Towards a Throughput and Energy Efficient Association Strategy for Wi-Fi/LiFi Heterogeneous Networks

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ABSTRACT

In very dense or ultra-dense scenarios wherein Wi-Fi alone may not be enough to accommodate the needs of all stations, LiFi (Light Fidelity) access points can help alleviate the strain on the Wi-Fi by offloading some Wi-Fi traffic to LiFi. We study the issue of associating stations in a Wi-Fi/LiFi heterogeneous network composed of a Wi-Fi access point and multiples LiFi access points. We propose a conceptually simple and easy to implement solution to search and find an efficient mapping for the associations between stations and access points using analytical performance models for the individual throughput of each station and for the overall network energy consumption. Using two realistic deployments of heterogeneous networks for offices, we have evaluated the effectiveness of our solution at discovering better trade-offs than baseline strategies. Our numerical results show that significant gains can be obtained in terms of the throughput of the stations as well as overall energy consumption.

CCS CONCEPTS

• **Networks → Wireless access networks**.

KEYWORDS

heterogeneous, Wi-Fi, LiFi, association, energy consumption, strategy, local search, score

ACM Reference Format:
Esther Guérin, Thomas Begin, Anthony Busson, and Isabelle Guérin Lassous. 2021. Towards a Throughput and Energy Efficient Association Strategy for Wi-Fi/LiFi Heterogeneous Networks. In *Proceedings of the 18th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN'21), November 22–26, 2021, Alicante, Spain.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3479240.3488514

1 INTRODUCTION

LiFi (Light Fidelity) is an optical wireless communication technology that uses visible light to transmit data at short range with relatively high data rates. Similarly to Wi-Fi, LiFi is mostly operated in infrastructure mode wherein access points (APs), directly connected to a wired network, provide wireless connections to a set of stations (STAs). Although the standards defining LiFi are still in progress, LiFi is expected to provide shorter communication ranges and lower data rates than Wi-Fi. Shorter ranges of communication can in fact be an asset in dense scenarios as this allows a more efficient spatial reuse of frequencies. Unlike Wi-Fi, LiFi operates distinct channels for uplink and downlink communications, and is commonly viewed as more energy-efficient than Wi-Fi (e.g., the chipsets of LiFi can be embedded in the light fixtures) and more secure (since the propagation of light waves can easily be blocked).

In very dense or ultra-dense scenarios, Wi-Fi alone may not be enough to accommodate the needs of all STAs despite the different available radio channels and the advancements of its latest amendments (i.e., 802.11ac or 802.11ax). Some STAs may be suffering from throughput starvation as a result of a poor access to the radio channel. A promising avenue to alleviate the strain on the Wi-Fi is to introduce LiFi as a complement communication protocol enabling thereby some Wi-Fi traffic to be offloaded to LiFi. The network under study becomes a heterogenous network combining both Wi-Fi and LiFi.

There are multiple ways of deploying, configuring, and operating a Wi-Fi/LiFi heterogeneous network. In particular, different strategies can be considered on how to associate STAs to the APs (be they on Wi-Fi or LiFi). A possible strategy can consist of having STAs connected to the closest LiFi AP and, if not possible, to the closest Wi-Fi AP. Another simple strategy can be to associate each STA to the AP leading it to its maximal physical data rate (regardless of the number of STAs associated with each AP). Any chosen strategy will affect the throughput of STAs and the overall network energy consumption, but it is remains unclear to pinpoint the most adequate one.

In this paper, we explore the question of how to associate STAs and APs in a Wi-Fi/LiFi heterogeneous network. More precisely, using analytical performance models for the individual throughput

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PE-WASUN '21, November 22–26, 2021, Alicante, Spain

ACM ISBN 978-1-4503-9078-1/21/11…$15.00
https://doi.org/10.1145/3479240.3488514

of each STA and for the overall network energy consumption, we propose a strategy to search and find an efficient mapping for the associations between STAs and APs.

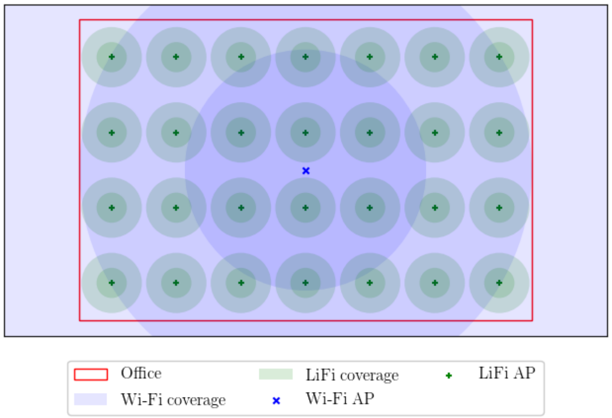
The remainder of the paper is as follows. Section 2 discusses the related work. We present our solution in Section 3 and the numerical results in Section 4. Section 5 concludes this paper.

