Industrial IoT: Role of IEEE 802.11be WLANs

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***Abstract*—Industry 4.0 ushered in an age of connected industrial systems. This interconnection is aimed at optimizing the industrial processes by collecting data at every stage of the manufacturing process and enabling greater autonomy. However, industry 5.0 has evolved to enable machines to coexist with skilled humans. To enable such synchronization, sensors and actuators should collect data continuously and process it in real-time. Therefore, the underlying network must be capable of supporting a large number of connected devices. IEEE 802.11 wireless local area networks (WLANs) are capable of handling dense deployments due to the introduction of orthogonal frequency division multiple access (OFDMA) that allows a simultaneous transmission to multiple nodes. This paper proposes a scheduling algorithm for IEEE 802.11be WLANs to serve a large number of users simultaneously in a fair manner in the context of the industrial Internet of things (I-IoT).**

***Index Terms*—Internet of things, industrial internet of things, massive machine type communication, IEEE 802.11be.**

I. INTRODUCTION

Internet of Things (IoT) has seen exponential growth in the past several years especially due to an increasing market for smart and connected devices. The statistics corroborate this claim as the global IoT market is forecast to grow to USD 1.8 trillion by 2028 from USD 381.30 billion in 2021 [1]. Among the key reasons for such exponential growth of IoT is the rise of smart cities and industries. In 2019, the European Innovation Partnership for Smart Cities and Communities (EIP-SCC) invested USD 1.12 billion in the development of 300 smart cities. The role played by the IoT in smart cities is to support the critical infrastructure such as monitoring of water and air quality, traffic management, smart grids, improvement of public utilities by analyzing the data. Big data and artificial intelligence (AI) are critical in analyzing the massive data generated by the connected infrastructure. Additionally, the innovation in the consumer IoT space and the impact of COVID-19 has accelerated the growth of the global consumer IoT market. The consumer IoT space includes smart homes and appliances connected to the internet. It is estimated that the consumer IoT market will grow seven-fold in the current decade from USD 70.52 billion in 2020 to USD 292.83 billion in 2030 [2]. There were an estimated 30 billion devices connected to the internet in 2020 [3]. To support this growth, the next generation of wireless communication networks are expected to deliver a high-throughput and low-latency connectivity. The beyond 5G (B5G) is the evolution of the current fifth-generation (5G) cellular network. It supports massive machine type communication (mMTC) vertical using 5G New Radio as well as narrow-band IoT (NB-IoT) [4]. The NB-IoT can offer low power operation for industrial IoT (I-IoT) applications [5]. However, in the case of the consumer sector, Wi-Fi is the dominant technology where the latest consumer electronics are equipped with Wi-Fi connectivity [6]. However, based on the applications and key performance indices (KPI), the communication technology can be selected. Wi-Fi is a reliable communication technology for high throughput applications but it couldn't support a large number of users simultaneously. However, the introduction of the orthogonal frequency division multiple access (OFDMA) in the latest IEEE 802.11ax standard began the transition towards supporting large deployments [7].

OFDMA is a multiple access mechanism that allows the simultaneous transmission to multiple stations (STA). OFDMA is especially beneficial in low bandwidth applications like IoT where multiple STAs can be served fairly and reliably. Therefore, Wi-Fi is now equipped with the capability to support the I-IoT and other use cases that fall in the mMTC category. The next IEEE 802.11 standard is expected to be approved in May 2024 and will be denoted as IEEE 802.11be. This amendment is also known as the Extremely High Throughput (EHT) and a task group (TGbe) has almost reached the half-time mark [8]. The scope of this amendment is to define the medium access control (MAC) layer and physical (PHY) layer specifications. Some of the key features that will help in improving the throughput and spectral efficiency include [9], operation in the 2.4, 6, and 6 GHz bands with backward compatibility, simultaneous multi-link operation between STA and AP, multiple Access Point (AP) coordination, enhanced

