5G Network Slicing for Wi-Fi Networks

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Abstract*—Future networks will pave the way for a myriad of applications with different requirements and Wi-Fi will play an important role in local area networks. This is why network slicing is proposed by 5G networks, allowing to offer multiple logical networks tailored to the different user requirements, over a common infrastructure. However, this is not supported by current Wi-Fi networks. In this paper, we propose a standard-compliant network slicing approach for the radio access segment of Wi-Fi by defining multiple Service Set Identifiers (SSIDs) per Access Point (AP). We present two algorithms, one that assigns resources according to the requirements of slices in a static way, and another that dynamically configures the slices according to the network's conditions and relevant Key Performance Indicators (KPIs). The proposed algorithms were validated through extensive simulations, conducted in the *ns-3* network simulator, and complemented by theoretical assessments. The obtained results reveal that the two proposed slicing approaches outperform today's Wi-Fi access technique, reaching lower error probability for bandwidth intensive slices and lower latency for time-critical slices. Simultaneously, the proposed approach is up to 32 times more energy efficient, when considering slices tailored for low-power and low-bandwidth devices, while increasing the overall spectrum efficiency.

I. INTRODUCTION

Introduced in the 5G context, network slicing consists of a virtual and physical division of network resources with customised functionality. This allows logical networks adjusted to the requirements of different use cases on top of a common network. Network slicing has been widely studied and multiple aspects must be considered, such as the used radio access technology and demanded isolation level [1]. Multiple radio-access technologies are available in 5G, including non-3rd Generation Partnership Project (3GPP) technologies such as Wi-Fi, which will play an important role in supporting indoor coverage [2]. In fact, interworking with Wireless Local Area Networks (WLANs) is an operational requirement of the next generation access technologies [3].

However, research on network slicing on the Radio Access Network (RAN) is still limited [4], focusing mostly on 3GPP's new radio. Thus, it remains unclear how different 5G classes of service can be supported when resorting to Wi-Fi coverage. Most studied on Wi-Fi slicing are based simply on time-scheduled resource allocation (which is proved to be inefficient for resource utilisation) and are limited only to downlink transmissions [4], [5], [6]. De Bast et al. present a Deep Learning (DL) algorithm to enable network slicing in an IEEE 802.11ac network [7]. However, isolation is not provided since all the Stations (STAs) are connected to the same channel, and the DL technique requires an extensive pre-training and a long time to converge. Makhlouf et al. propose a totally new Medium Access Control (MAC) scheme to realise network slicing, ending with an approach which is not standard compliant [8]. Finally, Gu et al. propose to realise a multi-tenant architecture on a single AP by installing different SSIDs on it [9]. Here, network slicing is not realised because each tenant is served with an opportunistic approach and users are not differentiated by their requirements. However, exploiting multiple SSIDs on a single AP opens up for new possibilities, overcoming the limitations of previous works.

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The aim of our study is to provide a methodology to efficiently create and maintain network slices in Wi-Fi-based RANs, that will accompany 5G in the coming years. We propose a slicing approach compatible with the IEEE 802.11 standard as well as two new algorithms that take into account the type of service during slice creation and in real-time for resource management. In particular, slices are created based on 5G's three main classes of services: *i)* Enhanced Mobile Broadband (eMBB), which requires support for high data rates, high data traffic volumes, and high user mobility; *ii)* Massive Machine-Type Communications (mMTC), which supports a large number of devices that transmit low volumes of delay insensitive data and do not involves mobility; and *iii)* Ultra-Reliable Low-Latency Communications (URLLC), that is the class of services requiring ultra-low latency, high reliability and availability [10].

The paper is organised as follows. In Section II we describe the Wi-Fi scenario which we want to study, and our proposed slicing solutions. We assess the performance of our solution in Section III followed by concluding remarks in Section IV.

II. WI-FI SSID NETWORK SLICING

In this paper we focus on slicing at the radio access segment of the network and consider a Wi-Fi AP providing different services to associated STAs in an indoor environment. We propose the definition of three slices, based on 5G's three main scenarios: Slice A for eMBB, Slice B for mMTC and Slice C for URLLC. This is achieved by defining three Wi-Fi channels, each of them characterized by its bandwidth, centre frequency (given by the channel number), Guard Interval (GI), Modulation and Coding Scheme (MCS) index, and transmission power P_{TX}. The channels are identified with distinct SSIDs, and treated as separated networks. Thus, the STAs associated with the AP access the relevant channel through a Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) scheme, as in IEEE 802.11.