2 RELATED WORK

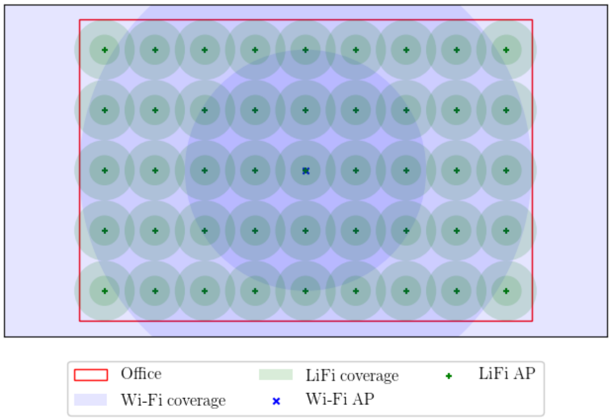
Associating STAs to APs can be realized either in a distributed way or in a centralized fashion. The distributed approach is currently used in Wi-Fi networks where each STA associates to the AP from which it receives the signal with the best RSSI. In the case of Wi-Fi/LiFi heterogeneous networks, the authors of [3] propose a distributed association solution in which each STA seeks to optimize the network quality while ensuring some QoS requirements. For each STA, the network quality is seen as the collection of the quality of the links that can be established between the STA and the different APs. In their framework, each STA selects its metric to evaluate the quality of links. For instance, a STA can consider link latency while another takes into account the link loss rate and the link capacity. In [6], the authors present another distributed solution based on an evolutionary game.

The advantages of distributed solutions are twofold: their implementation simplicity as STAs only require a couple of network measurements to make their decision, and their speed as each STA cares only for its own association irrespectively of the other STAs. Furthermore, those solutions are not designed to optimize the overall network performance, which can result in limited performance for some STAs. This drawback is now well-established in the case of Wi-Fi networks [2] and also applies to the case of Wi-Fi/LiFi heterogeneous networks. Conversely, centralized solutions are able to optimize the performance of the network as a whole thanks to the use of a network controller that collects and processes data from the network. Even though a centralized approach may require to collect a large amount of data, implying an increase in the association algorithm execution time and in the number of concurrent communications with the controller, several centralized solutions have been proposed for associating STAs and APs in Wi-Fi/LiFi heterogeneous networks. For example, in [4], a joint association and resource allocation solution is described. The authors seek to optimize the proportional fairness metrics (corresponding to the product of all the STAs' throughput) while allocating a proportion of time to each STA (used by the selected AP to serve the STA). The authors of [8] propose an association scheme to efficiently handle the potential mobility of the STAs. In a nutshell, they first select for a given time period the communication technology (namely, Wi-Fi or LiFi) with the goal of limiting the overhead due to handovers, and then they choose the AP with the best RSSI within the chosen technology. Another association solution is discussed in [7]. This solution consists of determining the STAs that will be served by Wi-Fi APs using a fuzzy logic approach. Afterwards, the remaining STAs are associated with LiFi APs based on their RSSI values.

Our solution belongs to the class of centralized association schemes. Unlike existing works [4, 7, 8], we account for the energy consumption of each device (APs and STAs) and we seek to optimize both the throughput of STAs and the overall network energy consumption. Additionally, unlike [4, 7, 8], our solution is based on a more realistic model for the sharing of the Wi-Fi radio medium and thus on a more realistic estimation of the STAs' and APs' throughput.



(a) Dense scenario.



(b) Ultra-dense scenario.

Figure 1: Considered scenarios.

3 OUR ASSOCIATION SOLUTION

3.1 Problem Statement

The studied network consists of an office where one Wi-Fi AP and multiple LiFi APs coexist. The Wi-Fi AP is able to cover the whole office. Despite their number, the LiFi coverage, on the other hand, is incomplete as some areas are not covered by the LiFi light waves. This is illustrated by Figures 1a and 1b for two different densities of LiFi APs. In the former case wherein the LiFi APs are dense, the office exhibits areas not covered by the LiFi network. In the latter case, the density of LiFi is ultra-dense and the blind spots in terms of LiFi coverage are reduced compared to the dense scenario. The locations of the STAs are randomly drawn across the office. Some STAs can be only covered by the Wi-Fi AP, whereas other STAs may be covered by the Wi-Fi AP and a LiFi AP or even several LiFi APs in the case of the ultra-dense LiFi network.

