Energy Saving in Fixed Wireless Access Networks Utilizing Scheduled Coordinated Sleeping Time

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Abstract

Fixed Wireless Access (FWA) networks are used to extend connectivity to areas with limited or no access, especially where the deployment of wired infrastructure is costly. In such networks, the infrastructure can take the form of a multi-hop mesh network consisting of Distribution Nodes (DNs) and Client Nodes (CNs). A CN is served by a DN and extends connectivity within homes by acting as an access point (AP). Due to fluctuations in traffic over time, network utilization also fluctuates. When the network is scarcely utilized, it leads to energy waste due to powering the network during these times. In this paper, we explore methods to reduce energy consumption in wireless mesh networks (WMNs) by implementing coordinated sleeping times for APs of the last hop and the DNs inside the FWA network. By dynamically scheduling sleep patterns in the last hop, the solution achieves network-wide energy savings without compromising the quality of service for traffic flows in terms of latency and reliability. Moreover, in this paper, we reduce the Orthogonal Frequency Division Multiple Access (OFDMA) overhead and utilize this to organize time-critical traffic in the last hop of FWA, benefiting from the coordinated sleeping time. Our results show that in medium-load scenarios, this approach can achieve up to 33% energy savings

in FWA mesh networks combined with NextGen Wi-Fi while maintaining bounded latency for time-critical applications and serving non-time-critical traffic.

Keywords: OFDMA, Fixed Wireless Access, Mesh Network, Energy Consumption, NextGen Wi-Fi

1. Introduction

Wireless mesh networks (WMNs) are multi-hop networks with a flexible structure. In WMNs, nodes such as routers extend the coverage area, gateways connect to external networks, and clients access services via connected devices like laptops and smartphones [1]. This technology is considered promising due to its features such as self-configuration, cost-effectiveness, self-organization, and adaptability to various use cases [2, 3]. WMNs are applied in diverse scenarios including industrial automation, disaster response, military operations, and healthcare, as well as extending network connectivity in rural areas and within homes [4].

Traditionally, extending connectivity to residential and commercial areas is performed by installing fiber or cables inside buildings.However, due to the overhead of cable deployment, wireless solutions are often a better fit. One such solution is Fixed Wireless Access (FWA) networks [5], which provide connectivity between and inside buildings without the need for cables. FWA is a type of wireless connection that provides broadband access to designated locations, as shown in Figure 1. While distribution nodes (DNs) enable such connectivity, client nodes (CNs) act as an access point (AP) in the last hop to provide indoor connectivity. To increase the offered bandwidth by FWA further, mmWave transceivers are adopted in mesh networks. mmWave links with higher frequencies than Wi-Fi are used between DNs and from DN to CN. While this increases communication challenges due to mmWave propagation characteristics and energy consumption [6], the ability to support large bandwidth makes mmWave-based FWA networks suitable for bandwidth-demanding applications [7]. In particular, 5G FWA offers high-throughput and low-latency communication services [8]. Such features are needed to comply with the needs of future time-critical and bandwidth-intensive applications such as camera sensors, AR/VR, video applications, video gaming, and different home automation applications. With the introduction of IEEE 802.11ay [9], it is possible to use Wi-Fi in these low-latency, high-throughput cases. Thanks to having new PHY and MAC layer specifications such as MIMO and enhanced beamforming, throughputs up to 100 Gbps can be achieved [6].

Today, Wi-Fi is the most widely used technology for indoor communication, supported by many end devices [10]. The upcoming Wi-Fi standard IEEE 802.11bn prioritizes ultra-high reliability (UHR) [11] as well as power saving mechanisms not only on device side but also at the AP side [12]. The focus on power saving on AP side comes from the fact that APs are becoming power hungry and an increasing number of soft APs, mobile hotspots, and mobile APs are running on a battery [13]. Several proposals on energy saving capabilities on the AP side are already under discussion, such as switching between high capability mode (HCM) and low capability mode (LCM), switching into sleep state - so-called doze state in IEEE 802.11bn, link disablement, and target-wake-time based solutions [14, 15].

While mmWave-based FWA provides internet connection to homes or commercial buildings, the final communication hop is typically enabled by Wi-Fi. The network load in the mmWave FWA mesh network fluctuates over time, with heavy usage during the day and significantly lower demand

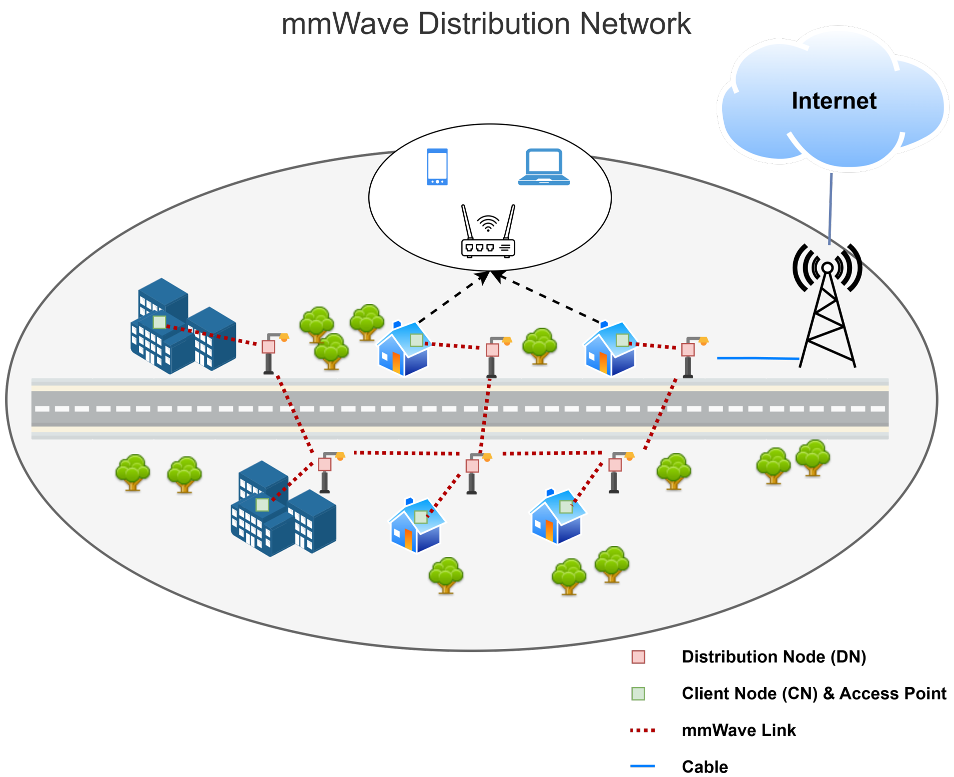


Figure 1: mmWave Fixed Wireless Access (FWA) network where mmWave links are used to extend the connections to the homes as well as inside homes.

at night or during off-peak hours. Continuing to operate the mmWave FWA mesh network with the same number of links and capacity during the network's low-utilization periods results in unnecessary energy consumption. Most energy-saving techniques focus on end devices, leaving APs and DNs out of protocol-based solutions. Particularly at night, when the network load is at its lowest level, energy is wasted at the network infrastructure side.

In this work, we combine Wi-Fi for the last indoor communication hop with an FWA mesh network, and research a coordinated sleeping solution to reduce the energy consumption of the network as a whole. To this end, we focus on energy saving in APs/DNs in an FWA mesh network, primarily focusing on network load over time and bring APs/DNs into a sleep state for short periods of time without impacting QoS of time-critical traffic flows in terms of latency and reliability. The trade-off in this work is, non-time-critical flow might be negatively affected in terms of performance in order to save energy network wide. Supporting short on/off time periods can be assisted by better traffic organization in the last network hop. This also gives more freedom in organizing sleeping times in the mesh network.

