Considering Frame Aggregation in Association Optimization for High Throughput Wi-Fi Networks

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ABSTRACT

Optimization of the association between wireless stations and access points (APs) has shown its effectiveness to improve the overall performance of wireless LAN. Most of the previous works do not consider the latest amendments of the IEEE 802.11 standard. The main challenges are to propose models that take into account recent enhancements such as spatial multiplexing (MIMO) at the physical layer and frame aggregation mechanism at the MAC layer. To assess these new features, we derive an association optimization approach based on a new metric, named Hypothetical Busy Time Fraction (H-BTF), that combines the classical Busy Time Fraction (BTF) and the frame aggregation mechanism. This metric is based on local measurements like throughput demand and frame error rate for each station. The model estimates the H-BTF of each AP for any configuration and is thus able to predict H-BTF for other association scheme. Association is then optimized to minimize the load of the busiest APs. This load balancing between APs aims to satisfy stations with regard to their throughput demands. Numerical evaluations performed with the network simulator ns-3 have shown the accuracy of the proposed approach for a large set of scenarios and a significant benefit for the stations in terms of throughput and satisfaction.

KEYWORDS

Wi-Fi, Association, Optimization, Frame aggregation

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1 INTRODUCTION

The majority of Wi-Fi commercial products, operating on the 2.4 and 5 GHz frequency bands, now implement the IEEE 802.11n version while many of those products also implement the IEEE 802.11ac version. These IEEE 802.11 solutions offer high to very high throughput thanks to major modifications of the initial versions of 802.11. These modifications include, among others, the use of the MIMO (Multiple Input / Multiple Output) technology, the possibility to aggregate channels to transmit on a wider channel as well as to aggregate frames in a single frame [2].

Although these versions offer high throughput (up to 600 Mb/s for IEEE 802.11n and up to almost 7 Gb/s for IEEE 802.11ac), it is always worthwhile to think to and design mechanisms that improve the performance of the WLANs (wireless local area networks) using these communication technologies. Indeed, even if it is very likely that these high throughput Wi-Fi networks will remain mainly not saturated, and this for a while, the use of the network may be very different from one point to another in the network and over time. In this case, some stations may require low traffic while some others may be unsatisfied due to a high traffic demand in some parts of the network. Balancing the load with a change in the stations' association is a possible solution to allow unsatisfied stations to use the remaining bandwidth not used by the satisfied stations.

In [3], we designed an association mechanism using the channel busy time estimation in order to improve the users' performance in non saturated Wi-Fi networks. This solution offers good performance by reducing the number of unsatisfied stations in the network and by improving the stations' throughput. This work only considers the initial versions of IEEE 802.11, like 802.11a/b/g and does not integrate the new features of IEEE 802.11n/ac. If some other works test their association solution with IEEE 802.11n/ac, none of these works integrates, in their models and algorithms, the specific features of IEEE 802.11n/ac. Yet, these features have a clear impact on the stations' throughput and consequently on the performance of a given association.

In this paper, we propose an association solution that embeds the main new features of IEEE 802.11n/ac. These features are integrated in the underlying model of our solution that estimates and predicts the share of the radio medium between the access points (APs) and the stations via the channel busy time fraction. If the MIMO property and the channel aggregation can be easily considered in the data rate parameter of our model, the frame aggregation is more difficult to estimate and to predict. We propose a model based on the conflict graph between APs and the stations' traffic demand. For this model, we compute a metric, named Hypothetical Busy Time Fraction (H-BTF), that combines the classical Busy Time Fraction (BTF) and the aggregation mechanism. This metric allows to express the network load at an AP through a single quantity.

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Based on this model, we design an association algorithm that aims to distribute the network load among the APs. Our solution is evaluated with ns-3 simulations that cover a large set of scenarios. The obtained results highlight the benefit of our approach and its ability to improve performance.

The paper is organized as follows. In Section 2, we present the related work. The main features of IEEE 802.11n, considered in this work, are discussed in Section 3. Note that we only describe IEEE 802.11n, because we have considered this version of 802.11 in our simulations. However, our solution can also be used with IEEE 802.11ac. The system model is described in Section 4.1. The H-BTF is defined in Section 4.2. The model estimating its value for any configuration is presented in the same section. Section 5 introduces the optimization problem and the heuristic used to propose approximate solutions. Numerical results are shown and discussed in Section 6. We conclude in Section 7.

2 RELATED WORK

A variety of metrics are used, in the literature, for optimizing the association in WLANs. These metrics are chosen according to the desired objective. In the context of unsaturated networks where each station requires a certain throughput, a classical goal is to unload the most loaded APs by balancing the load between them. The load of an AP can be expressed via different metrics. Metrics such as the number of stations per AP and the sending throughput of an AP do not give an accurate indication of the real load of an AP, because the load depends on the demand of its associated stations, the data rate of the links and the activity of the neighboring APs. On the other hand, metrics like the channel utilization or the busy time fraction seem more appropriate. In this paper, we focus our state-of-the-art on the association solutions based on the load metrics, as this is the metric we use in our work.

