Wi–Balance: Channel–Aware User Association in Software–Defined Wi–Fi Networks

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***Abstract*—In traditional 802.11 networks stations usually try to associate to the AP with the highest signal strength. However, especially in case of very dense deployments, this may lead to uneven wireless clients distribution, and thus to poor network performances. Software Defined Networking (SDN) has recently emerged as a novel approach for network control and management. In this paper we present *Wi–Balance*, a novel SDN–based solution for joint user association and channel assignment in Wi–Fi networks. An experimental evaluation in a real–world testbed showed that *Wi–Balance* outperforms the RSSI–based user association schemes in terms of throughput and channel utilization by up to 25% and 30%, respectively. We release the entire implementation including the controller and the data–path under a permissive license for academic use.**

***Keywords*—Software Defined Networking, IEEE 802.11, WLANs, channel assignment, mobility management**

I. Introduction

The past years have witnessed a sustained increase in mobile traffic demands that is forecast to reach 49 exabytes per month by 2021 [1]. Due to its low deployment and operational costs, Wi–Fi [2] has emerged as an efficient way to satisfy such demands. Originally relegated to residential and enterprise scenarios, Wi–Fi is becoming a viable traffic offloading solution for cellular networks. Nevertheless, its unplanned nature coupled with its contention–based channel access scheme lead to sub–optimal performances when the network density increases. Moreover, Wi–Fi networks operate in unlicensed bands as opposed to the licensed spectrum used by cellular networks. While this makes Wi–Fi networks extremely easy to deploy, it also makes them more vulnerable to interference from co–located deployments. The growing popularity of 5 GHz–capable devices is mitigating this issue in indoor settings, where the penetration through the walls of high frequency signals is limited. However this does not apply to outdoor scenarios or to networks in the 2.4 GHz band.

In addition to the mentioned pitfalls, Wi–Fi networks leave clients in charge of selecting the optimal Access Point (AP). The actual algorithm used by the clients for the AP selection is not specified by the standard and is left as implementation choice for the vendor. RSSI measurements are typically used to perform this operation, i.e. the client selects the AP with the highest RSSI. Such approach however does not consider the AP load and may lead to an uneven clients distribution across the network. Finally, only a limited number of channels are available in both the 2.4 GHz and the 5 GHz bands. As a result, a severe throughput degradation is expected when multiple APs are in the same collision domain, especially when the number of active APs per unit of area increases. Therefore, an effective collision domain isolation and channel assignment strategy becomes essential to ensure optimal performances [3].

In recent years different solutions have emerged to solve the aforementioned problems. Nevertheless, the traditional Wi–Fi architectures makes it hard to add new mechanisms without modifying the standard. Software Defined Networking (SDN) has recently emerged as a new way of refactoring network functions. By clearly separating data–plane from control–plane and by providing high–level programming abstractions, SDN allows to implement traditional network control and management tasks on top of a *logically* centralized controller. However, albeit SDN is already an established technology in the wired domain, with OpenFlow playing the role of de–facto standard [4], equivalent solutions for wireless and mobile networks have only recently started to appear [5], [6].

In this work we present *Wi–Balance*, a joint channel selection and user association scheme for Wi–Fi–based WLANs. Our contribution is two–fold. On the one hand, a constraint programming algorithm is designed to isolate possible collision domains among the APs. On the other hand, we present a user association scheme capable of detecting situations in which the traffic is not efficiently distributed and to transparently reschedule to other APs the clients whose transmissions are causing performance issues. Based on a real–world evaluation we have demonstrated an improvement of up to 25% and 30% in terms of network throughput and channel utilization compared to a standard RSSI–based user association mechanism. We release the entire implementation, including the controller and the data–path, under a permissive APACHE 2.0 license[1] for academic use.

The rest of the paper is organized as follows. In Sec. II we present the related work. The proposed user association and channel selection scheme is described in Sec. III. Section IV provides the implementation details. Section V reports the measurements campaign. Finally, Sec. VI concludes the paper and discusses the future work.

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II. Related Work

The amount of literature on user association mechanisms in WLANs is significant. The majority of the works in this domain set to achieve some of the following targets: (i) minimize the number of stations per AP; (ii) maximize the average signal quality; or (iii) maximize the average throughput of the network. Moreover, according to the entity responsible for these tasks, the approach may be distributed or centralized.

Regarding the first described target, authors in [7] propose an algorithm to balance the network load that aims to minimize the number of stations per AP based on the signal strength. A similar approach is followed in [8]. However, the number of attached clients alone is not an accurate estimator of the workload of an AP since traffic conditions may significantly vary among the stations.

Selecting the target AP according to the signal strength may lead to ping–pong effects, which are even more difficult to handle in the absence of communication and coordination among the APs. To address this problem, in [9] a station periodically looks for the most suitable AP in terms of both traffic load and RSSI level. However, the handover is not performed until a given AP is not identified as the best choice for n consecutive times. The signal perceived by the stations is also taken into account in [10], where two wireless adapters are used at the client side to simultaneously allow data exchange with the AP and channel monitoring. The AP selection is also performed at the stations side in [11]. Although these approaches aim to improve independently the throughput of each station, they do not consider the network–wide performance.

In [12] the average workload of the network is used to redistribute the traffic when a new station joins the network or when the signal quality of a client deteriorates. The proposed approach however requires changes to the standard beacon frames and is thus hardly a practical choice. A similar scheme is presented in [13] where the stations are migrated to the least loaded AP. Nevertheless, since the channel quality is not considered, this approach may significantly reduce the aggregated throughput of the network.