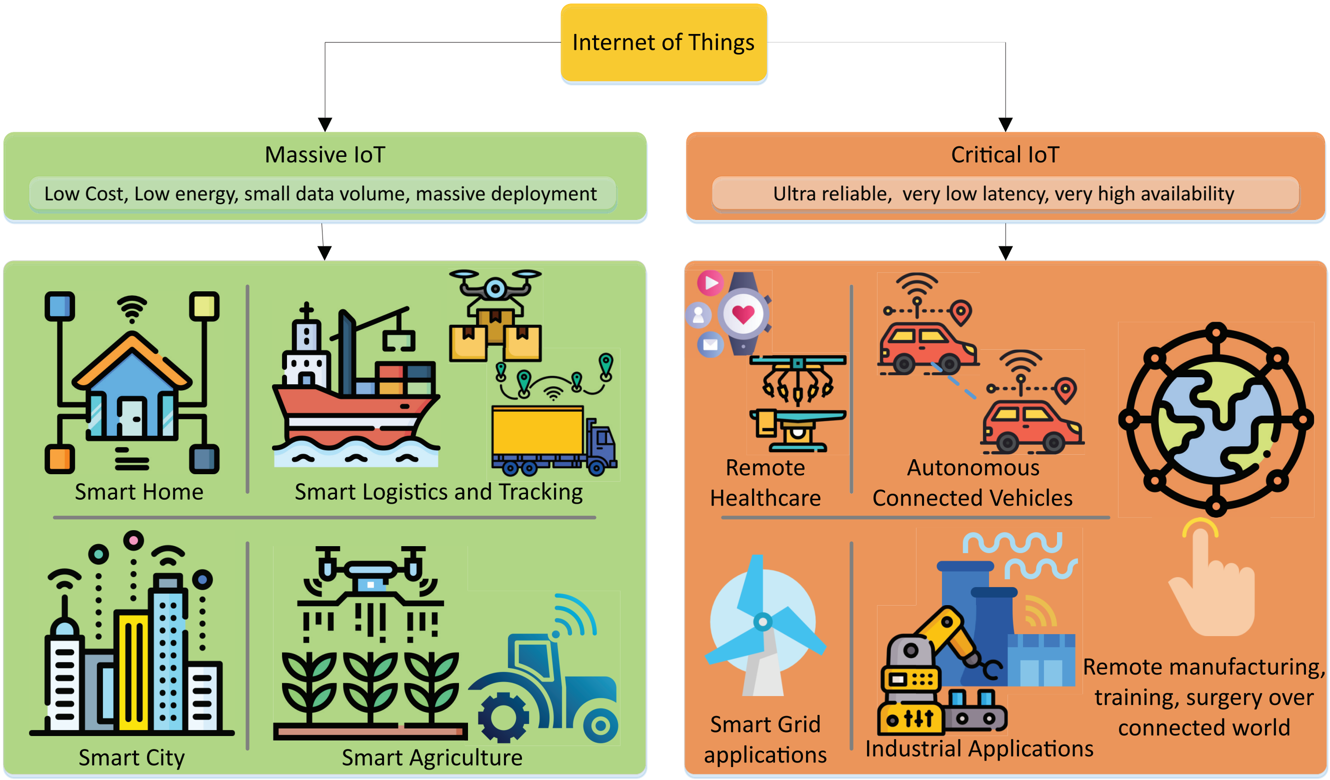

Fig. 1. IoT applications based on key performance indicators.

multi user multiple-input multiple-output (MU-MIMO), introduction of Hybrid Automatic Repeat Request (HARQ), and introduction of time-sensitive networking (TSN). However, there are some incremental enhancements as well from the previous IEEE 802.11ax or high-efficiency (HE) standard like, increased channel width, up to 320 MHz over the previous 160 MHz channel width 4096-Quadrature Amplitude Modulation (QAM) from the previous 1024-QAM, allocation of multiple resource units (RUs) to a single STA, and doubling the number of spatial streams in MU-MIMO.