We take into consideration the uplink communication between the STAs and the AP. This differentiates our work from previous studies which focus only on the downlink scheduling.

A. Static Slicing Algorithm

Our static network slicing algorithm creates three separate channels, one for each of the defined slice. These channels are placed in the $5\,\mathrm{GHz}$ region in order to have the maximum free distance between each other. More precisely, the channel number for Slice A is as low as possible depending on the bandwidth; Slice B is allocated in the centre of the $5\,\mathrm{GHz}$, with channel number 100; and the channel for Slice C has the highest channel number, thus minimising inter-channel interference. The GIs, the MCS indexes and the transmission powers have the same fixed values for all slices (1600 ns, 5 and $20\,\mathrm{dBm}$). These estimates are intended to cover most cases, and $P_{TX} = 20\,\mathrm{dBm}$ is the highest allowed in Europe [11]. Finally, the channel bandwidth $B_w(Th, mcs, gi)$ assigned in each slice is the minimum bandwidth which can accommodate the total throughput Th required in that slice with the given MCS index mcs and GI values gi [12].

B. Dynamic Slicing Algorithm

The dynamic slicing algorithm starts by assigning a channel per slice, which is then continuously monitored and updated at run-time, every time interval T. The algorithm exploits the network conditions and considers the reached performance to adapt slices to the network's needs. Three algorithms have been created for each slice type because of their distinct needs.

1) Dynamic Algorithm for Slice A (eMBB): P_{TX} is set to $20\,\mathrm{dBm}$ and the GI to $800\,\mathrm{ns}$ in order to enable the highest data rates. The maximum MCS mcs_{max} that ensures a packet error probability $P_e < 0.001$ to the STA with the lowest received power is calculated [12]. Now, the channel bandwidth is obtained, $B_w(Th, mcs_{max}, gi)$, the channel number is the lowest in the $5\,\mathrm{GHz}$ band, and the minimum MCS $mcs(Th, B_w, gi)$ that still supports the required throughput is used [12].

After the initialisation phase, every T, the needed bandwidth is recomputed and multiplied by a factor $s \in \{1, 2\}$: i.e. it can be duplicated if needed, as shown in the state machine of Fig. 1. A transition from states occurs if $P_e > 0.02$ for at least one STA, and the total P_e in the last T got worse. This transition is reversed if $P_e \leq 0.02$ holds for every STA and the total P_e improved. Once the bandwidth has been fixed, the MCS is determined as in the initialization phase.

2) Dynamic Algorithm for Slice B (mMTC): The objective of this algorithm is to minimise the P_{TX} since energy saving is crucial in Internet of Things (IoT). The channel bandwidth is fixed to $20\,\mathrm{MHz}$, the smallest possible in IEEE 802.11, and the GI is relaxed to $1600\,\mathrm{ns}$ given the low throughput requirements. The channel number is 100, at the centre of the $5\,\mathrm{GHz}$ region. The lowest MCS applicable is selected according to the function $mcs(Th, B_w, gi)$, with an additive margin $mcsAdd$ initialised to 1. Once the MCS is fixed, the minimum received power needed to ensure $P_e < 0.001$ is calculated. By summing this value to the highest path loss experienced by the users, the minimum usable P_{TX} is found[1]. An additive margin $P_{TX}Add$ (initialised to $3\,\mathrm{dB}$) is added to the minimum power needed. As explained below, this parameter is modified at run-time to adjust the P_{TX} based on the experienced Quality of Service (QoS).

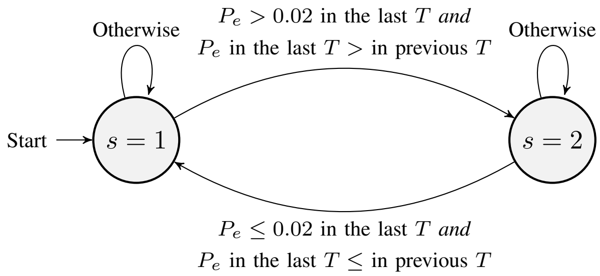

Fig. 1: State machine of the dynamic algorithm for Slice A.

TABLE I: Parameters setting for all the simulations.