Our study is based on several assumptions. First, we consider only downstream traffic. This simplifying assumption holds to the amount of upstream traffic is often negligible with respect to the downstream traffic for an office network. Note also that this assumption only pertains to Wi-Fi since in the case of the current LiFi products the downstream and the upstream links are operated on different technology (infrared spectrum for upstream) and thus independent. Second, we assume that the throughput demand of a given STA stays constant over time. Third, we consider only data traffic thereby assuming that there is no control or management traffic transmitted in the network. Fourth, in our study, the Wi-Fi AP is never switched off so as to ensure that any STA, regardless of its precise location, will be able to get connected. The STAs do not enter into hibernation, nor sleep modes. Fifth, any AP (be it on Wi-Fi or LiFi) can be associated with multiple STAs at the same time but can only serve a single STA at a time. This assumption corresponds to CSMA without multi-user mode. Lastly, we neglect the potential interferences that may occur at a given STA if multiple LiFi APs within its reach are transmitting simultaneously.

Let us remind that to communicate over the network, a STA must be associated with one and only one AP, be it Wi-Fi or LiFi. Thus, once the association has been made, the STA receives data only from its associated AP. As STAs can be covered by multiple APs, the association problem breaks down to selecting which AP each STA should be associated with. These decisions can have an impact on the network performance such as the throughput delivered to the STA and the overall network energy consumption. For instance, if an AP must serve more STAs than it can correctly handle, it becomes saturated and the associated STAs may obtain a lower throughput than their demand. On the other hand, it may be energy-wise inefficient to switch on certain APs if they happen to serve very few STAs that could be served, with about the same level of performance, by already turned on APs.

Several approaches exist to deal with the association of STAs and APs problem. In general, the existing methods are distributed: Each STA makes its decision locally based on the quality of the different signals it can perceive. The main advantage of these methods is that they can be applied in any circumstances. However, they cannot account for the specificity nor the current state of the network. On the other hand, centralized methods can make decisions with respect to a larger set of information. A device, often called a controller, harvests the necessary data from all over the network and then decides the association between STAs and APs.

Centralized approaches enable the optimization of performance metrics relating to the whole network but also to each individual STA. In practice, the performance metrics to be optimized depend on the network administrator's objectives. In this study, we consider the overall energy consumption of the network in addition to the STA throughput.

Our paper aims at quantifying the gains that can bring a centralized method whose objectives are to optimize both the throughput and the energy consumption over classical distributed association solutions in the context of Wi-Fi/LiFi heterogeneous networks.

Table 1: Principal notations.

Parameter	Description	Unit
A	Set of APs (Wi-Fi and LiFi)	-
A_L	Set of LiFi APs	-
m	Number of APs (Wi-Fi and LiFi)	-
U	Set of STAs	-
n	Number of STAs	-
$r_{\alpha,u}$	Link capacity between AP α and STA u	Mbps
δ_u	Throughput demand of STA u	Mbps
Y	Association matrix	-
$d_{\alpha,u}$	Throughput obtained by STA u when associated to AP α	Mbps
P_α	Energy consumed by AP α	Watts
P_u	Energy consumed by STA u	Watts
$\tau_{uti,\alpha}$	Utilization rate of AP α	-
$\tau_{uti,u}$	Utilization rate of STA u	-
Φ	Throughput metric	-
Ψ	Consumption metric	Watts
F	Objective function	-

3.2 Performance and Energy Models

Because our solution will explore different possible associations (see Section 3.3), we need a way to estimate the metrics included in the objective function, namely the throughput and energy consumption for any considered association. In this section, we present the analytical models we use, for the Wi-Fi and LiFi technologies, to estimate the throughput of STAs as well as the overall network throughput (called performance models hereafter) and the energy consumption of each STA and each AP (called energy models hereafter).

We use the following notation: A denotes the set of APs with $m = |A|$ representing the number of APs. U refers to the set of STAs with $n = |U|$ being the number of STAs. Table 1 summarizes the principal notations used in the paper.

3.2.1 Performance models. In Wi-Fi and in LiFi, the transmission rate (corresponding to the data rate of the network interface at the physical layer) can vary according to the link quality (itself being impacted by the environment). We use $r_{\alpha,u}$ to denote the selected transmission rate when AP α sends frames to STA u. In our study, $r_{\alpha,u}$ depends on the relative position between AP α and STA u. The possible values used for $r_{\alpha,u}$ are discussed in Section 4.

Since we assume that any AP (be it Wi-Fi or LiFi) can serve only one STA at a time (typically in a round-robin fashion), packet transmissions towards a STA may impact the throughput expected by another STA associated with the same AP. This applies when the AP is in saturation (*i.e.* when it has always at least a frame waiting to be sent to one of its associated STAs). Inspired by the analytical model proposed in [2] to evaluate the throughput of STAs demanding the same throughput, we extend the formula to account for the more general case wherein STAs may demand different levels of throughput. The obtained throughput for the STA u when the AP α is in saturation is expressed as:

$$d_{\alpha,u} = \frac{Y_{\alpha,u}\delta_u}{\sum\limits_{v \in U} \frac{Y_{\alpha,v}\delta_v}{r_{\alpha,v}}} \tag{1}$$

where δ_u corresponds to the throughput demanded by STA u (in Mbps), $r_{\alpha,u}$ represents the transmission rate between AP α and STA u (in Mbps, too), and $Y_{\alpha,u} = 1$ if STA u is associated to AP α (and 0 otherwise).