Two classes of IoT can be defined based on the KPIs, massive IoT and critical IoT. The EHT will be capable of supporting both classes due to the above-mentioned enhancements. The OFDMA and MU-MIMO are the key enabling technologies for massive IoT which is characterized by massive users, smaller data size, low-cost and low energy. While OFDMA and HARQ can power the critical IoT which is characterized by ultra-reliability, low latency, and high availability. Fig. 1 illustrates the IoT applications as identified by the KPIs. IEEE 802.11be or Wi-Fi 7 is a good candidate for providing a reliable network service. In this paper, we focus on scheduling the channel resources using OFDMA for dense I-IoT deployments as depicted in Fig. 2. OFDMA divides the available channels into sub-channels. In the case of I-IoT, the bandwidth requirements are low, therefore, we assume a 20 MHz channel. This 20 MHz channel is divided with a sub-carrier spacing of 78.125 kHz to yield 256 sub-carriers or tones. These tones are then grouped into resource units (RUs) comprising of 26, 52, 106, or 242 tones. This implies that the number of RUs differs based on the RU size. Since each RU can be uniquely allocated, therefore, a similar number of STAs can be simultaneously served. Accordingly, a 20 MHz channel divided into 26, 52, 104, 242 tone RUs can be allocated to a maximum of 9, 4, 2 and 1 STAs respectively. In the EHT amendment, the restriction on unique allocation will be removed to allow the allocation of resources based on the Quality of Service (QoS) requirements. As the I-IoT STAs have low bandwidth requirements, the smaller RUs will be allocated, thus improving the scalability of the I-IoT system.

The AP can perform the function of a scheduler in a Wi-Fi network. The AP is aware of the buffer status of each STA due to an explicit Buffer State Report, which informs the AP about the buffer status of each AP and is transmitted in response to a buffer state report poll (BSRP). Secondly, the STA may inform the AP about its buffer state in the QoS Control Field when transmitting a QoS data frame.

This work envisages a scheduler for improving fairness among I-IoT nodes (STAs) in a dense WLAN network. Taking into consideration the long-term history of resource allocation at the AP. Therefore, we propose a scheduler that tracks the history of transmissions in both downlink (DL) and uplink (UL). The STAs are scheduled to transmit if their usage of the airtime is below the maximum threshold as well as according to their buffer status. We introduce randomness to prevent starvation of the STAs. We evaluate the performance of this scheduler on a network simulator. The results show that the