In [14] a distributed algorithm is run on the APs, which makes use of an RSSI threshold to take handover decisions. In [15] the problem is addressed using a Mixed Integer Non Linear Programming (MINLP) problem formulation by taking into account the differences among the bandwidth demand of the users. An analytical model is also introduced in [16] with the novelty of assessing the Enhanced Distributed Channel Access (EDCA) parameters defined in 802.11e [17], along with the load–balancing problem. Lastly, a mixture of several parameters such as RSSI level, users location and link quality are considered for the association process in [18].

A handover usually leads to a re–association process, which in time can generate performance degradation due to the period needed by the station to reconnect to the target AP. In [19] the RSSI of the clients drives the association decision. However, the APs are required to operate on non–overlapping channels limiting the size of the deployment. A mechanism is proposed in [20] to set a different channel for each AP.

The client association problem is also studied from the point of view of the Software–Defined WLANs. In [21] the authors formulate the problem through a Markovian analytical model with the aim of minimizing the interpacket delay. In [22] an SDN–based scheme is proposed to reconfigure the transmission power of the APs when the controller detects that the load distribution is unbalanced. This, in time, forces the stations to perform a handover. However, this proposal uses a fixed relationship between transmissions bitrate and Signal–to–Noise Ratio. Moreover, the results are only shown via simulation. Mininet is used in [23] to test an algorithm where the SDN controller compares the load of each AP with a fixed value in order to decide whether to accept or reject new stations. The user association problem is modelled using graph theory in [24]. To make the association decision the channel busyness time and the interference are considered. However, the APs are also required to operate on the same channel.

In [25] the authors present the concept of virtual resource chain, which refers to all the resources in a WLAN, to improve the resource utilization and the network balance. A similar work is presented in [26], where a Mixed Integer Linear Programming (MILP) model is designed to maximize the total bandwidth assigned over different connection modes, i.e. 2.4 GHz Wi–Fi, 5 GHz Wi–Fi and Ethernet. A real implementation is proposed in [27], [28] to enable the balance over multiple channels by building on the use of virtual access points. In the first work the handover decision is based on the maximum and minimum traffic load of the APs and the RSSI perceived by the stations. A sniffer interface is also used in the second approach to gather the network statistics through a periodical scanning of the channels.

An effective user association scheme must consider the global network status and evaluate different load metrics in order to ensure optimal performances. Since interference is a determinant issue, a channel assignment procedure must be also performed along with the user association algorithm. Finally, the stations redistribution over the APs must not lead to a transmission interruption. To the best of the authors knowledge, *Wi–Balance* is the first scheme which supports all the above mentioned requirements and that can be implemented with no changes to the Wi–Fi standard.

III. Channel–aware user association

In this section we introduce the main features of the *Wi–Balance* channel–aware user association solution. Moreover, based on a preliminary analysis, the most determining factors in multichannel user association are identified and used to motivate this work.

A. Motivation

Interference and collisions are the most important cause of performance degradation in WLANs [29], [30]. When several clients attached to the same AP transmit at the same time, the network may suffer delays, service interruptions and

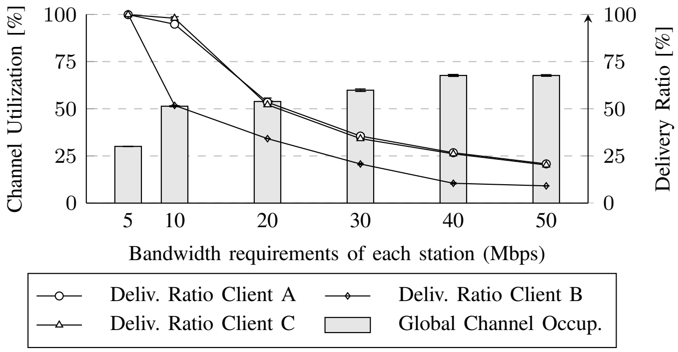

Fig. 1: Delivery ratio of three stations attached to a single AP performing uplink transmissions with different bandwidths.

performance drops. Figure 1 depicts the relationship between channel utilization and network performance. During the measurement three clients were transmitting with bandwidth requirements ranging from 5 to 50 Mbps towards the same AP. As can be seen, when the channel occupancy is higher than 60%, the delivery ratio dramatically drops. This is due to the collisions in the wireless medium and the decrease in the data rates used for the transmission. We remind the reader that the Modulation and Coding Scheme (MCS) adaptation algorithms tend to select lower data rates upon several failed transmissions, which in time increases the channel utilization.

This simple scenario demonstrates the importance of an efficient network resource allocation in terms of both channel assignment and user association. This aspect acquires even more relevance when considering mobile clients. In order to address this challenge we propose an SDN–based joint user association and channel assignment algorithm.

B. Channel Assignment Algorithm

Channel assignment must be done in such a way to minimize interference between APs that are in the same collision domain. Two APs are in the same collision domain if they are tuned on the same channel and if they are within carrier sensing range of each other. In this case, if multiple transmissions start at the same time they can either collide or one of the transmissions must be delayed. In either case a reduction in the aggregated network throughput is to be expected.

The efficiency of a channel assignment procedure depends on the number of available channels and on the number of APs in the same collision domain. The higher the number of available channels, the lower the probability of finding two APs using the same one. Therefore, it is crucial to identify the channels used by the APs in the neighbouring networks, since they may share the same collision domain. However, after identifying these channels, the set of available channels for the assignment may be very limited, especially in congested areas such as office buildings or universities.