The contributions of this study are as follows:

- Dynamic load-aware scheduling algorithm of coordinated sleeping periods for APs.
- Utilization of modified OFDMA mechanism for time-critical applications to reduce energy overhead in performing air-time usage organization in the last communication hop.
- Network-wide energy saving model.

- Implementation of the dynamic sleeping times for APs in a network simulator and use-case based simulations.

The outline of this paper is as follows: in section 2, related works about network energy efficiency are discussed. It is followed by enablers and background information that is presented in section 3. Section 4 explains the energy-saving method used in this paper. In section 5, the simulation setup is described and results are discussed. Lastly, section 6 concludes the paper with possible future works.

2. Related Works

Until now, studies on energy consumption in networks have focused mainly end devices [16]. The main reason for this is that end devices outnumber network devices, and they are usually battery-powered. However, an increase in the services and traffic amounts and extension of communication networks shifted the overall energy consumption towards network devices [17]. According to [18], there are several ways to reduce energy consumption in wireless networks. One of these is turning on/off some of the hardware components over time to reduce energy consumption, which is the approach we follow in this study.

The works in [19, 20, 21] are focused on the optimization of AP energy usage. Kholaif et al. [19] presented a QoS-enabled power-saving method in IEEE 802.11e networks. They utilized a network allocation map (NAM) to share a superframe, which depicts the service intervals and sleep time for the AP. In these superframes, there are sub-frames called service intervals, which can be dynamic. By sending this information with each beacon, AP communicates with stations in the network and dynamically adjusts service intervals. When a new station with the best effort or with a real-time application joins the network, AP adjusts the NAM and sends it with the next beacon to inform the stations in the network.

An AP being unable to sleep when its MAC queue is not empty led to a cross-layer queueing control solution that controls the layer 3 dequeuing mechanism. In [20], the author keeps packets in the layer 3 queue to utilize packet aggregation and to keep the MAC queue empty. In this way, the author ensures the AP stays in a sleep state for a longer time. Also, if possible, AP triggers the dequeuing mechanism just before the beacon interval to utilize the AP beacon interval since the AP will have a non-empty MAC queue anyway. The work focuses on best-effort communication and low-load networks.

Network interface cards (NICs) use the most energy while being in the transmit state. Researchers address this fact to create energy-efficient APs. In [21], the authors focus on decreasing the transmit power of AP and propose an algorithm called improved elite golden jackal optimization. The authors improved golden jackal optimization by using global search and elite evolutionary strategy. In this way, they create an energy-efficient network by minimizing the overall transmit power of the AP while considering other factors such as coverage. Similarly to this, authors in [22] aim to reduce energy consumption by transmit power optimization. Depending on the signal-to-noise ratio of the received signal, the proposed method modifies AP's TX power, thus leading to less energy usage.

Energy saving in central devices such as base stations is also considered by researchers in [23, 24]. Ghosh et al. in [23] present a method that reduces the energy consumption of LTE networks. This is done by monitoring the load in the network, and when the load in the network is low, such as at nighttime, they switch selected base stations (BSs) to sleep mode to save energy. The network load is divided into three different levels: low-load, normal load, and high-load. In low-load cases, there are still some clients that need connectivity in selected BSs. Modifications on other BSs are done to give service to those clients. These modifications include antenna tilting angle, height, and transmit power increase.

Optimizing single AP energy consumption is not sufficient for the whole network energy consumption. It requires better network-wide coordination and optimization, achieving a trade-off between energy consumption and traffic demands. As such, Samdanis et al. [24] proposed a self-organized network to reduce energy usage in a cellular network, turning off certain BSs during non-peak hours. They proposed centralized as well as distributed algorithms. In the centralized algorithm, data is collected in a management entity that decides the energy-saving formation. It looks for the most loaded BSs and searches for their neighboring BSs to look for an energy-saving opportunity. The main goal of this algorithm is to merge low/mid-loaded BSs into one BS, thus creating an opportunity for other BSs to sleep. In the distributed algorithm, neighboring information is used to create new energy formation. It also has a coordination mechanism to avoid conflicts between energy formations.

Energy efficiency in WMNs is mainly divided into two approaches, network layer operations optimization and data link layer (MAC layer) operations optimization [25]. The network layer ensures self-configuration and routing. Thus, modifications in this layer lead to optimized utilization of the routing, increased network performance, and reduced energy usage. On the other hand, the MAC layer mainly focuses on the channel access mechanisms. Better channel utilization not only increases the network performance but also helps to use the energy efficiently, such as by switching stations to sleep mode.

Works in [26, 27, 28] focus on node placement and routing in WMNs, considering energy consumption alongside other performance gains. In [26] authors focus on mesh router deployment by considering energy, connectivity, and coverage area. The authors proposed a model for distributing routers fairly among the cells which leads to using energy efficiently. Similarly to the previous work, authors in [27] propose a method to choose the best internet gateway in a WMN to increase network performance as well as reduce energy consumption. Routers with high traffic are selected to be the internet gateway to reduce overall routing overhead in WMN. Also, in [28], the authors address optimal gateway deployment in green mesh networks to increase overall network performance as well as energy efficiency.

Authors in [29] proposed a multi-hop sleeping MAC protocol based on TDMA scheduling in wireless mesh sensor networks to save energy. In clustered WMSN, stations learn about their neighbors by using a flooding technique. After routing information gathered by stations, stations send the information to their mesh routers. With this information, mesh routers create schedules, including sleeping slots, and broadcast the schedule with the information of their clock to ensure synchronization. By using these schedules, collisions in the network are decreased, affecting overall network performance, while energy usage also decreases.

The reviewed studies above show innovative methods for saving energy in wireless networks. Techniques such as AP sleep scheduling, transmit power optimization, and cross-layer solutions effectively reduce energy consumption while maintaining performance. For centralized devices like APs/BSs, load-based adaptations can be used in reducing energy usage during low-traffic periods. In WMNs, optimized node placement, routing, and MAC layer protocols improve both energy efficiency and network performance. However, there are several limitations in the works presented above. Single AP and cross-layer solutions focus on either low-load networks or do not consider load spikes in the network. On the other hand, WMN solutions focus on fair traffic distribution, which still leaves out the utilization of remaining unused airtime. Lastly, most of the works are focused on a single technology, such as cellular networks. In our work, we consider a heterogeneous wireless network and offer a solution that fits single-hop as well as multi-hop topologies. Energy saving schedules are distributed along the network, resulting in energy saving in multiple devices across DNs and CNs instead of a single device energy saving. Contrary to some of the works, which focuses on transmit power optimization [21, 22], our proposed solution can be used for both uplink and downlink traffic since the calculations are based on the air-time used. Additionally, our proposed solution is not restricted to very low load cases only, compared to [20, 19], but tries to find a schedule for a coordinated sleeping mechanism even for medium-load scenarios where air time usage reaches over 40%. Finally, our algorithm leads up to 33% energy saving in the mesh network and this is higher compared to works in [23, 29] which are presented as 25% and 22%, respectively.

3. Technology enablers

In this section, the technical enablers for reducing the energy consumption of the FWA network are described. The following sub-sections will focus on: (i) the application requirement (App-Req) sharing mechanism, (ii) modified OFDMA in the final network communication, (iii) dynamic scheduling technique to support coordinated sleeping times, and (iv) actual implementation in the ns-3 simulator.

