Hybrid-Fidelity: Utilizing IEEE 802.11 MIMO for Practical Aggregation of LiFi and WiFi

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Abstract—We present `Hy-Fi`, a system that aggregates light fidelity (LiFi) and radio frequency (RF)-based communication on the 802.11 (WiFi) physical layer by utilizing the MIMO capabilities in IEEE 802.11-compliant commodity WiFi chips. `Hy-Fi` is based on two key ideas. First, we use inexpensive commodity hardware to facilitate direct transmission of WiFi waveforms over the optical wireless channel, as this is proposed in the IEEE P802.11bb task group. Second, we use the MIMO signal processing from WiFi to aggregate LiFi and radio signals directly at the physical layer. `Hy-Fi` was implemented as a prototype and evaluated in a small testbed. Experimental results reveal that our approach offers excellent robustness against signal fading, blockage and external interference in both, the optical and radio channels making it suitable for applications with very strict requirements to the packet delay and loss ratio. Moreover, the two channels, LiFi and RF, can be aggregated to double the link capacity in the best case. Finally, we demonstrate how `Hy-Fi` could be used as wireless access technology in next-generation indoor enterprise networks providing both high capacity and seamless mobility.

Index Terms—Wireless Communication, Light Fidelity, WiFi, Visible Light Communication, Optical Wireless Communication, COTS

1 Introduction

Current solutions based on 802.11 WiFi are facing a great challenge as they have to keep up with the rapid increase of capacity hungry applications like high-fidelity multimedia streaming, mobile high-definition video, social networking, and cloud storage. As the spectral efficiency of radio frequency (RF) technologies is already close to the limit, crowded spectrum poses a serious problem and researchers are looking for new solutions. Moreover, new applications requiring Ultra Reliable Low Latency Communications (URLLC) appear, which pose great challenges for the next generation wireless networks, as very strict requirements to the packet delay and loss ratio need to be fulfilled even under mobility [1]–[3].

One promising approach is to free-up some of the resources in the RF band by off-loading all or part of the network traffic to the optical spectrum using networked Optical Wireless Communication (OWC). In the scope of this paper, we focus on the term light fidelity (LiFi), which is often used as a synonym for OWC, even though it certainly focuses on a very specific representation. In addition, both media, LiFi and RF, can be used simultaneously to achieve the robustness and low-latency required for URLLC.

LiFi is an attractive technology for future small-cells as it offers a very wide spectrum of hundreds of THz. Moreover, inexpensive Light-Emitting Diodes (LED) are already installed everywhere for lighting and this infrastructure can be easily reused for the purpose of communication as a way to densify existing wireless networks. In LiFi, data is transmitted by intensity modulation and direct light detection. The transmitter uses a LED or laser while the receiver is a Photodiode (PD). However, LiFi has some disadvantages over RF communication. Since propagation is mostly based on line-of-sight (LoS) and usually more directional, LiFi suffers from sudden link blockage due to shadowing of the LoS. Hence, a clear line-of-sight between transmitter and receiver is required. Another issue with LiFi is that the intense ambient light during daytime can saturate the PDs of the receiver and thus degrade its performance [4]. But there are also significant advantages of LiFi like the excellent spectrum reuse as the light does not penetrate through walls and can be well confined so that the risk of co-channel interference is low. Moreover, light is inherently robust against electromagnetic interference and has no health hazards [5][1], which makes it very interesting for industrial and medical applications. To leverage these advantages and make LiFi successful, the links need to be made robust through some form of diversity, e.g., space, time, and frequency [8]. In contrast, RF communication exhibits different characteristics from LiFi, as the radio propagation is mostly due to multi-paths. Moreover, due to coherent detection in RF, the path loss is lower in general. Consequently, RF offers a more homogeneous coverage as it is robust against shadowing due to obstacles and fully operational even in non-line-of-sight (NLoS) environments.

However, as radio waves penetrate everywhere, RF technologies like WiFi suffer from adverse impact from

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1. Some studies reported minor health concerns relating to flicker that might induce photosensitive epilepsy [6] and glare from blue-rich LEDs that may disrupt people's sleep patterns [7]

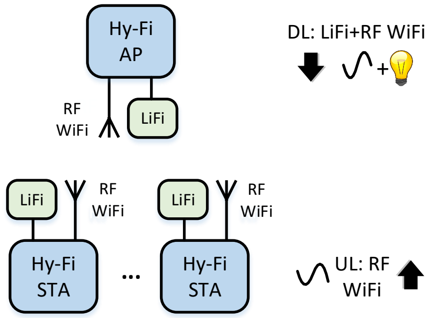

Figure 1. Envisioned scenario with aggregated LiFi plus RF WiFi channel used in the downlink.

co-channel interference, e.g., hidden terminals, and contention from co-located WiFi deployments. Furthermore, in unlicensed industrial, scientific, and medical (ISM) bands, several other RF technologies need to coexist (e.g., WiFi, Bluetooth, ZigBee) [9], which results in crowded spectrum and further reduces the efficiency and reliability of WiFi. Finally, device mobility has a different impact on RF. While a LiFi link changes rather slowly if LoS is unblocked as the instantaneous signal power is proportional to the integral of the optical power over the detector surface, an RF link is subject to fast fading where the radio channel can fade randomly over a few centimeters passed during a few milliseconds [10].

Due to the complementary characteristics of RF WiFi and LiFi, the simultaneous usage of both communication technologies is promising in order to achieve high reliability and high data rate communication [11]. Such aggregation can be performed on different layers of the communication protocol stack ranging from transport layer [12] to network layer [13] and to data link layer [14]. Note also that several standardization activities are ongoing for LiFi. There is a trend towards defining a common PHY/MAC layer able to operate over multiple media (e.g., power lines, plastic optical fiber, OWC) in order to lower the cost of equipment and deployment. As an example, commercial systems use the G.9991 recommendation of ITU-T, which is a legacy of powerline systems, where mobility support is rather limited. The IEEE P802.15.13 group has already come up with the idea to consider multi-user distributed MIMO techniques like in RF to provide mobility support in industrial scenarios. Recently, IEEE started the P802.11bb project, which aims to reuse the existing WiFi protocol stack and leverage advanced technology development on mobile networks as much as possible also for LiFi. In our previous work, we have successfully demonstrated that the WiFi protocol can be fully reused for communication over optical wireless media [15], [16]. In this work, we make the next step and show for the first time that the aggregation of both media, LiFi and WiFi, is possible directly at the physical layer. This is achieved by utilizing the multiple-input multiple-output (MIMO) capabilities of standard commercially available off-the-shelf (COTS) WiFi chips. Specifically, we suggest to use three different techniques for aggregation. First, there is the Maximal Ratio Combining (MRC) technique used at the receiver side to achieve diversity by combining the signal received over two channels, LiFi and RF WiFi. With MRC, it is possible to reconstruct the signal even if one of the channels, LiFi or WiFi, is either blocked or in a deep fade. Second, to achieve robustness against external interference, on either LiFi or WiFi, we use the selection combining technique at the receiver, which is a simplified version of MRC that can switch off the channel affected by interference. This way, the combined link becomes more robust than the two technologies alone. Third, in situations where the SNR of both channels is high enough, we use the spatial multiplexing capabilities of MIMO to aggregate both media and to double the data rate by sending different data signals over both channels simultaneously.

Contributions: In this paper we propose `Hy-Fi`, which stands for hybrid-fidelity. It aggregates wireless optical and radio frequency channels at the physical layer utilizing the MIMO capabilities of COTS WiFi chips. This allows the simultaneous usage of both media to either gain channel diversity and, therefore, achieve robustness against fading, shadowing, and external interference, as well as to increase the data rate by means of channel aggregation. We build a prototype of `Hy-Fi` using COTS hardware components. Figure 1 shows our envisioned scenario for `Hy-Fi`. Both the APs and the client STAs are equipped with RF WiFi and LiFi front-ends. While both technologies can be bidirectional, LiFi will be used for the downlink (DL) only, while RF is used for both DL and uplink (UL). This is meaningful as the data traffic demand is still dominated by the DL. In addition to our previous work [17], we also discuss how `Hy-Fi` could be used as wireless access technology in next-generation indoor enterprise networks by providing both high capacity and reliability. Here, we enable support for seamless mobility, which is of great importance as enterprise customers would like to enjoy mobility indoors.

2 Related Work

Related work falls into two categories: hybrid LiFi/WiFi networks and LiFi standardization activities.

Hybrid LiFi/WiFi Networks

Wu et al. [11] give an comprehensive overview of approaches for hybrid LiFi and RF WiFi networks. Accordingly, there are multiple options for the aggregation of wireless optical and RF channels ranging from solutions implemented on transport to network, data link (MAC), and to physical layer. With `Hy-Fi`, we showed for the first time that an aggregation is feasible at the physical layer using only COTS hardware components. Liu et al. [12] proposed the aggregation of LiFi and RF on the transport layer using a decoupled TCP extension protocol. Shao et al. [13] and Li et al. [18] proposed an aggregation at the interface level by using the network bonding technique of the Linux operating system. Moreover, Zhang et al. [19] proposed a centralized approach to aggregation on network layer. An aggregation on the data link (MAC) layer was proposed by Pratama et al. [14], where a hybrid packet scheduler allows to schedule packets for transmission over both media according to different criteria, e.g., optimizing throughput. A theoretical analysis of an aggregated LiFi and RF system which can be seen as an heterogeneous MIMO system was performed by Ma et al. [20]. They derived an optimal power allocation for this configuration. Finally, a practical framework termed LiFi HetNet, where both RF WiFi and LiFi technologies can coexist was proposed by Ayyash et al. [10]. Here, different diversity techniques for LiFi were discussed like the usage of multiple antennas (MIMO) and multiple links. On higher layers, channel bonding (MAC) and multi-path TCP can help exploiting the benefits from both a LiFi and a WiWi link as demonstrated in [21]. Orthogonal to this, in our previous work [15], we demonstrated that the standard 802.11 protocol can be used for communication over wireless optical channels by using WiFi commodity chips.