In [12], the authors propose an approach to evaluate the load of each AP during the admission process of a new station. To associate a station into a fully loaded access point, they implement an algorithm that distributes the load to neighboring APs until the bandwidth meets the needs of the incoming station. The algorithm takes into account the channel utilization, the spatial distribution of wireless stations and the QoS requirements of the user applications. A slightly different approach is adopted in the work of Krishan and Laxmi [8]. The goal of their algorithm is to balance the load on APs by associating mobile stations with a minimum signal power threshold and achieve the maximum bandwidth offered by each AP. The load balancer is triggered not only during new admissions, but also during station departures and station handovers to other APs. In [10], an adaptive load balancing scheme through association control, in a wireless software defined network, is proposed. This scheme consists of an event detection mechanism and an adaptive load balancing algorithm implemented on a controller. In the algorithm, the controller can derive an optimal association solution based on the traffic load and number of users on each AP. The APs implement a time fairness policy for their associated stations. Dwijaksara et al. [4] propose a joint user association and load balancing scheme for efficiently supporting the multicast transmission over the WLAN system with multiple APs. The first objective of the user association is to balance the load among the APs. The second objective is to associate each user with its best AP for maximizing the network throughput. The last objective is to decide whether to turn on/off each AP given the current load condition. In [6], the authors propose a distributed joint association and power adaptation scheme to maximize the throughput of the entire network. In this approach, the station selects the AP to associate with from a list of candidates selected among its neighboring APs based on a utility function. The utility of each station is defined as a function of the transmission power of the AP to associate with, which can reflect the users satisfaction to its throughput. A similar approach is adopted in the work of [9], but, the objective is to achieve min-max load balancing, namely minimizing the maximum AP utilization of the most congested AP while satisfying users traffic demands. The proposed approach in [13] designs a centralized on-line AP association algorithm that determines the appropriate AP association scheme to maximize the network throughput in a long-term period such as one day. Their algorithm associates stations to APs and allocates bandwidth for stations that require a fixed bandwidth. Gong and Yang [5] study AP association for IEEE 802.11n based WLANs with heterogeneous clients (802.11a/b/g/n). In particular, they address the new challenges introduced by the high data rates and frame aggregation mechanism of 802.11n. Based on a Markov model to estimate client throughput and a design of an optimization problem, they provide an AP association algorithm to improve the network throughput, fairness and load balancing.

In most of those works, the load induced by a station is considered as being the ratio between the traffic requirement of the station and the data rate of the link on which data will be transmitted. This estimation is not very accurate because it does not take into account the times to access the medium (backoff, DIFS, etc.) and the possibility of transmission errors implying retransmissions and potential larger backoff times. Moreover, none of these solutions integrates, in their models and algorithms, the specific features of the new versions of IEEE 802.11 like 802.11n/ac. Yet, these features have a clear impact on the stations' throughputs and consequently on the performance of a given association. In this paper, we consider some of the new features of the recent versions of IEEE 802.11 implemented in commercial products (*e.g.* 802.11n/ac).

3 FEATURES AND CHALLENGES IN IEEE 802.11n

In this section, we first give a brief overview of the new features introduced in recent standards as IEEE 802.11n and in particular frame aggregation. We then discuss the challenges of AP association in these new generations of WLANs.

3.1 Features of IEEE 802.11n

The IEEE 802.11n standard has introduced several new approaches to improve WLAN performance. First, at the physical layer, 802.11n stations can be equipped with multiple antennas and MIMO is used to increase data rates and reliability by transmitting multiple spatial streams simultaneously or by exploiting the spatial diversity. In addition, the maximum coding rate is increased from 3/4 to 5/6 and a short guard interval (400 ns) between orthogonal frequency division multiplexing (OFDM) symbols is introduced to improve spectral efficiency, and therefore the maximum physical flows. In addition, channel link technology, also known as the 40 MHz channel, is applied to further enhance data rate by combining two non-overlapping 20 MHz channels for data transmission.

The combination of the spatial streams, the modulation type and the coding rate are represented by a Modulation and Coding Scheme index (MCS). Coupled to the channel width and the guard interval length, different data rates are then possible for transmitting the frames.

3.2 Frame aggregation

At the MAC layer, the frame aggregation mechanism is used so that multiple frames or datagrams are aggregated into a single packet before transmission.

Two aggregation mechanisms have been proposed: A-MSDU is an aggregation of several SDUs (Service Data Units, typically IP packets) with one common MAC header, and A-MPDU (Aggregate MAC Protocol Data Unit) is a scheme where several IEEE 802.11 frames are aggregated into a single packet.

We focus on A-MPDU because it is mandatory in the standard and implemented in the products, whereas A-MSDU is optional. Each A-MPDU aggregated frame is acknowledged by a block ACK frame, in which a bitmap is used to acknowledge the subframes. In this way, both the MAC overhead (due to numerous acknowledgements) and the duration to access the medium (DIFS, SIFS, Backoff, etc.) are reduced with regard to the number of transmitted bits. ns-3 simulations with MCS 7 (corresponding to a maximal physical transmission rate of 150 Mbps) show that a throughput of 42.5 Mbps is attainable without aggregation and 136 Mbps with aggregation. Obviously, aggregation is a prerequisite to benefit from the physical transmission rate increase offered by the new standard.

