WiLiConnect: A Novel CSI Sharing Technique in Hybrid WiFi/LiFi Networks

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***Abstract*—In recent years, LiFi has become increasingly popular as an indoor communication technology that utilizes the unlicensed visible light and infra-red spectrum to transmit data. A major challenge of utilizing LiFi is that its area of coverage is limited. Thus, a large number of LiFi access points (APs) is often complemented by deploying a WiFi AP to form a hybrid WiFi/LiFi network. However, such deployment does not lead to any additional improvement in the performance of WiFi or LiFi APs. Recent WiFi APs are known to have high overhead due to the requirement of channel state information (CSI), which is essential for utilizing spatial multiplexing. Thus, in this work, we propose a system called WiLiConnect (WiFi-LiFi Connectivity with CSI), which communicates the CSI requirement of the WiFi channel through the LiFi APs, thereby reducing the overhead of WiFi APs. We formulate this problem of load-balancing the overhead of CSI sharing across the LiFi APs, and show that the general problem is NP-Hard. We then propose a round-robin algorithm to solve a special case of the problem, where all the users are assumed to have a single antenna. We further utilize extensive simulation to show that WiLiConnect significantly reduces the overhead of sending CSI. Specifically, WiLiConnect incurs only 0.06% overhead on a WiFi AP having 8 antennas on the total sum rate.**

***Index Terms*—LiFi, WiFi, CSI sharing, CSI Overhead.**

I. Introduction

Light Fidelity (LiFi) is known as a promising alternative technology to complement the existing RF solutions to increase the throughput, and provide better quality of service (QoS) to indoor users. Unlike WiFi, LiFi utilizes an optical spectrum such as visible light or infrared (VL/IR). It promises high-speed data transmission of the order of Gbps and availability of a massive optical spectrum of hundreds of terahertz (THz). LiFi utilizes light-emitting diodes (LEDs) at the transmitter and photodiodes (PDs) at the receiver for bidirectional communication. This has made LiFi an extremely popular technology for indoor communication.

To account for the limited coverage provided by LiFi, prior research have suggested a hybrid LiFi/WiFi network as an alternative where LiFi coexists with WiFi. LiFi complements WiFi by offering high data rates albeit with limited coverage, whereas WiFi provides a moderate data rate with good coverage. In addition, there is no interference between LiFi and WiFi as they operate on different spectrum bands. As a consequence, it is possible for the users to choose either a LiFi AP or a WiFi AP, or both, depending on their QoS requirements. A number of prior studies have proposed such coexistence [1], [2] and link aggregation [3] to improve the overall throughput of the users.

A related trend to improve the limited data rate of WiFi is to use multiple antennas at its APs. For example, WiFi 5 (IEEE 802.11ac) allows usage of up to 4 antennas, whereas WiFi 7 (IEEE 802.11be) proposes using up to 16 antennas [4]. Such multiple antennas increase the achievable data rate of WiFi by enabling spatial multiplexing through multi-user multiple input multiple output (MU-MIMO) if a sufficient number of uncorrelated channels exist. In an ideal scenario with such uncorrelated channels, spatial multiplexing can offer a linear increase in the data rate [5].

However, obtaining such high data rate improvements in practice for WiFi has been difficult. This is because effective utilization of spatial multiplexing requires estimating the channel conditions, known as channel state information (CSI). Since WiFi uses the same channel to handle both its uplink and downlink data requirements, feeding CSI back from the receiver to the transmitter incurs a substantial overhead to the data rate. Prior studies have shown that such overhead can even reduce the data rate by over 50% [6]. Although WiFi 6 and 7 allows sending of such channel feedback in parallel using smaller resource units, this only reduces the overhead by a relatively smaller amount. This problem of high overhead has even led to many APs not utilizing the full potential of multiple antennas [7] by disabling such spatial multiplexing.