LiFi Standardization Activities

The development of new communication chips is extremely expensive, i.e., 10-100 Million USD. Hence, re-using existing silicon is crucial as it allows easy adoption of a new technology with decent performance. Therefore, the aim of the IEEE P802.11bb project group is to integrate support for LiFi into the 802.11 WiFi standard. Therefore, three different PHY modes are provided: *i)* LC common mode, *ii)* LC optimized mode, and *iii)* LC HE mode. The first mode uses OFDM and is fully compatible with the 802.11a physical layer. However, in order to be able to modulate an LED, an appropriate center frequency for up-conversion was selected so that the resulting real-valued baseband signal can be directly used. A new PHY layer is defined in the LC optimized mode. It is based on adaptive OFDM, which is especially suitable for optical communication. The LC HE mode defines a PHY layer being compatible to the 802.11ax standard. The LC common mode assures compatibility and will be used for the transmission of management and control frames. Finally, a tight integration of RF and LiFi was discussed within IEEE P802.11bb in order to support LiFi in the Fast Session Transfer mechanism [22], which would allow a STA session to switch between the four bands, i.e., 2.4, 5, 60 GHz RF and LiFi. In contrast, our `Hy-Fi` approach is more powerful as it enables the simultaneous usage of both media, RF and LiFi.

3 Background

As background, we give a brief introduction into multiple antenna techniques and how they are used in the IEEE 802.11 standard. Moreover, we briefly introduce the dynamic frequency selection mechanism used in WiFi which is later exploited in order to enable seamless handover operations.

3.1 MIMO Primer

Spatial Multiplexing (SM) is a multiple antenna technique, which allows the transmission of multiple independent and separately encoded data signals called spatial *streams* in parallel over a single wireless channel. With SM the space dimension can be reused more than one time. The maximum spatial multiplexing order, i.e., the number of streams, equals $N_s = \min(N_t, N_r)$, where N_t and N_r are the number of antennas at the transmitter and receiver, respectively [23]. This means that in the optimal case the spectral efficiency can be increased by a factor of N_s as the number of streams that can be transmitted in parallel is N_s. However, in a practical system the multiplexing gain is often limited by spatial correlation leading to rank-deficient MIMO channels, i.e., some of the spatial streams may experience weak channel gains. 802.11n uses a very simple SM MIMO technique called direct-mapping [24], where each antenna transmits its own data stream. Note, that SM MIMO requires an RF environment with rich scattering. Here the m transmit streams are received by n antennas so that each receive antenna will measure an independent linear combination of the m signals. The signals are decodable when there are more or equal measurements (n) than unknowns (m), i.e., $n \geq m$. On the MIMO receiver side, simple techniques like zero-forcing (ZF) can be used to solve the linear equations for MIMO in real time. Note, that in IEEE 802.11n/ac, all spatial streams have to use the same modulation, coding, and transmit power.

Spatial Diversity (SD) is another multiple antenna technique. Here we distinguish between transmit diversity, which requires multiple transmit antennas (multiple input single output or MISO channels), and receive diversity, which uses multiple receive antennas (single input multiple output or SIMO channels). To achieve diversity in MISO the same signal is transmitted over multiple antennas and therefore received over multiple paths by the receiver. Here multiple options are possible. A sending node can either select the best antenna to transmit, use space-time-block codes like Alamouti [25], or ensure that the different signal copies are combined at the receiver side in a coherent way. The latter is referred to as transmit beamforming [24]. Note, that transmit beamforming requires channel knowledge at the transmitter side, hence, typically relying on channel feedback from the receiver side. In SIMO, the opposite happens where the signal transmitted by one antenna is received by multiple antennas. Here, techniques like Maximal Ratio Combining (MRC) are used to harness the useful power from all receive antennas by adding the signals in a coherent way [24]. With MRC, the effect of the channel is reverted, i.e., it delays signals from different receive antennas so that they have the same phase, weighs them proportionally to their signal power, and adds them up. In contrast, Selection Combining (SC) is a much simpler technique where only the signal from the receive antenna with either highest signal power, highest signal-to-noise power ratio (SNR), or signal-plus-noise power is selected [26].

3.2 MIMO in 802.11

In 2009, MIMO was introduced to WiFi with the 802.11n amendment. Most 802.11n/ac compliant WiFi chips support both receive diversity (via MRC) and spatial multiplexing (via directly mapped MIMO) with up to four spatial streams. However, transmit beamforming is only an optional feature in 802.11n. With the 802.11ac amendment, the MIMO dimensions were extended to 8×8. Moreover, since 802.11ac a technique called multi-user (MU)-MIMO is available, which allows to serve multiple client stations simultaneously in the downlink. With MU-MIMO it is possible to overcome the limitations of client stations like smartphones having only a few antennas. Here, the AP uses MIMO precoding technique to send different signals simultaneously towards multiple users so that inter-user interference is minimized. A common precoding technique is Zero-Forcing [27], which

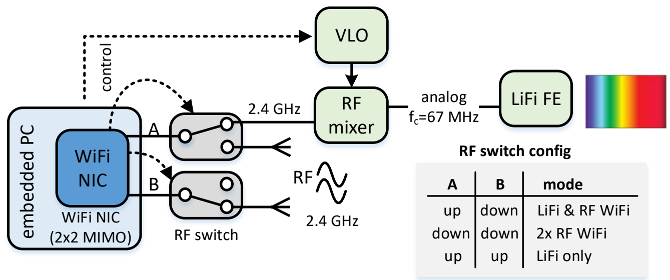

Figure 2. Hy-Fi transceiver design for aggregated LiFi and WiFi.

steers nulls into the directions of the interferers. Similar to transmit beamforming, MU-MIMO requires channel state information on transmitter side. Since 802.11ac precoding can also be used with the spatial multiplexing mode in single-user (SU)-MIMO.

3.3 Dynamic Frequency Selection in WiFi

A large number of WiFi channels in the 5 GHz spectrum band require a channel allocation scheme known as Dynamic Frequency Selection (DFS), which was introduced into WiFi in 2003 as part of IEEE 802.11h. The usage of DFS prevents electromagnetic interference with other users of the C band frequency band, i.e., 4-8 GHz used by military radar, weather radar, and satellite communication. When operating on a DFS channel, an 802.11 device, typically the AP, must continuously scan for non-WiFi signals like weather radars. In the event of detection, it must leave the current channel and switch to another one. To enable a coordinated channel switch among the members of a WiFi BSS, i.e., AP and associated clients, WiFi provides means to support such operation. Specifically, an AP in infrastructure mode is able to inform its serving clients about the detection of a radar signal by transmitting a beacon frame containing a Channel Switch Announcement Information Element (CSA-IE) together with the new radio channel to be used. This explicit signaling allows the AP and its associated stations to perform a time synchronized channel switch. After the channel switch the stations remain associated with the AP and the data traffic can continue. Note, there is also an option to deliver the CSA-IE in other types of management frames like action frames.

4 Hy-Fi Architecture

With Hy-Fi, we propose to utilize the MIMO capabilities of modern WiFi COTS hardware to aggregate the optical LiFi and the RF WiFi channels (media) directly at the physical layer. Figure 2 shows the schematic diagram of the proposed transceiver architecture. A Hy-Fi transceiver is composed of the following hardware components: host PC, WiFi network interface card (NIC) with two antenna ports (2x2 MIMO), variable local oscillator (VLO), RF mixer, two RF switches, and a LiFi optical front-end (LED, PD). Both antenna ports of the WiFi chip (NIC) can be configured using the RF switches. Here, the antenna port A of the WiFi chip can be configured for transmission/reception either over the LiFi or the normal RF channel. In case of LiFi, the analog 802.11 RF signal emitted by the WiFi NIC (e.g., $f_c = 2.412\,\text{GHz}$) on port A is down-converted using the RF mixer to meet the specification of our analog LiFi front-end using a low intermediate frequency (IF) of $f_c = 67\,\text{MHz}$. For reception, the reverse operation is performed, i.e., the analog IF signal received by the LiFi front-end ($f_c = 67\,\text{MHz}$) is up-converted using the RF mixer to the RF band (e.g., $f_c = 2.412\,\text{GHz}$) and fed into port A of the WiFi chip. The second antenna port B can be configured to use either RF for transmission/reception or to be disabled (i.e., selection of terminated RF cable). By disabling the second port the transceiver is running in SISO mode, i.e., RF WiFi SISO or LiFi SISO. Moreover, it is possible to run the transceiver in RF WiFi only mode (SISO or MIMO), which is beneficial for client stations being out of the LiFi coverage area or in case of having a permanent obstacle in the LoS path of the LiFi link. Other reasons are situations with strong and permanent interference on the optical channel, e.g., intense ambient light, which result in saturation of the LiFi receiver. Finally, running Hy-Fi in LiFi-only mode is beneficial as the data traffic can be fully offloaded to LiFi freeing up resources used in RF for other STAs. Moreover, such a mode is useful during situations with strong and persistent interference on the RF WiFi channel, e.g., from co-located WiFi deployments or other RF technologies.

The table in Figure 2 shows the three possible modes of operation of Hy-Fi using a 2x2 MIMO configuration of the WiFi chip. Note, that in the hybrid mode, where LiFi and RF WiFi are used simultaneously, the optical channel connected to port A becomes yet another media for the WiFi chip. The chip itself is unaware of the actual mode being used for transmission as the type(s) of media being used for transmission is fully transparent for him. Note that the up-/down-conversion is required as commodity WiFi chipsets integrate a baseband processing unit and radio transceiver into a single system-on-chip and expose only the analog RF signal in the 2.4 GHz or 5 GHz band. In a real modem, one would directly generate the LiFi waveform on its desired interface, e.g., by using an RF digital-to-analog converter (RF DAC).

In order to make a Hy-Fi transmission robust against signal blockage, shadowing and fading on both LiFi and RF channels, we exploit the MIMO capabilities of the WiFi chip. Therefore, Hy-Fi can operate in diversity mode, where the same signal is transmitted over both antenna ports A and B and hence received simultaneously over both channels, RF and LiFi, on ports A and B of the receiving WiFi NIC, respectively. At the receiver side, the two signals are received and combined in the WiFi NIC using the MRC technique which is implemented inside the WiFi chip (Section 4.2). Moreover, in environments with expected strong level of interference, either on RF WiFi or LiFi, Hy-Fi uses the SC technique in addition to MRC, which allows to dynamically switch off the interfered receive port A or B using the two RF switches (Section 4.5). Finally, in situations where the SNR of both channels is similar and sufficiently high, Hy-Fi is able to utilize the MIMO capabilities of the WiFi chip to perform carrier (channel) aggregation as a way to double the data rate by simultaneously sending different signals over both media, i.e., multiplexing (Section 4.1). The following subsections describe the Hy-Fi architecture in more detail.