When an AP is not in saturation, the transmissions of any of its STAs do not impact the performance of its other STAs. Therefore, in that case, the throughput obtained by STA u when associated to AP α is simply:

$$d_{\alpha,u} = Y_{\alpha,u} \cdot \delta_u \tag{2}$$

Note that we use the same performance model to evaluate the throughput of STAs be they associate with a Wi-Fi or LiFi AP as the same assumptions are made on the channel sharing. The numerical values for the parameters differ and are presented in Section 4.

3.2.2 Energy models. For the overall network energy consumption, we need to account for the contributions of every device involved in the network (APs and STAs). The energy consumption of each device differs with its activities, which consist of transmitting, receiving, or being idle. We use ρ_{rx}, ρ_{tx} and ρ_{id} to denote the energy consumed by a device in transmission, reception, or idle, respectively. Note that these latter parameters are expressed in Watts. To account for the fact that an AP and a STA have different levels of energy consumption, each of the three energy parameters is also indexed by the device's type. For instance, the energy consumed by STA u when idle is denoted $\rho_{id,u}$.

Let us consider a given AP α that is turned on. It is either idle or in transmission. Therefore, its energy consumption is simply:

$$P_\alpha = (1 - \tau_{uti,\alpha}) \times \rho_{id,\alpha} + \tau_{uti,\alpha} \times \rho_{tx,\alpha} \tag{3}$$

where $\tau_{uti,\alpha}$ is the AP utilization rate defined as the proportion of time the AP is transmitting. $\tau_{uti,\alpha}$ can be computed as follows:

$$\tau_{uti,\alpha} = \sum_{u \in U} \frac{d_{\alpha,u}}{r_{\alpha,u}} \tag{4}$$

Unlike the Wi-Fi AP, a LiFi AP with currently no associated STAs can be switched off. We account for this properties with the following relation:

$$\forall \alpha \in A_L, \quad \text{if} \sum_{u \in U} Y_{\alpha,u} = 0, \quad \text{then} \quad P_\alpha = 0 \tag{5}$$

where A_L is the set of LiFi APs.

In our study, we assume that STAs are either in idle mode or receiving data. For a given STA u associated with the AP α (i.e., $Y_{\alpha,u} = 1$), its consumption energy can be calculated as:

$$P_u = (1 - \tau_{uti,u}) \cdot \rho_{id,u} + \tau_{uti,u} \cdot \rho_{rx,u} \tag{6}$$

where $\tau_{uti,u}$ is the utilization rate of STA u defined as the proportion of time the STA is receiving data. $\tau_{uti,u}$ for STA u associated with AP α is obtained as:

$$\tau_{uti,u} = \frac{d_{\alpha,u}}{r_{\alpha,u}} \tag{7}$$

3.3 Optimization method

3.3.1 Objective function. Our goal is to optimize both the throughput of STAs and the overall energy consumption of the network. To evaluate the goodness of a configuration with respect to the throughput of STAs, we use the metric Φ defined as:

$$\Phi = \left(\prod_{\substack{\alpha \in A, u \in U \\ Y_{\alpha,u}=1}} \frac{d_{\alpha,u}}{\delta_u} \right)^{\frac{1}{n}} \tag{8}$$

Note that Φ is a dimensionless metric as it involves the ratio $d_{\alpha,u}/\delta_u$. This ratio measures the degree of satisfaction for each STA. Then, we apply the geometrical mean on all the ratios of STAs. Unlike its arithmetic counterpart, the geometric mean allows us to also account for the fairness between the different STAs, which is a highly desirable feature in our case.

We use Ψ to denote the overall energy consumption. Ψ is calculated as follows:

$$\Psi = \sum_{u \in U} P_u + \sum_{\alpha \in A} P_\alpha \tag{9}$$

To evaluate the goodness of a given configuration with respect to the throughput of STAs and the energy consumption, we must define an objective function, denoted by F. We use the following equation for F wherein the normalization for the energy consumption component leads to a dimensionless metric:

$$F = \left(\frac{\Phi - \Phi_{min}}{\Phi_{max} - \Phi_{min}} \right)^2 \cdot \frac{\Psi_{max} - \Psi}{\Psi_{max} - \Psi_{min}} \tag{10}$$

where Φ_{min} (resp. Φ_{max}) is the minimum (resp. maximum) STA satisfaction and equal to 0 (resp. 1). The exact value for the minimum Ψ_{min} (resp. maximum Ψ_{max}) can easily be derived from the number of STAs and APs in the considered scenario.