3.3 Challenges of AP Association in aggregation-based WLANs

For a given destination, the AP/station aggregates, in a single A-MPDU, the frames present in the buffer at the time it gets access to the medium. Consequently, the number of aggregated frames is not fixed and depends on the state of the buffer at the transmission time. This quantity is named *aggregation* rate in the rest of this paper, and is formally defined as the mean number of frames aggregated in a A-MPDU frame. In our model, this aggregation rate is computed for each station. The efficiency of the aggregation mechanism is directly related to the aggregation rate. We illustrate the impact of the aggregation rate on the performance of the network in Figure 1. We plot the aggregation rate and the BTF (Busy Time Fraction) as a function of the input rate for a simple scenario with an AP and a station. Simulations are performed with ns-3. The throughput is not shown in the figure, but corresponds exactly to the input rate until 136 Mbps where the network saturates.

The aggregation rate varies between 1 (no aggregation) and the maximum number of frames in a single A-MPDU (41 for this configuration). The BTF varies from 0 to 1. We notice that the BTF reaches 1 rapidly. Once it is close to 1, frames cannot access the medium immediately. The buffer is filling up and the aggregation rate increases. But, the aggregation mechanism still allows an enhancement of the throughput from approximately 64 to 136 Mbps.

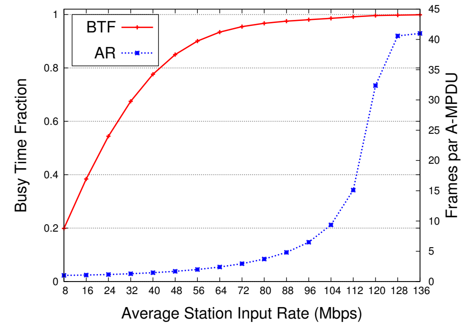


Figure 1: BTF and AR (Aggregation Rate) as function of the input rate.

These results show that BTF is not an appropriate metric to reflect the network load when frame aggregation is enable. Therefore, association optimization with the purpose of load balancing between APs cannot be based only on the BTF but must also consider the aggregation rates.

However, it is very difficult to forecast the aggregation rate for a new association as it depends on the statistical nature of the traffic and the contention between the different APs/stations.

In order to keep the model tractable, and to avoid introducing too many assumptions about the traffic nature, we systematically consider the maximum aggregation rate in the model/computation. The resulting BTF at a given AP represents a Hypothetical BTF (H-BTF) which is less than 1 until the network becomes saturated and that no throughput increase is possible. This metric has the benefit to express the network load through a single quantity. The optimization problem may then be simply expressed without considering complex combination of BTF and aggregation rates.

4 SYSTEM MODEL

4.1 Network model

We consider a fixed number of APs that belong to the same extended service set (ESS). A controller manages the APs, and, in particular, is in charge of determining the associations between stations and APs. As downlink traffic is predominant compared to upling traffic [11], we only take into account downlink traffic in our model. When a new station wants to connect to the ESS, it first associates with the default AP. For most of the implementation, the default criteria to select the best AP is the RSSI (Radio Signal Strength Indicator). The controller implements our algorithm to change the associations. It may be performed at regular interval or at certain events (e.g. arrival/departure of stations). These decisions are based on measurements made on each AP that allow the controller to know the performance level of the current association, and on our model that predicts the performance for other association schemes. The controller collects the following measures from the APs:

- The current association.
- The busy time fraction for each AP.
- The conflicts between APs (the conflict graph is formally defined later in this paper).

- The maximum aggregation rate that is the maximum number of frames aggregated in the same A-MPDU. Its practical computation is linked to three constraints. First, the maximum number of frames acknowledged within a single block acknowledgment is 64 frames. Second, the size of an A-MPDU is limited. The maximum size ranges from 8 to 64 kB (it depends on the Wi-Fi card). Third, the maximum A-MPDU transmission duration is 10 ms. As the transmission duration depends on the data transmission rate, the maximum aggregation rate can change when the station changes its association.
- For each station, it gets:
  - the data rates between the station and APs in its transmission range,
  - the throughput and the average frame size received by the station from its AP,
  - the error rate (or equivalently the probability of success) between the station and its AP.

These different measurements are already available on most of the commercial products (Cisco Aironet Series APs for instance). The controller applies the association changes through control frames sent to the AP, for instance through the IEEE 802.11v [1] BSS management frames.