4.1 Carrier Aggregation

Hy-Fi uses the MIMO spatial multiplexing technique implemented by a COTS WiFi chip to perform aggregation of the LiFi and RF channels directly at the physical layer. With the spatial multiplexing technique used in 802.11 SU-MIMO the data rate (capacity) can be increased by a factor of $2\times$ by multiplexing over both channels when using the proposed 2x2 MIMO configuration. From the theoretical point of view, we have a classical MIMO channel. Although multiple transmit antennas, $L = 2$, are used, their transmissions are orthogonal and there is no mutual influence, i.e., one is using the RF channel and the other LiFi for transmission. On the receiver side, the signal received over the LiFi channel is up-converted to RF so that it can be processed together with the signal received directly from RF. Hence, our channel can be described as follows:

$$y_l[m] = h_l[m] + n_l[m], l = 1 \dots L, \tag{1}$$

where h_l is the fixed complex channel gain from the lth transmit antenna to the lth receive antenna, and $n_l[m]$ is additive Gaussian noise independent across antennas. Note, that in our case $L = 2$ and h_l are

$$h_1 = \text{visual light channel} \tag{2}$$

$$h_2 = \text{radio frequency channel.} \tag{3}$$

The ergodic capacity of our MIMO channel considering no channel state information (CSI) on the transmitter side and equal power allocation while assuming perfect knowledge of CSI on receiver side can be computed as

$$C_{\text{eq}} = \left\| \log_2(1 + \frac{\overline{\gamma}}{L}\lambda(HH^*)) \right\|_1, \tag{4}$$

where $\overline{\gamma}$ is the average SNR, $\lambda(\cdot)$ computes the eigenvalues of a matrix, H^* is the complex conjugate-transpose of H and $||\cdot||_1$ is the 1-norm. Therefore, using open-loop SU-MIMO the capacity can be increased by almost $2\times$ when both channels have same $\overline{\gamma}$. This is larger than for a classical RF SU-MIMO system where spatial correlation exists due to the coupling between TX antennas as well as RX antennas (cf. Section 6.1). Note that in case of SU-MIMO, we have an additional limitation: all spatial streams have to use the same MCS.[2] Hence, both channels must have the same average SNR, $\overline{\gamma}$, to achieve the highest multiplexing gain of 2. To overcome this limitation, one can serve multiple users simultaneously using MU-MIMO. This is beneficial for Hy-Fi as in the DL one user can be served on RF while at the same time another user can be served on LiFi. Since MU-MIMO allows each user to be served on different MCS there is no need to have the same average SNR on both channels. For the future, we plan to extend Hy-Fi to support MU-MIMO.

4.2 Channel Diversity

Hy-Fi uses MIMO in spatial diversity mode to achieve robustness against signal blockage on the channel and signal distortions on RF due to shadowing and small-scale fading in case of client mobility. Therefore, Hy-Fi is run in hybrid mode and the same signal (with same MCS) is sent over both channels, LiFi (port A) and RF WiFi (port B), and it is afterwards combined at the receiver side using the MRC technique of the WiFi chip. Whenever only a single channel, LiFi or RF WiFi, is blocked or deeply faded, the transmission is still successful as a copy of the signal can always be received over the other channel.

From the theoretical point of view, we have a MIMO channel as described in Eq. 1. Using MRC, a sufficient statistic for the detection of $x[m]$ from $\boldsymbol{y}[m] := [y_1[m], \dots, y_L[m]]^t$ is

$$\tilde{\boldsymbol{y}}[m] := \boldsymbol{h} * \boldsymbol{y}[m] = ||\boldsymbol{h}||^2 x[m] + \boldsymbol{h} * \boldsymbol{n}[m], \tag{5}$$

where $\boldsymbol{h} := [h_1, \dots, h_L]^t$ and $\boldsymbol{n}[m] := [n_1[m], \dots, n_L[m]]^t$. Note that $||\cdot||$ represents the Euclidean norm. Setting $\mathbb{E}\{|n_l(t)|^2\} = \sigma^2$, we get the instantaneous SNR at the l-th element (γ_l) to be [23]

$$\gamma_l = \frac{|h_l|^2}{\sigma^2}. \tag{6}$$

Note that MRC obtains the weights $\boldsymbol{w}$ that maximize the output SNR (matched filter), i.e., $\boldsymbol{w} = \boldsymbol{h}$ is optimal in terms of SNR. With MRC, the instantaneous output SNR is given as

$$\gamma = \frac{|\boldsymbol{w}^H \boldsymbol{h}|^2}{\sigma^2} = \sum_{l=1}^{L} \gamma_l. \tag{7}$$

The output SNR is, therefore, the sum of the SNR at each element. With increased SNR, the outage probability decreases significantly. For Hy-Fi this is paramount, especially as the SNR of the LiFi channel can drop quickly and deeply in case of blockage of the LoS path, i.e., $\gamma_1 \approx 0$.

4.3 Carrier Sensing

WiFi belongs to the class of random access protocols, which uses a mechanism termed listen-before-talk, a.k.a. physical carrier sensing, for channel access. In our hybrid Hy-Fi system, we have three options: i) sensing on RF channel only, ii) sensing on LiFi channel only, and iii) simultaneously sensing on both channels, RF WiFi and LiFi. All three options have their pros and cons. In order to be compliant to the 802.11 standard, we have to perform carrier sensing on the RF band (2.4 or 5 GHz), which leaves us with options i) or iii). However, under some conditions carrier sensing on the LiFi channel might not be needed. First, as we consider to use LiFi for downlink only, there is only contention in the LiFi channel access among the few fixed installed APs with well-planned locations. Second, as the propagation characteristics of RF WiFi are better than that of LiFi, the region covered by RF sensing is in general larger than that of LiFi. Therefore, sensing on RF WiFi should be sufficient to avoid collisions on the LiFi channel as well. We finally decided for option iii) as the additional carrier sensing on the LiFi channel will not harm the operation due to the assumed non-overlapping LiFi cells (see Section 5, Figure 6). Moreover, such an option is also feasible from the practical point of view as disabling carrier sensing on a per port basis is in general not possible with WiFi COTS hardware.

2. This is true for most 802.11n WiFi chips.

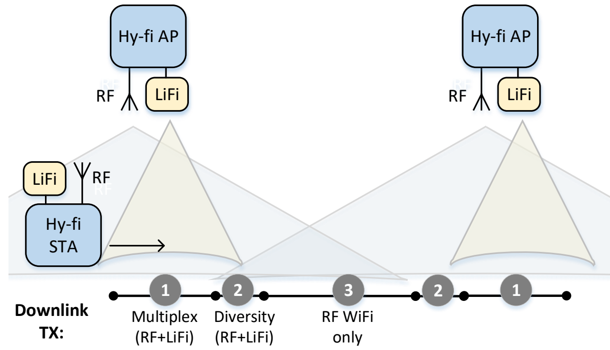

Figure 3. Hy-Fi in a mobile scenario with different modes selected for different STA positions.

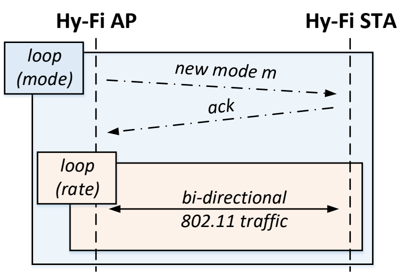

Figure 4. The Hy-Fi-AP performs joint mode and rate control. Any mode change is signaled towards the corresponding STA.

4.4 Adaptive Mode Control

An Hy-Fi-enabled AP needs to control the selection of the mode of operation to be used for DL transmissions. The following five modes are available for selection: i) *RF SIMO*, ii) *LiFi SISO*, iii) *Hy-Fi diversity*, iv) *RF MIMO*, and v) *Hy-Fi multiplex*. All the different modes have different pros and cons. While *Hy-Fi diversity* offers excellent robustness towards signal fading and shadowing on either the RF WiFi or LiFi channel (Section 4.2), the *Hy-Fi multiplex* mode gives higher data rate when operating at same average SNR on both channels, RF WiFi and LiFi (Section 4.1). In addition, the AP can run in pure LiFi or pure RF WiFi modes. Note, operating in pure LiFi mode is beneficial from the capacity point of view as the data traffic can be fully offloaded to LiFi freeing up resources used in RF WiFi.

Figure 3 illustrates a possible selection of modes for different user locations. In region 1, the STA is covered by both RF WiFi and LiFi. Here, the two channels LiFi and RF WiFi have high SNR and can therefore be aggregated so that the total data rate can be doubled in best case (*Hy-Fi multiplex*). In region 2, the STA is at the LiFi cell edge. Here, diversity mode should be used to achieve robustness as LiFi signal quality might drop quickly and significantly (*Hy-Fi diversity*). Finally, in region 3, the STA is fully out of LiFi coverage so that only the RF WiFi channel can be used (*RF SIMO/MIMO*).

In Hy-Fi, the mode switching is part of the rate control algorithm residing inside the AP. Hence, the AP performs a joint control of mode and rate control selection. The main goal is to pick the right mode and rate on a per-packet level basis.[3] Any mode change is signaled from AP and acknowledged by the corresponding STA (cf. Figure 4). Note, that the signaling packets are transmitted using *Hy-Fi diversity* mode on the lowest MCS to make sure that the STA receives that control information regardless of its own configuration (see Section 4.5). To determine the best configuration, a per-link (i.e., per-STA) mode-rate-control table is used that keeps the probability of success and achievable throughput for each Hy-Fi mode and rate (MCS) combination. The combination giving the highest expected throughput is selected for transmission. It also uses 10% of the data packets as sampling packets to try random mode and rate combinations. Those sampling packets are marked (using unused fields from 802.11 header) in order to be able to filter them out on the receiver side. For any other received unicast packet, the interference detection algorithm is executed (cf. Section 4.5).

A flush message is signaled back to the transmitting AP in case interference is detected and one of the ports needs to be blocked or a previously blocked port is unblocked due to a timeout. It is used to delete the old entries in its mode-rate-control table. This is needed in order to let the transmitting AP test highest MCS first after any blocking/unblocking of ports happened on the receiver side. Note, that our control algorithm works in open-loop fashion and could be implemented by extending the Minstrel Rate Control used by the WiFi subsystem in Linux kernel.[4] Table 1 shows the available modes of operation (mode) and modulation and coding schemes (MCS) when using 802.11n PHY.