Parameter	**Value**
Data Rate eMBB	$\sim U[80, 100]$ Mbit/s
Data Rate mMTC	$\sim U[30, 50]$ Kbit/s
Data Rate URLLC	$\sim U[20, 40]$ Mbit/s
Data Retransmission	none
Packet Size	1472 bytes
ns-3 PHY Layer Model	*SpectrumWifiPhy*
Positions (x, y)	$X \sim U[0, 20]$ m, $Y \sim U[0, 10]$ m
Standard – Band	802.11ax – 5 GHz

At each time interval T, if $P_e \leq 0.02$ does not hold in at least 90% of the STAs, and the average P_e got worse with respect to the previous interval T, the algorithm reacts by increasing the margin $P_{TX}Add$. When it reaches its maximum value, the $mcsAdd$ margin is also increased. In this way, the time on air will decrease and the number of collisions will be reduced. In the opposite case, the P_{TX} is decreased.

3) Dynamic Algorithm for Slice C (URLLC): P_{TX} is set to $20\,\mathrm{dBm}$ and the GI to $800\,\mathrm{ns}$ to reach low latency. At every interval of time T, the highest MCS mcs_{max} able to ensure $P_e < 0.001$ to the STA with the lowest received power is calculated. Then, the channel bandwidth is obtained with $B_w(Th, mcs_{max}, gi)$. The channel numbers in Slice C are selected to be the highest possible in order to allocate channels as distant as possible from each other.

C. ns-3 Simulation Setup and Methodology

In this study, we used *ns-3* simulator and focused on CSMA/CA access in an indoor Wi-Fi scenario consisting of

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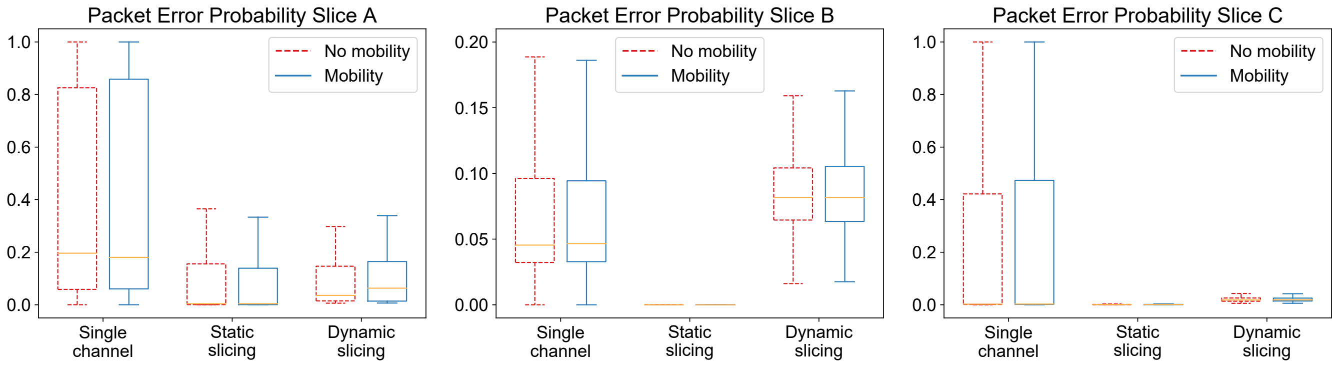
[1] Path loss is obtained by the AP by fixing STAs' transmission powers. By measuring the received power, we will have: $loss = P_{TX} - P_{RX}\ [dB]$.



(a) eMBB (b) mMTC (c) URLLC

Fig. 2: Packet error probability for the three slices A, B and C.

multiple STAs associated to one AP. All the STA devices are randomly placed in a rectangular room with dimensions $20 \times 10\,\mathrm{m}$, $1.5\,\mathrm{m}$ above the ground. The AP is situated at the centre of the room at the ceiling level, $3\,\mathrm{m}$ high.

Our scenario includes between 2 and 6 eMBB STAs. Mobility is taken into account by moving the STAs of this category at a pedestrian speed with variable direction. This represents a typical mobility pattern of an indoor user connected to Wi-Fi [2]. For each eMBB device, the required uplink throughput is random, uniformly distributed between 80 and $100\,\mathrm{Mbit/s}$. We consider 100 mMTC devices, in a fixed randomised position, connected to the AP to reflect a density of about $1\,\mathrm{device/m^2}$. Each of them transmits data at a random speed in the range 30–$50\,\mathrm{kbit/s}$. Finally, our simulations include 2 to 6 URLLC devices with a random throughput spanning from 20 to $40\,\mathrm{Mbit/s}$, which also follow an indoor mobility pattern.

