Hy-Fi: Aggregation of LiFi and WiFi using MIMO in IEEE 802.11

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***Abstract*—We present `Hy-Fi`, a system which combines light fidelity (LiFi) and radio based on the WiFi physical layer waveform by using the MIMO features available in IEEE 802.11-compliant commodity chip sets. `Hy-Fi` is based on two key ideas. First, we use inexpensive COTS 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 to aggregate LiFi and radio signals at the physical layer. The system was implemented as a prototype and evaluated in a small testbed. Experimental results show that our approach offers robustness against signal blockage (Shadowing) and external interference in both, the optical and RF channels. Moreover, the two media (LiFi and WiFi) can be aggregated to double the capacity in the best case.**

***Index Terms*—Wireless Communication Networks, LiFi, WiFi, Visible Light Communication, Optical Wireless Communication, Link Aggregation**

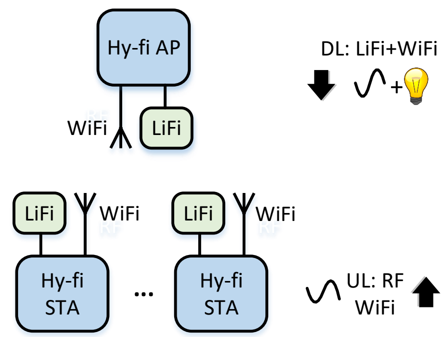

Figure 1. Aggregated LiFi and WiFi scenario.

I. Introduction

The rapid growth of wireless data traffic continues [1]. As the spectral efficiency of radio frequency (RF) technologies is already close to the limit, spectrum scarcity is looming on the horizon and researchers are looking for new solutions. A promising idea is to off-load some of the data traffic from RF bands to the optical spectrum using networked Optical Wireless Communication (OWC), which is also denoted as light fidelity (LiFi). LiFi has a huge potential as it has a wide spectrum of hundreds of THz available and inexpensive LEDs are everywhere for lighting, the infrastructure of which could be easily reused to densify wireless networks. In LiFi, data is transmitted through intensity modulation and direct detection (IM/DD) light. The transmitter uses a Light-Emitting Diode (LED) or laser while the receiver is a Photodiode (PD). LiFi has some significant drawbacks compared to radio. As propagation is mostly based on the line-of-sight (LOS) and usually more directional, LiFi suffers from sudden link blockage by shadowing the LOS. Hence, LiFi requires a clear line-of-sight (LoS) between transmitter and receiver. Another issue of LiFi is that the intense ambient light during daytime can saturate the PDs of receivers and thus degrade the performance [2]. But there are also major 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 small. Moreover, light is inherently robust against electromagnetic interference which is interesting for industrial and medical applications. To leverage these advantages and make LiFi successful, rendering links robust through some form of diversity, e,g. space, time, frequency, is key [3].

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RF communication exhibits different characteristics from LiFi, as radio propagation is mostly due to multi-paths. Due to coherent detection, path loss is lower in general. Consequently, radio offers more homogeneous coverage and is robust against shadowing and fully operational even in non-line-of-sight (NLoS) environments. As radio waves penetrate everywhere, WiFi suffers from adverse impact from interference, e.g. hidden terminals, and contention from co-located WiFi deployments. In unlicensed industrial, medical and scientific (ISM) bands, several RF technologies need to coexist (e.g. WiFi, Bluetooth, ZigBee) [4], what has an impact on the possible spectrum reuse and reduces the efficiency. Moreover, device mobility has a different impact on WiFi. While a LiFi link changes rather slowly, if the LOS is free, as the instantaneous signal power is proportional to the integral of the optical power over the detector surface, an RF WiFi link is subject to fast fading where the radio channel can fade randomly over a few centimeters passed during a few milliseconds [5].

Due to the complementary nature of WiFi and LiFi, the simultaneous usage of both technologies for data transmission is promising in order to achieve high reliability and capacity [6]. Such aggregation can be performed on different layers of the wireless and wired protocol stacks ranging from transport layer [7], network layer [8] and data link layer [9]. Note also that several standardization activities are ongoing for LiFi. 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 already came 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 this work, we show for the first time that the aggregation of both, LiFi and WiFi is possible at the physical layer (Fig. 1). This is achieved by utilizing the multiple-input multiple-output (MIMO) capabilities of standard commercially available off-the-shelf (COTS) 802.11 hardware. 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 links, 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 increase the data rate by sending different data signals over both channels simultaneously.