In this work, we propose a novel technique of utilization of LiFi APs to send a part or whole of the WiFi CSI information. Unlike WiFi, LiFi APs have the advantage that their uplink and downlink communication usually happens over separate channels, with the downlink using visible light and the uplink using infrared [8]. This ensures that sending the CSI data via LiFi APs does not lead to a loss of data rate for the other users. Furthermore, since LiFi APs are more in number, the CSI data can be sent in parallel, thus leading to a substantial reduction in the overhead. The additional overhead of sending the CSI data from the LiFi APs to the WiFi APs is typically much smaller, as they are connected via a wired backhaul network. We utilize this idea to propose an integrated WiFi/LiFi hybrid system called WiLiConnect (WiFi-LiFi Connectivity with CSI).

To utilize such parallelism in CSI data transmission, it is essential to balance the CSI sharing among all the available

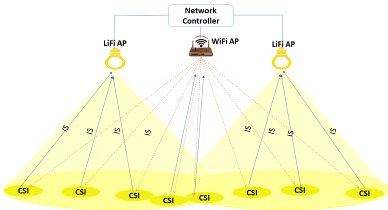

Fig. 1: WiLiConnect's CSI sharing.

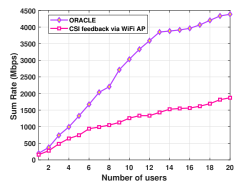

Fig. 2: Ideal vs actual sum rate over hybrid WiFi/LiFi network.

APs. This involves deciding the number of users that should share their CSI via each AP. We formulate this problem and show that it is in general NP-Hard. WiLiConnect, therefore, uses a round-robin algorithm, which optimally solves a special case of the problem where each of the users has the same size of CSI data. We show, using detailed simulations in multiple scenarios, that WiLiConnect reduces the overhead of sending CSI data as well as leads to substantial improvement of sum rate for the users using WiFi.

Motivation: We motivate the need for CSI sharing via LiFi through a simulation of an actual hybrid WiFi/LiFi network. Fig. 2 shows the total sum rate (throughput) obtained over a WiFi network for different numbers of users. We assume that the WiFi AP has four antennas and that the channel has a sufficient number of independent transmission paths. We plot two distinct cases – an ideal scenario hereby termed as (ORACLE) where the AP knows the CSI of each user and a realistic scenario where the AP collects CSI feedback via polling, as specified in the WiFi 5 standard (details of the experiments are mentioned in Section V). We note that there is a substantial gap in the sum rate between the ideal and the realistic scenario, with the gap being equal to 65% and 56% for 10 and 20 users, respectively. This shows that collecting CSI feedback that is required for WiFi to function imposes a significant overhead on the sum rate. Such substantial overhead has also been reported in prior works [6].

Summary and contributions: We summarize our contributions as follows:

1) We show the potential of utilizing CSI sharing via LiFi APs to improve the sum rate of WiFi.
2) We formulate the problem of information sharing to maximize its benefits in terms of improvement of the sum rate. Since this is an NP-Hard problem, we then solve its special case, i.e., users with a single antenna, which is frequently seen in practice.
3) Through the obtained simulation results it has been shown that the proposed scheme improves the overall sum rate by approximately 55% compared to the standard CSI feedback mechanism.

II. Related work

Existing works fall into two categories. The first set of works utilize link aggregation to satisfy the data demand of the users of the hybrid WiFi/LiFi system. These works focus on improving the overall throughput [2] and balancing the load across APs [1]. However, unlike our work, these works do not consider improving the individual performance of either LiFi or WiFi APs.

A second set of related works focus on improving the performance of WiFi protocol. Multiple prior works identified the problem of sending the CSI information from the user to the APs as a major overhead and suggested ways of mitigated it. Specifically, [6] quantizes the CSI, [9] uses parallel transmission of CSI via multiple orthogonal frequency division multiple access (OFDMA) channels, and [10] selects the users depending on requirement. Although these works do reduce the overhead, WiFi's overhead of sending back the CSI in terms of wasted bandwidth continues to be high [7]. However, to the best of our knowledge, no prior study has utilized LiFi APs to communicate the CSI feedback and thereby improving the performance via spatial multiplexing.