A channel assignment algorithm must have as input the interference map of the WLAN. In other words, it must consider for each AP, the set of surrounding APs that must not

Algorithm 1 Channel assignment procedure

Input:
$neighbors$: graph storing the neighbours of each AP.
$channels$: list of available channels.
$overlaps$: dictionary storing the overlapping channels.
Output:
$assignment$: dictionary of (AP, channel) assignment

procedure $\textsc{Solve}(neighbors, channels, assignment)$
  $remainingAPs \leftarrow APs \notin assignment$
  if $len(remainingAPs) == 0$ **then**
    return $assignment$ ▷ It becomes the ***solution***
  Sort $remainingAPs$ by the lowest number of available channels and the highest number of neighbors in $assignment$
  $nextAP \leftarrow remainingAPs[0]$
  $possibleCh \leftarrow channels$
  for each $AP \in neighbors\,[nextAP]$ **do**
    $APCh \leftarrow assignment[AP]$
    $possibleCh \leftarrow possibleCh - APCh$
    $possibleCh \leftarrow possibleCh - overlaps[APCh]$
  if not $possibleCh$ **then**
    $possibleCh \leftarrow min(assignment)$
  for each $channel \in possibleCh$ **do**
    $assignment[NextAP] \leftarrow channel$
    return $\textsc{Solve}(neighbors, channel, assignment)$

operate on the same channel, as well as the list of available channels. The interference map is built in the first step of the algorithm and its data is designated as the constraints of the problem. Moreover, a periodic analysis of the wireless medium must be carried out to update the network information. Notice that SDN–based solutions allow the channel assignment algorithm to have a complete view of the network (which is collected and maintained by the SDN controller).

In light of this, a constraint programming algorithm has been designed to solve the channel assignment problem. The recursive algorithm is shown in Algorithm 1. The algorithm first tries to assign a channel to the set of APs with the lowest number of available channels. We refer to available channels as those that have not been still assigned to the neighbouring APs of a certain AP and do not overlap with the ones already assigned to them. Then, the algorithm selects in this set of APs the one with the highest number of neighbours already assigned. Furthermore, if all the channels have been already taken by the neighbouring APs, the algorithm selects the channel that has been used by the lowest number of APs. In case that multiple channels match this condition, the channel with the lowest occupancy ratio is chosen. The algorithm finishes when it finds a configuration that minimizes the number of APs in the same collision domain.

Although after performing an efficient channel assignment the network interference may have been significantly reduced, there is still room for improvement. In the next section we will introduce the *Wi–Balance* user association algorithm.

C. User Association Algorithm

After the channel assignment, the controller performs a neighbour discovery process in order to build the channel quality map. This map includes for each station the channel quality with respect to all the APs in the network. The channel quality map is built by the SDN controller by retrieving from each AP the list of stations in its coverage area. Similarly, the controller periodically gathers the statistics of the rate adaptation algorithm maintained by each AP. In particular, for each station and for each supported MCS, the Exponentially Weighted Moving Average (EWMA) of the delivery probability and the expected throughput in the last observation window are reported. Moreover, the number of successful and failed transmissions are also reported. We remind the reader that this information is maintained by the rate adaptation algorithm implemented by the AP. Therefore, no extra computation is added to the APs. Gathering this statistical data needs some limited signalling between the controller and the APs. The details of this protocol are outside the scope of this paper and can be found online [31]. It is also important to highlight that *Wi–Balance* does not require any change to either to the IEEE 802.11 protocol nor to the wireless devices. The whole process is sketched in Fig. 2.

Let us define U as the set of stations in the network, M as the set of Wi–Fi APs and $\Omega(u) \subseteq M$ as the set of APs within the coverage area of the user $u \in U$. Using the statistical data collected by the controller, *Wi–Balance* computes the channel utilization $\mu(n)$ for each $n \in M$ and the average channel occupancy across all the APs in the network $\overline{\mu}$. If a significant difference between $\overline{\mu}$ and any occupancy ratio is found a user re–association process is triggered for the affected AP. In particular, *Wi–Balance* collects, for each user u attached to the affected AP n, the channel utilization of the surrounding APs, $\Omega(u)$, and the RSSI level between each AP $m \in \Omega(u)$ and the station u, let us call this quantity R_u^m.

After that, *Wi–Balance* selects as candidate AP for the handover the AP offering the lowest result of the product between the current occupancy ratio of AP n, i.e. $\mu(n)$, and the perceived signal strength R_u^m for each $m \in \Omega(u)$. Then, the client handover is performed. The average channel occupancy $\overline{\mu}$ is recalculated to check if the network redistribution was efficient. Otherwise, the handover is reverted. This process is also triggered in case of observing a sudden change in the RSSI value for any client, which could result from the movement of that client.

D. Complexity Analysis

In this section we will analyse the computational complexity of *Wi–Balance*, distinguishing between the channel assignment and the user association algorithms.

The channel assignment algorithm is a recursive procedure that is called n times until a channel has been selected for each AP. The recursive nature makes the algorithm have two cases: a base and recursive case. In order to solve this problem, we will use a recurrence relation denoted as $T(n)$. The base case encompasses the scenario in which all the APs have been visited, and thus, $n = 0$. At this point, the complexity of $T(0)$ is essentially constant and equals to $O(1)$. In the recursive case, i.e. when $n > 0$, two aspects must be considered: i) the function is recursively called with $n-1$; ii) the channel search operations are internally performed for that AP. The cost of (i) is $T(n-1)$, while the cost of (ii) must be further explored. First, the n remaining APs are sorted by the lowest number of available channels and the highest number of neighbours. The complexity of this step is $O(n \cdot log(n))$. Then, the list of neighbouring APs for the first AP in the list is traversed to discover the available channels, which results in a cost $O(n)$. In the worst case in which there are no available channels, the algorithm will select the channel less used by the neighbours, hence adding a complexity $O(n)$. After that, the algorithm must iterate through the list of possible channels, which in the worst case will be as long as n. On this basis, the cost of (ii) is estimated as $O(n)$, and hence the relation $T(n)$ can be expressed as $T(n) = T(n-1) + O(n)$. Thus, the complexity of the channel assignment is $O(n^2)$.