We used the *Buildings Module* to create a single room with all the devices, the *HybridBuildingsPropagationLossModel* as propagation loss model and the *RandomWalk2dMobilityModel* to add a pedestrian movement to nodes in slices A and C. The direction of each mobile device is uniformly chosen every second within the interval $[0{,}2\pi]$ radians and the speed in the range 2–$4\,\mathrm{m/s}$. Each simulation setting ran 20 times with a different seed, with $T = 1\,\mathrm{s}$, for the dynamic algorithms. For the sake of reproducibility, Table I summarises the used parameters for every carried out experiment.

Simulations have been run with different numbers of STAs in slice A and C to consider different proportions of users. The required throughput and the initial position of each user were randomised at every run and the simulation time was $15\,\mathrm{s}$, since a higher duration did not influence the performance.[2]

III. RESULTS

In this section, we present the results for the three resource-allocation algorithms. The *Single channel* approach represents typical Wi-Fi networks exploiting a channel width of $160\,\mathrm{MHz}$ on channel 50, MCS 5, a GI of $1600\,\mathrm{ns}$ and a transmission power of $20\,\mathrm{dBm}$. The *Static slicing* approach allocates resources at the beginning of the simulation without any change. The *Dynamic slicing* algorithm schedules resources at every time interval T, based on performance and network conditions.

A. Performance Analysis

Figure 2a reports the packet error probabilities experienced by eMBB devices (Slice A). When network slicing is not implemented, the network becomes highly congested, and interference increases the error probability, that can be as high as 100%. Considering the results for Slice B (i.e. mMTC), plotted in Figure 2b, we see that the packet error probability is always zero with the static network slicing algorithm. On the other hand, considering dynamic network slicing, we can see that the packet delivery performance is slightly worse than the single channel approach. This is due to the adaptive transmission power scheme, for saving energy. A lower transmission power results in a greater Signal-to-Noise Ratio (SNR), which worsens the error rate but allows for energy savings and justifies the resulting performance deterioration. Packet error probability experienced by URLLC devices is reported in Figure 2c. With single channel communication we get the worst error probability. Conversely, network slicing techniques outperform by far the single channel approach.

Figure 3a shows the End-to-End (E2E) latency for eMBB devices. When all the devices communicate over the same channel, the experienced latency is poor. It is difficult to accommodate the required total throughput and packets need to be queued. However, this problem is completely solved by the dynamic approach, which offers a flexible bandwidth scheduling. By doubling the bandwidth, the channel capacity increases allowing a higher flow of packets with good performance. The latency experienced in Slice B (i.e. by the mMTC devices) is reported in Figure 3b. Again, slicing techniques clearly outperform the single channel method. Latency results for mMTC users using the dynamic algorithm are slightly worse with respect to the ones obtained with static slicing since a lower MCS is used to enable low power consumption. However, this is not crucial for IoT devices. Finally, the slice characterised by URLLC services, is analysed in Figure 3c.

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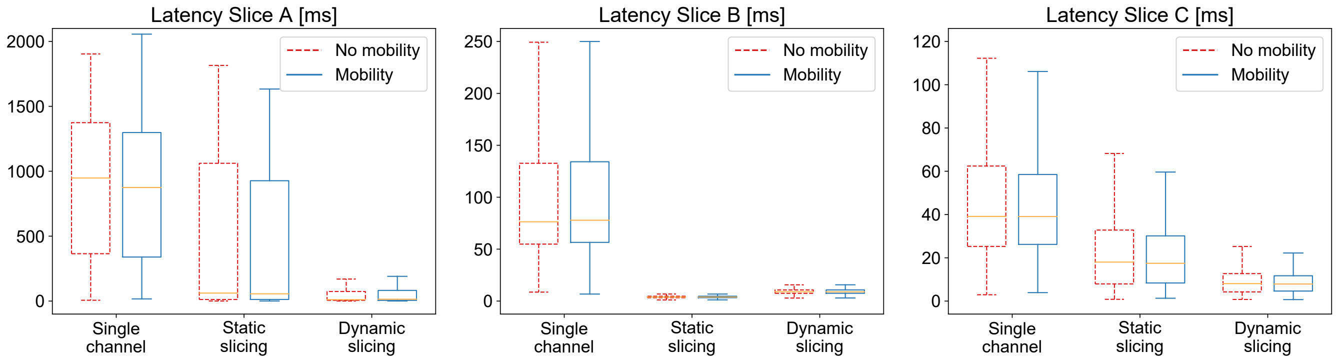
[2] All of the source code, including the *ns-3* scripts involved, is available at https://github.com/matteonerini/5g-network-slicing-for-wifi-networks.