III. Background & System Model

Working of MU-MIMO in WiFi: Since the standardization of IEEE 802.11ac (referred to as WiFi 5) in 2013, WiFi supports the utilization of parallel streams to communicate with different users. This technique, known as spatial multiplexing via MU-MIMO, requires both knowledge of the CSI to AP and the presence of multiple uncorrelated channels. Such uncorrelated channels are often available indoors, due to the presence of multiple scattering surfaces. However, obtaining CSI requires a procedure where the AP has to send a special null data packet (NDP), followed by polling each individual user and then collecting the CSI data (see Fig. 3(a)). Since WiFi utilizes a single channel for both uplink and downlink, this imposes a substantial overhead in terms of throughput.

Hybrid WiFi/LiFi Network: LiFi as a technology aims to utilize the large unlicensed spectrum of visible light. However, it does not have a large coverage area, making it essential to deploy a number of APs to cover a substantial part of a room. Furthermore, to mitigate the problem of low data rates at the edge of the attocells and/or additional dark zones, usually, one or more WiFi APs are also deployed. Such a hybrid network aims to incorporate the advantages of both WiFi and LiFi APs.

Our scheme, WiLiConnect, utilizes the LiFi APs to mitigate the overhead of collecting CSI of WiFi (Fig. 3(b)). This is possible by sending some of the WiFi's CSI via the LiFi APs. Since all the APs are connected via a wired network having high bandwidth and low latency, this has the potential of substantial reduction in the overhead of collecting CSI. Furthermore, there are a number of LiFi APs, allowing parallel transmission of the CSI. It also does not impact the downlink transmission of LiFi, since LiFi APs use different channels for uplink and downlink [11].

System Model: We consider a hybrid WiFi/LiFi system with n number of users, w WiFi APs, and l LiFi APs for an indoor scenario of known dimensions. The APs are mounted on the room's ceiling, and a set of users with both WiFi and LiFi network interfaces are present in the room. A central controller (CC) connected to all the APs, assigns APs to each user $u_i (i = 1, \ldots, n)$ based on their locations and channel

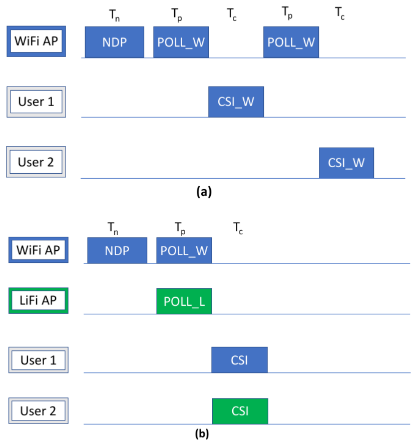

Fig. 3: The CSI feedback technique using (a) conventional WiFi AP and (b) proposed technique for parallel CSI sharing using LiFi APs. In (b), the frames marked in green denote communication via LiFi, whereas the ones marked in blue denote communication via WiFi AP.

conditions. We assume that each WiFi AP has n_t number of antennas, whereas each user device has n_r number of antennas. We further assume that the WiFi APs follow either the 802.11ac (WiFi 5), or the 802.11ax (WiFi 6), both of which support spatial multiplexing. In addition, WiFi 6 also supports parallel transmission using OFDMA.

To enable MU-MIMO framework, it is essential for the user device to send back its channel state information (CSI). According to the WiFi standard, sharing of CSI can be initiated by the AP by sending a preamble frame, called null data packet (NDP), to all the users. After that, the AP sends an individual poll to the user device. The user device on receiving it, sends back the CSI information. We denote the time required to obtain the CSI information of all the users as delay time T_d, since no data communication is possible during this period. We compute the time to send the null data packet, time to probe and time to send the CSI by T_n, T_p and T_c respectively. Thus, the total delay time can be expressed as:

$$T_d = T_n + T_p + T_c. \quad (1)$$

In a traditional feedback mechanism. if we denote the polling time and time to send the CSI per user by t_p^i and t_c^i respectively, we have:

$$T_p = \sum_{i=1}^{n} t_p^i \text{ and, } T_c = \sum_{i=1}^{n} t_c^i. \quad (2)$$

CSI Sharing Scheme (WiLiConnect): Our information-sharing scheme utilizes the LiFi APs as well as WiFi APs to send the CSI information. In this scheme, let N_j be the set of users sharing CSI information through each AP j. Note that each user can send the information through only one AP, i.e.