3.1. Application Requirement (App-Req) sharing mechanism

To take the application requirements into consideration in the network operation, we designed and implemented an application requirement sharing mechanism in a previous work [30]. This mechanism enables applications to express their characteristics, such as packet size, data rate, and wireless access category, towards APs and other network devices. Access categories (ACs) are traffic types used in enhanced distributed channel access (EDCA). The traffic can be assigned to 4 different ACs: best-effort, background, video, and voice. These ACs have slightly different chances to access the channel compared to each other through differences in their interframe space (IFS), contention window (CW), and transmit opportunity (TXOP) values. The order of prioritization is voice, video, best-effort, and background traffic. Since the ACs in EDCA are limited to 4, time-critical applications such as online gaming can use the voice or video AC thanks to having higher priority over the other ACs. In this study, we use both voice and video ACs for time-critical flows and the others for non-time-critical flows. Whenever a station has a time-critical application, it shares such information via the APP-REQ mechanism with the AP. Next, the AP adds the station to the OFDMA polling procedure based on the application characteristics. Polling in OFDMA is done by AP and takes a couple packet transfers to do so. However, knowing to which stations to poll in an UL OFDMA, resulting in saving time and energy by removing the need for frequent reports from end stations. In addition, this method is used for time-critical applications to ensure bounded latency in mixed network scenarios.

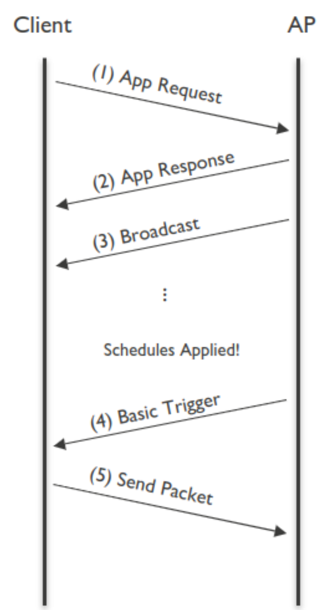


Figure 2: Application requirements sharing flowchart.

This procedure uses a request-response method as shown in Figure 2. After receiving the request, with the application information, AP sends a response back to the station with schedule information on which the station will be polled for UL. This is followed by a broadcast message to let all the other stations know when polling will happen, so the other stations will keep the channel free during the polling time. By doing this, it is possible to create a dedicated time slot and initiate the modified OFDMA procedure to ensure serving time-critical applications.

3.2. Modified UL-OFDMA for Time-Critical Applications

IEEE 802.11ax (Wi-Fi 6) [31] standard introduced Orthogonal Frequency Division Multiple Access (OFDMA) as the first multiplexing mechanism in Wi-Fi. It allows simultaneous data transmission over the same frequency band from/to different stations. While it reduces network contention, it also increases overall network capacity and leads to better spectrum utilization. OFDMA makes this possible by dividing bandwidth into smaller sub-carriers, so-called resource units (RUs). To perform an UL-OFDMA, the AP first needs to gain channel access utilizing distributed coordination function (DCF) to initiate the OFDMA procedure. Then, AP sends a buffer status report poll (BSRP), to which clients respond with their buffer status report (BSR) to inform AP about their queue status. Using this information, AP decides which stations to poll. Next, a Multi User Request to Send and Clear to Send (MU-RTS/CTS) packet exchange is performed between the AP and the stations. This is followed by a trigger frame to let stations know about which RUs to use in UL OFDMA. It continues with packet transmissions and ends with multi-user block acknowledgment (MU-BAR). Downlink OFDMA is performed without BSRP, while MU-RTS can be used as a trigger frame to let stations know about the RUs used to receive their DL traffic.

Using the information from the App-Req exchange, AP stores information about the STAs to be polled at a certain time. It is designed to work with schedules in the network to bring determinism for time-critical applications. Organizing the channel access in dedicated and shared time slots means that channel access can be prioritized for APs at certain time intervals to initiate UL-OFDMA transmission. This can be achieved by preventing other stations to access the channel during the OFDMA time slot, utilizing silent information elements. Additionally, having time-critical application information eliminates the need for BSRP packet exchange. Also, RTS-CTS packet exchange is optional to use, and it is disabled in Wi-Fi part (indoor network) of this study, since the clients of Wi-Fi network are supposed to be in the same apartment/room. As for the FWA network, the DNs are connected to each other with a bidirectional mmWave link to create a mesh network. Thus, we assume that there is no hidden node issue. As a result, all pre-steps in the OFDMA exchange can be removed. This approach takes less time, even compared to Wi-Fi transmission, after a certain number of stations are polled in an OFDMA transmission, as shown in [30].

3.3. Dynamic scheduling algorithm

Traffic scheduling and better organization help in two directions. It can support the fulfillment of traffic requirements for time-critical applications, as well as coordinated sleeping time for network devices. The latter is used to optimize the energy consumption in the network. We implement a cyclic scheduler that defines a communication cycle and periodic time slots (dedicated and shared time slots) for each station in the last hop of the mesh network.

Schedules are created dynamically based on the airtime traffic utilization. AP aims at increasing sleep time by grouping traffic, up-link and down-link, any clients, and any classes in certain time slots, in order to save more energy. When the load on the network is not too high, scheduling the flows immediately after another flow also helps combining the unused air times. Thus, network operations will not be severely interrupted, and all APs/DNs will use less energy utilizing the unused air time by switching to sleep state. At the boot-up phase of the network, an initial predefined schedule with sleeping slots is applied to all stations on the network. Depending on the airtime usage of the network, AP decides to increase or decrease sleeping slots and distributes the schedule to the network as shown in Algorithm 1 and in feedback control loop form in equation 1. Let S_t be the number of sleeping slots and R_t be remaining air-time usage over a control period at time t. S_{max} and S_{min} define the minimum and maximum number of sleeping slots available. θ represents the min and max remaining air time utilization thresholds. There are 2 thresholds to make such a decision: the lower and the upper thresholds. 35% is chosen as the lower threshold and 50% is the upper threshold. Moving beyond 50% air-time becomes risky, as collisions, channel access time, and packet losses start to increase after 60% airtime [10]. The lower threshold is chosen depending on the upper threshold. To ensure that the network responds to traffic bursts and is open to new applications, a gap between lower and upper thresholds is needed. Thus, we aim to keep the network stable by keeping the load between the thresholds, to ensure operation with low losses and delays while saving energy. These thresholds might be subject to change in different network and load scenarios. Also, number of sleeping slots are limited, leading to a situation where schedules can not be updated even if the remaining air-time usage are out of the thresholds. The initial schedules used for this work are provided in Section 5.

$$S_{t+1} = \begin{cases} \min(S_t + 1, S_{\max}) & \text{if } R_t < \theta_{\text{low}} \\ \max(S_t - 1, S_{\min}) & \text{if } R_t > \theta_{\text{high}} \\ S_t & \text{otherwise} \end{cases} \tag{1}$$

This operation is based on the states of the AP. We gather the state information from the physical layer, and in ns-3 there are 7 states defined, as follows [32]:

- **TX:** The PHY is currently sending a signal

Algorithm 1 The Dynamic Scheduling Algorithm used in the AP.