Note that our objective function must be maximized. Given its definition, a good solution will tend to have a large value for Φ and a small value for Ψ. Note also that we selected a weight of 2 for the throughput metric *Phi* and a weight of 1 for the energy metric Ψ. We give more weight to the throughput as, currently, most users expect to get a good throughput rather than reducing the energy consumption of the whole network.

3.3.2 Optimization problem formulation. Having defined the performance metrics and the objective function, we can now formulate the problem of associating STAs and APs as an optimization problem. We seek to optimize the objective function F while ensuring the following constraints:

$$\forall u \in U, \quad \sum_{\alpha \in A} Y_{\alpha,u} = 1 \tag{11}$$

$$\forall \alpha \in A_L, \quad \sum_{u \in U} Y_{\alpha,u} \leq 8 \tag{12}$$

Eq. (11) ensures that any STA is associated to exactly one AP. As for Eq. (12), it limits to 8 the number of STAs associated to a same LiFi AP (in agreement with most of the manufacturers' specifications, e.g., [5]).

3.3.3 Heuristic. To search for the optimal solution, we opted for a simple heuristic, based on a local search approach, that can quickly find a feasible solution. We define the neighborhood of a given association matrix as another matrix in which one and only one association has been changed. The heuristic starts with an initial random association matrix that is feasible: each STA is associated with an AP within its reach. We use $Y^{(0)}$ to denote this feasible association matrix. At iteration i, we evaluate the objective function for all the neighboring associations of $Y^{(i-1)}$. If the neighboring association of $Y^{(i-1)}$ with the largest objective function is higher than the score of $Y^{(i-1)}$, then this neighbor becomes the new $Y^{(i)}$ at iteration i. Otherwise, an optimal (local optimum) solution has been found and the heuristic ends.

Because of the relative simplicity of our analytical models, our heuristic is able to find very quickly an optimal solution. Therefore, we repeat it with a different initial setting (i.e., feasible association) and we retain only the best solution among all those obtained. This is a common way to reduce the risk of ending with a local optimum far from the global optimum.

4 NUMERICAL RESULTS

4.1 Parameter setting

To explore the benefits of a Wi-Fi/LiFi heterogeneous network, we consider two deployment scenarios and three possible strategies for associating STAs with APs. The selected values for the parameters in all this section are given in Table 2 unless specified otherwise. Note that the values chosen for Wi-Fi fit to the standard 802.11ax while those for LiFi were inspired by scientific papers and technical reports [1, 5]. In particular, we assume that the download channel of LiFi picks its data rate out of two possible rates (namely, 24 and 45 Mbps) depending on the perceived quality of the channel between the AP and its STA. Note that in the case of Wi-Fi, given the dimensions of the office, only the top three levels of data rates are possible, ranging from 154 up to 210 Mbps. Figure 2 reports the data rates chosen by the ideal Wi-Fi manager used by simulator ns-3 as a function of the distance between an AP and its STA, and used in this numerical study.

Both scenarios relate to a large office wherein a single Wi-Fi AP with the assistance of multiple LiFi APs aims at serving the traffic demands of STAs. The office is 30 meters long and 20 meters wide. The Wi-Fi AP is located right in the middle of the office such that its radio waves are able to reach all STAs of the office using the top three physical data rates. In the first scenario, there is a total of 28 LiFi APs while there are 45 LiFi APs in the second scenario. We refer to them as the dense and ultra-dense scenarios, respectively. Figures 1a and 1b illustrate the two scenarios.

STAs are randomly placed in the office. They may or may not fall within reach of a LiFi AP. In any case, the longer cover range of the Wi-Fi AP provides an alternate solution for connectivity. STAs are demanding throughput rates that are uniformly drawn between 10 and 20 Mbps.

Three different strategies are considered for the sake of our study. First, whenever a STA is within reach of a LiFi AP, it associates

Table 2: Values of the various parameters used throughout the experiments.

Parameter	Value
Scenario	
Office dimension	20m per 30m
Number of Wi-Fi APs	1
Number of LiFi APs	28 (dense) or 45 (ultra-dense)
Traffic	
Transport protocol	UDP
Packet size	1440 bytes
Wi-Fi settings	
Spatial streams	2
Channel width	20 MHz
Path loss	log-distance path loss model
Frame aggregation	yes
Standard	802.11ax
Wi-Fi range	51m
Reachable data rates	154 - 210 Mbps
Idle consumption $\rho_{id,\alpha}$	13.1 W
Transmission consumption $\rho_{tx,\alpha}$	18.24 W
LiFi settings	
LiFi range	2 m
Reachable data rates	24 - 45 Mbps
Idle consumption $\rho_{id,\alpha}$	4.5 W
Transmission consumption $\rho_{tx,\alpha}$	6.26 W
Station settings	
STAs' throughput demands	10 - 20 Mbps
Idle consumption $\rho_{id,u}$	1.4 W
Reception consumption $\rho_{rx,u}$	1.6 W
Objective function	
Throughput metric weight	2
Consumption metric weight	1