$$N_j \cap N_k = \phi, \forall j, k \in \{1, \ldots, w + l\}. \quad (3)$$

Then, the total delay can be expressed as:

$$T_d = T_n + \max_{j=1,\ldots,w+l} \sum_{u_i \in N_j} [t_p^i + t_c^i]. \quad (4)$$

Our goal is to select a set of users $u_i \in N_j$ such that the total overhead is minimized, i.e.

$$\text{Minimize } T_d. \quad (5)$$

We note that the above problem in general is NP-Hard, as it reduces to the number partitioning problem [12]. We now describe our solution for a special case of the problem.

Algorithm 1 Algorithm to share information across LiFi APs

INPUT: Set of users N_w that want to utilize WiFi,
set of users connected to each LiFi AP j,
set of APs A, set of users covered by a LiFi j, M_j, number of antennas n_t
OUTPUT: Set of users N_j which utilize information sharing via AP j

1: $T_p^j \leftarrow 0, \forall j$
2: $T_c^j \leftarrow 0, \forall j$
3: $N_j \leftarrow \phi$
4: **while** $|\bigcup_j N_j| \leqslant n_t$ or $A \neq \phi$ **do**
5: $l \leftarrow \arg\min_j T_p^j + T_c^j$
6: $k \leftarrow \arg\max_{i \in M_j} SINR(i, j)$
7: **if** $SINR(k, l) > t$ **then**
8: $T_p^l = T_p^l + t_p^k$
9: $T_c^l = T_c^l + t_c^k$
10: $M_j \leftarrow M_j \backslash \{u_i\}, \forall j$
11: **else**
12: $A \leftarrow A \backslash \{u_l\}$
13: **end if**
14: **end while**

IV. Proposed Solution Approach

We now propose a round-robin algorithm, shown in Algorithm 1. The algorithm initially starts with the situation that no user shares the CSI. We sort the LiFi APs in non-decreasing order of the number of users assigned and check the maximum signal-to-interference and noise ratio (SINR) between that AP and any user (Algorithm 1, Line 6). If the maximum SINR exceeds the minimum threshold needed for communication with the LiFi AP for any user (Line 7), we send that user's CSI via the corresponding AP (Lines 8-10). If it does not exceed the threshold, we assign the rest of the users to the WiFi AP itself and return (Line 12). We continue the process of sorting the APs and checking of maximum SINR until there is no user left whose CSI is not assigned to an AP (Line 4).

We note that the above algorithm provides the optimal solution in the special case of each receiver antenna having the same number of bits in CSI. This occurs in practice when they have the same number of antennas.

We compute the time complexity of the algorithm. We sort the list of APs according to a total of ‘n’ number of users, each of which takes $O(l \log l)$ time. Each AP needs to keep track of the maximum SINR, which takes $O(n)$ time. Thus, the total time needed is equal to $O(n + nl \log l) = O(nl \log l)$. In practice, the total number of APs is limited to $\leqslant 10$, and the total number of users $\leqslant 40$, which makes the computation possible in less than a millisecond on a personal computer.

V. Performance Evaluation and Discussion

A. Simulation settings

In this paper, we consider an indoor room of size $5 \times 5 \times 3$ m^3 for a hybrid WiFi/LiFi network setup. Four LiFi APs are placed at the center of four quadrants, and a single WiFi AP is placed at the center of the ceiling. The users are distributed randomly with uniform distribution on the floor of the room. The simulation parameters are listed in Table I. We assume the user device has both LiFi and WiFi transceivers. We consider both MU-MIMO and multiple access via OFDMA. For LiFi APs, multiple users are supported using carrier sense multiple access with collision avoidance (CSMA/CA). However, the WiFi AP has full coverage as opposed to limited coverage for a single LiFi AP in this indoor room. Therefore, four LiFi APs are placed to cover the whole room. The users are associated with the LiFi or WiFi AP based on their received signal strength or SINR values. The APs are assumed to allow the maximum data rate that the channel allows.