Input: Remaining Air-Time per 20-cycle basis

Output: Adjust Sleeping Slots based on Remaining Air-Time usage

```
while True do
    Calculate Remaining Air-Time according to formula
    if Remaining Air-Time < 35% then
        if Is there a remaining usable slot then
            Increase Sleeping Slots By 1
            Broadcast new schedule in the next cycle
        else if  then
            Do nothing
        end if
    else if Remaining Air-Time > 50% then
        if Is there a remaining usable slot then
            Decrease Sleeping Slots By 1
            Broadcast new schedule in the next cycle
        else if  then
            Do nothing
        end if
    else if 35% ≤ Remaining Air-Time ≤ 50% then
        Keep Current Schedule
    end if
end while
```

- **RX:** The PHY is synchronized on a signal and is waiting until it has received its last bit
- **CCA_BUSY:** The PHY is issuing a busy indication for the primary channel
- **IDLE:** The PHY is on but not in one of the states above (TX, RX, CCA_BUSY)
- **SWITCHING:** The PHY is switching channels
- **SLEEP:** The PHY is on power save mode and cannot send nor receive packets
- **OFF:** The PHY is powered off

The AP checks its states (tx, rx, cca, idle, sleep) constantly every 200 ms (20 cycles, 10 ms per cycle). This value and the lower&upper thresholds are chosen to prevent the ping-pong effect, avoiding the change of schedule from happening too often. During our tests, we encountered many unnecessary schedule changes when we used fewer than 20 cycles. Since in this work, 1 cycle is 10 milliseconds long, 20 cycles are sufficient to make a schedule update decision. However, it is important to serve the network and organize the schedules as soon as possible. Thus, we choose 20 cycles as control points. Based on the calculated percentages of each state, AP decides to increase or decrease the sleeping slots by 1 slot if the airtime usage is out of the thresholds boundaries. If not, AP keeps the current schedule running. Also, depending on whether the load is too high or too low, all sleeping slots might be utilized either for transmission or sleeping. In this case, AP keeps the same schedule since it can not go further than the one it is active. The AP calculates remaining airtime usage by using the formula in equation 2:

$$R_t(\%) = ((T_{TX} + T_{RX} + T_{CCA})/(T_{total} - T_{Sleep})) * 100 \qquad (2)$$

where R_t refers to the utilization of the remaining air time utilization and T refers to the time of the states of AP (TX, RX, and CCA which are gathered from the ns-3 simulation) in 20 cycles and hence the control points. To calculate air time correctly, the so-called remaining air time, we must remove sleeping time from the total time, which is 200 milliseconds in this work. Otherwise, the air time would remain more or less the same. Thus, when the sleeping slots are increased, the remaining air-time usage percentage also increases towards the desired range. As a result, the network tends to work between the thresholds while it sleeps as much as possible.

3.4. ns-3 implementation

To simulate scheduling features within a network simulator, we have modified the channel access mechanism of the ns-3 simulator version 3.37. We modified the EDCA mechanism to be compatible with scheduling usage. Schedules can be applied to any node in the network as well as to any queue at each node. As a result, nodes only try to access the channel when the gates are open and are not able to access the channel when the gates are closed for the relevant queue. By doing this, it is possible to create, update, and modify schedules during run-time. Lastly, it is also possible to change the EDCA parameters for time-slots created in the schedules.

4. Energy Saving Method

There are different ways to calculate energy consumption. The best way is to directly measure energy consumption using energy meters during online operations. This is indeed done in [16] since they had a real-world testbed. In this paper, since we perform network-scale simulations, we follow an approach to calculate the actual energy usage based on the states of each station. The total energy consumption can be calculated by the combination of energy consumption in different states, as shown in equation 3. Since the AP is in the listening mode during CCA and idle states, it consumes the same amount of energy as in the RX state, and the total amount is calculated as the sum of RX/CCA/IDLE, TX, and sleep states.

Each state consumes different amounts of energy, such as during transmission more energy is consumed compared to reception and sleep state. The energy consumption of these states is multiplied by the amount of time the state was encountered during operation, as in Equation 4. In the formula, I is the current of state, V is the voltage and T is the time spend on state. Since we use the IEEE 802.11ax standard in simulations, we use the 802.11ax device energy consumption values for calculations. The duration of these states is gathered from the ns-3 simulation. The energy consumption values of the states are taken from the work in [10], and the current values for TX, RX, and SLEEP states are 1950 mA, 819 mA, and 410 mA, respectively.

$$E_{Total} = \sum E_{Rx\&CCA\&Idle} + E_{Tx} + E_{Sleep} \tag{3}$$

$$E_{state} = I_{state} * V * T_{state} \tag{4}$$

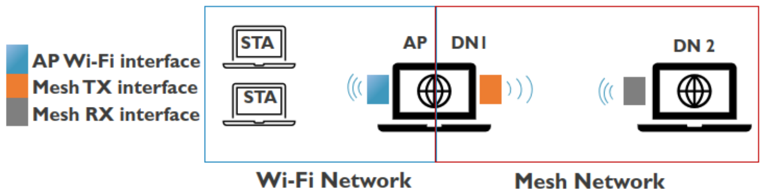


Figure 3: A general lookup of network topology.

5. Simulation & Results

In this section, we explain the simulation parameters, key performance indicators (KPIs), and discuss the results in detail.

5.1. Simulation Parameters & Environment

Figure 3 provides a general view of the topology used in tests. There are 8 stations in the Wi-Fi based home network and 1 DN between the home access point (AP) and the point of presence (PoP) of the mesh network. Traffic is sent from the stations to the PoP, which routes the traffic further towards the internet. The Wi-Fi based home network area is 10x10 meters, while DN and PoP are placed outside of this area. Mobility is not considered in this work, and all the stations are stationary.

In order to benchmark the impact of the dynamic scheduling algorithm and App-Req based OFDMA in the overall energy consumption of the network, as well as to check any impact on the traffic KPIs, such as latency and reliability we simulate two different scenarios. The first scenario utilizes vanilla Wi-Fi without any dynamic scheduling and traffic organization and updated OFDMA, while the second scenario utilizes dynamic scheduling with App-Req-based OFDMA. In addition, we also test for different numbers of time-critical traffic flows present in the network, 4 and 8, respectively, next to non-time-critical traffic flows. As such, we have 4 different use cases

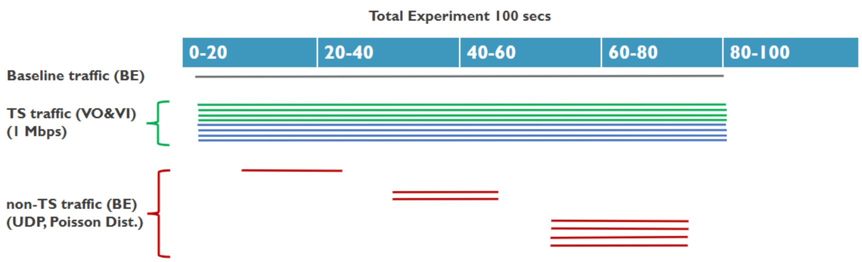


Figure 4: The scenario used in the simulations. In the most network-loaded case, there are 13 concurrent flows from STAs toward the destination.

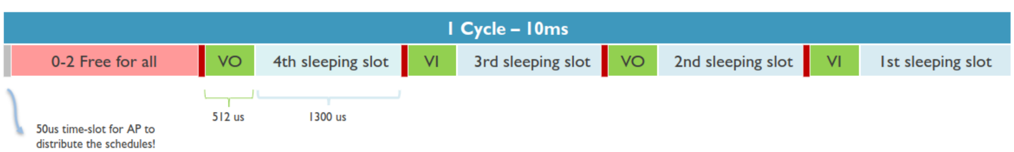
in total. To create load in the network, there are several non-time-critical traffic flows sent as best-effort AC. To show the effect of dynamic scheduling, different loads are applied to the network at different times as can be seen from the figure 4. Besides the baseline non-time-critical traffic flows, one non-time-critical flow is created in the first quarter. It is followed by 2 and 4 non-time-critical flows throughout the simulation. In total, there are 9 and 13 traffic flows, respectively, during each simulation round.

