Power Aware Non-Orthogonal Multiple Access for IEEE 802.11ah Based IoT Networks

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Abstract. IEEE 802.11ah is a Wi-Fi standard promoted for Internet of things (IoT) applications. We propose a power aware non-orthogonal multiple access (NOMA) method for improving the performance of IEEE 802.11ah network. The restricted access window (RAW) mechanism in this standard reduces contention in dense IoT networks. Initially, with the power-domain NOMA (PD-NOMA), the data rates of devices are computed. Further, the user-clusters are formed with devices from each region using the proposed method. This further reduces contention and the user-cluster devices concurrent transmissions is possible using PD-NOMA. Using analytical model, the throughput of network is computed. From results, the proposed power aware NOMA method provides substantial improvement in performance compared to conventional IEEE 802.11ah network. The results are validated with simulations.

Keywords: Internet of things · IEEE 802.11ah · power-domain NOMA

1 Introduction

The information technology have witnessed rapid changes and IoT plays major role in this aspect. The connectivity among the devices at any time is very essential for sharing information. Nowadays, the devices are exponentially increasing especially those are connecting to the Internet. Different IoT applications such as smart city, smart health, industrial IoT, etc. are facing daunting challenges towards connectivity issue [1]. The IEEE 802.11ah is an upcoming Wi-Fi standard promoted for IoT applications [2]. It specifies physical and medium access control (MAC) layer features. The RAW mechanism is an innovative feature in IEEE 802.11ah which minimizes the contention. The RAW period (δ_R) is divided into RAW slots, devices into R groups. Every group is alloted with one RAW slot [3].

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For wireless communication, the spectrum resources are very congested and limited. Due to the limited resources in wireless spectrum, the proper multiple access technique can utilize the resources efficiently in dense IoT networks. Thus, the IEEE 802.11ah standard with a suitable multiple access technique can provide an excellent improvement in network performance in dense networking scenarios for next-generation IoT applications [2,4]. Recently, NOMA got attention of researchers because of their advantages over OMA techniques. Also, multiples transmissions in a resource block can be possible using NOMA non-orthogonally [5]. In PD-NOMA, the devices use different power levels for transmission of data [6]. In this paper, a power aware NOMA method is proposed to enhance the performance of IEEE 802.11ah network. The connectivity is very important for upcoming IoT applications.

2 Related Work

From literature, very limited works were endowed for NOMA in WLANs [7–10]. Authors of [7] targeted a mechanism for data transmission using uplink NOMA in Wi-Fi networks. From [8], a NOMA technique was included in WLAN that allowed to transmit simultaneously. In [9], an uplink NOMA was introduced in CSMA/CA networks. Authors of [10] used PD-NOMA in IEEE 802.11ah that provides improved network performance.

3 Network Architecture

The IEEE 802.11ah based network architecture with N devices as showed in Fig. 1 are deployed over access point (AP). The transmission range of AP is

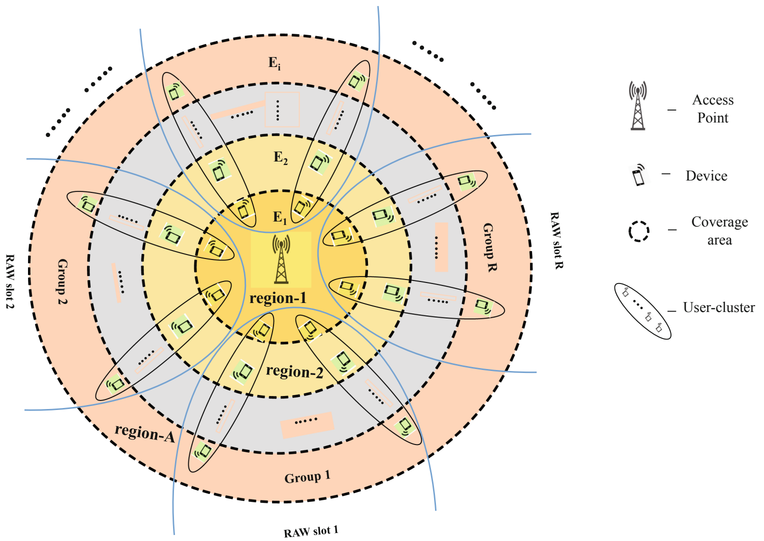

Fig. 1. Network architecture

Table 1. Data rates

Regions	1	2	3	4
$M_i^{(E_i)}$ (m)	$0.16A$	$0.38A$	$0.63A$	$0.88A$
E_i (Mbps)	8.85	2.59	0.60	0.16

