Real-Time Software-Reconfigurable Hybrid In-House Access with OFDM-NOMA

Jin Shi, Yang Hong, Rui Deng, Jing He, and Lian-Kuan Chen

***Abstract*—In this paper, a real-time software-reconfigurable orthogonal frequency division multiplexing based non-orthogonal multiple access (OFDM-NOMA) scheme with dynamic power allocation is proposed and experimentally demonstrated for hybrid in-house access over single-mode fiber (SMF) and visible light communication (VLC). Such hybrid access can provide both wired and wireless transmission, which can accommodate the increasingly heterogeneous in-home network and realize seamless coverage. The fiber link is used to provide high-speed and stable transmission for a wired user whilst the VLC link can support flexible and secured wireless access. With the help of power-domain multiplexing based NOMA, the power ratio between both the fiber user and the VLC user can be adjusted in a software-reconfigurable manner, which can satisfy various user demands and also ensure user fairness. Experimental results validate that an aggregate data rate of 1.84 Gbit/s can be achieved in a 1-GSa/s hybrid access system. In addition, it is demonstrated that the power ratio between the fiber user and the VLC user can be adjusted in real-time, facilitating the optimal overall system bit error rate (BER) performance and hence the balanced user fairness. The proposed real-time software-reconfigurable dynamic power allocation scheme for OFDM-NOMA is a promising scheme for the future heterogeneous in-house network, as it allows the flexible power allocation according to users' demands and enables better user fairness.**

***Index Terms*—Hybrid in-house access, FPGA real-time, SMF, VLC, OFDM, NOMA.**

I. Introduction

To satisfy high-speed accesses for in-home end-users, the future access network requires the delivery of various multimedia and real-time services for both fixed and mobile users through an integrated wired and wireless network. The ever-increasing demand for high data rate makes fiber to the home (FTTH) an attractive solution [1]. It is known that the standard single-mode fiber (SMF) can provide ultra-large bandwidth and capacity, but it has very limited mobility and hence cannot realize seamless coverage [2]. To address the issue and support a wide range of user access, wireless communication is an indispensable technology for the in-house network. Recently, visible light communication (VLC) is emerging as an attractive technology, which has many advantages over the traditional radio-frequency (RF) communication [3]–[5]. Compared to the RF communication, it can employ existing light-emitting diodes (LEDs) for simultaneous illumination and data transmission, which significantly reduces the deployment cost. Moreover, it has the advantages of low power consumption, simple installation, more spectrum availability and immunity to electromagnetic interference [6]. Therefore, it can be applied in some places such as hospitals and airplanes, where RF communication is prohibited. While LEDs have much lower modulation bandwidth, which limits the achievable data rate, laser diodes (LDs) are more promising for realizing beyond gigabit data transmission, hence are more favorable to be adopted in hybrid in-house accesses. By delivering the wired and wireless services simultaneously through a single fiber, it can make full use of the existing optical communication network and thus significantly reduce the deployment cost.

To support the simultaneous transmission of wired and wireless services and meanwhile avoid interference between different services, fiber wired service and wireless service are generally allocated with different wavelengths (WDM) [7, 8] or different frequencies (FDM) [9] in most prior works. In [8], a scheme wherein hybrid fiber-wired and fiber-wireless data were carried by different wavelengths of optical carriers was proposed to provide broadband-integrated services for fixed and wireless users. Though it can double the system capacity, thanks to the parallel transmission by using multiple optical carriers, it is required to generate multiple optical carriers at the transmitter and thereby needs optical filters at the receiver, resulting in increased system complexity and higher cost. In [9], a FDM based hybrid access protocol was utilized in high-speed VLC access networks. The whole bandwidth is divided into multiple sub-bands to support hybrid user access, where each sub-band serves a specific wired or wireless user/cell. The scheme is realized by digital signal processing (DSP) and does not require extra optical components. Thus, it is simple and promising for the hybrid access network. However, the total system capacity is limited by the whole system bandwidth. Moreover, with the increase in the number of end-users, each sub-band is allocated with much less signal bandwidth since the usable system bandwidth is fixed and limited. As a result, the achievable data rate of each end-user has to be reduced. In addition, user fairness is difficult to be guaranteed due to the difference of propagation paths for fixed and mobile users as

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well as the severe frequency fading in the VLC system.

Recently, power-domain multiplexing based non-orthogonal multiple access (NOMA) has been gaining tremendous interests from both industry and academia [10]–[17]. It uses an additional dimension, i.e., the power domain, to multiplex more users and the signals are overlapped in time and frequency domain simultaneously. It has been investigated in both fiber based optical access network [10-14] and VLC systems [15-17] that NOMA can achieve enhanced spectral efficiency and allow more user connectivity in comparison with OFDM. Due to the user overlapping in the power domain, multiple users sharing the same time-frequency resources are capable of transmitting signals simultaneously with different power weights, leading to superior user fairness and better system controllability. In our prior work [17], real-time NOMA has been demonstrated in multi-user VLC system only, without considering fiber link and its potential for hybrid in-house access. To provide another feasible route in hybrid in-house access with higher throughput and better flexibility, it is highly desirable to employ NOMA in the fiber-wired and fiber-VLC system.