Contribution: In this paper we propose `Hy-Fi`, which stands for hybrid-fidelity. It combines LiFi and WiFi at the physical layer using MIMO. This allows the simultaneous usage of both media to either gain diversity and achieve robustness against shadowing and external interference or to increase the data rate by means of aggregation. We demonstrate how to achieve that by reusing the existing MIMO capabilities of modern COTS 802.11 RF hardware. Besides the COTS hardware, only open-source software is needed. To the best of our knowledge, this is the first approach to combine LiFi and WiFi on the physical layer using COTS hardware. Fig. 1 shows our envisioned scenario. Both the `Hy-Fi` APs and the `Hy-Fi` STAs are equipped with RF and LiFi front-ends. While both technologies can be bidirectional, LiFi will be used for the downlink (DL), while RF is used for both, DL and uplink (UL). This is meaningful as the data traffic demand is still dominated by the DL.

II. Background

As background, we given an overview of the multiple antenna techniques, i.e. spatial multiplexing and diversity used by the IEEE 802.11 standard.

A. MIMO – A Primer

Spatial Multiplexing (SM) enables the transmission of multiple independent and separately encoded data signals called spatial *streams* in parallel over a wireless channel. By spatial multiplexing, the space dimension is reused more than one time. If the transmitter is equipped with N_t antennas and the receiver has N_r antennas, the maximum spatial multiplexing order (the number of streams) equals $N_s = \min(N_t, N_r)$ [10]. This means that N_s streams can be transmitted in parallel, ideally leading to an N_s increase in spectral efficiency. In a practical system, the multiplexing gain is often limited by spatial correlation, which leads to rank-deficient MIMO channels meaning that some of the spatial streams may have weak channel gains. Direct-mapping [11] is the simplest MIMO technique where each antenna transmits its own data stream, which is used in 802.11n. In a rich scattering RF environment where m transmit streams are received by n antennas, each receive antenna will measure an independent linear combination of the m signals. This is decodable when $n \geq m$ so that there are more or equal measurements (n) than unknowns (m). A MIMO receiver may use simple techniques like zero-forcing to solve the linear equation for MIMO in real time. In 802.11n/ac WiFi, all streams use the same modulation, coding and Tx power.

Spatial Diversity (SD) distinguishes between transmit diversity, using multiple transmit antennas (multiple input single output or MISO channels) and receive diversity, using multiple receive antennas (single input multiple output or SIMO channels). MISO techniques can be used to transmit the same signal over multiple antennas to leverage the power from all transmitter antennas and enable transmit diversity likewise. SIMO techniques like Maximal Ratio Combining (MRC) are used to harness the useful power from all receive antennas by adding the signals in a coherent manner and realize receive diversity in this way [11]. Spatial diversity can be obtained on the transmit-side. Here the sending node can either select the best antenna to transmit or ensure that different signal copies combine coherently at the receiver side, which is physically interpreted as transmit beamforming [11]. However, transmit diversity requires channel knowledge at the transmitter side, hence typically relying on receiver feedback. In general, the receiver needs to estimate the channel (between each pair of TX and RX antennas). MRC reverts the effect of the channel, i.e. it delays signals from different antennas so that they have the same phase, weights them proportionally to their SNR, and adds them up. In contrast, the Selection Combining (SC) technique simply selects a signal with the highest Rx power.

B. MIMO in WiFi

MIMO is an integral part of WiFi since 2009 when the 802.11n amendment of the standard was published. Most 802.11n/ac NICs support both receive diversity (via MRC) and up to 4×4 spatial multiplexing (via directly mapped MIMO). Transmit diversity (i.e. beamforming) is an optional feature in 802.11n, however, it is mandatory in newer generations.

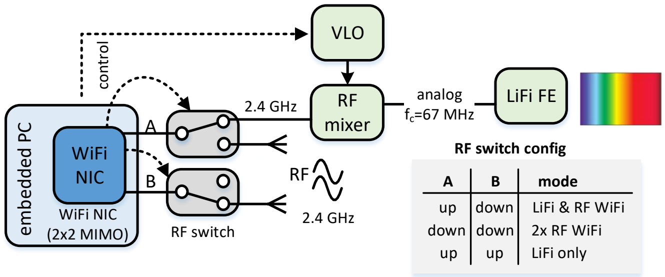

Figure 2. `Hy-Fi` architecture of aggregated LiFi and WiFi.

MIMO dimensions were extended by the 802.11ac amendment to 8×8. Moreover, since 802.11ac, multiple users can be served simultaneously using a technique called multi-user (MU)-MIMO also known as Space-Division Multiple Access (SDMA). With MU-MIMO it is possible to overcome the limitations of client stations having only a few antennas. It is intuitive that a single user receives only a single (or two polarization-multiplexed) spatial streams effectively while more streams can be multiplexed for multiple users at multiple locations. Here the transmitter, the AP, uses MIMO precoding to send different signals simultaneously towards multiple users, STAs, so that inter-user interference is minimized. A common beamforming technique is the Zero-Forcing that steers nulls into the directions of the interferers. MU-MIMO requires channel state information on both, transmitter and receiver side. Since 802.11ac precoding can also be used with single-user (SU)-MIMO.