Every time the user association algorithm is called, the list of APs must be traversed to compute their channel occupancy ratio. Therefore, the complexity of this operation is $O(n)$. Computing this ratio requires to calculate the fraction of time used by the stations attached to each AP. In the worst case, all the stations in the network, s, will be attached to the same AP, which results in a computational complexity $O(s)$. On this basis, the cost of computing the channel utilization will be as high as $O(n \cdot s)$. Moreover, the average channel utilization must be calculated. Notice that this estimation depends on the number of APs, hence it being as complex as $O(n)$. Then, the individual ratio of each AP must be compared with the average one to find imbalances in the distribution of the network load. Therefore, the list of APs must be once again traversed, resulting in a complexity of $O(n)$. In case of finding an imbalanced AP, the list of all its clients must be traversed, and for each client, the algorithm must iterate through all its possible APs to perform a handover. Thus, the complexity of the use association algorithm is $O(n \cdot s)$.

Finally, the overall computational complexity of the joint channel assignment and user association algorithm is $O(n \cdot s + n^2)$ which can be approximated as $O(n \cdot s)$ since in most cases $s >> n$.

IV. Implementation Details

A. Overview

The proposed user association algorithm has been implemented on the 5G–EmPOWER platform [5]. 5G–EmPOWER is a Multi–access Edge Computing Operating System (MEC–OS) which converges SDN and NFV into a single platform supporting lightweight virtualization and heterogeneous radio access technologies[2]. A high level view of the the 5G–EmPOWER MEC–OS architecture is sketched in Fig. 3.

The 5G–EmPOWER MEC–OS consists of a hardware abstraction layer converging several radio access networks

[2]Online resources available at: http://empower.create-net.org/

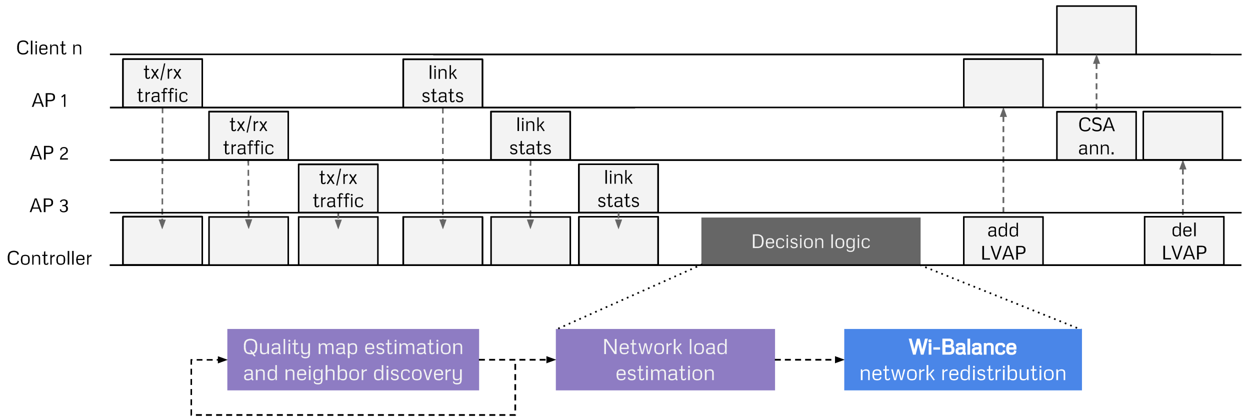

Fig. 2: Scheme of the working mode of *Wi–Balance*.

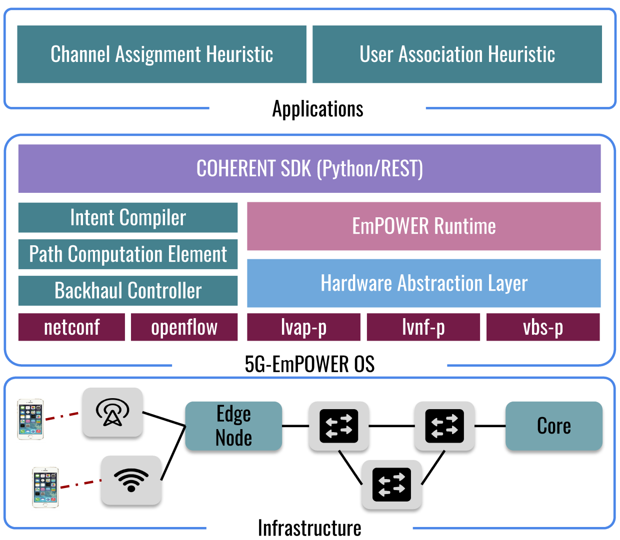

Fig. 3: The 5G–EmPOWER MEC–OS System Architecture.

control and management protocols into a unified set of abstractions that are then exposed to the application layer. Such abstractions allow the applications layer to implement joint NFV and SDN resource management operations. This includes, for example, joint mobility management and NFV placement/migration schemes as well as radio access and backhaul load–balancing. The 5G–EmPOWER MEC–OS currently supports Wi–Fi and LTE radio access nodes. Interaction with SDN–based backhauls is enabled trough an Intent–based networking interface. In the rest of this section we will provide a short summary of the *Light Virtual Access Point* and of the *Network Graph* abstractions used to implement the user association algorithm presented in this paper. For a more extensive description we refer the reader to [5].

B. Light Virtual Access Point (LVAP)

The *LVAP* abstraction [6] provides a high–level interface for the state management of the wireless clients. The implementation of such an interface handles all the technology–dependent details such as association, authentication, handover and resource management. A client attempting to join the network will trigger the creation of a per–client virtual access point (the *LVAP*) which becomes a potential candidate AP for the client to perform an association. Similarly each AP will host as many *LVAPs* as the number of wireless clients that are currently under its control. Removing an *LVAP* from an AP and instantiating it on another AP effectively results in a handover.