Moreover, Hy-Fi can be directly integrated into a so-called multi-rate retry (MRR) chain, which is used by the majority of 802.11 chips like Atheros [28] for efficiency reasons [29]. MRR works as follows. For each packet to be transmitted the rate control computes the transmission descriptor, which is a list of transmission rates and number of transmission counts to be used in case the packet is not acknowledged [29]. The classical transmission descriptor used by MRR is $(r_0/c_0, r_1/c_1, r_2/c_2, r_3/c_3)$, where r_{0-3} is the bitrate (i.e., the MCS) and c_{0-3} are the transmission count, respectively. Note, the maximum number of (re-)transmissions is $R_{\max} = c_0 + c_1 + c_2 + c_3$ before a packet is discarded. With Hy-Fi, the MRR chain becomes aware of the channel aggregation (Figure 5). Here, in addition to the bitrate and transmission count, the

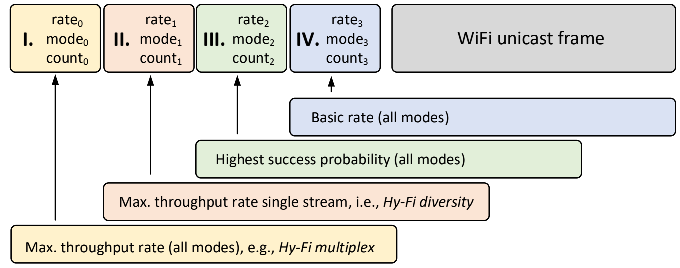

Figure 5. Transmission descriptor set for MRR chain adapted for Hy-Fi.

3. Our current prototype does not support this as switching between modes involves tight synchronization of packet transmissions with reconfiguration of the RF switches.

4. https://wireless.wiki.kernel.org/en/developers/documentation/mac80211/ratecontrol/minstrel

Table 1
Available mode of operation (mode) and modulation and coding schemes (MCS, 0=BPSK 1/2, . . ., 7=64QAM 5/6) for different number of spatial streams (SS) when using 802.11n PHY (data rate in Mbit/s).

			20 MHz guard interval		**40 MHz** guard interval	
MCS	**#SS**	**mode**	0.8 μs	0.4 μs	0.8 μs	0.4 μs
0	1	RF SIMO	6.5	7.2	13.5	15
...	...	...	...	...	...	...
7	1	RF SIMO	65	72.2	135	150
0	1	LiFi SISO	6.5	7.2	13.5	15
...	...	...	...	...	...	...
7	1	LiFi SISO	65	72.2	135	150
0	1	Hy-Fi diversity	6.5	7.2	13.5	15
...	...	...	...	...	...	...
7	1	Hy-Fi diversity	65	72.2	135	150
0	2	RF MIMO	13	14.4	27	30
...	...	...	...	...	...	...
7	2	RF MIMO	130	144.4	270	300
0	2	Hy-Fi multiplex	13	14.4	27	30
...	...	...	...	...	...	...
7	2	Hy-Fi multiplex	130	144.4	270	300

`Hy-Fi` mode of operation m_i to be used can be specified: $(r_0/m_0/c_0, r_1/m_1/c_1, r_2/m_2/c_2, r_3/m_3/c_3)$. This has the major advantage that the `Hy-Fi` modes of operation can be changed within the (re-)transmissions of the same packet.

4.5 Dealing with Interference

In challenging environments with strong and not sporadic interference from either RF or ambient light, the channel diversity enabled by MRC is not helpful. The former can happen with non-WiFi devices sharing the same RF spectrum but failing to detect ongoing WiFi transmissions, e.g., ZigBee or LTE-U/LAA, whereas the latter is a form of impairment on the LiFi channel as it saturates the photodiodes of the LiFi receivers. It is even counterproductive as whenever an 802.11 NIC discovers a valid WiFi preamble, it combines the signals it receives from each available antenna port. However, in case of, e.g., strong external RF interference, even the signal received over a clear LiFi channel at high SNR can be corrupted when combined with a strongly interfered signal from RF resulting in low SINR. The same can happen in case the LiFi receiver frontend is exposed to intense ambient light. Since in `Hy-Fi` the LiFi channel is only used for the DL communication, we propose an additional interference avoidance scheme which is performed on the client side (STA). Therefore, we use SC as the first stage in addition to MRC (cf. RF switches in Figure 2). Whenever the level of interference on the receiver side, i.e., STA, becomes too high for too long time, the affected channel, LiFi or RF WiFi, is disabled temporarily by switching off the corresponding antenna port on the receiver side. Hence, from the perspective of SC, we select the port with the lowest interference level. This can be done by the client station itself without informing the AP as long as the AP operates in the *Hy-Fi diversity* mode (Section 4.4) only. The AP will simply notice an improvement in terms of data rate as higher MCS become available.

The following heuristic is used on the receiver side to detect external non sporadic interference on either the RF or LiFi channel. The `Hy-Fi` transmitter, i.e., AP operating in *Hy-Fi diversity* mode, uses rate control to adapt the MCS to the quality of the channel. Here, the idea is to let the receiver side observe the MCS used for packet transmissions and their signal strength, i.e., RSSI. A discrepancy between the used MCS and the packet's RSSI is an indication for interference on at least one of the two channels. A too low MCS is an indication that the transmitter needs to select low MCS to make packet transmissions robust against interference, i.e., sufficiently high packet success rate (PSR), which is in general not obtainable from the RSSI value. The algorithm is described in more detail in Listing 1.

Algorithm 1: Interference handling on RX side when operating in *Hy-Fi diversity* mode only.

```
Result: detect and handle interference by switching off affected ports
/* variables: updated during runtime                                 */
backoff ← minBO, last_blocked_port ← RF
/* backoff parameters                                                */
minBO ← 100, maxBO ← 400
/* min interval a port should remain active                          */
min_t_active ← 10
/* Noise floor on Rf/LiFi channels in absence of interference        */
N0_rf ← -95 dBm, N0_lifi ← -95 dBm
/* schedule timers for both ports                                    */
timer_blocked[RF].schedule(∞, activate_port(RF))
timer_blocked[LiFi].schedule(∞, activate_port(LiFi))
timer_running[RF].schedule(∞, check_backoff(RF))
timer_running[LiFi].schedule(∞, check_backoff(LiFi))
/* interference detection heuristic executed for each received packet
   pck                                                               */
def detect_interference(pck):
    /* MCS feasible when there is no interference on both channels   */
    max_MCS ← get_max_MCS('HyFi-div', pck.RSSI, N0_rf, N0_lifi)
    /* suspected interference if selected MCS is too low             */
    if pck.MCS < max_MCS & pck.probing = False then
        if both_ports_active() then
            /* block port that was blocked last                      */
            deactivate_port(last_blocked_port)
            /* set backoff timer for blocked port                    */
            timer_blocked[last_blocked_port].reset(backoff)
        else
            /* interference persists so wrong port was blocked: swap
               blocked with open port                                */
            activate_port(last_blocked_port)
            last_blocked_port ← 1 - last_blocked_port
            deactivate_port(last_blocked_port)
            /* reset backoff time                                    */
            backoff ← minBO
            /* set backoff timer for blocked port                    */
            timer_{last_blocked_port}_blocked.reset(backoff)
        /* port config changed; tell TX side to reset rate control table
           */
        send_flush_msg()
def activate_port(p):
    /* activate port after timer_blocked expired                     */
    unblock(p)
    timer_blocked[p].reset(∞)
    /* start timer to track active time and if necessary increase backoff
       */
    timer_running[p].reset(min_t_active)
    /* port config changed; tell TX side to reset rate control table */
    send_flush_msg()
def check_backoff(p):
    /* if the re-activated port's timer fired, check whether it is blocked
       again meaning that it was not active for enough time,
       consequently, increase the backoff                            */
    if blocked(p) then
        backoff ← min(2 × backoff, maxBO)
        timer_blocked[p].reset(backoff)
    timer_running[p].reset(∞)
```

The logic for detection and avoidance of interference on the client side is executed for each received unicast data packet, while probe packets are ignored. Each packet is analyzed by estimating the maximum possible MCS (*max_MCS*), based on the packet's RSSI and some assumed noise floor for both channels in absence of external interference, which is compared to the actually used MCS. If the current packet's MCS is below *max_MCS* this is an indication for interference and the receiver tries to mitigate it by blocking one of the two channels, RF WiFi or LiFi. By default, we switch off the port that was blocked the last time. In case one of the ports was already blocked, the open port is swapped with the blocked one. The rationale behind this is that we previously blocked the wrong port as the interference persists. Whenever the port configuration is changed, i.e., one port is closed or opened, the transmitter side, i.e., the AP, is informed by sending a flush message which allows him to reset his rate control table so that he starts again using the highest available MCS.

To avoid permanent blacklisting of a channel, from time to time a blocked channel is reactivated to see whether the interference still exists. This is achieved by having two additional timers. One to re-activate ports after a certain backoff time and the second timer to increase the backoff time if necessary. This second timer tracks whether a re-activated port remains open for a minimum time before being blocked again. If the port has been open for a too short time, the backoff is doubled until it reaches some maximum value.

In summary, our key idea is to control on the STA side which ports and hence, media or channels, RF WiFi or LiFi or both, are being used for DL signal reception. In the absence of external interference, it is beneficial to combine the received signals from both LiFi and RF WiFi to achieve diversity for robustness against shadowing and fading. In case of persistent interference, it is beneficial to switch off the affected channel entirely in order not to mangle the signal with interference. Note that our prototype implementation is implemented fully in software *above* the (unmodified) WiFi chip. In theory, this functionality can be realized easier by changing the signal processing chain. For example, the usage of an SDR-based WiFi implementation (e.g., [30]) would enable the implementation of more advanced signal selection (or combining) schemes. Specifically, it would be possible to simultaneously decode WiFi frames using three signals (i.e., each antennas independently and the combined signal) and select the one without errors (e.g., valid CRC check-sum). However, in this work we aim for a solution using COTS WiFi hardware, so we leave modifications of the WiFi receive chain for future work.