III. Architecture

Here we propose to use the MIMO capabilities of COTS 802.11 hardware to aggregate LiFi and RF channels at the physical layer. Figure 2 shows the schematic diagram of our architecture. The `Hy-Fi` transceiver design contains the following components: Host PC, single WiFi network interface card (NIC) with two antenna ports (2x2 MIMO), variable local oscillator (VLO), RF mixer, two RF switches and LiFi optical front-end (LED, PD). Here the antenna port A of the NIC can be configured using the RF switch for transmission/reception either over LiFi or normal RF channel. In case of LiFi the 802.11 RF signal emitted (2.412 GHz, WiFi channel 1) 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 $f_c = 67$ MHz. For reception, the reverse operation is performed, i.e. the analog IF signal received by the LiFi front-end ($f_c = 67$ MHz) is up-converted using the RF mixer to the RF band and passed into port A. The second antenna port B can be configured to use either RF for transmission/reception or to disable the port (i.e., selection of terminated RF cable). Note that disabling a port is required in order to run the system in SISO mode. One option (i.e., RF WiFi only) is needed if the LOS link is blocked, for example when the user is out of the coverage area for LiFi or in case of intense ambient light resulting in saturation of the LiFi receiver. The other option (LiFi-only) is needed in case of strong interference in the RF channel, e.g. from WiFi or other RF technologies.

The table from Fig. 2 shows the three possible modes of operation using a 2x2 MIMO configuration of the COTS 802.11 modem. In the hybrid mode, where LiFi and RF WiFi are used simultaneously, the optical channel on port A becomes yet another medium for WiFi. This operation is fully transparent to the COTS WiFi chip which is unaware of the mode of operation. Note that the up-/down-conversion is required as COTS WiFi chipsets integrate a baseband processing unit and radio transceiver in a single system-on-chip (SoC) and expose only RF signal in 2.4 GHz or 5 GHz band. In a real modem, one would directly generate the LiFi waveform on its desired IF, e.g. by using an RF digital-to-analog converter (RF DAC). In order to make the system robust against signal blockage, shadowing and fading on both LiFi and RF WiFi links, we exploit the MIMO capabilities of the WiFi NIC. In particular, we can operate the system in diversity mode where the same signal is transmitted over both antenna ports A and B and hence received simultaneously over both RF WiFi and LiFi on the ports A and B in the receiving WiFi NIC. At the receiver side, the two signals are received and combined in the WiFi NIC using the Maximum Ratio Combining (MRC) technique (§ III-B). In situations where the SNR of both channels is high we use the MIMO capabilities to perform carrier aggregation as way to increase the data rate by simultaneously sending different signals over both media (§ III-A). In order to deal with strong external interference either on RF or LiFi we can use Selection Combining (SC) instead of MRC. This is achieved by dynamically switching off the interfered receive port A or B by using the two RF switches (§ III-C). The following subsections describe our architecture in more detail.

A. Carrier Aggregation

`Hy-Fi` uses MIMO spatial multiplexing technique of WiFi COTS hardware to perform aggregation of the LiFi and RF WiFi channels at the physical layer. With spatial multiplexing technique used in SU-MIMO the data rate (capacity) can be increased by a factor of $2\times$ by multiplexing over both channels. From the theoretical point of view we have a classical MIMO channel. Altough 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 down-converted to RF so that it can processed together with the signal received directly from RF. Our channel can be described as follows:

$$y_l[m] = h_l[m] + n_l[m], l = 1 \dots L \quad (1)$$

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 is:

$$h_1 = \text{visual light channel} \quad (2)$$

$$h_2 = \text{radio frequency channel} \quad (3)$$

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 follows:

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

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 nearly by $2\times$ when both channels have same $\overline{\gamma}$. This is larger as compared to a classical RF SU-MIMO system where spatial correlation exists due to coupling between TX antennas as well as RX antennas (cf. § IV-A). Note that in case of SU-MIMO we have an additional limitation - all spatial streams have to use the same MCS. 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 on LiFi. As with MU-MIMO each user can be served on different MCS there is no need to have similar SNR on each channel. For future we plan to extend `Hy-Fi` to support MU-MIMO.

B. Dealing with Shadowing & Fading

`Hy-Fi` uses MIMO in spatial diversity mode to achieve robustness against blockage of the LiFi signal and signal distortion of RF due to shadowing and small-scale fading in case of mobility. Therefore, the same signal (with same MCS) is sent over both channels, LiFi (port A) and RF (port B), and afterwards combined at the receiver side of a single receiver using Maximum Ratio Combining (MRC) technique. Whenever only a single channel, LiFi or RF, is blocked or deeply faded, the transmission is still successful.