C. Network Graph

The Network Graph provides network programmers with a full view of the network state. The network graph is exposed as a directed graph $G = (V, E)$ where V is the set of clients and radio access network elements (i.e. the Wi–Fi APs) and E is the set of edges or links. A weight $\omega_e(e_{n,m})$ is assigned to each link $e_{n,m} \in E : \omega(e_{n,m}) \in \mathbb{R}$. Another weight $\omega_v(n)$ is assigned to each node $n \in N : \omega_v(n) \in \mathbb{R}$. The weights assigned to nodes and links can model different aspects of the wireless system. In the current implementation of the 5G–EmPOWER MEC–OS the following types of complex data structures can be associated to the vertexes and the edges of the Network Graph:

- *RSSI*. The received signal strength indicator as reported by the Wi–Fi APs (uplink direction) and wireless clients (downlink direction). Measurements in the downlink direction are taken using the radio resource management features introduced by the 802.11k amendment [2].
- *Rate Control Statistics*. The statistics of the MCS selection algorithm at the AP (downlink). For each supported MCS, the frame delivery ratio and the estimated throughput in the last observation window are reported. Historical, EWMA–filtered values, are also available.
- *Channel Occupancy*. The fraction of the time the channel is busy at each Wi–Fi AP. This is an estimated value computed using the rate control statistics and by sniffing the transmissions within the decoding range of the AP. Corrupted frames are however not taken into account.
- *Traffic Matrix*. The number of packets and bytes transmitted/received by each wireless client. The absolute packets/bytes values as well as the bitrate in the last observation window are available to applications.

D. Seamless Handover Across Different Channels

Notice how the original seamless handover enabled by the *LVAP* concept does not work when the APs operate on different channels. In this work we remove this limitation by using the Channel Switch Announcement (CSA) defined by the IEEE 802.11 standard. The CSA procedure was originally designed to allow APs to inform the attached client that the operating channel of the hotspot was about to change. This information is delivered inside the standard beacons frames. In particular, an AP that is planning to switch the operating channel will start advertising the new channel in its beacons. A countdown is started and the channel is switched after a configurable number of beacons (three usually).

In traditional Wi–Fi networks, beacons are sent as broadcast management frames. Conversely, in our case each *LVAP* sends its own beacons using unicast frames. This is possible because an *LVAP* is created for each station attached to an AP. Such a design choice allows us to target a CSA message to a particular station by enabling it only for the *LVAP* that was created for that station. The seamless handover across APs tuned on different channels and/or bands is enabled by first creating an *LVAP* on the target AP. This *LVAP* is initially inactive since the station that it is mapping is tuned on a different channel. Then the controller instructs the *LVAP* on the source AP to start a CSA procedure. At the end of this CSA procedure the *LVAP* at the source AP is automatically removed. In the meantime, the station will have switched channel and will have found its *LVAP* on the target AP. The full process is sketched on the right–hand side of Fig. 2.

It should be also noted that the performance impact of these unicast beacons is very low given their short duration and length. However, a trade–off can be set between the duration of the handover and the number of beacons in the network. If this feature is disabled, the impact on the network will be decreased at the price of a longer period of time to perform the handover. If it is enabled, a faster handover is possible at the price of a little increase in the management traffic.

V. Performance Evaluation

In this section we report on the results of the performance evaluation. In particular we compare the network performance using *Wi–Balance* with the network performance using an RSSI–based user association algorithm.

A. Evaluation Methodology

The performance evaluation is carried out on a real–world testbed composed of three APs. The layout of the testbed is depicted in Fig. 4. The APs are built upon the the PCEngines ALIX 2D (x86) processing board and run OpenWRT 15.05.01. The Wi–Fi cards are based on the Atheros AR9220 chipset. All the experiments are carried out on the 5 GHz frequency band using the IEEE 802.11n physical layer [32]. The channels used by the APs are selected by the channel assignment algorithm presented in Sec. III-B. The scenario also comprises the 5G–EmPOWER controller (not shown in the picture) and a set of 10 stations. One of these stations moves following the path marked in blue in Figure 4. The remaining stations are static and are deployed randomly across the entire floor. Dell–branded laptops powered by an Intel i7 CPU and running Ubuntu 16.04.02 are used as wireless clients. It should be noted that our solution can be applied to other scenarios in the 2.4 GHz band and including both uplink and downlink traffic, as well as different number of stations and APs.

Nine experiments, identified with the letters from A to I, have been conducted. Each test has a duration of 5 minutes and consists of a single UDP or TCP stream between wireless clients and a server sharing the same backhaul with the APs. In the case of UDP traffic, different bitrates are used. The set of 10 users is divided into 2 groups with 5 stations each for the tests from A to F. The first group performs transmissions with a constant bitrate that is maintained for the entire duration of the measurement. By contrast, the second group uses intermittent transmissions. These stations transmit traffic for 40 seconds, and after that, they stop the transmission for 20 seconds. This pattern is repeated until the end of the experiment. Then, the role of the groups is inverted, i.e. the stations with constant bandwidth perform intermittent transmissions, and vice versa. In the experiments from G to I, all the stations generate constant bitrate traffic. A summary of the different scenarios can be found in Table I.