5 Hy-Fi for Enterprise Networks

We envision to use Hy-Fi as the wireless access technology in next-generation enterprise networks. Such communication networks have to be optimized to support high-density client scenarios, while providing a high level of QoS, e.g., very high throughput and very low latency. Moreover, the need to deploy small cells requires strong support for (indoor) mobility, client load balancing, and interference management. Hy-Fi builds upon the BIGAP [31] architecture, enabling seamless client handover which can be fully controlled by the infrastructure. Similar to BIGAP, the idea is to use a single global Basic Service Set (BSS) ID for the whole Extended Service Set (ESS) and, thereby, for all Hy-Fi APs. Hence, from the STAs point of view, the whole ESS including all APs looks like a single BSS or AP, i.e., all APs have the same MAC address. In order to achieve full coverage, the Hy-Fi APs are very densely deployed, i.e., the RF cells are overlapping. However, such densification is often not sufficient to have overlapping LiFi cells.

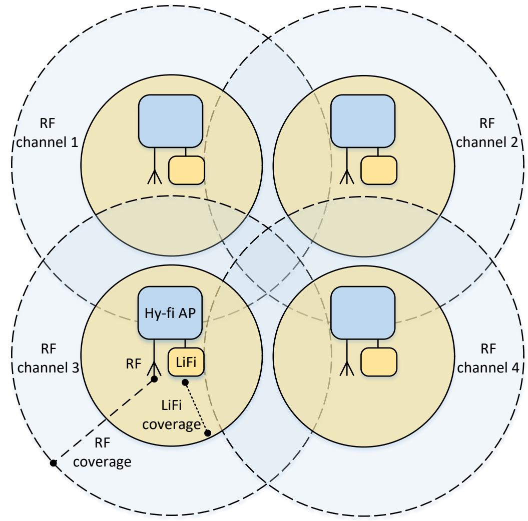

Figure 6. Hy-Fi AP placement in dense enterprise deployments. While adjacent AP use different RF channels, the LiFi channel is the same for all APs as the LiFi cells are non-overlapping.

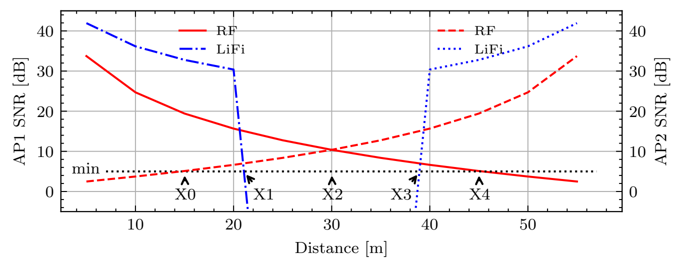

Figure 7. Hy-Fi handover opportunities when client STA is moving from AP1 to AP2.

Figure 6 illustrates the scenario. Adjacent APs are operating on different non-overlapping RF WiFi channels. The same BSS-ID operated on the same RF channel would cause collisions of WiFi acknowledgment packets in the uplink and would lead to duplicated frames and, hence, high load in the wired backbone. However, the same LiFi channel can be reused by all Hy-Fi APs, because LiFi cells do not overlap.

Figure 7 illustrates for our hybrid network at which positions a handover (HO) can be performed by a client STA moving from AP1 to AP2. Here, the pathloss was computed for RF WiFi and LiFi using an indoor picocell model based on COST 231 and an indoor model for infrared optical communication [32], respectively.[5] The earliest point for an HO is *X0* as the STA enters the RF coverage of the AP2. Note, that after the HO the STA would be served by RF WiFi only even in Hy-Fi diversity mode as it is outside the LiFi range of AP2. A better option would be to delay the HO to *X1*. Here the client is leaving the LiFi coverage of AP1 and can only be served by RF WiFi. At *X2*, the RF signal strength from AP2 exceeds the one from AP1. Here the STA is still out of LiFi coverage. Waiting until *X3* has the advantage that

5. Note the sudden drop in SNR for LiFi at around 20 m which is due to the selected field of view.

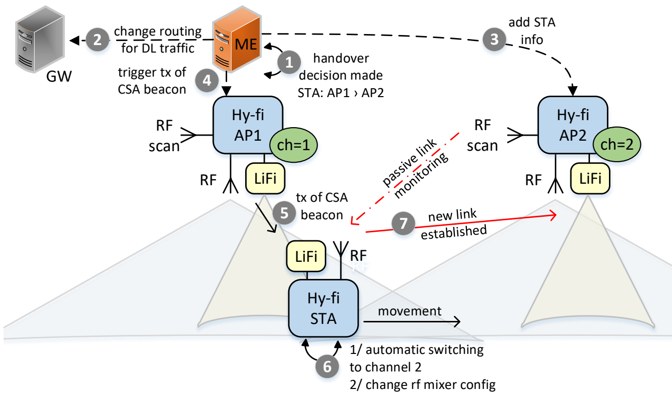

Figure 8. Hy-Fi handover operation triggered by the infrastructure: client STA is moved from AP1 to AP2.

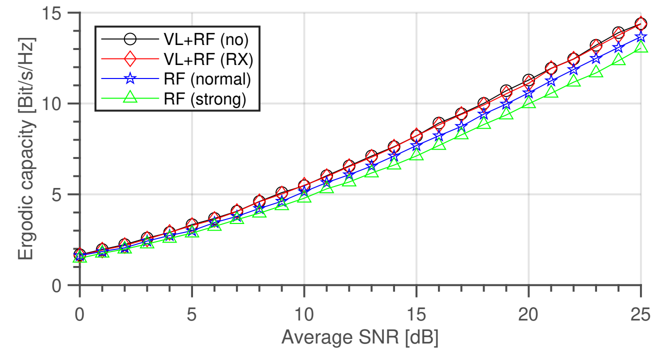

Figure 9. Ergodic MIMO channel capacity.

after the HO the STA can be served by RF WiFi and LiFi simultaneously. Finally, the latest point for the HO is *X4*. For Hy-Fi, we selected an approach where the handover decision is based on the signal strength of the RF channel only. This has the advantage that the impact of device orientation is small. Hence, the handover is triggered around point *X2*.

Hy-Fi supports seamless HO operation, which attempts to reduce the outage during HO to a minimum. This is achieved by performing the HO operation below the data link layer and triggered by the infrastructure.[6] Figure 8 illustrates this. HO opportunities are discovered using an additional RF scanning interface at each AP which is continuously jumping over all used RF channels. In doing so, it collects information about all active STAs in proximity together with wireless statistics such as the average SNR of the RF channel. This information is delivered from each AP to the Hy-Fi mobility entity (ME), which makes HO decisions, e.g., based on signal strength, network load or other factors. When a handover decision is made, the ME instructs the gateway (GW) to change the routing for incoming packets such that it takes the new AP. Moreover, the ME associates the STA to the new AP by adding the STA to the list of associated STAs maintained by the new AP.[7]. Finally, the ME is instructing the serving AP to send out a unicast channel switch announcement (CSA) packet with the STA as the destination.

As in BIGAP, we exploit the 802.11 Dynamic Frequency Selection (DFS) functionality (cf. Section 3.3). A CSA packet is transmitted from the serving AP to the STA that leads the STA to believe that the serving AP will perform a RF channel switch, because of detecting a radar signal on its operating channel. In fact, the serving AP remains on its current RF channel but the target AP is operating on the new RF channel. The STA believes that the new AP is the old AP, which has also switched the RF WiFi channel. This happens because all APs use the same BSS ID and because the current state of the STA was transferred from the old to the new AP. By relying on these principles, the communication can be continued without any further communication outage except the time needed for performing the actual channel switching inside the client STA. In contrast to BIGAP, in Hy-Fi, we have the additional LiFi communication. However, as the LiFi cells are non-overlapping, there is no need for a channel switch in LiFi.[8]

6 Discussion

In this section, we discuss the relevant characteristics of the proposed Hy-Fi architecture.

6.1 High Data Rate

An important advantage of Hy-Fi is the possibility to increase the link data rate by aggregating both channels (cf. Section 4.1). There is even an advantage compared to classical RF SU-MIMO systems with spatial multiplexing. The main reason is that the Hy-Fi MIMO channel is significantly less correlated. In contrast, in RF we can observe spatial correction due to correlation between TX antennas as well as RX antennas. For example, a strong correlation on the TX side and also on RX side for short range links was observed in [33], which leads to significant reduction in the achieved MIMO capacity. In contrast, in Hy-Fi, we have no such correlation on the transmitter side, as the signals are transmitted on two fully orthogonal channels, i.e., optical LiFi and RF WiFi. On receiver side, there is no or very small correlation. The latter might be because of cross-talk between the two RX antenna ports or the closely-spaced antenna cables. Figure 9 shows the ergodic MIMO channel capacity for different configurations. The channel is assumed to be (spatially) correlated according to a Kronecker model but temporally uncorrelated. We used SU-MIMO with $N_t = N_r = 2$, with equal power allocation and a Rayleigh channel. Here, we see that Hy-Fi offers highest capacity due to no or just RX antenna correlation (see *VL+RF* in Figure 9). In classical RF SU-MIMO, the spatial correlation leads to worse channel conditions and lower capacity (see *RF* in Figure 9).

However, from a system-level point of view, aggregating the two channels on each link to increase the capacity is not beneficial in ultra-dense deployments like in the envisioned enterprise network (cf. Section 5). Here, it is sometimes beneficial to fully offload the traffic from RF WiFi to the LiFi channel in order to free up the valuable RF resources for

6. Note, according to the 802.11 standard the HO is initiated by the client STA itself.

7. Note, in our prototype this is achieved by executing a remote procedure call on the hostapd daemon of the new AP.

8. However, in our prototype the RF mixer in the STA needs to be reconfigured to make the RF WiFi channel switch not affecting the LiFi communication.

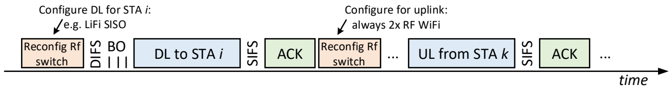

Figure 10. Hy-Fi AP operation: the RF switches need to be reconfigured before and after each DL transmission.

other STAs. This can be achieved by running Hy-Fi in *LiFi SISO* mode, which is reasonable for static or slowly moving STAs that are very close to an AP. Only fast moving or cell-edges STAs will utilize channel aggregation to achieve the required robustness against fading and shadowing.

Finally, note that our Hy-Fi approach currently supports only a bandwidth of 20 or 40 MHz, even so larger bandwidths are supported by newer generations of WiFi, e.g., 80 or even 160 MHz with 802.11ac. However, for such larger channel bandwidth WiFi needs to operate in the 5 GHz spectrum band, which would require RF mixers supporting 5 GHz making the system more costly. Moreover, there are additional practical constraints due to the used LiFi frontends. These are based on LEDs and PDs where intensity modulation limits the rate and the bandwidth. The Lifi frontend would support at most a 80 MHz channel (see Figure 12).