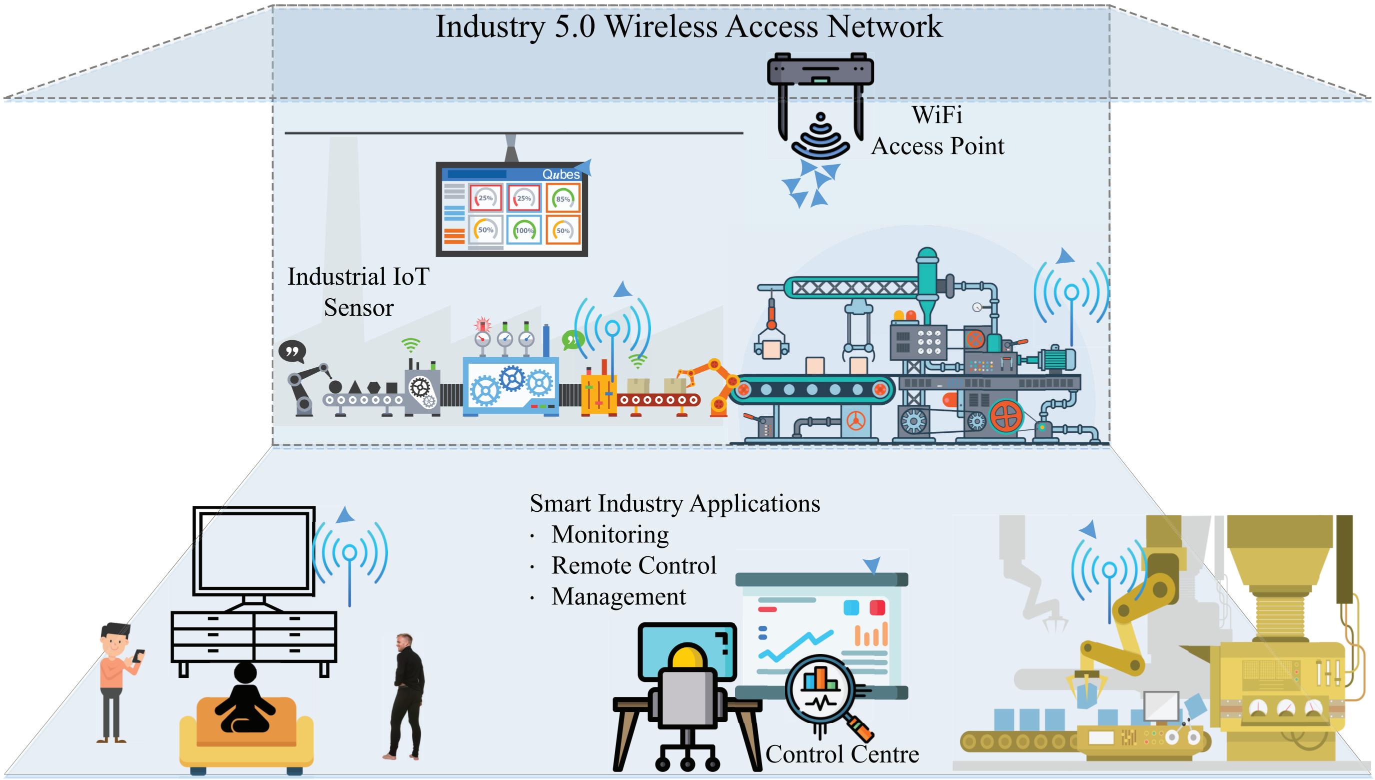

Fig. 2. I-IoT over a Wi-Fi network. The figure shows the scope of applications in I-IoT scenario.

proposed algorithm is fairer when compared to the round-robin scheduler which has been validated in NS-3 simulator.

This paper is organized as follows. Section II is the related work on this issue while section III introduces the proposed methodology. Section IV describes the evaluation of the proposed method and presents a discussion based on the evaluation results. Section V concludes the paper and lists the future road-map for our research.

II. RELATED WORKS

OFDMA is a key enabler in IEEE 802.11ax as well as 5G New Radio (NR) [10]. Therefore, several proposals to optimize the OFDMA operation in Wi-Fi exist in the body of literature. For the UL, the Wi-Fi 6 standard has defined a default random access procedure known as Uplink OFDMA Random Access (UORA), but for the DL, no standard method is defined [11]. The majority of the schedulers proposed in the literature have one key goal, which is to maximize the throughput. However, several works consider latency as well. [12] studies the effect of using higher modulation indices and DL-OFDMA on throughput. The DL allocation takes into consideration the buffer size only. The use of central 26-tones can positively affect the throughput but the effect of OFDMA is visible only when the number of users increases drastically. In [13], authors propose a scheduling and resource allocation methodology that relaxes a key constraint of a single RU allocation and use a divide and conquer approach while considering the bandwidth requirements. In [14], authors develop a scheduler for maximizing the throughput considering the channel bandwidth, and STA traffic and transmission parameter status. Authors devise an aging mechanism that is considered in the optimization problem and represents the previous allocations. Their simulations were implemented on NS-3 to reveal the OFDMA throughput gains. [15] validates the NS-3 implementation of the IEEE 802.11ax with UL and DL multi-user transmissions. [16] and [17] target UL OFDMA scheduling. They explore the conventional algorithms like the Proportional Fair (PF), Max Rate, and Shortest Remaining Processing Time (SRPT) to schedule uplink transmissions. [17] introduces deep reinforcement learning to allocate the channel resources. The learning of channel conditions helps in dynamically allocating the resources and exceeding the heuristic algorithms in performance owing to its adaptability to the changing channel conditions.

The current schedulers primarily focus on increasing the throughput of the system. However, in dense deployments, the issue of fairness is a key consideration, where some STAs may enjoy the most of the resources, while others might starve. Therefore, we focus our study on a fair resource allocation among the STAs for I-IoT networks in dense deployments. The use of AI is increasingly becoming a norm, however, due to an added computational and energy overhead, its benefits may not outweigh the cons in the I-IoT scenarios. Therefore, low complexity mechanisms with no additional overheads are more favorable then computationally complex methods.