classified into A regions with $a_i|i \in [1, A]$ is the radius of region-i. The data rates supported are $E_i|i \in [1, A]$. We consider the channel gain with near region has high gain and region at the fringes has low gain $\{\phi_1 \geq \phi_2 \geq \cdots \geq \phi_i\}$. From AP, the average distance of devices in region-i is,

$$M_i^{(E_i)} = \int_{a_{i-1}}^{a_i} a f_A(a)\, da \tag{1}$$

The power levels are computed using the path loss expression $L(M_i^{(E_i)}) = 8 + 37.6 \log_{10}(M_i^{(E_i)}) + (F)_{dB}$ with the constrained nonlinear minimization using MATLAB R2021b and F is fade margin. The signal to interference noise ratio (SINR) with region-i devices is expressed as [10],

$$S_i = \frac{\mathbb{P}_{ti}\phi_i}{\mathbb{T} + \mathbb{U} + \mathbb{W}}, \tag{2}$$

where $\mathbb{W}$ is AWGN, $\mathbb{P}_{ti}$ is transmit power and the channel gain is given by,

$$\phi_i = \frac{\mathbb{G}_{ti}\mathbb{G}_{ri}}{L(M_i^{(E_i)})}$$

The residual terms that exists during successive interference cancellation (SIC) process are represented in the denominator of Eq. (2), which are,

$$\mathbb{T} = \sum_{k=i+1}^{A} \mathbb{P}_{tk}\phi_k$$

.

$$\mathbb{U} = \eta \sum_{j=1}^{i-1} \mathbb{P}_{t(i-j)}\phi_{i-j}.$$

where η is SIC parameter. Further, the data rate of devices are provided in Table 1 using following relation [10],

$$E_i = \omega \log_2(1 + S_i), \tag{3}$$

where ω is bandwidth.

The power aware NOMA based user-clustering algorithm for IEEE 802.11ah based IoT network is explained in Algorithm 1 [4,10]. Here, the data rates of devices are computed based on the assigned power levels. Further, these data rates are share with the AP through PLCP header. Now, the user-clusters are created

Algorithm 1. Power aware NOMA based user-clustering algorithm

1: Initialize δ_R, N, regions;
2: With PD-NOMA, compute the data rate of devices using the assigned power levels;
3: Share these data rates with the AP;
4: The user-clusters are created with one device from every region;
5: These user-clusters are uniformly divided into groups. Every group allot with a RAW slot as given in Fig. 1;
6: The devices in a particular group can contend in a RAW slot;

with one device from every region. These user-clusters are uniformly divided into groups and allot a group for every RAW slot. The devices in a particular group can contend in RAW slot. Once, the devices in near region got the channel access, it sends request to send (RTS) frame and AP reply with clear to send (CTS) with address of device won the contention. Now, the user-cluster devices transmit simultaneously in a RAW slot and the decoding is possible with the SIC technique.

For the analysis, the network does not have hidden devices and saturated conditions. The channel has mini-slots (δ_m) in a RAW slot. The r^{th} group devices starts contention process with distributed coordination function (DCF). The transmission probability of r^{th} group device is determined using mean value analysis in a RAW slot, which is given by [3],

$$\tau_r^{(E_i)} = \frac{\mathcal{M}_r[Y]}{\mathcal{M}_r[B] + \mathcal{M}_r[Y]}, \tag{4}$$

here $\mathcal{M}_r[B] = \frac{1}{2}\sum_{x=1}^{m} 2^{x-1} W_0 \left(P_{c,r}^{(E_i)}\right)^{x-1}$ is mean count of back-off slots, retry limit $m = 7$, and $\mathcal{M}_r[Y] = \sum_{x=1}^{m}\left(P_{c,r}^{(E_i)}\right)^{x-1}$ gives retransmission attempts.