Unless mentioned otherwise, we assume that the WiFi AP is equipped with four antennas as this is the most common configuration. The WiFi AP sends the NDP to all the users to estimate the channel condition. After channel estimation, a set of users share their CSI feedback via the uplink channel of the LiFi APs. This CSI, in turn, goes from the LiFi AP to the controller and finally to the WiFi AP. The rest of the users directly send their CSI via the WiFi AP. WiLiConnect minimizes the overhead by choosing the optimal subsets of users. We assume a channel coherence time of $15ms$ for the WiFi APs, i.e., the CSI needs to be collected after every $15ms$ [6]. Based on the channel condition, the controller facilitates the spatial multiplexing of four users with the WiFi AP whereas the other WiFi-associated users are provided access via OFDMA (each user is provided one time/frequency resource unit). Consequently, the resource bandwidth allocated to each WiFi user can be written as:

$$B_u = \frac{B_w}{\max(1, N_w - N_m + 1)}, \quad (6)$$

where B_w is the total WiFi bandwidth. Here, N_w and N_m are the total number of WiFi users and MU-MIMO channels utilized respectively. The per-user data rate R_u^i and $R_{u,k}^i$ of the WiFi and LiFi channels are calculated according to Shannon's formula as in [**?**] and [11]. We then evaluate and analyze the sum rates of the hybrid WiFi/LiFi network for different numbers of users:

$$R_u = \sum_{u_i \in W} R_{u,w}^i + \sum_{u_i \in L} R_{u,l}^i, \quad (7)$$

where W and L are the sets of users served by WiFi and LiFi APs, respectively. We assume that the WiFi APs do not send any user data when the process of CSI collection is running. However, since LiFi APs have distinct channels, their sum rate is not considered to be affected by the CSI being sent via uplink channel. Furthermore, although LiFi APs have much higher bandwidth, for a fair comparison, we have assumed a bandwidth of 40 MHz, as in the prior works [8].

B. Comparison of Sum Rates

We have evaluated the sum rate for our proposed hybrid WiFi/LiFi network with CSI sharing for the variable number of users in the network. Here we consider the sum rate as the sum of the achieved data rate of all users in the network for a large number of instances.

TABLE I: Simulation parameters [13], [14]

LiFi channel parameters	
Height of the AP from user level (h)	2.15 m
PD's Area (A_{PD})	1 cm^2
Optical filter's gain (g_{f})	1
PD's FOV	60°
Optical to electric conversion efficiency ($\mathbf{K}$)	3
Responsivity of the detector (R_{PD})	0.53 A/W
LiFi AP's optical transmit power (P_{opt})	3 Watts
LiFi AP's bandwidth (B_{LiFi})	40 MHz
LiFi noise PSD (N_{LiFi})	-210 dBm/MHz
WiFi channel parameters	
Central carrier frequency (f_{c})	2.4 GHz
Transmit Power of WiFi AP (P_{WiFi})	20 dBm
Bandwidth of WiFi AP (B_{WiFi})	20 MHz
WiFi noise PSD (N_{WiFi})	-174 dBm/Hz
Number of antennas at WiFi AP (n_t)	4, 8
Number of antennas at each user (n_r)	1
NDP time T_{NDP}	80 μs
Poll time per user T_p	52 μs
CSI time per user T_c	258 μs
Channel coherence time τ_c	15 ms

We show the sum rates for four different cases for uncorrelated spatial channels in Fig. 4. As in §I-A, we assume that ORACLE is a priori aware of the CSI of all users, whereas a conventional network disables spatial multiplexing. We also show the performance of proposed WiLiConnect followed by the traditional feedback mechanisms used in WiFi 5 and WiFi 6 (with OFDMA) respectively. We observe in Fig. 4 that a traditional CSI feedback collection via WiFi AP mechanism enabled hybrid WiFi/LiFi network performs better than the spatial multiplexing disabled mechanism, especially when the number of users exceeds 2. This shows the reason behind WiFi AP obtaining spatial multiplexing gain in the case of N_t = 4 as well as 8. Furthermore, disabling such spatial multiplexing reduces the sum rate by around 23% and 56% in the case of N_t = 4 and 8, respectively. Our proposed information-sharing scheme WiLiConnect improves the sum rate, though it does not reach the ideal value of ORACLE. The proposed scheme provides a sum rate of only 8% and 12% below the ORACLE for 10 and 20 users in the case of N_t = 4 (Fig. 4(a)). Note that our scheme still sends the CSI feedback but shares it over multiple APs. Thus, it is not possible to get the ideal sum rate. However, utilizing our scheme leads to significant benefits collectively for the users of the entire network. This is because of the parallelism built into WiLiConnect, where the APs collect the CSI in parallel.