As already mentioned, our model aims to predict the performance of the network through the H-BTF quantity for different association schemes. The H-BTF computation relies on the following assumptions:

- **Data rate**: APs are able to determine the best data rate for all the stations in its transmission range (associated or not).
- **Throughput**: a station, associated with a new access point, will request the same throughput as in the current configuration if its throughput request is satisfied (in that case, the station is currently associated with an unsaturated AP), otherwise we consider an increase of 25% with regard to its current throughput. It allows us to take into account the fact that an unsatisfied station will probably increase its throughput once associated to an uncongested AP. As the exact traffic demand is unknown, we consider this arbitrary increase of 25%.
- **Probability of success**: the probability of success for each station (probability that a frame is correctly received) is measured between APs and their associated stations. Its prediction for another association is difficult. In our model, we assume that this probability remains the same if the station does not change its channel when it reassociates. In case of a channel change, the success probability is set to the smallest probability of success among the stations already associated with the new AP.

4.2 Hypothetical Busy Time Fraction estimation

The BTF of a given AP is defined as the proportion of time the channel is sensed busy by this AP. It is composed of its own transmissions, and transmissions from its neighbors. This quantity is generally available on the current products through logical registers of the Wi-Fi card, and may also be obtained with the IEEE 802.11k measurement reports. But, in the context of our optimization, we need to estimate this fraction for any other configuration. Consequently, we propose the following model. The busy time fraction of an AP j is formally defined as:

Parameter	Definition
S_j	the set of stations associated with AP j
$\overline{T}$	average time required to transmit one frame
$T(k)$	time required to transmit one frame at backoff stage k
$T_c(k)$	time required to consider that the transmission failed at backoff stage k
T_{Phy}	duration of the preamble and the header of the physical layer
T_{DIFS}	DCF Inter Frame Space
T_{SIFS}	DCF Short Inter Frame Space
T_{BA}	duration of the block acknowledgment frame
$T_{BO}(k)$	average backoff after k unsuccessful successive transmission attempts
T_{slot}	duration of a slot
CW_{min} / CW_{max}	minimum and maximum sizes of the contention window
m	maximum number of retransmissions
R_{ij}	link data rate between AP j and station i
L	frame size
p_{ij}	probability of success to transmit one frame between AP j and station i
q	probability of transmission failure of at least one frame in an A-MPDU
τ	average number of aggregated frames
τ_{max}	maximum number of aggregated frames

Table 1: Notations.

$$b_j = b_j^L + b_j^N. \tag{1}$$

b_j^L referred to the local busy time corresponding to the transmission from the AP itself (AP j). b_j^N corresponds to the transmissions from the other APs and detected by the local AP according to the CCA mechanism [2]. Notations used to compute these different quantities are given in Table 1.

4.2.1 *Local Busy Time Fraction.*

The local busy time b_j^L is the sum of the transmission times over the set of stations associated with AP j (denoted S_j):

$$b_j^L = \sum_{i \in S_j} b_{ij}^L$$

b_{ij}^L is thus the BTF corresponding to the transmissions from AP j to station i. It may be expressed as the product of the average number of datagrams transmitted to station i per second (denoted D_i) and the average time $\overline{T}$ required for AP j to successfully transmit a frame of size L to station i with transmission rate R_{ij}:

$$b_{ij}^L = \overline{T} \times D_i$$

To compute $\overline{T}$, we consider, when the system is in the k^{th} backoff stage, the time for AP j to transmit a frame of size L in the case it is properly acknowledged (this time is denoted $T(k)$) and in the case the aggregated frame is not acknowledged ($T_c(k)$) due to transmission errors:

$$T(k) = (T_{DIFS} + T_{BO}(k) + 2 \times T_{Phy} + T_{SIFS} + T_{BA})/\tau + \frac{L}{R_{ij}} \tag{2}$$

Eq. 2 takes into account the different times to access the medium (T_{DIFS}, T_{Phy}, $T_{BO}(k)$) and related to the acknowledgment (T_{SIFS}, T_{BA}). Note that in this equation, T_{BA} is the duration of the block acknowledgment frame. $\frac{L}{R_{ij}}$ is the time required to send the datagram of size L with the transmission rate R_{ij}. The backoff ($T_{BO}(k)$) is computed as:

$$T_{BO}(k) = min\left(\frac{2^k(CW_{min}+1)-1}{2}, CW_{max}\right) \times T_{slot}$$

The times to access the medium and send the acknowledgment are divided by the aggregation rate τ since they are shared by several aggregated frames. When the frame is not acknowledged due to transmission errors, the transmission time becomes:

$$T_c(k) = (T_{DIFS} + T_{BO}(k) + T_{Phy} + T_{BATO})/\tau + L/R_{ij} \quad (3)$$

It takes into account the block acknowledgment timeout T_{BATO} at the AP.

Finally, we condition the computation of $\overline{T}$ by the number of times the AP j retransmits the same frame to station i and the initial backoff stage. Indeed, a new frame can be sent with a backoff stage $k > 1$ if the previous frames (present in the previous aggregated frame) have undergone errors. In the formula below, $\overline{T}$ is thus a function of the initial backoff stage h with which the new frame (from AP j to station i) is sent, and the number of errors that occur for this frame (variable k).

$$\begin{aligned}\overline{T} \;=\; & \sum_{h=0}^{\infty}\Bigg[pT(h) + \sum_{k=1}^{m}\Bigg(p(1-p)^k\Big(\sum_{l=0}^{k-1}T_c(l+h) \\ & +T(k+h)\Big)\Bigg) + (1-p)^{m+1}\sum_{l=0}^{m}T_c(l+h)\Bigg].q^h(1-q)\end{aligned}$$

In this equation, the parameter R_{ij} may be different at each retransmission, but is constant during a retransmission. It is consistent with current Wi-Fi manager implementations like Minstrel. To ease the writing of the equation, p_{ij} is simplified by p.