3.1 Power Aware NOMA for IEEE 802.11ah Based IoT Network

The data rates are computed based on the assigned power levels as provided in Sect. 3. Using the proposed method, near region devices in r^{th} group can only compete for channel contention in a RAW slot. The collision probability having rate E_1 in a RAW slot is given by [10],

$$P_{c,r}^{(E_1)} = 1 - (1 - \tau_r^{(C_1)})^{(g_r^{(E_1)}-1)}. \tag{5}$$

The Eqs. (4) and (5) are solved using MATLAB R2021b. The success probability having rate E_1 in a RAW slot is given by,

$$P_{s,r}^{(E_1)} = \frac{g_r^{(E_1)} \tau_r^{(E_1)} (1 - \tau_r^{(E_1)})^{g_r^{(E_1)}-1}}{P_{tr,r}^{(E_1)}}. \tag{6}$$

Here, $P_{tr,r}^{(E_1)}$ is expressed as,

$$P_{tr,r}^{(E_1)} = 1 - (1 - \tau_r^{(E_1)})^{g_r^{(E_1)}} \tag{7}$$

Further, the transmission duration is considered with lower rate devices, i.e., the highest rate devices can transmit within that time. Hence, the r^{th} group device with rate $E_i|i \in [1, A]$ of user-cluster in a RAW slot is expressed as [10],

$$\Delta_{nh}^{(E_i)} = \sigma_R + \sigma_C + \sigma_h^{(E_i)} + \max\,(\sigma_{\mathbb{E}[P]}^{(E_1)}, \sigma_{\mathbb{E}[P]}^{(E_2)}, \cdots, \sigma_{\mathbb{E}[P]}^{(E_i)}) + 3\sigma_s + \sigma_a + 4\delta. \quad (8)$$

In Eq. (8), the terms sequentially denotes the duration of RTS, CTS, header, payload, SIFS, acknowledgement, and propagation delay. The probability of Δ_ζ having ζ transactions in a RAW slot with λ mini-slots used can be expressed as [2,3],

$$P_{\Delta_\zeta}(\lambda) = \binom{\lambda - \zeta\Delta'_{nh} - 1}{\lambda - \zeta\Delta'_{nh} - \zeta}(P_{tr,r}^{(E_i)})^{\zeta}(1 - P_{tr,r}^{(E_i)})^{\lambda - \zeta\Delta'_{nh} - \zeta}, \quad (9)$$

where $\Delta'_{nh} = \Delta_{nh}^{(E_i)} + \sigma_d$. The random variable $\mathcal{D}$ gives the transactions in effective slot duration $\delta_{R',r} = \delta_{R,r}-$holding period. Then, the following term gives the count of mini-slots used for ζ-transactions in a RAW slot.

$$P_{\mathcal{D},r}^{(E_i)}(\zeta) = \sum_{x=\zeta}^{\delta_{R',r} - (\zeta-1)\Delta'_{nh} - \sigma_d - \delta_m} P\left\{\sum_{r=1}^{\zeta} \lambda_{b,r} = x\right\}, \quad (10)$$

Here, the mean value of $\mathcal{D}$ in a RAW slot is,

$$\mathbb{M}_r^{(E_i)}[\mathcal{D}] = \sum_{\zeta=1}^{\mathbb{N}_t(\delta_{R',r})} \zeta P_{\mathcal{D},r}^{(E_i)}(\zeta).$$

where $\mathbb{N}_t$ is the maximum transmissions,

$$\mathbb{N}_t = \lfloor \frac{\delta_{R',r}}{\Delta'_{nh} + \delta_m} \rfloor$$

The throughput of user-cluster devices in r^{th} group in a RAW slot is [3,10],

$$\mathbb{T}_{nr} = \sum_{i=1}^{A} \frac{R\,\mathbb{M}_r^{(E_i)}[\mathcal{D}]\;P_{s,r}^{(E_i)}\mathbb{E}[P]}{\delta_R}. \quad (11)$$