The total duration of the simulation is 100 seconds. The simulation parameters are given in Table 1. To simulate a wireless mesh network, we utilize ad-hoc wireless mode communication between DN and PoP. The links between DNs do not interfere since each connection is established over a different channel to mimic the behavior of bidirectional mmWave links. The physical data rate in the Wi-Fi-based home network is set at 122.5 Mbps, and in the FWA mesh network it is set at 1020.8 Mbps.

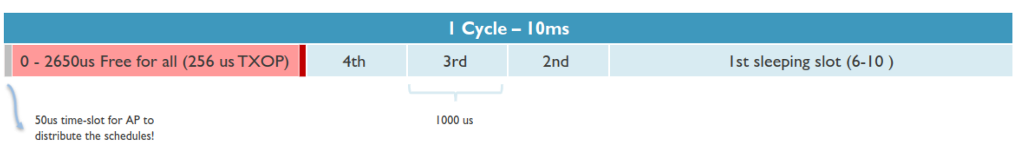
To support both TC and non-TC traffic, an initial schedule is created and applied to the nodes. At the beginning of the simulations schedules are similar to vanilla Wi-Fi, without any sleeping or dedicated time-slots. Over time, they are changed based on the load, and are distributed to the whole network. The initial schedules used in the dynamic scheduling use case are

Table 1: Simulation Parameters

Parameter	Value
Number of Stations	8
Number of APs	1
Number of DNs	3 (AP included)
Wi-Fi Standard	802.11ax
Data Mode and Bandwidth (Wi-Fi)	HeMcs3, 80MHz
Data Mode and Bandwidth (Mesh)	HeMcs11, 160MHz
TS App Data Rate	1 Mbps
TS Traffic Type	Constant Bit Rate (CBR)
TS Traffic packet size	640 bytes



(a) Schedule used in the Wi-Fi network



(b) Schedule used in the mesh network

Figure 5: Schedules used in Wi-Fi and Mesh Network. In our case, the total transmission time is generally lower in the mesh network compared to Wi-Fi due to having a higher physical data rate. Thus, it is possible to sleep more without harming networking services.

shown in Figure 5. It contains shared time slots, dedicated time slots, and a couple of sleeping slots to be used by dynamic scheduling depending on the network load. Slightly different schedules are used for different network parts, the Wi-Fi-based home network and the FWA mesh network, respectively. There are shared time slots at the beginning of a cycle in both schedules, followed by possible sleeping time slots. Due to a higher physical data rate, in our case DNs in the mesh network are able to sleep longer than the AP. Considering these schedules in the best-case scenario, stations in the Wi-Fi network can sleep up to 52%, and stations in the mesh network can sleep up to 70% thanks to having much higher phy data rate. At the very beginning of the cycle, a $50\mu s$ time slot is reserved for AP to distribute the schedule updates, if there are any. This dedicated mini-time slot ensures the distribution of the new schedule by the AP and helps to keep the network updated. Another important point of the schedules is guard bands depicted as red time slots. Since transmission started in a time slot that can continue beyond the time slot boundary, it is possible to occupy the part of the next time slot that can be used for an important transmission, such as a time-critical transmission or a sleeping time slot. To avoid this, guard bands must be used to make sure the channel is available just before an important event, or the transmission does not happen during sleeping time slots. These guard bands are set at $100\mu s$ long, and it is not possible for any transmission to start during the guard band interval. The $100\mu s$ is chosen based on the transmission time of a packet during our tests. It is slightly less than 1 packet transmission duration to minimize the chances of occupying an important event time slot. During the tests, such cases never occurred. Next to this, green time slots (Figure 5) are reserved for time-critical applications and are used by App-Req based UL-OFDMA transmission. There are 2 slots for each TC application type, meaning that beyond 2 packets per cycle would lead to overloading the communication cycle. Parameters (1 Mbps data rate and 640 packet size) of the TC applications are selected by considering this overloading limitation, which leads to generation of $\sim$1.9 packets per cycle for TC applications. In real world you have certain examples of traffic flows with such low throughput requirements. Slow-paced casual gaming [33], VoIP applications [34], and video calls[35] can be examples of such TC applications which can perform with less than 2 Mbps data rate. Before applications are started, an App-Req exchange happens as explained in section 3.1, and AP saves the information of stations to poll them at the beginning of the next relevant time slot. This modified UL-OFDMA approach leads to sending fewer packets, using less transmission/reception time, and saving more energy, respectively.

5.2. Results

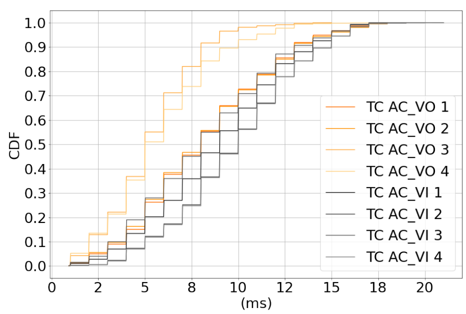
In this subsection, we will describe the achieved results in terms of traffic flow KPIs such as latency and packet delivery ratio (PDR), as well as energy usage-related KPIs, namely interface state percentage, energy consumption over time, and energy comparison between each use case. The states of interfaces are provided to show the effect of dynamic scheduling, and energy consumptions are calculated based on these states. Energy consumption values are calculated and compared to each other for each interface as shown in Figure 3.

5.2.1. Traffic flows' KPIs

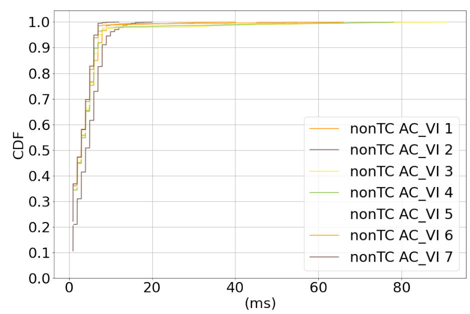
The latency cumulative distribution function (CDF) graphs for each flow and use case with four time-critical traffic flows are shown in Figure 6. When dynamic scheduling is employed, the majority of packets from time-critical flows are transmitted within a maximum of two cycles, resulting in latencies below 20 ms (Figure 6a). The 99th percentile latencies for all flows range from 16 ms to 17 ms. For non-time-critical flows, delays remain below 40 ms in 99% of cases (Figure 6b).

In contrast, when neither dynamic scheduling nor App-Req-based OFDMA is applied (Figures 6c and 6d), the latencies are significantly lower, with time-critical flows achieving latencies below 2 ms and non-time-critical flows below 12 ms for 99% of the time. This reduction occurs because there is no sleeping time or traffic organization, which minimizes overall communication latency. As such, in case of vanilla Wi-Fi, due to absence of sleeping time slots the energy saving is not possible.