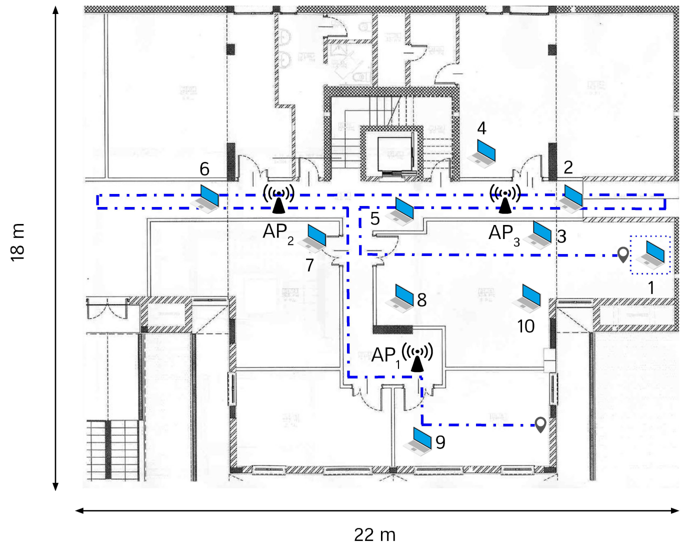

Fig. 4: Testbed deployment layout and APs–users distribution.

TABLE I: Configuration of the measurements campaign.

Test	Traffic type	User groups traffic dist.	Bandwidth (Mbps)
A	UDP	Constant - Intermittent	10
B	UDP	Constant - Intermittent	5
C	TCP	Constant - Intermittent	-
D	UDP	Intermittent - Constant	10
E	UDP	Intermittent - Constant	5
F	TCP	Intermittent - Constant	-
G	UDP	Constant - Constant	10
H	UDP	Constant - Constant	5
I	TCP	Constant - Constant	-

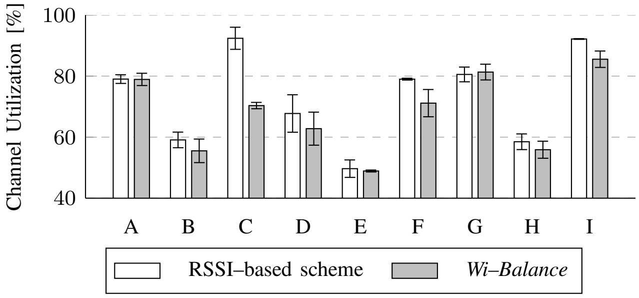

Fig. 5: Network–wide channel utilization for both the UDP and the TCP traffic transmissions.

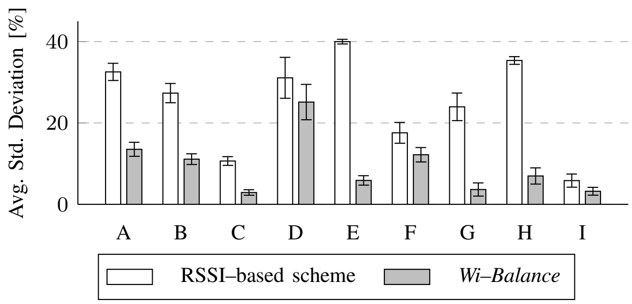

Fig. 6: Average deviation of the channel utilization of each AP with regard to the network–wide ratio for both the UDP and the TCP traffic transmissions.

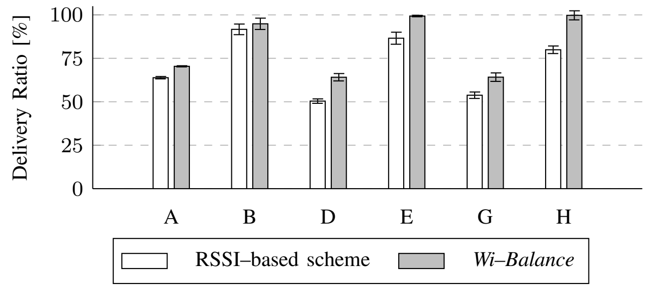

Fig. 7: Average delivery ratio for the UDP traffic transmissions at 5 and 10 Mbps.

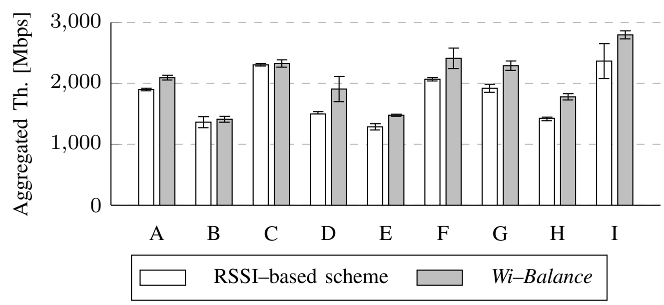

Fig. 8: Network–wide aggregated throughput for both the UDP and the TCP traffic transmissions.

The effectiveness of our proposal is compared with the RSSI–based scheme, in which the stations intend to associate to the AP providing the strongest signal. As evaluation metrics we have considered the delivery ratio, the aggregated throughput, the wireless channel utilization, the Jain's fairness index [33] and the retransmission ratio. Apart from the uplink transmissions, no downlink traffic exists between the APs and the stations.

B. Experimental Results

Especially in situations of congestion, an uneven distribution of the stations may cause some of the APs to be saturated, while some others are idle. As a consequence, the users connected to first group of APs will share the available bandwidth which in time could result in a lower aggregated network throughput compared to a situation with an even distribution of the stations across the various APs. From the results shown in Fig. 5 it can be observed that the average channel occupancy ratio with *Wi–Balance* is up to 30% lower than the channel occupancy ratio with the RSSI–based scheme. This is achieved through a more efficient users distribution, which results in a more balanced network and a decrease in the channel contention.

In addition to reducing the overall channel utilization, it is even more important that the APs have an occupancy ratio that is as similar as possible. This situation is displayed in Fig. 6, where the average deviation of the channel utilization of each AP with regard to the average network–wide ratio using *Wi–Balance* is compared with the channel utilization obtained using the RSSI–based scheme. As can be seen, the utilization of each AP widely differs for the reference scheme, while this ratio is more balanced in the case of *Wi–Balance*.