6.2 Support of Multiple Users

In Hy-Fi, multiple users, i.e., multiple STAs associated with the same AP, are supported as the Hy-Fi mode of operation can be changed on a per-packet basis. Therefore, for each outgoing DL packet the Hy-Fi AP needs to set the proper mode by re-configuring the RF switches just before the actual transmission takes place. Moreover, after transmission of data packet and possibly receiving the acknowledgment frame, the RF switches need to be configured again for possible reception in uplink, which is always 2x RF WiFi as LiFi is only used in DL. This operation is illustrated in Figure 10.

The reconfiguration of the RF switches happens via General Purpose Input/Output (GPIO). Note, that an embedded low-cost device like a Raspberry Pi is able to toggle GPIO within just 10 ns.[9] Moreover, changing the RF switch configuration takes only 150 ns of switching time.[10] Therefore, the total overhead of around 160 ns is negligible as it is two orders of magnitude smaller than the Short Interframe Space (SIFS) time used by WiFi.

6.3 Beyond Data Communications

The hybrid Hy-Fi approach also offers unique features beyond reliability and increase in data rate, such as enhanced security and improved ranging and positioning. The former is some type of physical security as an attacker has to eavesdrop on both the RF WiFi and the LiFi channel in case Hy-Fi is operating in multiplexing mode, which is not trivial because both media have very different propagation characteristics. Being able to intercept only the stream delivered over the RF channel is not sufficient. Hence, an attacker has to be very close to the victim in order to capture also the stream sent over the optical channel as light does not penetrate through walls. Finally, we also expect improvements in indoor ranging and positioning. This is due to the special characteristics of LiFi as it requires LoS for communication. In contrast, using RF the distance could be incorrectly estimated over a reflected path (NLOS), which is not the case with visible light. Protocols like the Fine Time Measurement (FTM) protocol for WiFi ranging defined in the IEEE 802.11-2016 standard can be directly used with Hy-Fi as several WiFi chipsets already have hardware support.

9. https://github.com/hzeller/rpi-gpio-dma-demo#direct-output-loop-to-gpio

10. https://www.analog.com/media/en/technical-documentation/data-sheets/HMC7992.pdf

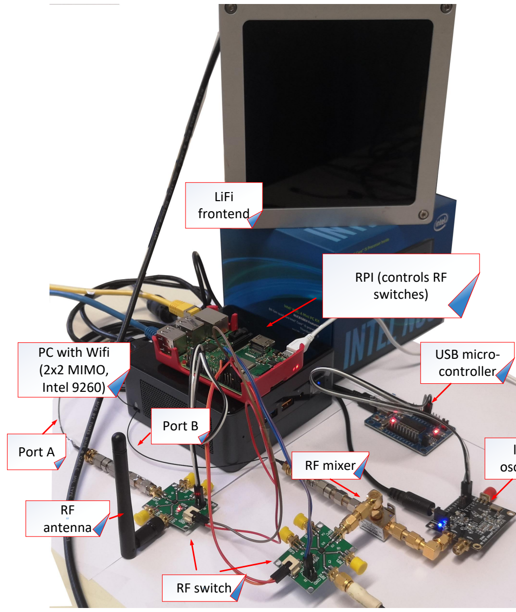

Figure 11. Hy-Fi prototype (AP+STA).

7 Hy-Fi Prototype

In this section, we present implementation details of our Hy-Fi prototype, which is shown in Figure 11.

7.1 Hardware Components

For our prototype, we use mini computers (x86 Intel NUC) equipped with Intel 9260 WiFi COTS chips. The Intel 9260 is an IEEE 802.11ac wave 2 compliant radio with 2x2 MIMO. A pair of such nodes was used during our experiments. The optical LiFi transmitter and receiver front-ends were designed and developed by Fraunhofer HHI in Berlin. The transmitter front-end consists of an LED driver and an infrared light-emitting diode (LED). The LED driver modulates the incoming voltage signal into the instantaneous optical power of the LED, which emits at a wavelength of 850 nm. As the optical power can be modulated between zero and some maximal value, the input signal cannot be negative and a proper biasing is required. To this end, the driver circuit adds a DC bias to the incoming AC signal. In order to support transmissions with higher-order MCS, the LED driver provides linear operation in a wide input signal range. This is especially important for the transmission of OFDM signals, which have high peak-to-average power ratios. The LiFi receiver front-end consists of highly sensitive,

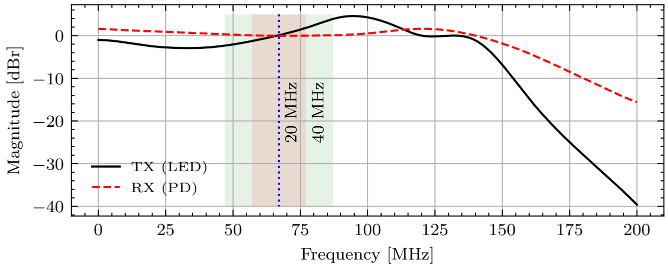

Figure 12. The frequency response of the LiFi front-end (TX & RX).

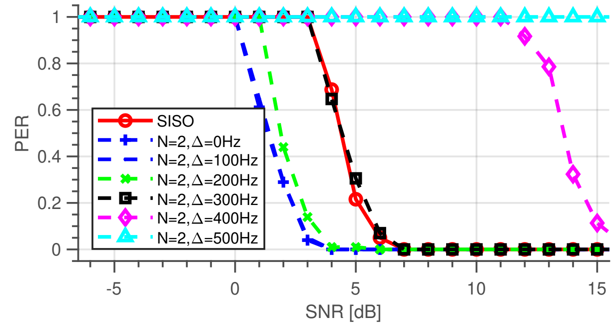

Figure 13. Impact of CFO on a SIMO 802.11 transmission when two same signals with different CFO are received at receiver (MCS=0).

broadband photo-diodes (PD), with concentrators glued onto. The PD converts the light intensity into the photo-current, which is converted into a voltage signal by a built-in linear transimpedance amplifier (TIA). LiFi front-ends operate close to DC and are broadband, i.e., the signal is rather frequency flat over the range from 25-225 MHz (cf. Figure 12). The lower frequencies up to a few hundred kHz are typically filtered out to avoid flickering. The available bandwidth, angular emission characteristic, and optical power varies for different realizations.

The components used for up/down conversion of the WiFi signals are the RF mixers (Mini-Circuits, ZX05-C60-S+), variable local oscillator (ADF4351) and USB controller (CY7C68013A) for control of VLO. Finally, each `Hy-Fi` node is equipped with two RF switches. At the transmitter side, they are needed to steer the WiFi signal from each WiFi NIC port to antenna (i.e., RF WiFi channel) or LiFi transceiver (i.e., LiFi channel), while at the receiver side they are used to select the proper communication link or to switch-off the RX port completely (by selection of the RF cable terminated with 30 dB attenuator instead of an RF antenna). Note that some WiFi cards (e.g., Intel 5300 card with support of 802.11n standard) provide an option to switch-off its RF ports by means of setting proper value in its registers. Unfortunately, we were not able to find any 802.11ac NIC providing the same feature.

7.2 Software

The proposed aggregation of the RF WiFi and LiFi channels at the physical layer is *transparent* to the higher layers of the communication protocol stack. Even the WiFi chip is not aware of the fact that the signal from one of its antenna ports is transmitted over a LiFi channel and not RF. Therefore, no modifications on the software side are needed except the control logic for the RF switches (i.e., the selection of the communication links) as well as the interference detection module described in Section 4.5. Both were implemented in Python language. For our prototype, we use standard Ubuntu 18.04 operating system with Linux kernel version of 5.5.1 and an unmodified WiFi NIC driver (i.e., Intel `iwlwifi`). In most of the experiments, we run both the transmitter and receiver in WiFi `injection` and `monitor` mode, respectively. At the transmitter side, we inject unicast 802.11n/ac frames with various MCSs and lengths, while the receiver sniffs frames using the `tcpdump` tool.

8 Simulations

In this section, we present results from simulations. First, in order to understand the level of clock stability needed by `Hy-Fi`, we run link-level simulations. Second, we analyzed the interference robustness of `Hy-Fi`. Third, we run system-level simulations in order to understand the gain from `Hy-Fi` for the total system performance.

8.1 Required Clock Stability

`Hy-Fi` uses commodity hardware components for down-conversion of the analog RF signal emitted by the WiFi chip so that it meets the specification of our analog LiFi front-ends (cf. Figure 2). On the receiver side, an up-conversion to the RF band is needed so that the signal can be processed by the WiFi chip. Unfortunately, the usage of inexpensive local oscillators (LO) creates distortions to the signal. Because different LOs have to be used by the RF mixers for LiFi on the transmitter and receiver side, we artificially introduce carrier frequency offset (CFO) into the signal. This complicates the signal reception, because in `Hy-Fi` the receiver combines the two received signals from RF WiFi and LiFi at the physical layer. As the two received signals have different CFOs, it appears as the two signals has been transmitted by two different transmitter nodes. Unfortunately, a standard 802.11n/ac receiver is not designed to work under such conditions.

We performed link-level simulations in Matlab using the WLAN toolbox to understand the performance of an 802.11 node receiving a signal being a mixture of two different CFO values. Here, a SIMO configuration was used, i.e., a node with single antenna was transmitting over an AWGN channel and that signal was received by a node with two antennas and combined using MRC technique. In addition, we artificially introduced CFO to the signal received by each antenna to simulate the impact of having imperfect LOs. As physical layer we used 802.11n HT transmission using BPSK (MCS 0) and 20 MHz channel.

Figure 13 shows the impact of different CFO configurations on the Packet Error Rate (PER) for different SNR values. We can conclude that as long as the CFO difference between the two received signals is small, i.e., <300 Hz, the impact on the PER is only minor. Hence, to make our system working

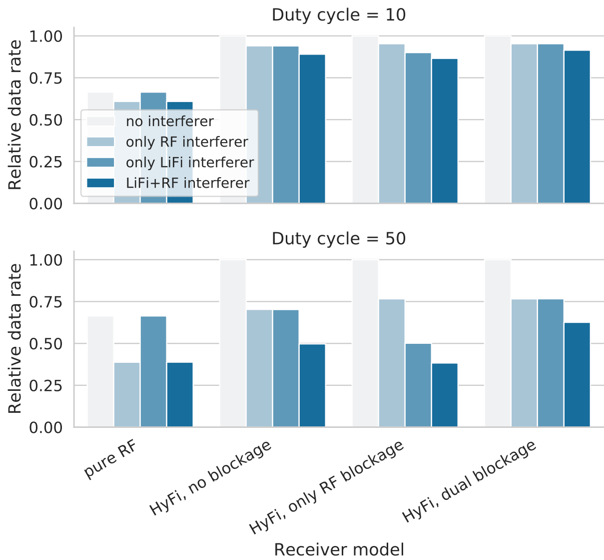

Figure 14. Relative data rate for different receiver and interferer models for the duty cycles 10%, and 50%.