4.2.2 Neighbor Busy Time Fraction. The computation of the time b_j^N where the medium is sensed busy by AP j due to the transmissions of its neighbors is the same as in [3]. Its resolution relies on a conflict graph, the CSMA/CA rules, and on an assumption that states that the random variables describing the transmission states at each AP form a Markov Network on the conflict graph. The used conflict graph is formally defined as a graph where the vertices are the APs, and where an edge exists between two vertices/APs when they detect each other's transmissions according to the CCA rules.

4.2.3 Hypothetical Busy Time Fraction. The formulas derived in the previous computations take into account the measured aggregation rate τ. In practice, this rate is difficult to forecast for a new association as it requires to model the buffer state at each AP for the new association. As already mentioned, we rely instead on the maximum aggregation rate denoted τ_{max}. The computation of the metric H-BTF consists in substituting the parameter τ by τ_{max} for all the equations. It expresses the current load with regard to the maximum BTF and the maximum aggregation rate through a unique quantity.

5 ASSOCIATION OPTIMIZATION

The model proposed in Section 4.2 is used to predict the H-BTF for any association configuration. The value of H-BTF indicates the load level at each AP. So, an H-BTF value less than 1 means that the AP is not saturated and the associated stations are satisfied. Also, it means that a part of the bandwidth is available and more stations can associate with this AP. On the other hand, an H-BTF value close to 1 indicates that the AP is saturated or close to saturation. This means that all the stations associated with this AP are not satisfied and cannot request more throughput.

We propose an optimization approach based on two functions. A first objective function aims to minimize the H-BTF of the most heavily loaded AP:

$$minimize\ f_1(X) \quad (4)$$

$$\text{with } f_1(X) = \max_{j\in A}\left[h_j(X)\right] \quad (5)$$

where A is the set of APs and $h_j(X)$ the H-BTF of AP j for a given association X. This objective function unloads saturated APs and then allows stations associated with these APs to have more throughput. Once the optimal is found for the first objective function, a secondary objective function is used to share the load between the APs:

$$maximize\ f_2(X) \quad (6)$$

$$\text{with } f_2(X) = \sum_{j\in A} log(1 - h_j(X)) \quad (7)$$

The first function is used to unload saturated APs and to satisfy a maximum number of stations. But it is a min-max approach that is focused on the most loaded AP. On the other hand, the second function helps to share the load between the APs (once they are decongested). Moreover, note that with the min-max problem, several association schemes may lead to the same value of f_1. The second optimization is thus a way to choose a better association among the set of solutions minimizing $f_1(.)$.

To solve this optimization problem, we propose an iterative heuristic based on the local search principle. Local search is an important class of heuristics for solving combinatorial optimization problems [14]. This method allows, from an initial solution, to iteratively search for a better solution according to an objective function. Since the search space associated with a combinatorial optimization problem is often non-enumerable in a reasonable time, the local search defines a neighborhood relationship. At each step, the algorithm searches for a better solution in the neighborhood of the current one. This better neighbor becomes the new solution and so on. Among the existing procedures to choose a better neighbor, two approaches are widely used. The first one is an exhaustive exploration of the neighborhood to choose the best neighbor. The second approach consists in exploring partially the neighborhood and choosing the first neighbor that obtains a better objective function. The search procedure stops when the current solution is better than all its neighbors, this solution is then a local optimum.

The main benefits of local search lie in its simplicity and its iterative process which can stop the optimization process at any time to comply with a constraint like the computation time for instance. This is supported by the fact that the local search algorithms consider only complete feasible solutions during the search. The proposed algorithm has then the advantage to improve Wi-Fi

Algorithm 1 H-BTF association algorithm

```
//Initialization
Collect measurements for current solution X_0
Infer the APs conflict graph for each channel
//The optimization loop
while (Convergence() = false) do
    N = Neighbor(X_0);
    X = arg min_{U∈N} f_1(U);
    if (f_1(X) < f_1(X_0)) then
        X_0 = X;
    else
        X = arg max_{U∈N} f_2(U);
        if (f_2(X) > f_2(X_0)) then
            X_0 = X;
        end if
    end if
end while
end procedure
```

associations at each iteration, and can be stopped at any time with a feasible solution. The time that the system spends in computing a solution can thus be bounded and tuned.

For our optimization problem we propose a neighborhood structure that consists of changing the association of a single station in the current solution. In other words, the neighborhood of a given solution X is defined as being the set of feasible solutions such that each solution is identical to this solution X except for a single change of association. So, at each iteration, the local search changes the association of a single station.