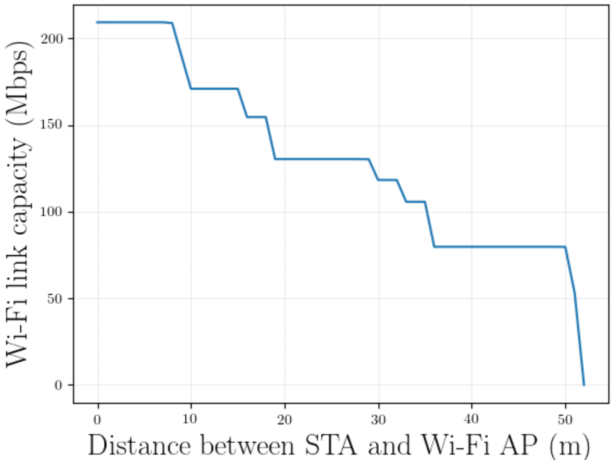


Figure 2: The capacity of a Wi-Fi link decreases with the distance between the STA and the AP.

with its nearest LiFi AP. The remaining STAs get their connection through the Wi-Fi AP. We denote this first strategy by "LiFi prioritized". The second strategy is our solution where the mapping for the association between STAs and APs is found using the analytical models and local search/optimization procedure described in Section 3. Note that the execution of our solution is very fast and typically converges in less than a few tens of iterations. To cope with the issue of suboptimal solutions, we replicate 10 times the search using a different initial setting for the STAs association. The last strategy is simply to connect all STAs using Wi-Fi so that the LiFi chipsets in the light fixtures can be turned down. We refer to this strategy as "Wi-Fi prioritized".

4.2 Scenario with a dense deployment of LiFi APs

We start our numerical analysis with the dense scenario and we let the number of STAs vary from 1 to 45. The corresponding results are depicted in Fig 3. Fig 3a shows that, until a number of STAs of 10, all strategies manage to entirely cover the throughput demands of the STAs. If the number of STAs grows, the Wi-Fi prioritized strategy rapidly leads many STAs to experience issues with their throughput. This result is in line with the commonly admitted idea that a Wi-Fi AP is able to cover the needs of generally more or less 20 STAs. We also observe that both LiFi prioritized and our solution strategies manage to meet the throughput demands of STAs up to about 25 STAs. Beyond that number, both start to experience unsatisfied STAs, yet to a lesser extent for the LiFi prioritized. Fig 3b displays the overall energy consumption of the network. Note that the dashed lines represent the minimum and maximum possible level of energy consumption regardless of the selected strategy. The minimum (resp. maximum) strategy consists in having the Wi-Fi AP turned on, all LiFi APs down (resp. on) and the STAs being constantly silent (resp. in transmission). As expected, the Wi-Fi prioritized strategy is the least consuming one as it is able to turn off all the chipsets of the LiFi APs. We also notice that our solution falls somehow in the middle between the LiFi prioritized and the Wi-Fi prioritized strategies. In Fig 3c, we represent the average amount of energy used to transmit a bit. Clearly, this metrics peaks when there is only one STA since the whole AP energy consumption is shared by only one STA. We observe that the energy consumed per transmitted bit attains its lowest value when the number of STAs is close to 10. before growing nearly linearly with the number of STAs. Fig 3d reports the scores (see Eq. (10)) obtained by each strategy. Recall that the score is a geometric mean combining the satisfaction of STAs in their throughput demands and the network energy consumption. Here, we observe that for a number of STAs between 1 and 12, the Wi-Fi prioritized and our solution strategies score the highest values whereas for a larger number of STAs our solution outperforms the two other strategies. Finally, we represent in Fig 3e the percentage of STAs that are connected to LiFi given that they are within reach of a LiFi AP. Of course, this last curve is only relevant for our solution (the two other strategies are static). We observe that our solution solely relies on Wi-Fi up to a number of STAs of 10 and then gradually increases this number up to a percentage of 90% as the number of STAs grows.

