2 respectively) are given by $\gamma_1 = \frac{\eta_1}{\eta_2+1}$, $\gamma_2 = \frac{\eta_2}{\epsilon\eta_1+1}$, where $\eta_i = \frac{P_i G_{tx} G_{rx}}{PL(r_i)\ E[r_i]\ N_o}$ is the SNR with which the signals from the near/far device arrives at AP. Here, G_{tx} and G_{rx} are the respective gains of the transmit and the receive antennas, and $N_o = n_0 B$ is total noise power, where n_0 is noise spectral density and B is the bandwidth. Further, $\epsilon \in [0, 1]$ represents the SIC inefficiency and $\epsilon = 0$ represents perfect SIC i.e., an increase in the value of ϵ indicates the receiver with higher SIC inefficiencies. Therefore, the achievable data rate of a i^{th} device (near/far) can be estimated as,

$$R_i = B \log_2 (1 + \gamma_i), i \in \{1, 2\}. \tag{3}$$

Due to the distinct data rates, the time taken for a paired transmission depends on the transmission time of the far device. Hence, the channel time is wasted due to the difference $\delta = |\theta(R_1) - \theta(R_2)|$ between the transmission times of near and far devices. In order to improve the channel utilization and maximize the throughput, we ensure that $\lceil \frac{\mathcal{M}_\theta^{(R_1)}}{\mathcal{M}_\theta^{(R_2)}} \rceil \approx \lceil \frac{R_1}{R_2} \rceil$ for $T_{slot} \geq 2\theta(R_2)$, enabling the near device to send more packets than the far device.

2.3 *Analysis*

In this subsection, we analytically evaluate the throughput of NOMA based IEEE 802.11ah WLAN with the RAW mechanism by considering non-saturated traffic conditions. The analytical model employed in this section is based on [1]. During a RAW slot T'_{slot}, all the devices belonging to the group access the channel using DCF. Therefore, the average throughput per RAW slot is defined as the amount of information successfully transmitted in a j^{th} RAW slot by a group of devices [1] and is given by,

$$Th_j = \frac{G\ E[P]}{T_{RAW}} \sum_{i=1}^{2} \sum_{z=1}^{\mathcal{M}_\theta^{(R_i)}} z \mathbb{P}\{\mathcal{Z} = z\} \mathbb{P}_{s,j}^{(R_1)}. \tag{4}$$

where $\mathcal{Z}$ is discrete random variable that represents the number of transmissions and $\mathbb{P}_{s,j}^{(R_i)}$ is probability of having a successful transmission by a device with data rate R_i in a j^{th} RAW slot, as mentioned in [1].

3. Results and discussion

This section presents the analytical and simulation results to study the throughput performance of IEEE 802.11ah WLAN under the legacy RAW mechanism and the proposed RAW-NOMA integrated mechanism. The analysis considers 512 devices, which are deployed around the AP with a coverage radius of 750 m and divided into groups of size $G \in \{4, 8\}$. Due to spatial separation from the AP, the data rates of the near and the far devices are computed as 3 Mbps and 0.8 Mbps by using Eq. (3) respectively. To validate the analytical findings, we conduct extensive simulations using ns-3 [8]. The simulations are run for multiple RAW durations lasting for 100 s, thirty times and are averaged to find the throughput per RAW slot. Besides, all other specific parameters used for analysis and simulations are listed in table 1.

Figure 2 illustrates the uplink throughput of the WLAN under the proposed RAW-NOMA integrated mechanism for N upto 512 devices, $\beta = 0.1$, $R_c = 750$ m and $\epsilon = 10^{-6}$, and $G \in \{4, 8\}$, by varying the network size. The results are compared with the legacy RAW mechanism. The gradual decrease in the throughput is due to the increase in the

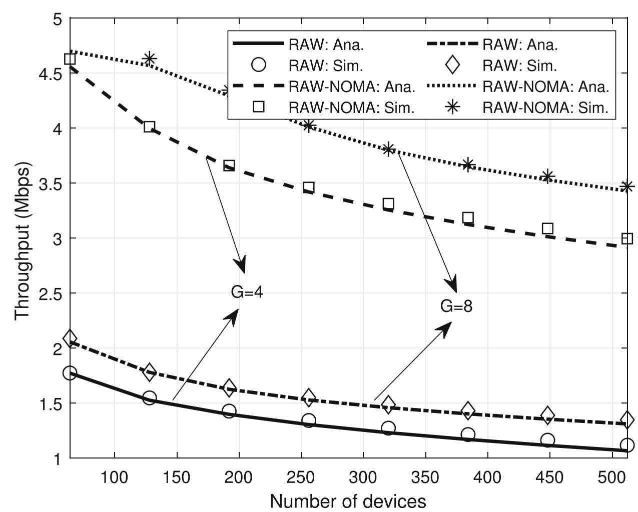

Figure 2. Variation of throughput with the network size.

Table 1. Analytical and simulation parameters.

Parameter	Value	Parameter	Value	Parameter	Value
E[P]	256 bytes	G_{tx}, G_{rx}	0 dB	t_p, t_m	1 μs, 52μs
Header	268 bits	α	3.76	n_0	−173.9 dBm
ACK	14 bytes	B	2 MHz	T_{RAW}	500 ms
t_s, t_d	160 μs, 264 μs	P_{tx}	10 mW	m_b	5
RTS,CTS	20,14 bytes				

contention with an increase in the network size. However, the throughput of WLAN under the proposed RAW-NOMA integrated mechanism is improved due to the reduction in the contention by the user pairing. Further, the channel contention is reduced by increasing the number of groups. We attribute this to the fact that when G becomes higher, the T_{slot} available for each group is reduced, due to which the throughput decreases. On the other hand, the throughput of the RAW mechanism with NOMA is observed to be more than that of the legacy RAW mechanism. The reason behind this is the reduction in the number of contending devices to $\frac{N}{2}$ because of the user pairing scheme as well as the improved spectral efficiency offered by the NOMA scheme compared to the conventional radio access technologies. Hence the performance of the RAW mechanism with NOMA is significantly enhanced compared with the legacy RAW mechanism.

4. Conclusion

In this article, we have proposed a NOMA based RAW mechanism for IEEE 802.11ah dense IoT network to improve throughput and scalability. We have evaluated the throughput of the IEEE 802.11ah WLAN under the proposed RAW-NOMA integrated mechanism and compared it with the legacy RAW mechanism. It is observed from the results that the proposed scheme outperforms the legacy scheme and improves the throughput per RAW slot and scalability.

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