Finally, the aggregate throughput using proposed method is computed as,

$$\mathbb{T}_{tn} = \sum_{r=1}^{R} \mathbb{T}_{nr}. \quad (12)$$

4 Results and Discussion

We provide analytical results with MATLAB R2021b and simulations with ns-3 [11]. An IEEE 802.11ah network having 5000 devices considered around AP. The network is divided into 4 regions. The user-clusters are created using proposed

Table 2. System parameters

Parameter	Value
$\mathbb{E}[P]$	64 bytes
δ_m	52 μs
Physical header	156 bits
RTS	20 bytes
CTS	14 bytes
DIFS, σ_d	264 μs
SIFS, σ_s	160 μs
σ_a	14 bytes
W_0	32
δ_R	1000 ms
δ	1 μs
m	7

method and devices compete in respective RAW slot. The parameters are given in Table 2. For results, the data rates with respect to four regions considered as given in Table 1. The region-1 devices have 8.85 Mbps data rate and far devices have 0.16 Mbps [10].

The aggregate throughput analysis of power aware NOMA with IEEE 802.11ah network using RTS/CTS is provided in Fig. 2. With the assigned power

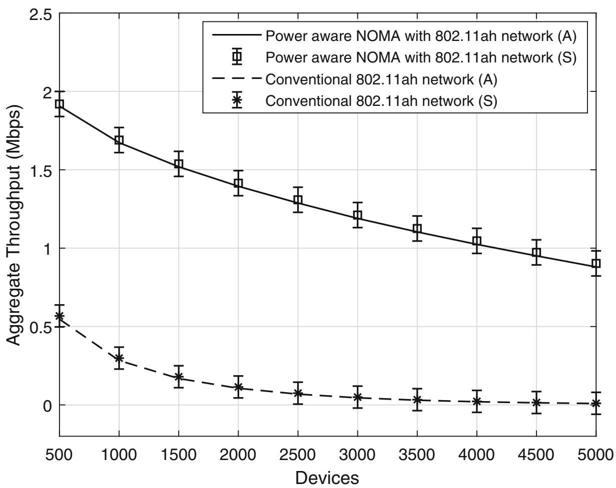

Fig. 2. Aggregate throughput

Table 3. Connectivity analysis

N	Aggregate throughput (Mbps)			
	Power aware NOMA with 802.11ah network		Conventional 802.11ah network	
	Analytical	Simulation	Analytical	Simulation
500	1.9062	1.9196	0.5471	0.5675
1500	1.5191	1.5376	0.1684	0.1798
2500	1.2877	1.3085	0.0687	0.0750
3500	1.1033	1.1254	0.0301	0.0335
4500	0.9507	0.9731	0.0134	0.0152

levels using NOMA, the user-cluster devices can start concurrent transmissions. Also, the number of competing devices will be reduced, which results in decreased collisions. Hence, the power aware NOMA with IEEE 802.11ah network shows superior performance than the conventional IEEE 802.11ah.

Table 3 explores the connectivity point of view for network sizes $N \in \{500, 1500, 2500, 3500, 4500\}$. The proposed method with the devices of $N = 4500$ depicts improved aggregate throughput than conventional network for $N = 500$. The reason for this is because of proposed method using PD-NOMA. The above results clearly shows improved performance in power aware NOMA with IEEE 802.11ah network than the conventional network.

5 Conclusion

For the IEEE 802.11ah standard, a power aware NOMA method has been proposed for enhancing the performance of dense 802.11ah based IoT network. Here, the data rates are computed based on PD-NOMA and user-clusters are created using proposed method. Furthermore, analytical model has been presented for the IEEE 802.11ah using NOMA and computed the throughput. From results, it is evident that the IEEE 802.11ah network using power aware NOMA showed improved performance in terms of saturation throughput.

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