4.3 Scenario with an ultra-dense deployment of LiFi APs

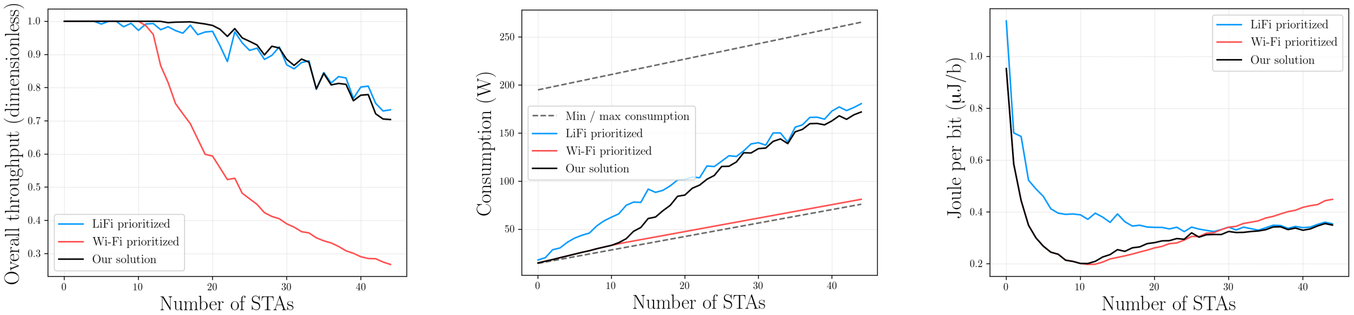
We now focus on the ultra-dense scenario where the combination of the 45 LiFi APs cover the vast majority of the office (see Figure 1b). As before, we apply the three studied strategies to determine the associations between APs and STAs for a number of STAs ranging from 1 to 65. Note that we can consider a larger number of STAs than in the former scenario because of the higher number of LiFi APs. Figure 4 reports the corresponding results found for the three different strategies. Unlike the dense scenario where the LiFi prioritized and our solution strategies perform roughly the same with respect to the satisfaction of the STAs throughput demands, our solution here is steadily outperforming the two others. This is because the LiFi prioritized strategy sometimes associates too many STAs to a same LiFi AP leading to a drop of performance. As for the Wi-Fi prioritized strategy, it does not scale with the number of STAs and rapidly fails to meet the STAs throughput demands. Figure 4b shows the overall energy consumption for the three strategies. We notice that the Wi-Fi prioritized strategy is the least consuming (since the LiFi APs are turned down) and that our solution outperforms the LiFi prioritized strategy. It follows that our solution leads to the best trade-off between satisfying the throughput demands of STAs and reducing the network energy consumption. This is depicted by the score function represented in Figure 4c.

4.4 Discussion

Through what may be two typical network deployments for offices combining multiple LiFi APs and a Wi-Fi AP, our results can be summarized in three points. First, as commonly admitted by Wi-Fi specialists, we confirmed that a single Wi-Fi AP may not be enough to meet the STAs throughput demands as soon as the latter number more than a dozen. Then, LiFi may become helpful to complement the communication resource of the network. However, because of its limited signal range - this is our second point - LiFi alone would not be applicable either. Third, our numerical results indicate that the best option for a Wi-Fi/LiFi heterogeneous network is typically to let the Wi-Fi AP serve around a dozen STAs regardless of the total number of STAs and of the number of deployed LiFi APs. While this may sound surprising at first, we explain it as follows. The upper limitation results from the inherent behavior of Wi-Fi that tends to rapidly deliver poor throughput performance when the number of associated STAs excesses a dozen. The lower limitation stems from the necessity of having the Wi-Fi AP turned on (for the sake of bringing connectivity in every corner of the office). It is then desirable to fully exploit this already turned on AP through the association of STAs that could be served by a LiFi AP. In fact, it is up to our proposed strategy to discover a set of STAs to be efficiently served by the Wi-Fi AP that typically together enables to turn off some LiFi APs resulting thereby in a decrease of the overall energy consumption.

5 CONCLUSIONS

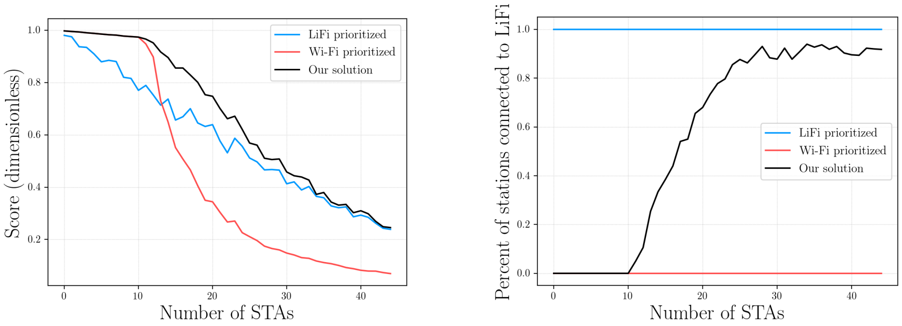
We have studied the issue of associating STAs in a heterogeneous network composed of a Wi-Fi AP and multiple LiFi APs. We have proposed a conceptually simple and easy to implement solution to search and find an efficient mapping for the associations between



(a) Satisfaction level for the stations in meeting their throughput demand (max value is 1, and min value is 0).

(b) Overall energy consumption of the network.