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

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

where $\boldsymbol{h} := [h_1, \ldots, h_L]^t$ and $\boldsymbol{n}[m] := [n_1[m], \ldots, n_L[m]]^t$. Note that $|| \cdot ||$ represents the Euclidean norm. Setting $\mathbb{E}\{|n_l(t)|^2\} = \sigma^2$ and we get the instanteneous SNR at the l-th element (γ_l) to be [10]:

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

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 proability decreases signficantly. For `Hy-Fi` this is paramount especially as the SNR of the LiFi channel can drop quickly and deeply in case of blockage of LOS path, i.e. $\gamma_1 \approx 0$.

C. Dealing with Interference

The channel diversity enabled by MRC is not helpful in case of strong interference from either RF or from ambient light. The former can happen with non-WiFi devices sharing the RF spectrum, e.g. ZigBee, 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 the 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 is exposed to itense ambient light. `Hy-Fi` solves this problem by using Selection Combining (SC) as the first stage in addition to MRC (cf. RF switches in Fig. 2). Whenever the level of interference becomes too high, the affected channel, LiFi or RF, is disabled temporarily by switching off the corresponding antenna port on the RX side. Therefore the following heuristic for the detection of external interference is used on the receiver side, i.e. STA. Whenever the receiver node observes unusual high number of packet retransmissions, i.e. WiFi unicast frames with retry flag set, on a link with good signal quality, i.e. high RSSI, it assumes the channel to be interfered. Another heuristic could be the discrepancy between the used MCS of received packets and the receive signal quality. Too low MCS are an indication that the transmitter needs to use those to make packet transmission robust against interference which is in general not visible from the RSSI value. To avoid permanent blacklisting of a channel from time to time `Hy-Fi` is reactivating it to see whether the interference still exists. In summary: our key idea is to control which RX antenna ports and hence channels, RF or LiFi or both, are being used for signal reception. In the absence of external interference it is beneficial to combine the received signals from both LiFi and RF to achieve diversity for robustness against shadowing/fading or spatial multiplexing for data rate increase. In case of sporadic interference it beneficial to switch off the affected channel in order not to mangle the signal with interference. Note, that our prototype implementation is implemented fully in software *above* the WiFi chip. In theory this functionality can be realized easier by changing the signal processing chain. For example, the usage of the SDR-based WiFi implementation (e.g. [12]) would enable 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, as in this work we aim for a solution using COTS

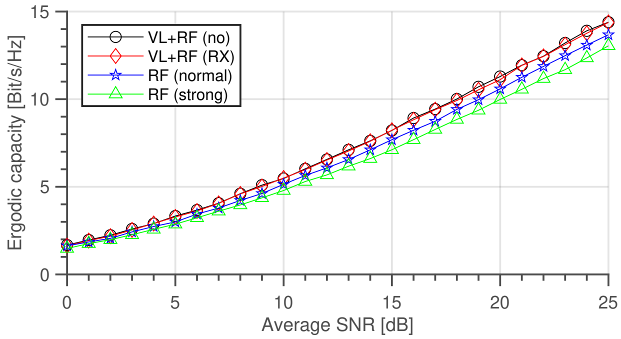

Figure 3. Ergodic MIMO channel capacity.

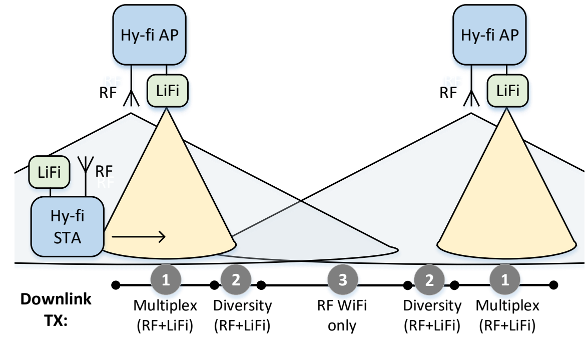

Figure 4. Hy−Fi in a mobile scenario.

WiFi hardware, we leave modification of the WiFi RX chain for the future work.

D. Carrier Sensing

Random access protocols like 802.11 use listen-before-talk, aka physical carrier sensing (PCS), mechanism for channel access. With Hy−Fi we have three options for PCS: i) sensing on RF only, ii) sensing on LiFi only or iii) simultaneously sensing on both channels, RF and LiFi. All the three options have their pros and cons. In order to be standard compliant to 802.11 using 2.4/5 GHz bands we have to perform sensing on RF leaving us with options i) or iii). However, sensing on LiFi might not be needed. First, as we consider to use LiFi for DL only there is only competition in the LiFi channel access among the fixed installed APs. Second, as the propagation characteristics of RF are better than that of LiFi, the region covered by RF sensing is larger than that of LiFi. We finally decided for option i) as we use LiFi only in the DL (Fig. 1) making collisions on LiFi channel unlikely as the installation of Hy−Fi-APs can be well planed. Note, 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.

IV. Discussion

In the following section we discuss the relevant characteristics of the proposed Hy−Fi architecture.