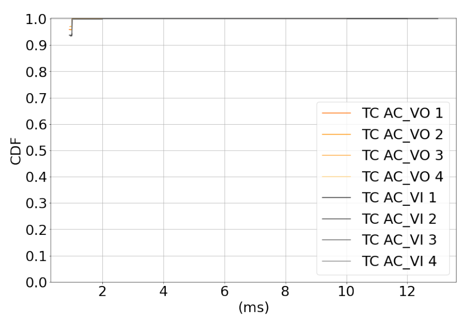
Figure 7 shows the latency CDF in the case when 4 time-critical flows were present in the network. In general, latency is lower compared to the case in Figure 6 due to having less traffic over the air. Time-critical packets are sent in a maximum of 2 cycles, having latencies below 20 ms when dynamic scheduling and App-Req-based OFDMA is used. 99th percentiles of latency for the flows range between 11 ms and 12 ms (Figure 7a). In the case when no dynamic scheduling is used, communication latencies result below 2 ms and 12 ms, for time-critical and non-time-critical flows, respectively. Latency CDF graphs show that it is possible to send packets under a latency boundary of 20 ms for time-critical flows while serving non-TS flows and reserving some time for sleeping. This level of bounded latency indeed complies with requirements for bounded latency of cyclic traffic in industrial applications which is between 2-20 ms. [36]. In terms of PDR, all traffic flows in all cases have reached more than 99.99%.



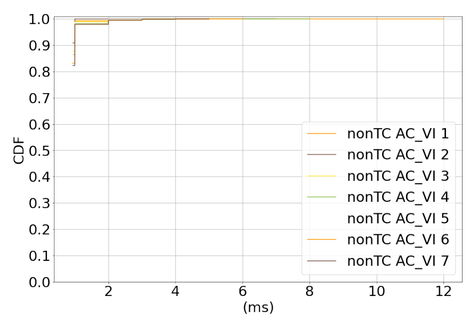
(a) TC Flows Delay (with schedules)



(b) non-TC Flows Delay (with schedules)

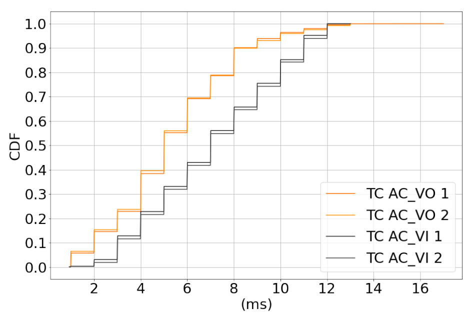


(c) TC Flows Delay (vanilla Wi-Fi)

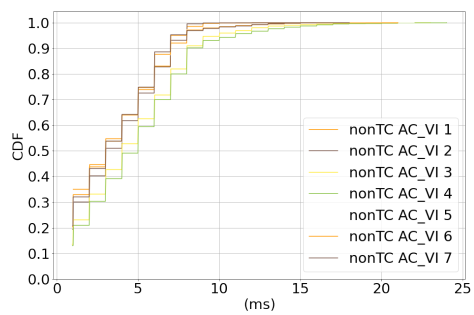


(d) non-TC Flows Delay (vanilla Wi-Fi)

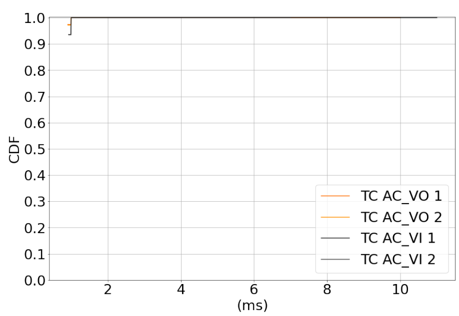
Figure 6: Delays of TC and non-TC traffic flows in CDF format. The results of the tests are shown for 8 total time-critical application cases.



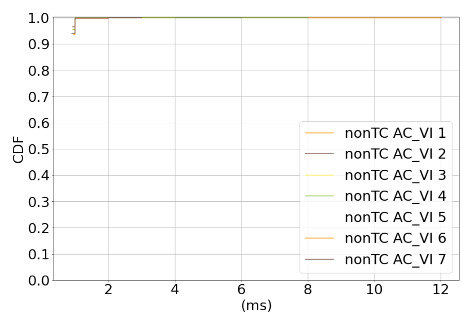
(a) TC Flows Delay (with schedules)



(b) non-TC Flows Delay (with schedules)



(c) TC Flows Delay (vanilla Wi-Fi)



(d) non-TC Flows Delay (vanilla Wi-Fi)

Figure 7: Delays of TS and non-TS traffic flows in CDF format. The results of the tests are shown for 4 total time-critical application cases.

5.2.2. State management

The operational state of each communication interface in the network is essential to be monitored as it impacts the energy consumption of the overall network. Also, it gives a good understanding of how a station spends its time. By considering the interface state, we can dive more into optimizing energy consumption or utilizing airtime usage. Figure 8 shows the relation between actual sleep percentage and remaining air-time percentage depending on actual air-time usage. According to the dynamic scheduling algorithm, lower remaining air-time usage threshold is selected as 35%, meaning that after 35% network doesn't switch to sleep any more to give room for new incoming traffic. Below that value, depending on the traffic, up to 52% sleep can be achieved. Most importantly, the orange line shows that the network tries to keep itself between thresholds. This is also important for being resistant against burst and available to possible incoming traffic. This figure shows what our algorithm can achieve theoretically at the best scenario since it is based on certain air-time percentages without fluctuations.

Figure 9 shows which percentage of the time the interface resides in a certain state for each of the 4 use cases. For UL traffic we monitored states at 3 different interfaces, as shown in Figure 3, Wi-Fi AP interface, Wi-Fi AP mesh interface towards DN, and DN mesh interface towards PoP.

Figure 9a and 9b show the states when no dynamic scheduling and no App-Req based OFDMA is used. Throughout the whole simulation, more than 70% of the time, all of the interfaces are in the idle state. This idle state increases even more when it comes to mesh interfaces, reaching up to 87% (Figure 9a). When dynamic scheduling is used, part of the idle time

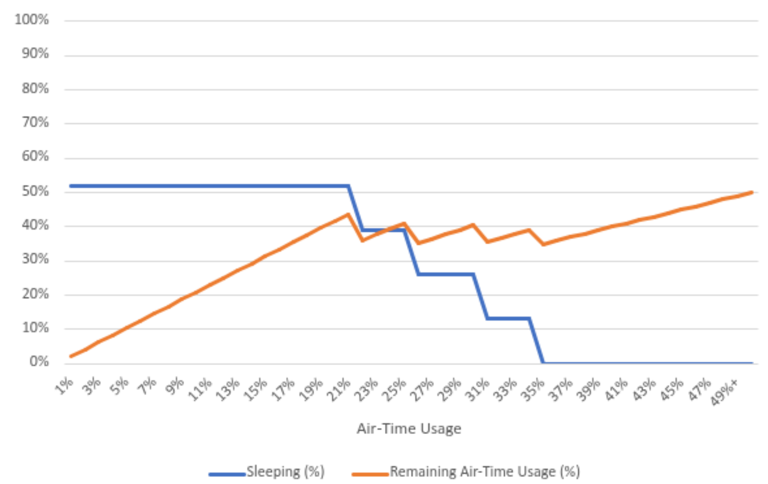
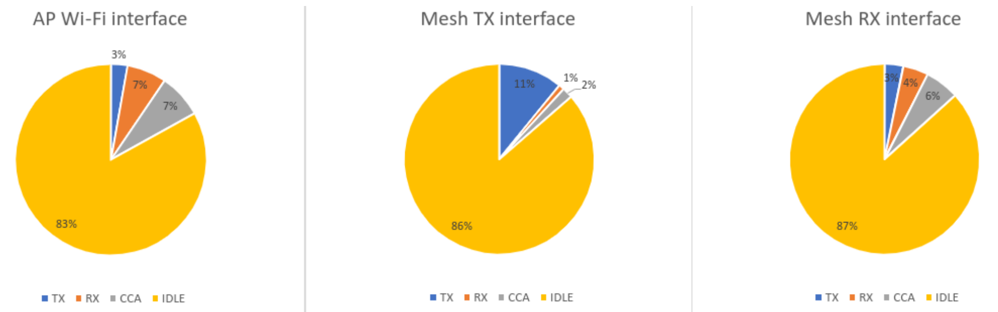