In this paper, a real-time flexible and software-reconfigurable hybrid in-house access system over SMF and VLC with OFDM-NOMA is proposed and experimentally demonstrated. Thanks to the use of NOMA decoding, the wired and wireless signals can be simultaneously transmitted through single SMF, at the end of which the signals are detected by a fiber user for the fixed access and by a VLC access point (VAP) for the subsequent wireless access, respectively. The power ratio between wired and wireless access users is software-reconfigurable and thus can flexibly satisfy various user demands, e.g., quality of service (QoS). Experimental results show that the fiber based wired user and fiber-VLC based wireless user can achieve nearly identical performance at the optimal power ratios for different received optical power (ROP). The proposed hybrid access over SMF and VLC with OFDM-NOMA demonstrates its promising potential for heterogeneous in-house network as it guarantees enhanced user fairness, ubiquitous coverage, and more user connectivity.

II. HYBRID IN-HOUSE ACCESS WITH NOMA

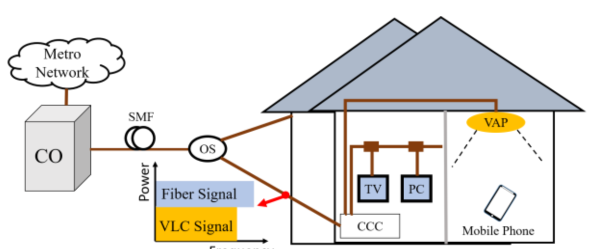

Fig. 1. The schematic diagram of hybrid In-House access over SMF and VLC

Fig. 1 shows the schematic diagram of the hybrid in-house access over SMF and VLC enabled by the power-domain NOMA. We consider that the fiber interface is generally connected to fixed devices, e.g., PC and high definition TV. By integrating VLC in the in-house access system, it is possible to provide seamless coverage to mobile users. Compared to the fixed users with fiber transmission, mobile users with fiber-VLC transmission suffer extra free space path loss and severe bandwidth limitation, which leads to poorer signal-to-noise ratios (SNRs). By using traditional multiple access schemes, fixed users will achieve better performance than VLC-based mobile users, resulting in unfair user access. To address this issue, NOMA, as a promising MA technique, has been adopted, as it can multiplex multiple users with different SNRs in the power-domain while sharing the same time-frequency resources. Note that as shown in Fig. 1, the bandwidth of the fiber user and VLC user does not necessarily to be the same. By using flexible power-and-subcarrier allocation scheme [17], the achievable data rates of the two users can be maximized independently. Moreover, NOMA has better compatibility with the VLC system than the RF system. It is because that NOMA requires channel state information (CSI) to assist the functionalities of user de-multiplexing, decoding order, and power allocation. Whereas, obtaining CSI is a major challenge in RF systems but not in VLC systems[16]. It is because user terminals are usually stable and the channel is deterministic in VLC system. In this proposed hybrid in-house access system, the fiber users with high SNRs have an extra margin of power budget and thus are allocated with less power. Whereas, VLC users with low SNRs require more power to achieve comparable performance with fiber users. Enabled by the NOMA, the fiber users and VLC users can be firstly transmitted at the same time via the SMF. Their power weights are flexibly adjusted at the central office (CO) according to the user demand. Because our demonstration is considered in the physical layer, after demultiplexing, the two data stream can also be sent to any local area network (LAN) and shall be compatible to the network protocols defined in the network layer in the system.

III. EXPERIMENTAL SETUP

Fig. 2 illustrates the experimental setup of the real-time software-reconfigurable hybrid in-house access via SMF and VLC with OFDM-NOMA signals. A Xilinx FPGA evaluation board (VC707) and a 4DSP daughter card (FMC110) that provides dual-channel analog-to-digital converters (ADCs) and dual-channel digital-to-analog converters (DACs) are used to implement all the DSPs of both TX and RX in the OFDM-NOMA system. The two independent pseudo-random binary sequences (PRBSs) are firstly mapped into quadrature phase shift keying (QPSK) symbols. Then the mapping symbols are scaled according to the power allocation ratio, which is software-configurable by using the Chipscope. After symbol overlapping with different power allocations for the two users, the symbols are modulated on 60 subcarriers (index 2–61) of each OFDM symbol. The direct current (DC) subcarrier (index is 0), 1-st, 62-nd, and 63-rd subcarriers are set to zero to mitigate the DC blocking induced fading at low frequencies and bandwidth limitation induced fading at high frequencies. Generally, in order to obtain real-valued signals for the 128-point inverse fast Fourier transform (IFFT), Hermitian extension is required. In this paper, in order to reduce the complexity of real-time processing, the other half of subcarriers are set to zero, which is referred to as Zero-tailed scheme [17]. After the IFFT operation, although the obtained signal is