Figure 7 plots the delivery ratio achieved in the tests using UDP traffic. It can be seen that in all the experiments *Wi–Balance* outperforms the results obtained by the RSSI–based scheme by an average of 17%, and up to 25% in the experiments D and H. The network–wide aggregated throughput is presented in Fig. 8 for the UDP and TCP traffic. The figure shows that the efficient scheduling of the stations leads to an increase in the throughput by an average of 16% and up to 25% in the scenarios D and H.

In addition to enhancing the performance, an efficient load–balancing algorithm must distribute the bandwidth evenly among the stations. To demonstrate this effect, Fig. 9 compares the Jain's fairness index of the stations throughput using *Wi–Balance* and the RSSI–based scheme. As can be seen, *Wi–Balance* delivers a better fairness in all the experiments.

Wi–Balance performs better than the RSSI–based scheme also for the mobile users, as can be observed in Fig. 10. This is because when a station moves over the coverage area, the AP to which it is connected is not chosen only according to the signal strength, on the contrary also the AP traffic load is considered. For this reason, the throughput improvement

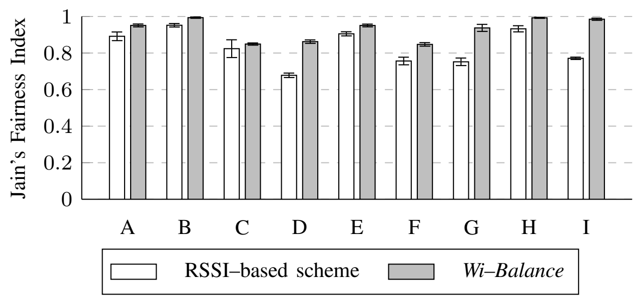

Fig. 9: Jain's fairness index of the throughput achieved by all the wireless clients for both the UDP and the TCP traffic transmissions.

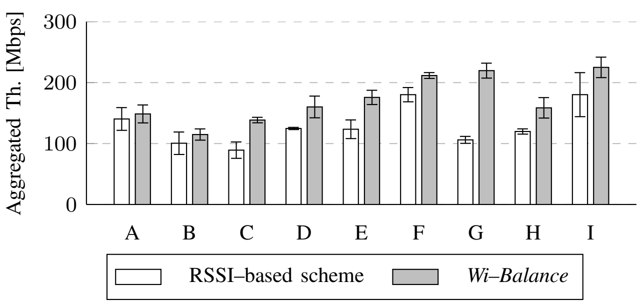

Fig. 10: Average throughput achieved by the mobile station for both the UDP and the TCP traffic transmissions.

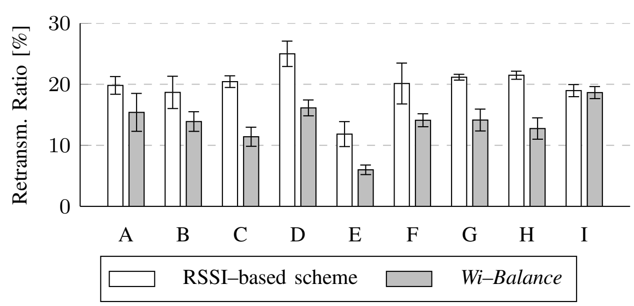

Fig. 11: Network–wide average retransmission ratio for both the UDP and the TCP traffic transmissions.

is notably higher for the mobile users. Finally, the efficient usage and scheduling of the network resources makes also possible to enhance the network reliability. Since *Wi–Balance* results in a more uniform wireless client distribution, the retransmission ratio is also decreased by an average of 30%. This phenomenon is displayed in Fig. 11.

VI. CONCLUSIONS

In this paper we presented *Wi–Balance*, a novel SDN–based solution for joint user association and channel assignment in WiFi networks. Moreover, we also introduced a seamless handover mechanism for Wi–Fi networks capable of operating in a multi–channel environment.

The performance of *Wi–Balance* has been evaluated in a real–world testbed under different scenarios considering mobile and static users. More specifically, compared to RSSI–based user association schemes, *Wi–Balance* can reduce the channel utilization by up to 30% and can improve the aggregated network throughput by up to 28% without penalizing the network fairness. Conversely a slight improvement in the Jain's fairness index can be noticed when using *Wi–Balance*.

As future work we aim to extend *Wi–Balance* to consider the wired backhaul in the user association algorithm. Moreover, we plan to support the traffic prioritization and aggregation features supported by the 802.11e and 802.11n standards.

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REFERENCES

[1] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021," Cisco, Tech. Rep., 2017.

[2] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, ANSI/IEEE Std 802.11, LAN/MAN Standards Committee of the IEEE Computer Society Std., 2012.

[3] S. Chieochan, E. Hossain and J. Diamond, "Channel assignment schemes for infrastructure-based 802.11 WLANs: A survey," *IEEE Communications Surveys Tutorials*, vol. 12, no. 1, pp. 124–136, 2010.

[4] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "OpenFlow: Enabling Innovation in Campus Networks," *ACM Computer Communication Review*, vol. 38, no. 2, pp. 69–74, 2008.

[5] R. Riggio, M. K. Marina, J. Schulz-Zander, S. Kuklinski, and T. Rasheed, "Programming abstractions for software-defined wireless networks," *IEEE Transactions on Network and Service Management*, vol. 12, no. 2, pp. 146–162, 2015.

[6] L. Suresh, J. Schulz-Zander, R. Merz, A. Feldmann, and T. Vazao, "Towards Programmable Enterprise WLANS with Odin," in *Proc. of ACM HotNets*, New York, NY, USA, 2012.

[7] S.-T. Sheu and C.-C. Wu, "Dynamic Load Balance Algorithm (DLBA) for IEEE 802.11 Wireless LAN," *Journal of Science and Engineering*, vol. 2, no. 1, pp. 45–52, 1999.

[8] G. Bianchi and I. Tinnirello, "Improving load balancing mechanisms in wireless packet networks," in *Proc. of IEEE ICC*, New York, NY, USA, 2002.