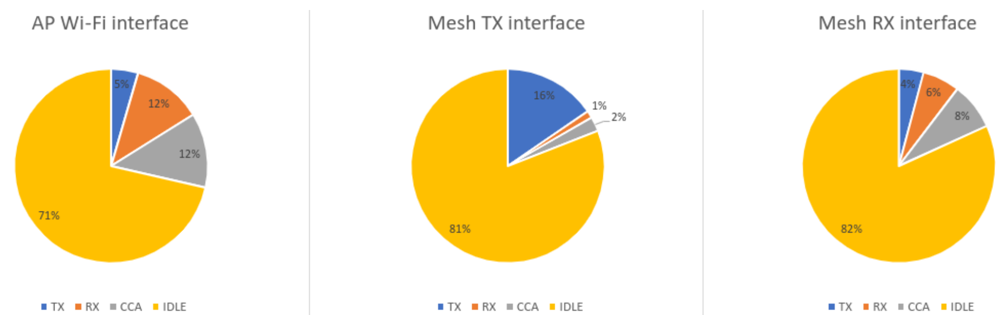
Figure 8: Relation between actual air-time, remaining air-time, and sleeping time according to calculations based on dynamic scheduling formula.

is utilized to set interfaces in coordinated sleep. The state percentage of each interface when dynamic scheduling is used is shown in Figure 9c and 9d. AP interface towards stations utilizes sleep between respectively for 4 and 8 TC cases 42% and 45%, depending on the number of traffic flows in the network, while AP and DN interface in the mesh network utilize sleep between 62% to 67%. It means that more than half of the time DN network can go to sleep with limited impact on traffic flows KPIs. Apart from sleeping, using dynamic scheduling and App-Req UL-OFDMA makes the network more organized, and as a result of this *RX* and *CCA_BUSY* state of AP drops drastically (Figure 9c and 9d) compared to vanilla Wi-Fi case (Figure 9a and 9b), meaning more utilized air-time.

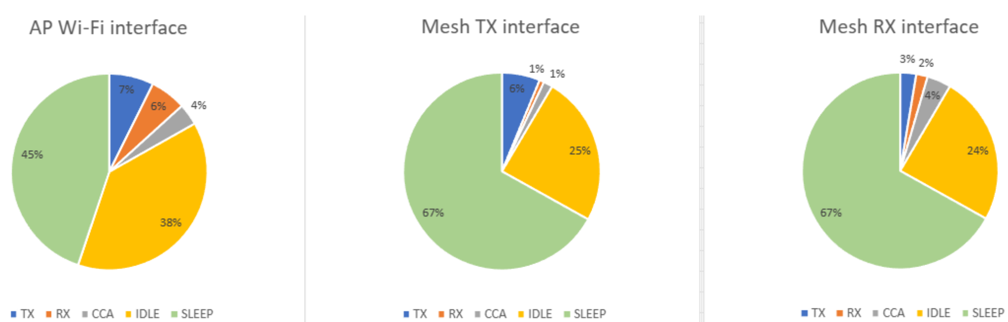
Along with the total interface state charts, it is important to show how airtime is utilized over time as well. In Figures 11 and 10, airtime usage over time is shown across all cases for AP interfaces, both towards stations



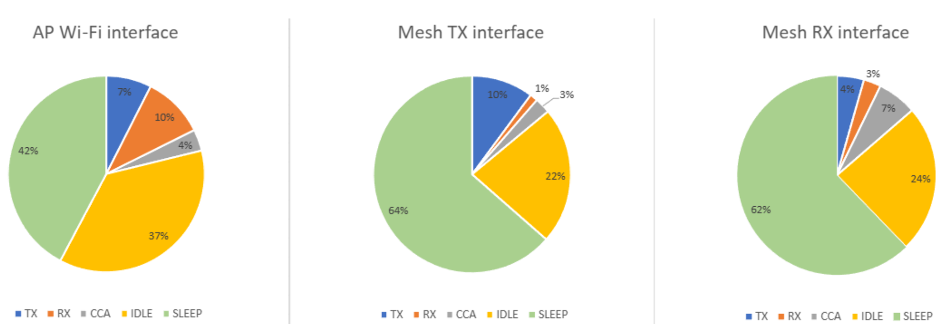
(a) Interface states when 4 TC apps are used in vanilla Wi-Fi case



(b) Interface states when 8 TC apps are used in vanilla Wi-Fi case



(c) Interface states when using Wi-Fi with schedules and UL-OFDMA for 4 TC apps



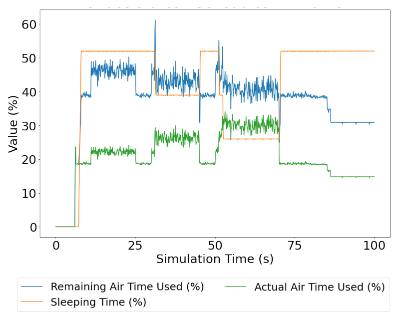
(d) Interface states when using Wi-Fi with schedules and UL-OFDMA for 8 TC apps

Figure 9: States of interfaces across all of the scenarios presented in pie charts. From left to right, the first column graphs are the Wi-Fi interface of the AP. Graphs in the middle column are the mesh TX interface of the AP, and graphs in the last column are the mesh RX interface of the DN's. Interfaces are provided in Figure 3.

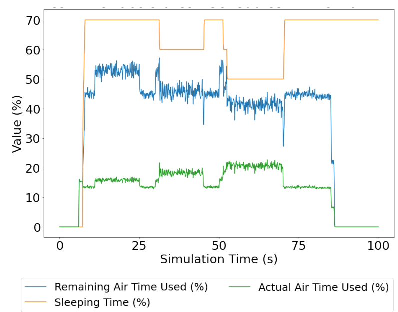
and towards DN. In the graphs, blue lines are the remaining airtime calculated with the formula 2, and the green line is the airtime usage calculated without removing sleeping slots, hence the actual airtime. Over time, the airtime increases as more loads are applied to the network, also timings can be compared with Figure 4. The effects of this are reflected in all of the graphs. However, in dynamic scheduling cases (figures 10a, 10b, 11a, and 11b), sleeping slots are applied to keep the network load at an optimum level. Until new applications join the network or stations stop sending packets, sleeping slots do not change very often. Compared to Figure 8, the results show similarity in terms of keeping the network load under control while consuming less energy. When no dynamic scheduling is applied (figures 10c, 10d, 11c, and 11d), green and blue lines (remaining and actual air-times) perfectly overlap due to not having a sleeping mechanism.