LOs with a clock stability of at least 0.07 ppm at a carrier frequency of 2.4 GHz are required.[11]

8.2 Analyzing Interference Robustness

In order to analyze the interference robustness of `Hy-Fi` (see Section 4.5), we run simulations for `Hy-Fi` diversity mode. We implemented an environment with a single transmitter, two sources of interference on both LiFi and RF WiFi, and a single receiver node. As a baseline, we selected a *pure RF* configuration. Additionally, we implemented three variations of the `Hy-Fi` receiver: i) without interference handling (*HyFi, no blockage*), ii) with interference detection and handling as described in §4.5 (*HyFi, dual blockage*), and iii) with our interference detection but blocking only the RF port (*HyFi, only RF blockage*). We implemented two sources of periodic interference, one on the RF WiFi channel and one on the LiFi channel. We analyzed different duty cycles for the interferer nodes. During the active period, the interferer interfered with the data packets with a probability of 90%. The transmitter node run an open-loop MCS selection whereas the total number of MCS was five. As performance metric, we selected the relative data rate that was achieved for the different receiver models under different interferer configurations. The data rate is normalized with the highest achieved data rate for all receiver models.

Figure 14 shows the results for different interferer configurations, duty cycles 10% and 50%, and different types of receiver. It can be noted that the `Hy-Fi` receiver always achieves higher data rates than the baseline, i.e., *pure RF* receiver. The only exception occurs if only the LiFi channel is interfered with a very high duty cycle, i.e., >70%, since the *pure RF* receiver is not affected by this source of interference. However, even then `Hy-Fi` achieved almost the same data rates as the *pure RF* receiver "without" interference. For a duty cycle of 10%, the data rates are very similar for all `Hy-Fi` receivers. As the duty cycle increases, the *HyFi, dual blockage* receiver is more advantageous. For duty cycles higher than 10%, the *HyFi, dual blockage* receiver achieves higher data rates than that without blockage for all interferer models. For instance, for a duty cycle of 50%, the data rate of the *HyFi, dual blockage* receiver is significantly higher than that of the *HyFi, no blockage* receiver. The `Hy-Fi` variation that blocks the RF port only (*HyFi, only RF blockage*) mostly achieves even higher data rates than *HyFi, dual blockage* for interferer models where solely the RF channel is interfered. However, if only the LiFi channel or both channels are interfered, the data rate drops significantly. Since we cannot know in advance which channel will be interfered, the *HyFi, dual blockage* solution should be preferred. Nevertheless, the *HyFi, only RF blockage* receiver is a valuable alternative, if it is known that interference can occur on the RF channel only. Overall, the interference handling described in Section 4.5 seems beneficial. However, it should also be noted that even the `Hy-Fi` implementation without interference handling achieves very high data rates and is much more robust against interference than a receiver that uses only a single channel.

Table 2
System-level simulation parameters.

Parameter	Value
AP deployment	4 APs in grid, Figure 6
RF channels	4× 20 MHz
LiFi channel	same 20/80 MHz for all
Transmit power	20 dBm
Noise floor	-90 dBm
Cell radius	RF: $\sim 50\,m$, LiFi: 20 m
RF pathloss model	indoor picocell (based on COST 231)
LiFi pathloss model	infrared optical inside aircraft [32]
MIMO configuration	2×2
STAs placement	uniform
AP selection	by STAs based on strongest signal
No. STAs	$1 - 33$
No. seeds	1000

8.3 System-level Performance

In Section 5, we introduced `Hy-Fi` as the wireless access technology in next-generation enterprise networks, whereas in Section 6.1, we discussed the expected improvements on the system-level from such an architecture. A substantial gain can be achieved when fully offloading the network traffic from RF WiFi to LiFi in order to save RF radio resources, which can be used for STAs being in RF coverage only. Moreover, STAs at the LiFi's cell edge can be served in hybrid mode in order to improve their SNR and hence data rate. The most important parameters used in our network simulations are shown in Table 2. Note the difference in the channel bandwidth between RF WiFi and LiFi. In case a STA is served by `Hy-Fi`'s LiFi SISO mode, a wide channel with 80 MHz of spectrum becomes available. This is different when using the two hybrid modes of `Hy-Fi`, where the channel width needs to be the same for RF WiFi and LiFi, i.e., 20 MHz. As performance metric, we selected the sum data rate over all STAs. We compared classical MIMO RF WiFi (with spatial multiplexing) with our `Hy-Fi`. For the

11. Current commodity VLO hardware only offers 0.5 pm which is an order of magnitude too high. Therefore, in our experiments we used an ultra-low phase noise signal generator.

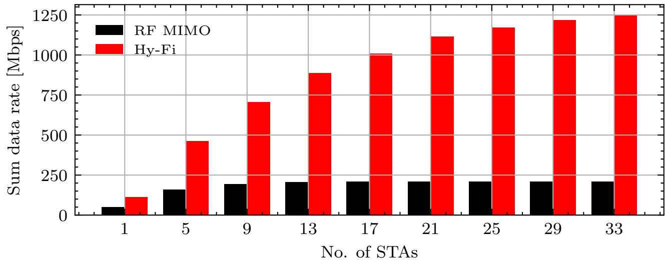

Figure 15. Comparing system-level performance of 2×2 MIMO RF WiFi with `Hy-Fi`.

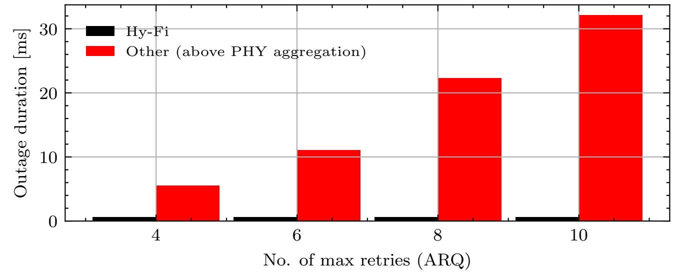

Figure 16. Outage duration in case of sudden blockage of the LiFi channel when operating in the multiplexing mode.

latter, for each STA placement the optimal `Hy-Fi` mode (cf. Section 4.4) was selected using the knowledge from a global view.

The results are shown in Figure 15. As expected with the increase in the number of STAs the sum data rate also increases. However, the saturation happens much earlier for MIMO RF WiFi at around 9 STAs. This is different to `Hy-Fi`, where the saturation happens only at around 30 STAs. The reason is the additional capacity offered by LiFi cells which can be exploited in case of sufficient high density of client STAs. With 33 STAs, the sum data rate of `Hy-Fi` is around 1.25 Gbps which is a factor of 6 higher than our baseline, which uses RF WiFi only.

8.4 Comparison with other Aggregation Techniques

In this section, we compare `Hy-Fi` with aggregation approaches operating above the PHY layer like aggregation on transport layer [12], network layer [13], and data link layer [14]. We aim to quantify the outage duration in case of sudden blockage of the LiFi channel when operating in the multiplexing mode, i.e., aggregating the two channels for the purpose of increased data rate. Here, we assume that both the RF and LiFi physical layers provide multi-rate capabilities and a MRR chain is being used. A major advantage of `Hy-Fi` is its aggregation-aware MRR chain (cf. Section 4.4) allowing us to optimize for low outage operation (cf. Figure 5). The MRR chain is configured in such a way that the first retransmission is performed in *Hy-Fi diversity* mode. This ensures that a packet previously sent in *Hy-Fi multiplex* mode is most likely to be received correctly even if it failed due to a blockage of the LiFi channel, as the same information is sent redundantly in *Hy-Fi diversity* mode. With all other aggregation techniques, operating above the PHY layer is not possible. Here, in case of a LiFi link blockage, the packet scheduled for transmission on the LiFi channel needs to finish the whole MRR chain before it can be discarded or retransmitted on the RF link. This leads to significant increase in outage duration, especially if both LiFi and RF WiFi use random access MAC protocol (i.e., CSMA/CA) with exponential backoff.

In the following, we assume that both LiFi and RF WiFi are using a PHY/MAC based on 802.11a. Here, we assume the worst-case situation, where the LiFi channel is blocked immediately after the MRR for an outgoing packet was computed. Figure 16 shows the resulting outage duration. We see that only for `Hy-Fi` the outage duration is very low at 0.6 ms and independent from the number $R_{\max}$ of maximum retransmissions used in MRR. With all other aggregation techniques, the outage duration grows exponentially which is due to the used exponential backoff. Already with only $R_{\max} = 4$, the outage duration of `Hy-Fi` is $9\times$ smaller. With $R_{\max} = 10$, the outage of other aggregation techniques is around 32 ms, which makes those approaches unsuitable for URLLC applications.

9 Experimental Evaluation

We also conducted indoor experiments using our `Hy-Fi` prototype. First, as a baseline, we analyzed and compared `Hy-Fi` in diversity mode with traditional LiFi/RF WiFi SISO systems in order to show the feasibility of our approach. Second, we show that the two channels and, hence, media, RF WiFi and LiFi, can be aggregated through MIMO multiplexing technique in order to double the data rate of the wireless link. Third, we analyze the robustness of `Hy-Fi` against signal blockage on the LiFi or RF WiFi channel. Fourth, we show that `Hy-Fi` is able to deal with strong interference on the RF channel. The following configuration was used, unless otherwise stated. The transmitter and receiver were run in frame injection and monitor mode, respectively. Moreover, we disabled Automatic Repeat-reQuest (ARQ), i.e., no retransmissions on data link layer. In order to remove the impact of imperfect LOs and hence CFO, the same VLO was used by the RF mixers of both the transmitter and receiver.