The controller runs the iterative local search Algorithm 1. In this algorithm, the search procedure starts from the current solution (association). The optimization is performed through the local search algorithm on the first objective function f_1 until it reaches a local minimum. Then, the neighborhood of this solution is explored with the second objective function f_2. It improves load sharing between APs and gives the opportunity to exit from local optimum with regard to f_1. The process is repeated until no improvement is observed.

6 EVALUATION

In this section, we present the simulation environment, the performance metrics, and the different simulation scenarios. We then discuss the simulation results.

6.1 Simulation configuration

In order to evaluate the proposed approach, we use the network simulation tool "Network Simulator 3 (ns-3)". The optimization algorithm is implemented in the C++ programming language. The parameters used in the simulations are summarized in Table 2. The number of APs and stations is fixed for each of the two evaluated topologies. The stations are associated according to the RSSI value in the initial configuration.

For each scenario, we increase the input rates for all stations. For each input rate, the simulations are repeated 30 times with different station positions. Flow rates are randomly set with a given

Parameter	Definition
Standard	IEEE 802.11n
Signal loss	log-distance path loss model
Rate Adaptation Algorithm	Ideal Wi-Fi manager
Packet sizes	1500 bytes
Simulations duration	60 seconds
confidence interval	95 %

Table 2: Simulation parameters

average (different from a station to another), but constant during a simulation. We use constant bit rate (CBR) flows with the same packet sizes (1500 bytes).

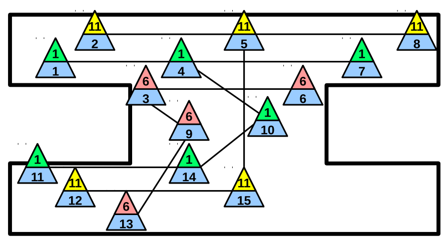


Figure 2: WLAN topology at one floor in our university. The upper number corresponds to the used channel and the lower number corresponds to the AP number.

6.2 Evaluation

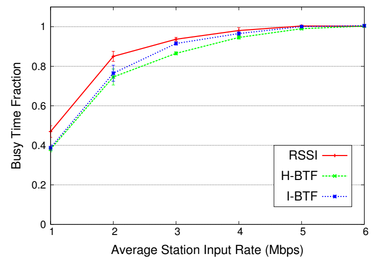
To evaluate the improvements offered by our approach, we compute the following performance parameters:

- Busy Time Fraction: for each simulation we consider the greatest BTF in the network.
- Number of unsatisfied stations: it represents the proportion of stations that are not satisfied in terms of throughput (i.e. when the ratio between the obtained throughput and the demand is less than 98%).
- Throughput Satisfaction Ratio: it is the ratio between the throughput obtained and the throughput requested for each station.
- Jain's Index: we compute the Jain's Index [7] to evaluate the fairness in terms of load (load balancing) achieved in the network. It is defined as follows:

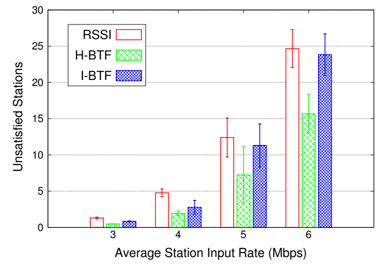
$$Jain = \frac{\left(\sum_{j=1}^{n} b_j\right)^2}{n \sum_{j=1}^{n} b_j}$$

where n is the number the APs in the network.

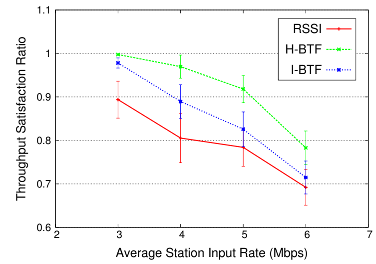
In this paper we compare the results obtained by our H-BTF algorithm with the initial configuration, where the stations associate to the APs according to the value of the RSSI. It is denoted RSSI in the figures. Also, we compare our results with a model that uses the current aggregation rate of each station for the predicted τ in the



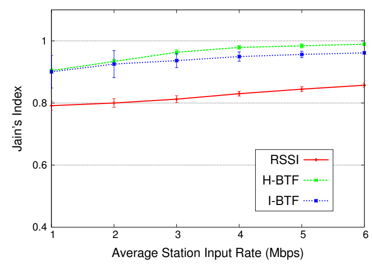
(a) BTF of the most loaded AP



(b) Unsatisfied stations



(c) Throughput Satisfaction Ratio



(d) Jain's Index

Figure 3: Results for the ENS topology with UDP flows.

equations of the model. This solution is denoted I-BTF for Initial BTF.

We have considered two different topologies.

ENS topology. The first scenario considers the topology of our university "École Normale Supérieure de Lyon (ENS)" at a given floor of the building. This network is composed of 15 APs as shown in Figure 2. APs use the ISM frequency band (2.4 Ghz). In this band the number of non-overlapping channels is limited (three orthogonal channels: 1, 6 and 11). This figure also shows the three conflict graphs (one for each orthogonal channel).