A. Improved Capacity

An important advantage of Hy−Fi is the data rate increase due to the aggregated usage of both channels (cf. Section III-A). There is a gain compared to classical RF SU-MIMO where spatial multiplexing is used. The main reason is that the Hy−Fi channel is much less correlated. In RF we can observe spatial correction due to correlation between TX antennas as well as RX antennas. In [13] a strong correlation on the TX side and also on RX side for short range links was observed which leads to significant reduction in the MIMO capacity. In contrast in Hy−Fi, we have no correlation on the TX side, as the signals are transmitted on two fully orthogonal channels, LiFi and RF. On RX 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 3 analyzes the ergodic MIMO channel capacity. The channel is assumed to be (spatially) correlated according to a Kronecker model but temporally uncorrelated. SU-MIMO with $N_t = N_r = 2$, with equal power allocation and a Rayleigh channel is used. Here we see that Hy−Fi offers highest capacity due to no or just RX antenna correlation. In classical RF SU-MIMO the spatial correlation leads to worse channel conditions and lower capacity.

B. Seamless Mobility

Our solution is fully transparent and remains 802.11 standard-compliant, i.e. no special functions are needed to deal with how a Hy−Fi-STA attaches to the network, how mobility is supported as a device moves from one BSS to another BSS and between networks, and how multiple users are accommodated. However, maintaining continuous connectivity for mobile STAs is a challenge which is solved as follows. We utilize the different modes of operation available in Hy−Fi. From the perspective of the DL transmission we can distinguish between three different regions (Figure 4). In region 1, the STA is covered by both RF WiFi and LiFi. Here the two channels LiFi and RF are aggregated so that the total data rate can be increased. In region 2, the STA is at the LiFi cell edge. Here diversity mode is used to achieve robustness as the signal quality might drop significantly. Finally, in region 3 the STA is fully out of LiFi coverage so that only the RF channel is used. Note, that the switching between the Hy−Fi modes can be part of a rate control algorithm residing inside the AP.

C. Additional Features

Our proposed hybrid system also offers new interesting features beyound reliability and increase in data rate, such as enhanced security and improved indoor positioning. The former is some type of physical layer security as an attacker has to eavesdrop on both the RF and the LiFi channel in case Hy−Fi is operating in multiplexing mode. Being able to decode only one stream is useless so that an attacker has to be very close in order to capture the visible light communication as it does not penetrate through walls. Finally, we also expect improvements in indoor positioning. This is due to the characteristics of LiFi

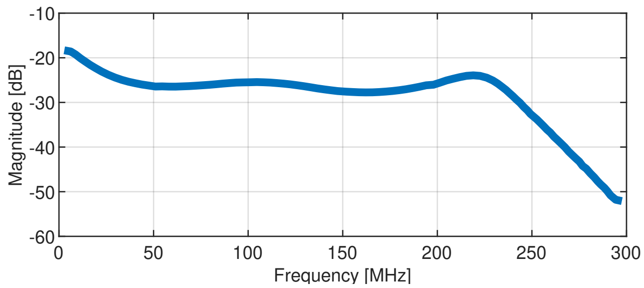

Figure 5. The magnitude response of the LiFi transmitter front-end

as it requires LOS for communication, i.e. in 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 offer hardware support.

V. Implementation Details

This section contains implementation details of our `Hy-Fi` prototype shown in Figure 6.

A. Hardware

As experimentation platform, we use mini computers (Intel NUC) equipped with Intel 9260 WiFi COTS NICs. The Intel 9260 is an IEEE 802.11ac wave 2 compliant radio with 2x2 MIMO. A pair of such nodes was used during the experiments. The LiFi transmitter and receiver front-ends are 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, 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 (Fig. 5). The lower frequencies up to a few hundred kHZ are typically filtered 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 used to steer the WiFi signal from each NIC port to antenna (i.e., RF channel) or VLC 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 (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.

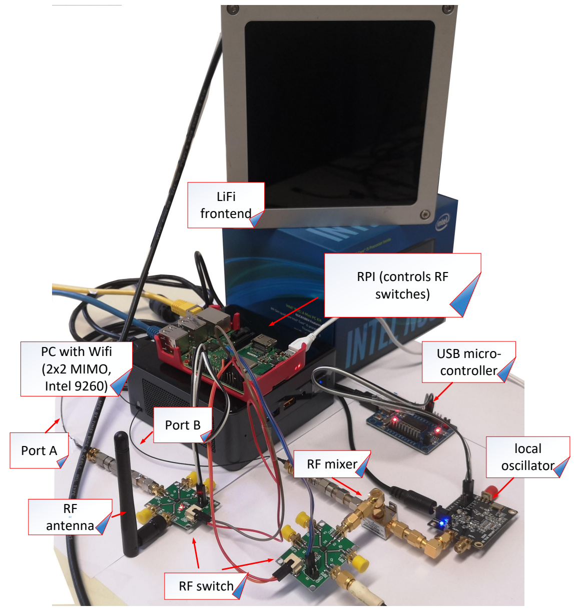

Figure 6. `Hy-Fi` prototype.