(a) eMBB (b) mMTC (c) URLLC

Fig. 3: Latency for the three slices A, B and C.

Overall, having a single channel which serves all the connected STAs is the worst choice. The dynamic algorithm clearly outperforms the other two thanks to the higher MCS index used.

B. *Resource Utilisation Analysis*

The performance, both in terms of error probability and latency is greatly enhanced when slicing techniques are applied. However, we want to investigate if this improvement is only possible because more resources are allocated, or if better efficiency can be achieved. Thus, it is important to study the energy and bandwidth efficiency of our algorithms.

For Slice B, which includes mMTC devices, energy saving is the main concern. In our simulations, the dynamic network slicing algorithm decreases the average transmission power for these devices from $20\,\mathrm{dBm}$ to $5\,\mathrm{dBm}$. In particular, considering the conversion from dB to linear units, a difference of $15\,\mathrm{dB}$ means that the transmission power is decreased by $10^{15/10} \approx 32$ times in linear units. Battery powered IoT devices in the mMTC slice with dynamic network slicing approach could extend the battery life by up to 32 times.

To compare the three approaches in terms of spectrum efficiency, we consider the total throughput achieved in each run, defined as the sum of the throughput of all the STAs. From the number of received packets on the i-th link, $rxPackets_i$, the total throughput can be obtained as:

$$Th_{sum} = \sum_{i=1}^{nSta} Th_i = \sum_{i=1}^{nSta} \frac{rxPackets_i \times pktSize \times 8}{simTime} \tag{1}$$

where $nSta$ is the total number of STAs connected, Th_i is the throughput of the i-th device, $pktSize = 1472\,\mathrm{bytes}$ as in Table I, and $simTime = 15\,\mathrm{s}$. Thus, the spectrum efficiency in each run is the ratio $\mu = Th_{sum}/\overline{B_w}$, where $\overline{B_w}$ is the total bandwidth allocated in each run, averaged over the time in case of the dynamic algorithm.

In Figure 4, the spectrum efficiency of the network is reported for each tested approach. Interestingly, even though the dynamic algorithm may periodically double the amount of used bandwidth, it has the best spectrum efficiency over the two other approaches, reaching up to $2.6\,\mathrm{bit/s/Hz}$. Thus, we can state that allocating more bandwidth is not necessarily a waste of resources if carefully done.

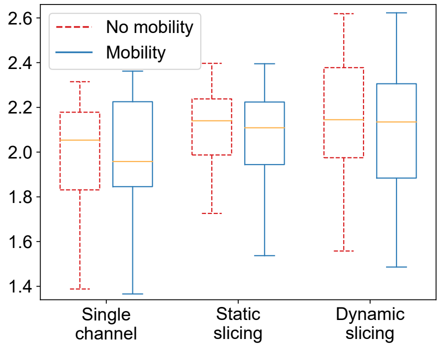


Fig. 4: Spectrum efficiency $[\mathrm{bit/s/Hz}]$.

IV. CONCLUSION

In this paper we show how network slicing can be implemented in Wi-Fi networks using different SSIDs. We present two slicing algorithms where three network slices are allocated, supporting multiple STAs based on the expected performance regarding throughput, latency, energy and spectrum efficiency. One of the proposed slicing algorithms statically allocates three channels according to the expected throughput requirements. The other, dynamically adapts the allocated channel resources at run-time, according to the network needs.

We validate the proposed approach and algorithms with extensive simulations using the *ns-3* network simulator. The obtained results reveal that our slicing approach outperforms today's access scheme in which an AP serves all the connected users with a single wireless channel. We achieve lower packet error probabilities and lower latencies. Furthermore, slicing is able to reduce the energy needed by low-power devices and increase the spectrum efficiency. Thanks to these promising results, this study may pave the way for a future implementation of network slicing in Wi-Fi networks.

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