C. Percentage of CSI Sharing Overhead

Fig. 5 compares the amount of overhead in terms of the reduction of the sum rate for four different schemes for 10 users. Our first observation is that the overhead of sending CSI is significant considering that many users only use WiFi, with the median overhead being 15% while rising to 27% in a few cases for N_t = 4. Since this overhead comes entirely on WiFi, this hurts the users in poor LiFi coverage more strongly. Second, using information sharing even with a naive algorithm (as in Scheme 2) also shows a substantial reduction in the overhead, with the median overhead falling to 7%. Third,

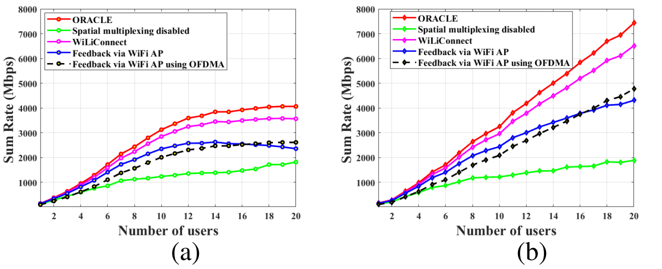

Fig. 4: Sum rate performance comparisons for proposed and conventional hybrid WiFi/LiFi network over an ideal and actual WiFi network for uncorrelated MIMO channel for (a) N_t = 4 and (b) $N_t = 8$, respectively.

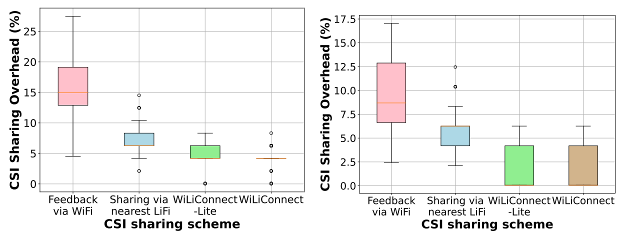

Fig. 5: Percentage of overhead due to CSI feedback to the APs in hybrid WiFi/LiFi network using actual WiFi network and CSI sharing through LiFi AP for N_t = 4 and 8, respectively.

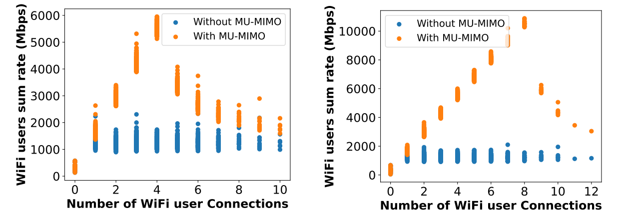

Fig. 6: Number of WiFi connections with respect to sum rate using MU MIMO and without MU MIMO for N_t = 4 and 8 in HWLN, respectively.

WiLiConnect-Lite reduces the median overhead to only 4% of the total sum rate. Allowing both LiFi and WiFi APs to collect CSI (as in Scheme 4, WiLiConnect) does not reduce the median overhead any further, but leads to a reduction in the higher percentile values, indicating more stable and predictable performance. Thus, WiLiConnect reduces the total overhead by around 7× for $N_t = 4$. We see a similar trend for $N_t = 8$, with our scheme giving only 0.06% median overhead. This shows the promise of both CSI sharing in a hybrid WiFi/LiFi network and the advantage of using round-robin algorithm.