In Figure 3a, we plot the values of the BTF of the most loaded AP as a function of the load of the WLAN for the three solutions. Both approaches H-BTF and I-BTF reduce the value of BTF when the network is not heavily loaded. But, when the average station input rate ranges from 2 to 5 Mb/s, the H-BTF approach becomes better. For example, at 3 Mb/s, the decrease in BTF for H-BTF is 8% and 2% for I-BTF.

Figure 3b illustrates the number of unsatisfied stations. The H-BTF approach reduces this number up to 64% compared to the RSSI association. For I-BTF the decrease does not exceed 35%. The gap between the two approaches increases to the benefit of the H-BTF approach when the load increases.

Figure 3c plots the average throughput satisfaction ratio. With H-BTF, the stations associated with saturated APs, gain in average between 12% and 20% in throughput after the reassociation. With I-BTF the average gain does not exceed 10% compared to the RSSI association.

Figure 3d shows the Jain index. Both the H-BTF and I-BTF approaches provide close results in terms of fairness with a slight advantage for our approach H-BTF. The I-BTF approach also allows a good load balancing but without unloading the most congested APs.

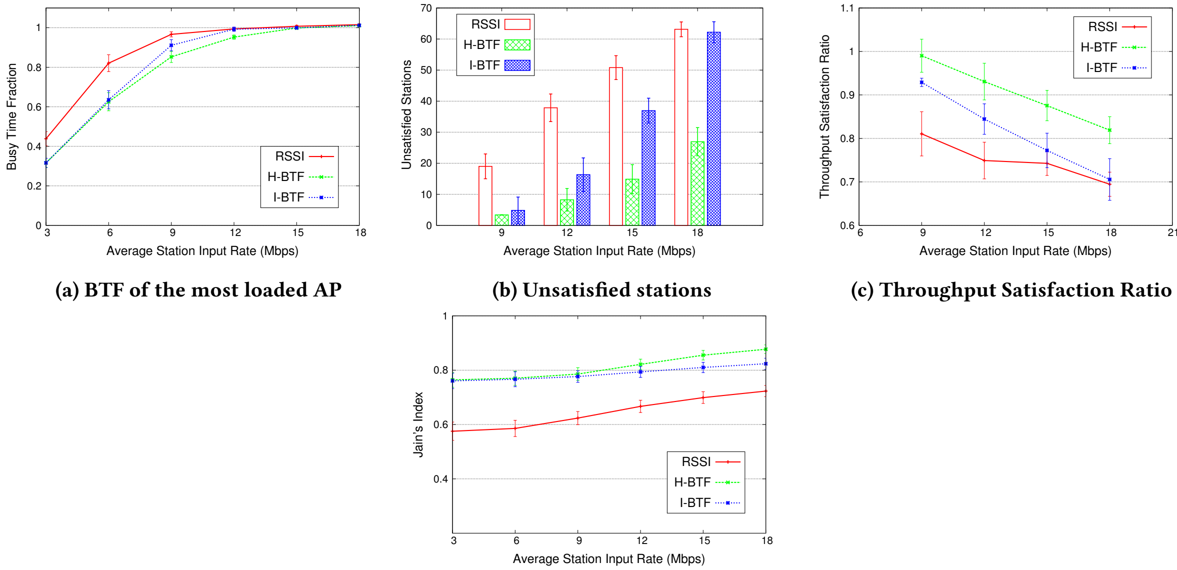
These results show that our approach is better than the I-BTF approach regardless of the evaluation criterion. This confirms the effectiveness of the H-BTF approach and the advantage of taking into account the maximum aggregation ratio in the association optimization algorithm.

Random topologies. To evaluate our approach with denser topologies and more complex conflict graphs between APs, we performed simulations on random topologies. Each topology consists of 25 APs uniformly deployed in a square of size $500m \times 500m$. 100 stations are distributed in the coverage area of these APs. APs are configured in the 5 Ghz frequency band with 8 orthogonal channels. In this scenario, APs location is changed at each simulation. This randomness allows us to consider an important number of different topologies (30 for each set of parameters).

Figure 4a plots the average BTF value of the most loaded AP according to the WLAN load. Our H-BTF approach reduces this value up to 28% when the network is not very loaded and by 5% when the average rate per station is around 12 Mb/s. I-BTF has similar results in networks with a low load, but, with the load increase, the gain is less important than with H-BTF.

In Figure 4b, the number of unsatisfied stations with different load levels is given. The H-BTF approach decreases this number by 82% compared to the RSSI association and by 30% compared to I-BTF for an average input rate per station of 9 Mb/s. The performance of H-BTF decreases when the load increases to reach a reduction of 57% compared to RSSI at 18 Mbps. But the advantage over I-BTF rises from 30% to 56%.

Figure 4c plots the station satisfaction ratio according to the average input rate per station. The H-BTF approach gives, to unsatisfied stations, twice much throughput than with the I-BTF approach. The gain, compared to the RSSI solution, varies between 17% and 22% for H-BTF and between 2% and 14% for I-BTF.