B. Software

The proposed low-level integration of RF and LiFi channels (i.e., in the PHY layer) is *transparent* to the higher layers of the protocol stack. Note that even the WiFi NIC is not aware of the fact that signal from one of its RF ports is transmitted over LiFi channel. Therefore, no modifications to the software are needed. 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 `monitor` mode. 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. The control logic for RF switches (i.e., the selection of the communication links) as well as the interference detection module described in Section III-C were implemented in Python.

VI. Link-level Simulations

As described in Section III (Figure 2), `Hy-Fi` uses COTS hardware components for down-conversion of the signal emitted by the WiFi NIC so that it meets the requirements of the analog

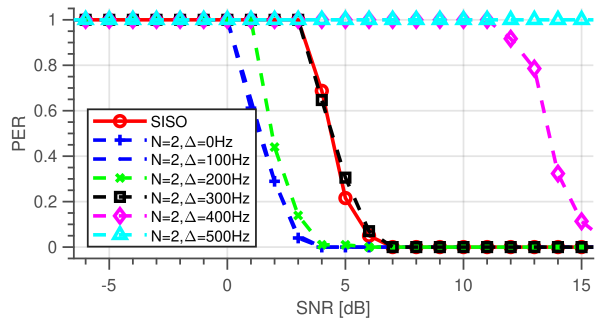

Figure 7. Impact of CFO on 802.11 transmission when two same signals with different CFO are received at receiver (MCS=0).

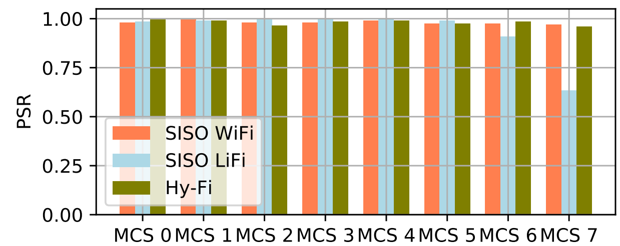

Figure 8. Comparing SISO RF WiFi and SISO LiFi with `Hy-Fi`.

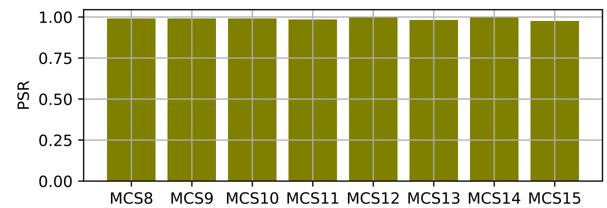

Figure 9. `Hy-Fi` in multiplexing mode (802.11n HT).

LiFi front-end. In the reverse direction, an up-conversion is needed as well. Unfortunately, the usage of inexpensive COTS local oscillators (LO) creates distortions to the signal. As the RF mixers used for LiFi on the TX and RX side use different LOs we artificially introduces carrier frequency offset (CFO) in the signal. The receiver which combines the two received signals from RF and LiFi has to deal with that. As the two received signals have different CFOs it appears as the signals were transmitted by two different transmitters. Unfortunately, a standard 802.11 receiver was not designed to work with signals having different CFO values.

In this section we perform link-level simulations in order to understand the performance of an 802.11 node receiving a signal being a mixture of two different CFO values. For our simulations we use Matlab and WLAN toolbox. A single node was transmitting over an AWGN channel and received by a node with two antennas and combined using MRC. However, we artificially introduced CFO into the signal received on each antenna to simulate the impact of imperfect LOs. A typical 802.11n HT transmission using BPSK (MCS 0) was used.

The results are shown in Figure 7. We can see the impact is minor as long as the CFO difference between the two received signals is small, i.e., <300 Hz. This means that the LOs need a clock stability of at least 0.07 ppm at a carrier frequency of 2.4 GHz to make our system working[1].

VII. Experimental Evaluation

In this section, we present results from experiments using our `Hy-Fi` prototype. First, as a baseline, we compare the link performance of our `Hy-Fi` approach with RF and LiFi in SISO configuration. Second, we show that the two channels, RF and LiFi, can be multiplexed with each other for the purpose of increased data rate. Third, we present results showing the robustness of `Hy-Fi` against shadowing due to signal blockage and fading on both the LiFi and the RF channel. Fourth, we show the performance in a scenario with strong interference on the RF channel. All experiments are performed in a small indoor testbed. We run both the transmitter and receiver in monitor mode and ARQ was disabled, i.e., no retransmissions on data link layer. To remove the impact of imperfect LOs and hence CFO we connected the RF mixers of both the transmitter and receiver node to the same VLO.