5.2.3. Energy Consumption Comparison

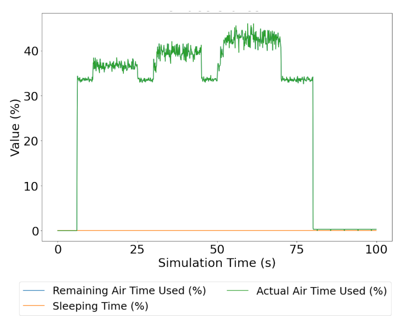
The relative energy consumption of the interfaces is shown in Figure 12. Each interface is compared to the other in Wi-Fi and dynamic scheduling cases. In the dynamic scheduling with 8 time-critical traffic flows case (Figure 12b), the Wi-Fi network interface spends less energy, around 12.5%. Converting unused idle time results in spending less energy. However, 12.5% energy saving is less than expected compared to the sleeping percentage, which is around 45%. The main reason for this is the usage of OFDMA. Due to the use of OFDMA in Wi-Fi interface, total TX time increases because of trigger frames for time-critical applications; hence, the energy consumption decrease does not follow the percentage of sleeping time. In the mesh network, savings are much higher compared to Wi-Fi. Utilization of a higher physical data rate leads to sleeping more and saving even more energy, which



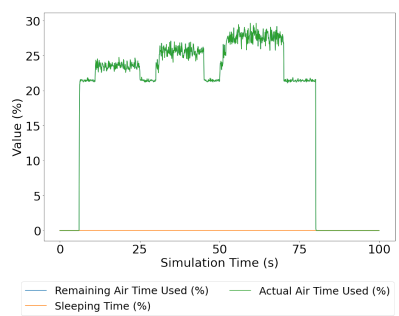
(a) AP interface states w/ schedules and UL-OFDMA



(b) Mesh interface states w/ schedules and UL-OFDMA

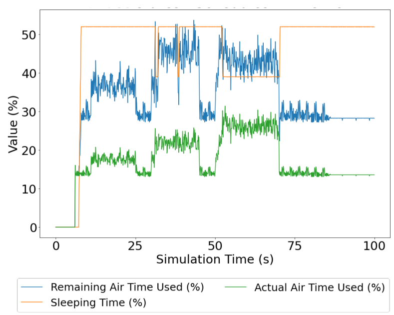


(c) AP interface states w/ vanilla Wi-Fi

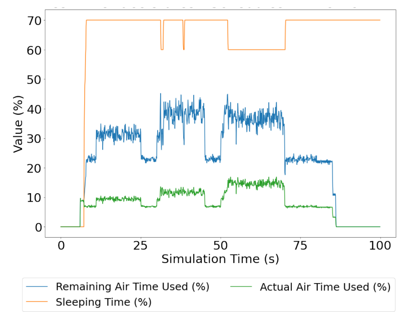


(d) Mesh interface states w/ vanilla Wi-Fi

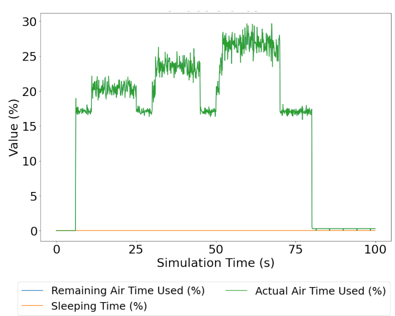
Figure 10: Remaining air-time, actual air-time, and sleep duration over time for interfaces -Wi-Fi and mesh- on the AP of the 8 TC applications test case.



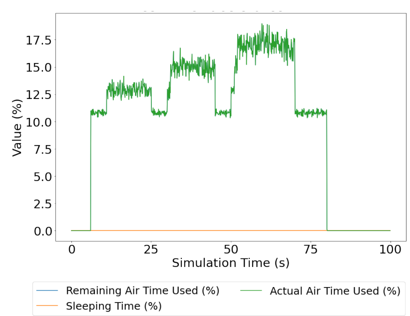
(a) AP interface states w/ schedules and UL-OFDMA



(b) Mesh interface states w/ schedules and UL-OFDMA

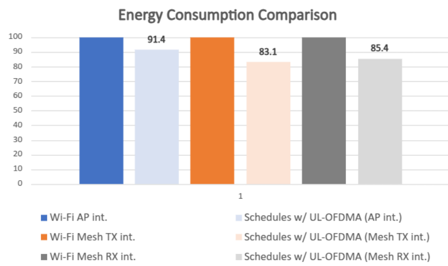


(c) AP interface states w/ vanilla Wi-Fi

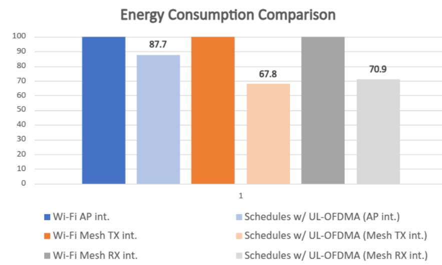


(d) Mesh interface states w/ vanilla Wi-Fi

Figure 11: Remaining air-time, actual air-time, and sleep duration over time for interfaces -Wi-Fi and mesh- on the AP of the 4 TC applications test case.



(a) Energy consumption percentage when 4 TC apps are used



(b) Energy consumption percentage when 8 TC apps are used

Figure 12: Energy consumption and comparison between the interfaces mentioned above. The values are given in percentages to make the comparison easier. Thus, values in the graphs are 100% in all Wi-Fi cases.

is around 33%. Another effect that helps to save energy is the drop in the TX percentage, especially in mesh TX interfaces. This happens because of TXOP utilization in the FWA network and helps to save energy indirectly. If a queue is emptied before the duration of TXOP, a contention-free packet (CF-END) is sent to release TXOP. However, if there are packets in the queue, instead of the CF-END packet, a data packet is sent. Due to use of schedules, packets are building up in the queues during sleeping periods, then they are sent when the gates are open. This leads to better TXOP utilization and less TX time compared to normal Wi-Fi in our tests. This is visible if one compares the TX state of the mesh TX interface between Figure 9a and 9c. In Figure 9a it is only 10.8% compared to Figure 9c where it drops to only 6.2%. Similar comparison can be done for Figure 9b, where it is only 15.5%, with Figure 9d where this value drops to 10.1%.

6. Conclusion

This study explores a method that utilizes dynamic scheduling for coordinated sleeping time in the network stations to save energy in wireless mesh networks. A heterogeneous network is considered, where the last hop of the fixed wireless access (FWA) utilizes Wi-Fi. First, we achieve better traffic organization by utilizing a modified OFDMA with reduced overhead, to give more opportunities for APs to go to sleep more often. This, in return, allows for the whole network to utilize coordinated sleeping time slots for increased energy utilization.

Through the proposed approach, we achieve up to 33% energy savings in medium-load scenarios for FWA distribution nodes and around 13% for Wi-Fi APs without compromising the performance of traffic flows in the network (time-critical or best-effort ones) in terms of latency and reliability. These findings show the importance of using energy-efficient strategies in wireless network environments, paving the way for more sustainable wireless communication systems.

There is still room for improvement in this work. Advanced routing algorithms, load-balancing methods, node placement optimization, and etc. can further help our algorithm to save more energy. AI/ML methods can be used to predict traffic patterns, leading to faster decisions on schedules. Also those methods can be used to optimize the parameters used in this work, such as lower-upper thresholds and control points. This also makes this operation more dynamic and autonomous. On the other hand, testing this approach in real-world environments to validate simulation results, identify practical challenges, and refine the method for large-scale networks remains as work that needs to be done in the future. Indeed, in order to bring the proposed solution to life there are some changes that one need to implement in the physical layer and firmware of the radio interface. First of all, the gating mechanism should be implemented closer to physical layer or at low MAC, so the switching between states can be as deterministic as possible. In addition to this, the gating mechanism should be linked to updating the AP state from TX/RX to idle and sleep. A practical challenge is how fast AP can go from one state to the other, and how this will impact the accuracy of the gating mechanism. This remains a challenge for future work to be solved.

Acknowledgment

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