(a) BTF of the most loaded AP

(b) Unsatisfied stations

(c) Throughput Satisfaction Ratio

(d) Jain's Index

Figure 4: Results for the random topology with UDP flows.

The Jain index, shown in Figure 4d, indicates that the H-BTF and I-BTF approaches provide similar performance to share load between APs when the network load is low. But when the network load increases, the gap between the two approaches to improve fairness increases to reach 53% at 18Mbps.

7 CONCLUSION

In this paper, we propose to evaluate the load of a Wi-Fi AP through a new metric named H-BTF (Hypothetical Busy Time Fraction). This metric takes into account the classical busy time fraction and the frame aggregation mechanism offered by the latest IEEE 802.11 amendment. We propose a technological and mathematical framework to compute this metric at each AP of an extended service set. A controller is then able to optimize association between stations and APs in order to share the load between APs and satisfy a maximum number of stations in terms of throughput. Our proposal has been evaluated through a large set of simulations performed with ns-3. We have considered several performance criteria to compare this approach with the RSSI association and with a similar approach that uses the initial aggregation ratio. The obtained results illustrate the effectiveness of our proposed approach. It improves performance as station satisfaction and load balancing between APs.

REFERENCES

[1] 2011. IEEE Std 802.11v-2011 — Amendment 8: IEEE 802.11 Wireless Network Management (Feb 2011), 1–433. https://doi.org/10.1109/IEEESTD.2011.5716530

[2] 2016. IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std 802.11-2016 (December 2016), 1–3534. https://doi.org/doi:10.1109/IEEESTD.2016.7786995

[3] M. Amer, A. Busson, and I. Guérin-Lassous. 2018. Association Optimization in Wi-Fi Networks based on the Channel Busy Time Estimation. In Proceedings of Networking.

[4] Made Harta Dwijaksara, Wha Sook Jeon, and Dong Geun Jeong. 2016. A Joint User Association and Load Balancing Scheme for Wireless LANs Supporting Multicast Transmission. In Proceedings of the 31st Annual ACM Symposium on Applied Computing (SAC '16). ACM, New York, NY, USA, 688–695. https://doi.org/10.1145/2851613.2851852

[5] D. Gong and Y. Yang. 2014. On-Line AP Association Algorithms for 802.11n WLANs with Heterogeneous Clients. IEEE Trans. Comput. 63, 11 (Nov 2014), 2772–2786. https://doi.org/10.1109/TC.2013.156

[6] Chin-Ya Huang and P. Ramanathan. 2011. Joint Association and Power Adaption in WiFi Community Networks. In 2011 45th Annual Conference on Information Sciences and Systems. 1–6. https://doi.org/10.1109/CISS.2011.5766251

[7] R. Jain, D. M. Chiu, and W. R. Hawe. 1984. A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer System. Digital Equipment Corporation (1984). https://books.google.fr/books?id=M2QLGwAACAAJ

[8] Ram Krishan and Vijay Laxmi. 2015. IEEE 802.11 WLAN Load Balancing for Network Performance Enhancement. Procedia Computer Science 57 (2015), 493 – 499. https://doi.org/10.1016/j.procs.2015.07.371 3rd International Conference on Recent Trends in Computing 2015 (ICRTC-2015).

[9] X. Li, J. Luo, W. Wu, and M. Yang. 2017. Joint AP Coverage Adjustment and User Association Optimization for Load Balancing in Multi-rate WLANs. In 2017 IEEE 21st International Conference on Computer Supported Cooperative Work in Design (CSCWD). 390–395. https://doi.org/10.1109/CSCWD.2017.8066726

[10] C. Y. Lin, W. P. Tsai, M. H. Tsai, and Y. Z. Cai. 2017. Adaptive Load-Balancing Scheme through Wireless SDN-Based Association Control. In 2017 IEEE 31st International Conference on Advanced Information Networking and Applications (AINA). 546–553. https://doi.org/10.1109/AINA.2017.16

[11] F. Malandrino, C.-F. Chiasserini, and S. Kirkpatrick. 2017. Cellular Network Traces Towards 5G: Usage, Analysis and Generation. IEEE Transactions on Mobile Computing PP, 99 (August 2017), 1.

[12] G. Sawma, I. Aib, R. Ben-El-Kezadri, and G. Pujolle. 2008. ALBA: An autonomic load balancing algorithm for IEEE 802.11 wireless networks. In NOMS 2008 - 2008 IEEE Network Operations and Management Symposium. 891–894. https://doi.org/10.1109/NOMS.2008.4575240

[13] Liang Sun, Lei Wang, Zhenquan Qin, Zhuxiu Yuan, and Yuanfang Chen. 2018. A Novel On-Line Association Algorithm for Supporting Load Balancing in Multiple-AP Wireless LAN. Mobile Networks and Applications (20 Jan 2018). https://doi.org/10.1007/s11036-018-1022-2

[14] J. P. Walser. 1999. Integer Optimization by Local Search: A Domain-independent Approach. Springer-Verlag, Berlin, Heidelberg.