A. Basic Performance

The focus is to compare our approach with traditional SISO RF and SISO LiFi. `Hy-Fi` was configured in spatial diversity mode. Different MCS from 802.11n HT were tested, i.e., BPSK1/2 to 64-QAM 5/6, using a 20 MHz channel. The Packet Success Ratio (PSR) was computed over 250 packets. The distance between the two nodes was 2 m and we used attenuators to reduce the RF signal strength. From Figure 8 we see that up-to MCS6 all three approaches have a similar PSR of around 1. The spatial diversity used by `Hy-Fi` helps for transmission of highest MCS, 6 and 7, where LiFi alone is unable to reach PSR of close to 1.

B. Channel Aggregation

In `Hy-Fi` the two channels, RF and LiFi, can be aggregated in order to increase the data rate. This is achieved by using spatial multiplexing from 802.11 SU-MIMO. The configuration is as in previous experiment (§ VII-A) except that we tested MCS from 802.11n having two spatial-streams. Moreover, a 40 MHz channel and short guard interval (SGI) was used.

The results are depicted in Figure 9. We see that even MCS15 is possible which transmits two streams each with 64-QAM 5/6 resulting in a data rate of 300 Mbps.

C. Impact of Shadowing

`Hy-Fi` uses channel diversity to achieve robustness against signal blockage on either LiFi or RF. In this experiment we transmitted packets with an interval of 0.1 s for the duration of 21 s. Occasionally we blocked the LiFi channel for some seconds with a sheet of paper. We compare `Hy-Fi` running

[1]Note, current COTS VLO hardware only offers 0.5 pm which is an order of magnitude too high. Hence, a ultra-low phase noise signal generator has to be used.

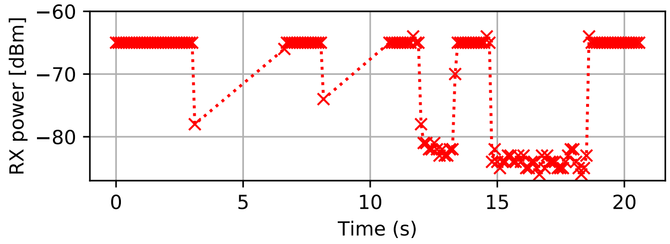

Figure 10. SISO-LiFi link with temporary signal blockage.

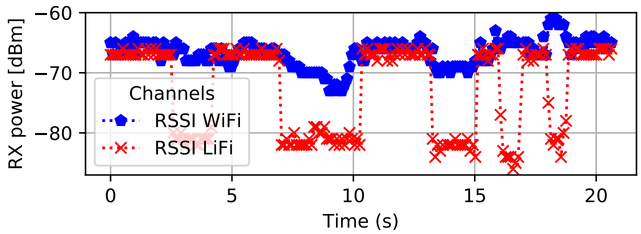

Figure 11. `Hy-Fi` link with temporary signal blockage.

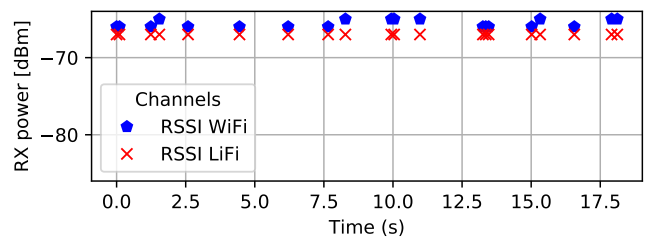

Figure 12. `Hy-Fi` under continuous RF signal jamming with deactivated interference management. Gaps indicate missing packets due to jamming.

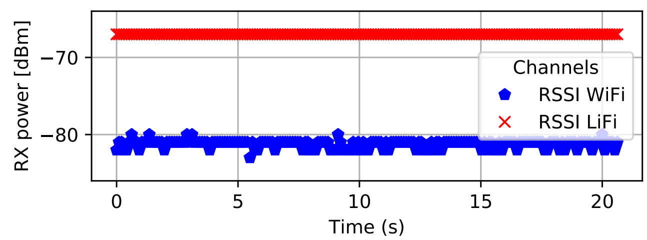

Figure 13. `Hy-Fi` under continuous RF signal jamming with activated interference management. No packet losses were observed.

in spatial diversity mode with the baseline where only SISO LiFi is used.

The results for SISO-LiFi are shown in Figure 10. We see communication outage for multiple seconds due to shadowing on LiFi channel resulting in PSR ≈ 0 for the first two regions and very low PSR for the other regions. Note, that the RX power was obtained using the information provided by the WiFi driver.

The results for `Hy-Fi` are shown in Figure 11. We see dramatic improvement. Not a single packet was lost, i.e., PSR $=$ 1, even at times where the LiFi link was fully blocked by some obstacle as the signal was received over the RF channel.