[9] Li-Hsing Yen and Tse-Tsung Yeh, "SNMP-based approach to load distribution in IEEE 802.11 networks," in *Proc. of IEEE VTC*, Melbourne, Vic., Australia, 2006.

[10] N. Papaoulakis, C. Patrikakis, C. Stefanoudaki, P. Sipsas and A. Voulodimos, "Load balancing through terminal based dynamic AP reselection for QoS in IEEE 802.11 networks," in *Proc. of IEEE Percom*, Seattle, WA, USA, 2011.

[11] M. Abusubaih, J. Gross, S. Wiethoelter and A. Wolisz, "On Access Point Selection in IEEE 802.11 Wireless Local Area Networks," in *Proc. of IEEE LCN*, Tampa, FL, USA, 2006.

[12] T. D. I. Jabri, N. Krommenacker and A. Soudani, "IEEE 802.11 Load balancing: an approach for QoS Enhancement," *Journal of Wireless Information Networks*, vol. 15, no. 1, pp. 16–30, 2008.

[13] Y. Bejerano, S. J. Han, and L. Li, "Fairness and Load Balancing in Wireless LANs Using Association Control," *IEEE/ACM Transactions on Networking*, vol. 15, no. 3, pp. 560–573, 2007.

[14] M. Collotta, G. Pau, V. M. Salerno and G. Scat, "A distributed load balancing approach for industrial IEEE 802.11 wireless networks," in *Proc. of IEEE EFTA*, Krakow, Poland, 2012.

[15] L. Yang, Y. Cui, H. Tang and S. Xiao, "Demand-Aware Load Balancing in Wireless LANs Using Association Control," in *Proc. of IEEE Globecom*, San Diego, CA, USA, 2015.

[16] M. Ertrk, L. Vollero, M. Aydin, O. Turna and M. Bernaschi, "A framework for modeling and implementing QoS-aware load balancing solutions in WiFi hotspots," in *Proc. of IEEE ISWCS*, Barcelona, Spain, 2014.

[17] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 7: Medium Access Control (MAC) Quality of Service (QoS)*, ANSI/IEEE Std 802.11e, LAN/MAN Standards Committee of the IEEE Computer Society Std., 2005.

[18] F. Cao, Z. Zhong, Z. Fan, M. Sooriyabandara, S. Armour and A. Ganesh, "User association for load balancing with uneven user distribution in IEEE 802.11ax networks," in *Proc. of IEEE CCNC*, Las Vegas, NV, USA, 2016.

[19] Y. Chan and D. Lin, "The Design of an AP-Based Handoff Scheme for IEEE 802.11 WLANs," *International Journal of e-Education, e-Business, e-Management and e-Learning*, vol. 4, no. 1, pp. 72–76, 2014.

[20] M. E. Berezin, F. Rousseau and A. Duda, "Multichannel Virtual Access Points for Seamless Handoffs in IEEE 802.11 Wireless Networks," in *Proc. of IEEE VTC*, Yokohama, Japan, 2011.

[21] J. Chen, B. Liu, H. Zhou, Q. Yu, L. Gui and X. Shen, "QoS-Driven Efficient Client Association in High-Density Software-Defined WLAN," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 8, pp. 7372–7383, 2017.

[22] C. Y. Lin, W. P. Tsai, M. H. Tsai and Y. Z. Cai, "Adaptive Load-Balancing Scheme through Wireless SDN-Based Association Control," in *Proc. of IEEE AINA*, Taipei, Taiwan, 2017.

[23] N. Kiran, Y. Changchuan and Z. Akram, "AP load balance based handover in software defined WiFi systems," in *Proc. of IEEE IC-NIDC*, Beijing, China, 2016.

[24] T. Lei, X. Wen, Z. Lu and Y. Li, "A Semi-matching Based Load Balancing Scheme for Dense IEEE 802.11 WLANs," *IEEE Access*, vol. PP, no. 99, pp. 1–1, 2017.

[25] J. Feng, L. Zhao, C. Chen, Z. Ren and J. Du, "User-Oriented Load Balance in Software-Defined Campus WLANs," in *Proc. of IEEE VTC*, Nanjing, China, 2016.

[26] T. De Schepper, S. Latr and J. Famaey, "A transparent load balancing algorithm for heterogeneous local area networks," in *Proc. of IEEE IM*, Lisbon, Portugal, 2017.

[27] Y. Han, K. Yang, X. Lu and D. Zhou, "An adaptive load balancing application for software-defined enterprise WLANs," in *Proc. of IEEE ICTC*, Jeju, South Korea, 2016.

[28] A. K. Rangisetti, H. B. Baldaniya, P. K. B and B. R. Tamma, "Load-aware hand-offs in software defined wireless LANs," in *Proc. of IEEE WiMob*, Larnaca, Cyprus, 2014.

[29] C. Karupongsiri, "Negative impact of CSMA/CD on WLAN IEEE 802.11," in *Proc. of IEEE TENCON*, Penang, Malaysia, 2017.

[30] C. Yuan, Z. Yuan and G. Xiqi, "Collision and Corruption Awareness Enhancement to IEEE 802.11 DCF: Scheme and Performance Analysis," in *Proc. of IEEE CMC*, Yunnan, China, 2009.

[31] "The EmPOWER Protocol." [Online]. Available: https://github.com/5g-empower/5g-empower.github.io/wiki/EmPOWER-Protocol

[32] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 5: Enhancements for Higher Throughput*, ANSI/IEEE Std 802.11n, LAN/MAN Standards Committee of the IEEE Computer Society Std., 2009.

[33] H. SHI, R. V. Prasad, E. Onur and I. Niemegeers, "Fairness in Wireless Networks:Issues, Measures and Challenges," *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 5–24, 2014.