9.1 Channel Diversity

In this experiment, we compare `Hy-Fi` in diversity mode with traditional RF WiFi and LiFi systems, both in SISO mode. We tested different MCS from 802.11n HT, i.e., BPSK1/2 to 64-QAM 5/6, on a 20 MHz channel. As performance metric, we selected the Packet Success Ratio (PSR), which was calculated over 250 packets. The distance between the transmitter and receiver node was 2 m and the channel was LoS for both RF WiFi and LiFi. Moreover, we used attenuators to reduce the RF WiFi signal strength to have equal signal strength on both channels.

From the results shown in Figure 17, we see that for MCS ≤ 6 all three approaches have a similar PSR of around 1. However, `Hy-Fi` in diversity mode is beneficial for the two highest MCS, 6 and 7, where LiFi alone is unable to reach PSR of close to 1. The results confirm the feasibility of our hybrid approach. There is no noticeable delay introduced over the optical channel since all operations for LiFi communication

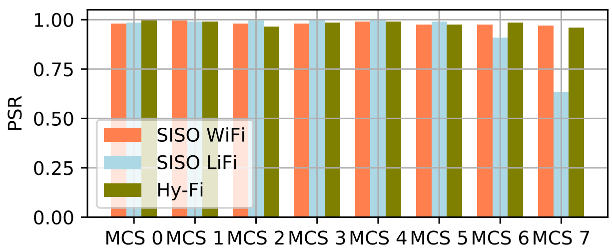

Figure 17. Comparing `Hy-Fi` in diversity mode with RF/LiFi SISO.

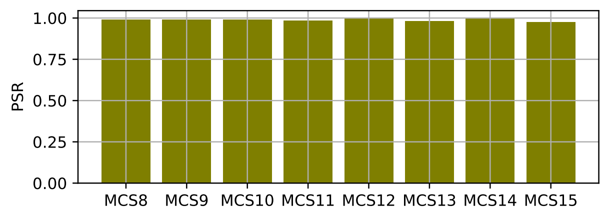

Figure 18. `Hy-Fi` in multiplex mode (802.11n HT).

like the up/down conversion or the modulation of the LED are performed in analog domain. Otherwise the combination of the two signals received over the two channels, RF WiFi and LiFi, would fail.

9.2 Channel Aggregation

With `Hy-Fi`, we can aggregate the two channels (media), RF WiFi and LiFi, on the physical layer to double the data rate of the wireless link. This becomes possible when both channels have the same average SNR. Therefore, we utilize the spatial multiplexing capabilities from SU-MIMO of 802.11. The experiment setup is the same as in the previous experiment (cf. Section 9.1) except that we tested only the MCS from 802.11n having two spatial-streams. Moreover, the channel bandwidth was doubled to 40 MHz and a short guard interval (SGI) was used.

Figure 18 shows the results. We see that packet transmissions even on the highest MCS are possible. At MCS $= 15$, two streams, each modulated with 64-QAM 5/6, are transmitted resulting in an effective data rate of almost 300 Mbps on the physical layer (Figure 19).

9.3 Influence of LiFi Shadowing

`Hy-Fi` uses channel diversity to achieve robustness against signal fading and blockage on either LiFi or RF. In the following experiment, we analyze the impact of signal blockage on the optical channel, i.e., LiFi. Therefore, the setup consists of a pair of `Hy-Fi` nodes, i.e., transmitter and receiver. During the experiment, the transmitter was sending packets at a constant rate of 10 Hz for the duration of 21 s. From time to time, we blocked the LiFi channel with a sheet of paper for some seconds. We compare `Hy-Fi` running in diversity mode with a baseline where only LiFi is used, i.e., LiFi SISO.

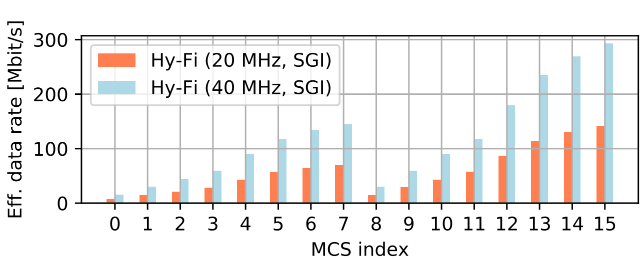

Figure 19. `Hy-Fi` effective data rate in PHY layer (802.11n).

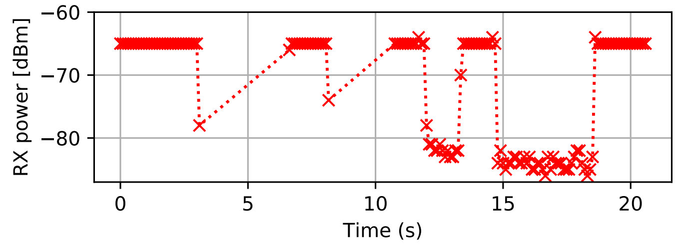

Figure 20. LiFi SISO link with temporary signal blockage.

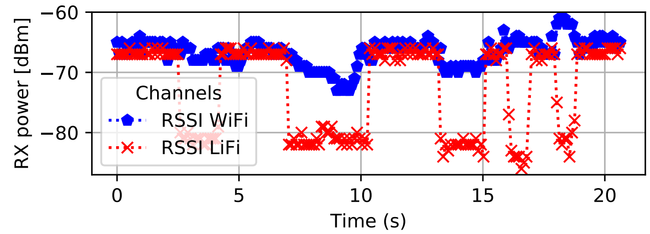

Figure 21. `Hy-Fi` link with temporary signal blockage.

Figure 20 shows the results for the baseline. We can observe longer periods of multiple seconds with no packet reception. This is because of the shadowing of the LiFi channel resulting in full communication outage for the first two regions and very low PSR for the other two regions. Note, that the shown receive power was obtained using the information provided by the WiFi chip.

In contrast, the performance of `Hy-Fi` is much better (Figure 21). For the whole experiment duration of 21 s not a single packet was lost, i.e., the link was never in communication outage. During periods of time with full blockage of the LiFi link a copy of the signal was received over the never blocked RF channel. Note the very low receive power on the LiFi channel corresponds to the noise floor.

9.4 Influence of RF Interference

`Hy-Fi` running in diversity mode provides excellent robustness against interference on both the optical and the radio channel. In environments with prolonged, i.e., non-sporadic interference, `Hy-Fi` performs an additional interference avoidance scheme (cf. Section 4.5), which is analyzed in the following experiment. The setup consists of two `Hy-Fi` nodes, i.e., transmitter and receiver, and an additional external jamming node. The external node was jamming the entire RF channel by transmitting a continuous stream of 802.11a packets from a Software Defined Radio with carrier-sensing disabled. It was placed close to `Hy-Fi` receiving node and far enough away from the `Hy-Fi` transmitter not

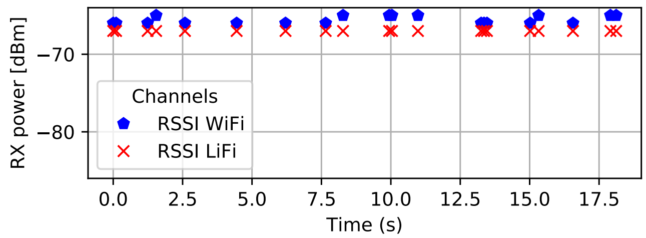

Figure 22. Hy-Fi under continuous jamming on the RF channel with disabled interference management (baseline).

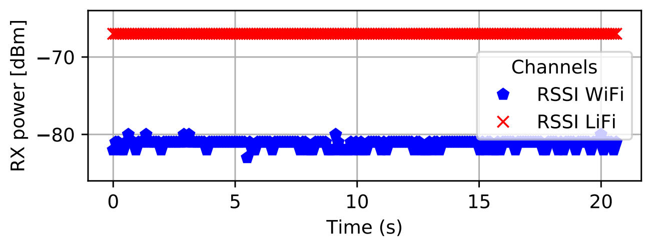

Figure 23. Hy-Fi under continuous jamming on the RF channel with proposed interference management scheme.

to trigger its carrier sensing mechanism, i.e., the RF channel is sensed idle on transmitter side but the interference is strong enough to corrupt the packets on the receiver side. The LiFi channel was not blocked (LoS). As baseline we selected Hy-Fi, however, with deactivated interference robustness (cf. Section 4.5).

Figure 22 shows the results for the baseline where the receive power for each received packet on both channels is depicted. During the experiment, the transmitter was sending packets with a rate of 10 Hz. From the results we see that the majority of packets was not received due to the RF jamming, i.e., visible through the large gaps between subsequent packets. Even so the signal received over the LiFi channel had a high SNR, the Hy-Fi receiver was not able to correctly receive the packets, resulting in substantial outage. This is because the MRC signal combining technique used on the receiver side is unaware of the fact that the RF signal is corrupted by interference. Hence, it combines the clean signal received over LiFi with the corrupted one over RF, resulting in signal which cannot be decoded correctly.

The situation substantially improves when enabling our proposed interference management scheme (cf. Figure 23). Not a single packet was lost in the course of the measurement even though the RF channel was fully jammed. This is because in environments with high and prolonged interference the signal received over the affected channel, here the RF channel, is excluded from reception. Hence, the Hy-Fi link runs effectively in LiFi SISO mode. Note that the detection takes some time depending on the selected parameters. Figure 23 shows the operation after the interference was detected.

10 Conclusions

This paper introduces Hy-Fi, the first system that aggregates wireless optical and radio frequency channels at the physical layer using inexpensive COTS hardware components. We made use of the existing MIMO capabilities of modern IEEE 802.11n/ac WiFi chips. A prototype of Hy-Fi was implemented and tested in a small indoor testbed. Results from our experiments confirm that our hybrid system is robust against LoS blockage in the optical channel and impacts like shadowing and fading in the RF channel due to the provided channel diversity . Hy-Fi can be operated in environments with prolonged external interference, either on the optical or the RF channel. Furthermore, under optimal conditions, the data rate can be doubled by multiplexing over both channels if both channels have high SNR. We also presented how Hy-Fi can be used as wireless access technology in next-generation indoor enterprise networks providing both high network capacity and seamless client mobility. While our current approach targets indoor usage, we believe it can be easily applied outdoors as well, e.g., for vehicular communications [34]. Finally, we believe it will accelerate the research and development of novel hybrid wireless solutions as it has low deployment costs and is extensible, e.g., towards MU-MIMO. As future work, we plan to perform extensive field tests to compare our approach with aggregation techniques performed on higher layers (e.g., data link and transport layer). Moreover, this would allow us to analyze the impact of Hy-Fi AP density on the overall network performance under real conditions.

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