Algorithm 1 RU allocation algorithm for DL/UL transmission

```
Initialize: $C_l(n_i) and C_{rand}(n_i)$
Compute $r$ number of STAs that can be granted RU
while AP has TXOP: do
    for all $i$ in candidate list do
        if $C_l(n_i) < C_{lmax}$ && $QueueSize! = 0$ then
            Generate $C_{rand}(n_i)$
            Compute: $priority = C_l(n_i) - C_{rand}(n_i)$
        else if [ then$C_l(n_i) > C_{lmax}$ && $QueueSize! = 0$]
            Generate $C_{rand}(n_i)$
            Compute: $priority = C_{rand}(n_i)$
        end if
    end for
    Sort candidate list according to $priority$
    Assign RUs to top $r$ candidates
end while
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III. PROPOSED SCHEDULER FOR MULTI-USER OFDMA OPERATION

To ensure a fair allocation of resources, we propose a transmission history-aware algorithm that tracks the previous transmission of all the STAs associated with the AP. Consider an AP that serves a basic service set (BSS) with n STAs. Each STA that has frames to transmit can inform the AP about its queue size. A STA can transmit its queue size by either replying to a BSRP frame transmitted by an AP before transmitting a trigger frame (TF) for UL transmission or by transmitting the queue size in the QoS control field of a QoS frame, or both [11]. When the AP attains transmission opportunity (TXOP) using the enhanced distributed channel access (EDCA), it can transmit in the DL based on its buffer status and solicit UL transmissions within that TXOP. All the STAs maintain a parameter named as long-term (C_l) history that records the resource allocation over STA's lifetime. Another randomizing parameter avoids the starvation of STAs. The goal of the scheduler is to assign a RU to the maximum number of allowed STAs in a TXOP. Since, the I-IoT STAs do not require a large bandwidth, we assume that each STA is allocated only a single RU. Even though, TGBe is considering multiple RU allocation for a single STA, but we can relax this condition for I-IoT scenario. Both parameters are initialized when the STAs are associated with the AP. $C_l(n_i)$ is updated with every RU allocation to a STA n_i. Similarly, $C_{rand}(n_i)$ determines the RU allocation in the current TXOP. If the $C_l(n_i)$ reaches a ceiling value, the STA n_i loses any priority. After that, $C_{rand}(n_i)$ becomes the sole parameter which determines if a STA should be allocated an RU in the current TXOP. Algorithm 1 summarizes our proposed methodology.

IV. EVALUATION AND DISCUSSION

To evaluate the performance of our proposed algorithm, we simulate it on network simulator-3 (NS-3). NS-3 currently supports OFDMA in IEEE 802.11ax on which the IEEE 802.11be amendment builds upon. We configure our simulation to evaluate traffic on a 20 MHz channel. We use modulation and coding scheme index 11 along with 800 ns guard interval. We analyze the performance by varying the number of nodes associated with the AP. We evaluate the performance in terms of fairness among the stations by monitoring the successful transmissions from individual stations. Fig. 3 shows the standard