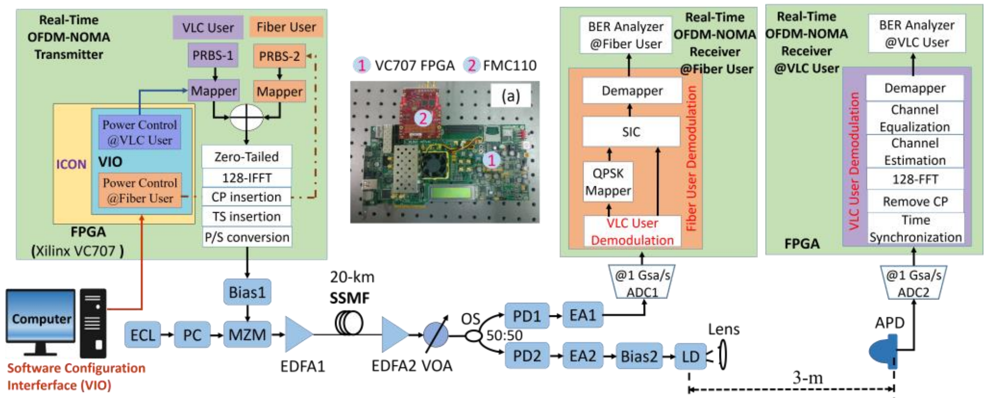

Fig. 2. Diagram of the real-time hybrid in-house access via SMF and VLC with OFDM-NOMA. Inset is the FPGA and FMC110 with dual-channel ADCs/DACs.

complex-valued, the real component of the generated complex signal is identical to the real-valued signal generated by the Hermitian extension, except that the amplitude is halved. Therefore, only the real component is used for subsequent processing whlist the image component is discarded. After that, the cyclic prefix (CP) is inserted to each OFDM symbol. Then, two training symbols are appended to the beginning of each frame for symbol synchronization and channel estimation. The obtained digital signal is further converted into an analog signal by using a 12-bit, 1-GSa/s DAC. The analog signal (Vpp is around 0.6 V) combined with a bias voltage of 2.1 V via a bias tee is used to drive the Mach-Zehnder modulator (MZM) for optical signal generation. The Vpi of the MZM is 4 V. An external cavity laser (ECL) with a wavelength of 1550 nm and a linewidth of 100 kHz is used as the optical carrier. A polarization controller (PC) is utilized at the input of the MZM to align the polarization state. Subsequently, the optical launch power is optimized to 6.5 dBm through an erbium-doped fiber amplifier (EDFA1).

After 20-km length of standard SMF (SSMF) transmission, the received optical signal is then fed into EDFA2. A variable optical attenuator (VOA) is used to adjust the received optical power of the fiber user. The optical signal is evenly split by using a 1 x 2 optical splitter (OS). One of the split optical signals is directly detected by a photodiode (PD1). After amplified by an electrical amplifier (EA1), the resulting electrical signal is sampled by a 10-bit 1 GSa/s ADC. The other optical signal is detected by PD2 and further amplified by EA2. The model of EA2 is *Mini Circuits* ZX60-14012L, whose bandwidth and gain are 14GHz and 12 dB, respectively. The emitted power from the LD is 40 mw and the sensitivity of the APD is ~5 A/W at 450 nm. After combining with an optimized bias voltage of 4.85 V, the electrical signal is used to re-modulate a 450-nm blue laser diode (LD). A biconvex lens is placed in front of the LD to collimate the light. After 3-m free-space transmission, an avalanche photodetector (APD) is used to convert the optical signal to the electrical signal for further ADC at a sampling rate of 1 GSa/s.

To recover the information of the fiber user from the overlapped digital signal, it is required to firstly decode the information of the VLC user, so as to eliminate the multi-user interference (MUI). The MUI elimination at the fiber user is realized by a SIC operation, which subtracts the decoded the VLC user's information from the overlapped signal. In contrast, for the demodulation of VLC user which has a large power allocation, it can be directly decoded by treating the fiber user's interference as noise. It is worth noting that the focus of this work is to investigate the performance of the downstream transmission in the in-house hybrid fiber and VLC access. For the realization of the upstream, solutions like using a different wavelength [9] can be readily adopted in our proposed system.