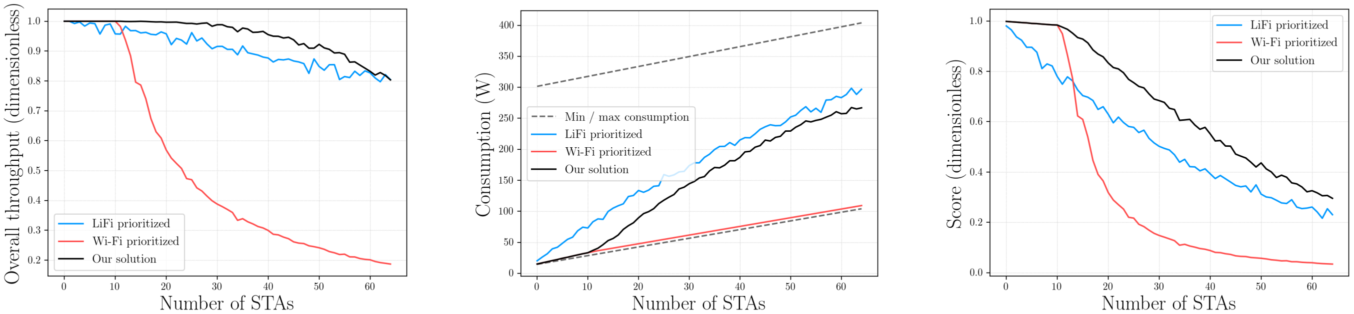
(c) Energy consumed per bit transmission.



(d) Score of the objective function combining the satisfaction of stations in their throughput demands and the overall energy consumption of the network.

(e) Percentage of stations associated with a LiFi AP given that they are within reach of a LiFi AP.

Figure 3: Dense scenario: Performances of various strategies for the associations between STAs and APs.



(a) Satisfaction level for the stations in meeting their throughput demand (max value is 1, and min value is 0).

(b) Overall energy consumption of the network.

(c) Score of the objective function combining the satisfaction of stations in their throughput demands and the overall energy consumption of the network.

Figure 4: Ultra-dense scenario: Performances of various strategies for the associations between STAs and APs.

STAs and APs using analytical performance models for the individual throughput of each STA and for the overall network energy consumption.

Using two realistic deployments of heterogeneous networks for offices, we have evaluated the effectiveness of our solution at discovering better trade-offs than baseline strategies. Our numerical results show that significant gains can be obtained in terms of the throughput of the STAs as well as overall energy consumption. It is worth noting that these gains were obtained only by changing the network association, i.e., no hardware was changed or moved.

Our future works will be mostly twofold. First, we will extend our study to the case of two or more Wi-Fi APs. Second, we will strengthen the realism of our study by considering non-uniform distributions for the location of STAs in the office leading to clusters of STAs.

REFERENCES

[1] Hamada Alshaer and Harald Haas. 2020. Software-Defined Networking-Enabled Heterogeneous Wireless Networks and Applications Convergence. *IEEE Access* 8 (2020), 66672–66692. https://doi.org/10.1109/ACCESS.2020.2986132

[2] Mohammed Amer, Anthony Busson, and Isabelle Guérin Lassous. 2016. Association Optimization in Wi-Fi Networks: Use of an Access-Based Fairness. In *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems* (Malta, Malta) *(MSWiM '16)*. Association for Computing Machinery, New York, NY, USA, 119–126. https://doi.org/10.1145/2988287.2989153

[3] Muhammad Asad, Saad Qaisar, and Abdul Basit. 2020. Client-Centric Access Device Selection for Heterogeneous QoS Requirements in Beyond 5G IoT Networks. *IEEE Access* 8 (2020), 219820–219836. https://doi.org/10.1109/ACCESS.2020.3042522

[4] Xuan Li, Rong Zhang, and Lajos Hanzo. 2015. Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi. *IEEE Transactions on Communications* 63, 4 (2015), 1319–1329. https://doi.org/10.1109/TCOMM.2015.2409172

[5] pureLiFi. [n.d.]. Data sheet. https://purelifi.com/wp-content/uploads/2017/12/LiFi-XC-Data-sheet-Snapshot.pdf

[6] Yunlu Wang, Xiping Wu, and Harald Haas. 2015. Distributed load balancing for Internet of Things by using Li-Fi and RF hybrid network. In *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. 1289–1294. https://doi.org/10.1109/PIMRC.2015.7343497

[7] Xiping Wu, Majid Safari, and Harald Haas. 2017. Access Point Selection for Hybrid Li-Fi and Wi-Fi Networks. *IEEE Transactions on Communications* 65, 12 (2017), 5375–5385. https://doi.org/10.1109/TCOMM.2017.2740211

[8] Xiping Wu, Majid Safari, and Harald Haas. 2017. Joint Optimisation of Load Balancing and Handover for Hybrid LiFi and WiFi Networks. In *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. 1–5. https://doi.org/10.1109/WCNC.2017.7925839