deviation of the per-STA throughput. Lower the standard deviation, fairer the scheduler. The proposed method is quite unfair in the smaller deployments, but as the number of nodes increases, the proposed method tends to perform better than the round-robin scheduler (RRS). At 50 nodes, the proposed algorithm clearly performs better than the RRS and shows a stable fairness. Even though, the per STA throughput is not very high for both the schedulers, the proposed method shows a better performance in terms of avoiding starvation of STAs. This is illustrated in the Fig. 4 where zero normalized throughput shows that the STAs are not allocated any RU throughout the simulation period. The graph shows the throughput per-STA of the proposed method is higher than the RRS and the number of troughs (zero RU allocations) in the graph are lower than the RRS. The average flow delay is tracked using Flow Monitor in NS-3. Fig.5 depicts the performance of the proposed system compared to RRS in terms of average flow delay. The average flow delay is the average delay incurred by the STAs for the successful transmission of packet including the time to schedule the transmission. Fig. 5 shows a decreasing trend with the increase in the number of STAs as a higher STA count improves the average flow delay performance. However, when the number of nodes is doubled from 25 to 50, the average delay increases due to the additional time required to compute the scheduling information. Therefore, the proposed algorithm is able to ensure a fair RU allocation in a dense WLAN based I-IoT network.

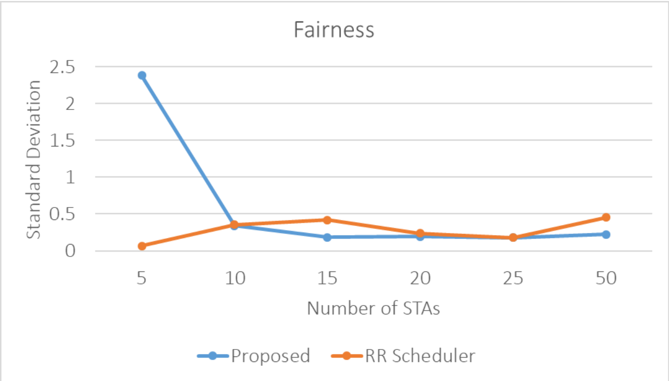

Fig. 3. Performance of the I-IoT in terms of fairness. The standard deviation shows that imbalance between the allocation among the STAs.

V. CONCLUSION

The I-IoT networks are becoming economically significant due to their widespread adoption. The IEEE 802.11 WLANs

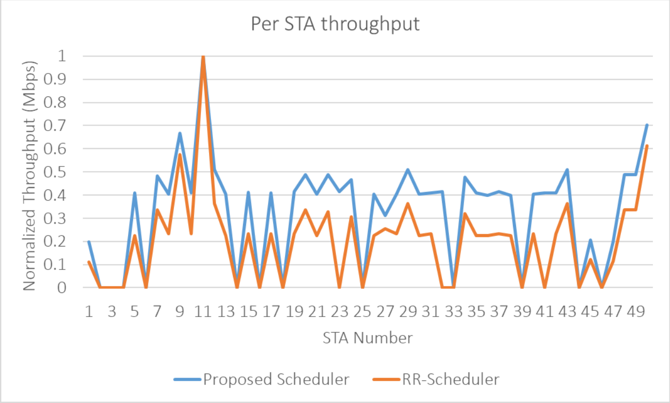

Fig. 4. The per-STA throughput for 50 node BSS. The zero value of throughput implies starvation.

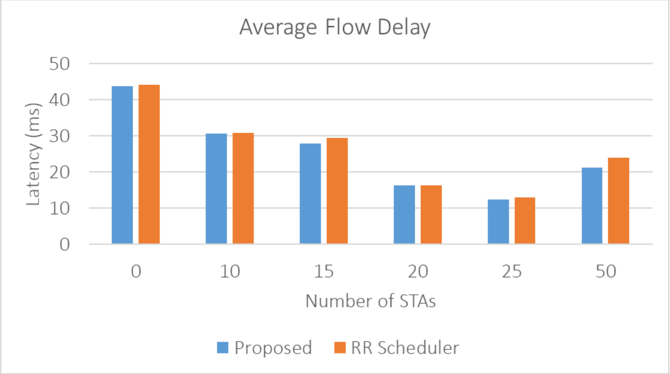

Fig. 5. The average flow delay performance.

are a reliable communication technology for I-IoT applications. The introduction of OFDMA in Wi-Fi will lead to a massive growth in the number of Wi-Fi enabled IoT systems which will need to meet the defined QoS requirements. The IEEE 802.11be standard is an incremental update to the IEEE 802.11ax networks which can support massive deployments due to OFDMA and MU-MIMO. To enable a fair allocation of resources in the IEEE 802.11be networks which are set to provide extremely high throughput while supporting large deployments, we propose a scheduling algorithm for UL/DL transmission. We simulate the proposed algorithm on NS-3 to evaluate its performance. Our evaluation shows an improved fairness and per-STA throughput when compared with the state-of-the-art algorithm. As our future work, we plan on designing an UL scheduler to improve the performance of the default UORA mechanism that is defined in the standard.

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