III. Experimental Results and Discussions

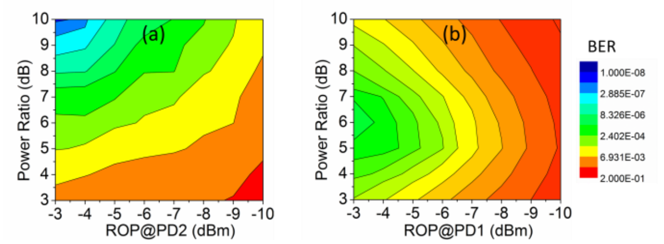

Fig. 3. BER maps with regard to ROP and power ratio for (a) VLC user and (b) fiber user.

Figs. 3(a-b) illustrate the real-time measured bit error rate (BER) with regard to ROP and power ratio for the VLC user and the fiber user, respectively. In the case when the power ratio is fixed, the BERs of both users gradually increase with the decrease in ROP, which results from the reduced signal power. In the case when the ROP is fixed, it can be seen from Fig. 3(a) that the BER performance of the VLC user is improved when increasing the power ratio, i.e., the VLC user is allocated with more power. This is because more power results in higher achievable SNR for the VLC user. In contrast, for the BER distribution of the fiber user, as shown in Fig. 3(b), the optimal BER lies in the intermediate power ratio range. Increasing the power allocation to the fiber user (i.e., the power ratio is reduced) firstly improves the BER performance. Then the BER performance becomes deteriorated when allocating more power to the fiber user. This is due to the error propagation from the decoding of the VLC user. As aforementioned, the fiber user needs to firstly demodulate the information of the VLC user for MUI elimination. When the fiber user receives a very large power, the VLC user can only obtain a small power since the total power is fixed. As a result, the data of the VLC user will be decode incorrectly. This decoding error will propagate to the fiber user even though it has a relatively large power allocation. Therefore, to ensure the fairness between the two users, i.e., to maintain comparable BER performance, an appropriate power ratio is required. As aforementioned, in our proposed real-time system, the power ratio can be flexibly adjusted in a software-reconfigurable manner by using the Chipscope [17], [18]. We note that the power ratio, i.e., power allocation, is updated in real-time via VIO IPcore without stopping or restarting the whole system, and each reconfiguration of the power ratio takes around 0.8 µs.

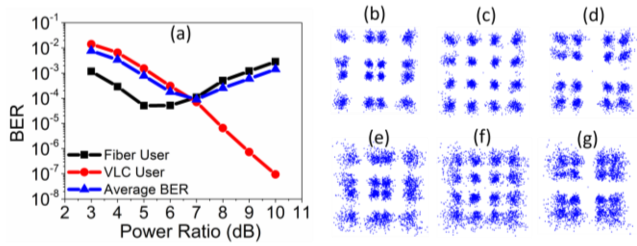

Fig. 4. (a) BER versus of power ratio for fiber user and VLC user and the corresponding average BER at the ROP of -4 dBm. (b-g) are the corresponding constellation diagrams at the power ratios of 3, 6, and 9 dB for fiber user and VLC user, respectively.

To further investigate the optimal power ratio of the system, we evaluate the BER performance versus power ratio of both users as well as their average BER as illustrated in Fig. 4(a). The average BER is taken as the metric in our experiment to identify the optimal power ratio. It can be found that at a power ratio of 7 dB, the minimum average BER can be obtained, which corresponds to the optimal performance of the overall hybrid access system. Meanwhile, compared to other power ratios, at the power ratio of 7 dB, the fiber user and the VLC user can achieve the best fairness, i.e., BERs of 1.1×10^{-4} and 7.1×10^{-5}, are achieved for the two users, respectively. Fig. 4(b)–(g) show the corresponding constellations at power ratios of 3, 6, and 9 dB for the fiber user and the VLC user, respectively. It can be seen that for the VLC user, a higher power ratio leads to clearer boundaries of the four quadrants, resulting in better BER performance. While our experimental demonstration focused on the case in which only one VLC user exists, it is also worth noting that feedback CSI should be required to accommodate the simultaneous support for multiple users. However, increasing the number of access user in the hybrid NOMA system might result in a lower order of modulation format and/or lower modulation bandwidth in the system to ensure acceptable transmission performance.

V. Conclusion

In this letter, a hybrid in-house access over SMF and VLC with OFDM-NOMA is proposed and experimentally demonstrated in real-time. Thanks to the real-time reconfigurable power allocation, the VLC user, who exhibits severe frequency fading due to limited system bandwidth, can achieve a comparable BER performance with the fiber user, leading to optimized fairness. Moreover, since the power ratio can be software-reconfigurable in real-time, it is feasible to ensure different user demands in practical scenarios. The real-time demonstration of such SMF and VLC hybrid system with OFDM-NOMA is a very promising solution for the heterogeneous in-house network.

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