D. Impact of RF Interference

Being robust against RF interference is important as WiFi uses the unlicensed spectrum. Sources of interference could be from same technology, e.g. co-located hidden terminal WiFi, or different one, e.g. 802.15.4 (Zigbee). In this experiment we jam the RF channel by transmitting a continuous stream of 802.11a packets from a Software Defined Radio with carrier-sensing disabled. The jammer was installed close to RX node and far enough from TX node so that not to trigger carrier sensing, i.e. channel is sensed idle on TX side and packets are transmitted and possibly corrupted on RX side. The LiFi channel was clear (LOS). As baseline we used `Hy-Fi`, however, with deactivated interference robustness (cf. § III-C). The results are shown in Figure 12. We see dramatic outage due to RF jamming, i.e. only a few packets are correctly received, even so the signal over the LiFi channel had high SNR. This is because the MRC is combining the desired signal received over LiFi with the signal corrupted by interference from the RF.

When enabling interference management in `Hy-Fi`, the performance is dramatically improved (Figure 13). We observe no packet losses even as the RF channel is fully interfered. Such situation is dynamically detected by our approach and the interfered path, here the RF path, is disabled from reception. Hence only the signal received over the LiFi channel is used.

VIII. Related Work

An extensive survey on hybrid LiFi and WiFi networks is presented by Wu et al. [6]. The aggregation of VLC and RF can be performed on different layer of the protocol stack ranging from transport layer over the network layer, data link layer to the physical layer. `Hy-Fi` is the first work showing that an aggregation is feasible at the physical layer. Liu et al. [7] proposed an aggregation on transport layer by using a decoupled TCP extension protocol for a LiFi/RF hybrid network. Shao et al. [8] proposed to aggregate WiFi with LiFi by leveraging the network bonding technique of the Linux operating system. A similar approach was proposed later by Li et al. [14]. Pratama et al. [9] suggest to aggregates both LiFi and RF on the level of the data link (MAC) layer using a hybrid packet scheduler which allows to schedule outbound packets for transmission over LiFi or RF communication. Different scheduling policies were proposed, e.g. optimize throughput, and a prototype using COTS WiFi hardware was presented. Ayyash et al. [5] proposed practical framework termed LiFi HetNet where for both WiFi and LiFi technologies can coexist. Diversity techniques for LiFi were discussed like the usage of MIMO and multiple links at same time. In our previous work we showed that the standard RF WiFi signal can be transmitted over LiFi media, i.e. optical channel, using COTS hardware components [15]. Moreover, in [16] we proposed a full MIMO-LiFi transceiver system based on COTS hardware as well.

Standardization in IEEE 802.11bb

The IEEE P802.11bb project aims to integrate support for LiFi into the WiFi standard. The group decided to support three physical layer modes: *i)* LC Common mode, *ii)* LC Optimized mode and *iii)* LC HE mode. The LC Common mode is compatible with the OFDM PHY specified in 802.11a. However, the center frequency for up-conversion is selected so that the resulting real-valued baseband signal can be used to modulate an LED. The LC optimized mode describes a new PHY layer, based on adaptive OFDM, which is especially suitable for light communication. The LC HE mode allows to use the new PHY layer that was defined in 802.11ax, in the baseband. Supporting existing silicon aids to ease adoption with decent performance, as the development of new silicon is expensive, typically ranging in the order of multiple 10s to 100 Million USD. The common mode will be used as a compatibility mode, e.g. for transmission of management and control frames. Furthermore, the integration of radio and LiFi was discussed in IEEE P802.11bb and it was proposed to integrate support for LiFi in the Fast Session Transfer mechanism [17]. As a result, a STA session could switch between 2.4, 5, 60 GHz radio and LiFi. In contrast, `Hy-Fi` is more powerful as it enables the simultaneous usage of both RF and LiFi.

IX. Conclusions

With `Hy-Fi` we presented an approach to aggregate LiFi with RF WiFi at the physical layer using inexpensive COTS hardware components. Therefore, we utilized the existing MIMO capabilities of modern 802.11 WiFi NICs. `Hy-Fi` was prototypically implemented and evaluated in small testbed. Experimental results show that our approach offers channel diversity making it robust to signal blockage in LiFi and/or shadowing and fading in RF. Moreover, our system is robust to external interference either on RF or LiFi. Finally, when having a clear channel on RF and LiFi the capacity can be doubled by multiplexing over both channels. This concept can also easily be applied for outdoor usage, e.g., in the context of vehicular communications [18]. Our platform is inexpensive and easy to extend e.g. to use MU-MIMO, hence, we believe it will encourage and speed up further research and development in the area of hybrid LiFi/WiFi research.

As future work, we plan to compare our approach under real conditions with aggregation techniques performed on higher layers (e.g., data link layer) in order to understand the cases where it performs better but also those with worse performance. Moreover, we would like to perform system-wide analysis in order to understand the impact of `Hy-Fi` AP density on the overall performance. Finally, we plan an exhaustive analysis of our interference mitigation technique in environments with real sources of interference (WiFi and non-WiFi) and mobility.

Acknowledgement

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