D. Sum Rate of WiFi Users versus Number of Connections

We now show the impact of our scheme on the sum rate of only the WiFi APs in Fig. 6. We only compare against conventional channel feedback, as our prior experiments show that it performs best. We compare the effect of the number of WiFi users on the sum rate on 1000 cases. We observe that the sum rate of WiLiConnect is around 3× and 7× using spatial multiplexing for four users and eight users, respectively. The improvement in the sum rate falls when the number of users is beyond 4 and 8 in the case of N_t = 4 and 8, respectively, but in general, it still outperforms the case of not using spatial multiplexing. This is because our scheme allows only a single group of users to use spatial multiplexing, with the rest using a traditional SISO transmission. This reduces the efficiency of spatial multiplexing if the number of users increases. It also shows that utilizing such an information-sharing scheme benefits users connected to the WiFi APs.

VI. Conclusion

In this work, we propose a framework called WiLiConnect that mitigates the large overhead of sending CSI for utilizing spatial multiplexing via MU-MIMO in the case of WiFi. WiLiConnect leverages the LiFi APs in a hybrid WiFi/LiFi network to collect the CSI, and then forwards it to the WiFi APs via a controller. This allows to collect CSI in parallel, and frees up the WiFi bandwidth for data communication. We further propose a round-robin algorithm to associate each user with an AP, while balancing the amount of CSI collected by each AP. We prove the efficacy of WiLiConnect using simulations and show that it reduces the overhead by around 4× and 24× compared to the traditional feedback strategy with 4 and 8 transmitting antennas respectively.

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References

[1] F. Jin, R. Zhang, and L. Hanzo, "Resource allocation under delay-guarantee constraints for heterogeneous visible-light and RF femtocell," *IEEE Transactions on Wireless Communications*, vol. 14, no. 2, 2014.
[2] Y. Wang and H. Haas, "Dynamic load balancing with handover in hybrid Li-Fi and Wi-Fi networks," *Journal of Light-wave Technology*, vol. 33, no. 22, pp. 4671–4682, 2015.
[3] A. Zubow, P. Gawłowicz, K. L. Bober, V. Jungnickel, K. Habel, and F. Dressler, "Hy-Fi: Aggregation of LiFi and WiFi using MIMO in IEEE 802.11," in *2021 IEEE WoWMoM*, 2021.
[4] C. Taylor, "The ultimate wi-fi access point: Which wi-fi 6 features define the new premium tier?" Strategy Analytics: Research, Experts and Analytics, Tech. Rep., June 2019, accessed on May 20, 2023.
[5] E. G. Larsson, P. Stoica, and G. Ganesan, *Space-Time Block Coding for Wireless Communications*, may 8 2003.
[6] X. Xie, X. Zhang, and K. Sundaresan, "Adaptive feedback compression for MIMO networks," in *ACM Mobicom*, 2013, pp. 477–488.
[7] Y. Daldoul, D.-E. Meddour, and A. Ksentini, "Performance evaluation of OFDMA and MU-MIMO in 802.11ax networks," *Computer Networks*, vol. 182, p. 107477, 2020.
[8] H. Haas, L. Yin, C. Chen, S. Videv, D. Parol, E. Poves, H. Alshaer, and M. S. Islim, "Introduction to indoor networking concepts and challenges in LiFi," *J. Opt. Commun. Netw.*, vol. 12, no. 2, Feb 2020.
[9] K.-H. Lee, "Using OFDMA for MU-MIMO user selection in 802.11 ax-based Wi-Fi networks," *IEEE Access*, vol. 7, 2019.
[10] X. Xie and X. Zhang, "Scalable user selection for MU-MIMO networks," in *IEEE INFOCOM 2014*. IEEE, 2014, pp. 808–816.
[11] R. Ahmad, M. D. Soltani, M. Safari, and A. Srivastava, "Load balancing of hybrid LiFi WiFi networks using reinforcement learning," in *IEEE PIMRC*, 2020.
[12] M. R. Garey and D. S. Johnson, *Computers and intractability*. freeman San Francisco, 1979, vol. 174.
[13] N. M. Karoti, S. Paramita, R. Ahmad, V. A. Bohara, and A. Srivastava, "Improving the performance of heterogeneous LiFi-WiFi network using a novel link aggregation framework," in *IEEE WCNC*, 2022.
[14] H. Yu and T. Kim, "Beamforming transmission in IEEE 802.11 ac under time-varying channels," *the scientific world journal*, vol. 2014, 2014.