Coexistence of WiFi and LiFi towards 5G: Concepts, Opportunities, and Challenges

Moussa Ayyash, Hany Elgala, Abdallah Khreishah, Volker Jungnickel, Thomas Little, Sihua Shao, Michael Rahaim, Dominic Schulz, Jonas Hilt, Ronald Freund

***Abstract* — Smart phones, tablets, and the rise of the Internet of things are driving an insatiable demand for wireless capacity. This demand requires networking and Internet infrastructures to evolve to meet the needs of current and future multimedia applications. Wireless heterogeneous networks (HetNets) will play an important role towards the goal of using a diverse spectrum to provide high quality-of-service (QoS), especially in indoor environments where most data are consumed. An additional tier in the wireless HetNets concept is envisioned using indoor gigabit small-cells (SCs) to offer additional wireless capacity where it is needed the most. The use of light as a new mobile access medium is considered promising. In this article, we describe the general characteristics of WiFi and visible light communications (VLC) (or LiFi) and demonstrate a practical framework for both technologies to coexist. We explore the existing research activity in this area and articulate current and future research challenges based on our experience in building a proof-of-concept prototype VLC HetNet.**

Index Terms—Heterogeneous wireless network, Optical Wireless (OW), Visible Light Communications (VLC), MAC Layer, Li+WiFi

1. Introduction

The number of multimedia-capable and Internet-connected mobile devices is rapidly increasing. Watching HD streaming videos and accessing cloud-based services are the main user activities consuming data capacity now, and in the near future. Most of this data consumption occurs indoors, and increasingly, in spaces such as aircraft and other vehicles. This high demand for video and cloud-based data is expected to grow and is a strong motivator for the adoption of new spectrum including the use of optical wireless media. In terms of network topology, heterogeneous networks (HetNets) will play an important role in integrating a diverse spectrum to provide high quality-of-service (QoS), especially in indoor environments where there is localized infrastructure supporting short-range directional wireless access. We envision multi-tier HetNets that utilize a combination of macrocells providing broad lower-rate services, RF small-cells (RF-SCs) providing improved coverage at locations occupied by users, and LiFi small cells that provide additional capacity through use of the optical spectrum. Indoor RF-SCs, including licensed femtocells and/or unlicensed WiFi access points (APs), deployed under coverage of macrocells, can take over the connection when moving indoors. In this manner, WiFi enables traffic offloading from these capacity-stressed licensed macrocells or RF-SCs [1]. According to Cisco Visual Networking Index (*Global Mobile Data Traffic Forecast Update (2014-2019)*), about 50% of this traffic is expected to be offloaded to WiFi in 2016.

a. The state of wireless and mobile communications

Except in dense WiFi networks, where contention is possible, high signal strength in indoor access WiFi networks is an indicator of a fast and reliable WiFi connection. In a building with different types of walls and other obstructions, and as distance increases, the WiFi signal strength is attenuated. Accordingly, if in one room the signal strength is much attenuated, WiFi users experience poor connectivity and slow speed. A slow connectivity is also caused by high interference signal from neighboring WiFi APs and/or multiple active users sharing the limited bandwidth of a WiFi AP.

The WiFi evolution considers higher frequencies with new spectrum to reach multi-Gbps peak data rates (WiGig (www.wigig.com) at 60 GHz) indoors and to serve multiple users in parallel. While the IEEE 802.11ad (WiGig) wireless local area network (WLAN) implementations are beginning to reach the consumer market in tri-band products (2.4 GHz, 5 GHz, and 60 GHz), optical wireless communications (OWC) systems, and specifically based on the visible light communications (VLC) technology, also called LiFi, offer dual-functionality to transmit data on the intensity of optical sources (lighting concurrent with data communication) [2]. Reference [3] describes an integrated architecture for 5G mobile networks that includes SCs and enhanced WiFi as the main scaling factor for wireless capacity. However, and especially in dense deployments, the sustainable performance of WiFi can be reduced, as the carrier sense multiple access with collision avoidance (CSMA/CA) allows only one link to be active at once as it is somewhat random, demand-driven and not always fair. For example, the first user detecting an unused channel is allowed to start transmission, independent of its channel quality. However, if there is a demand from another user having a better channel at some later time, such demand cannot be served because the first link is not interrupted due to the CSMA/CA rule that the next transmission starts only if the channel is free. This situation is exacerbated with the increased adoption of IP video streaming which both increases data utilization and the need for continuous gap-free data delivery.

Therefore, concurrent multiuser transmission is used in WiFi as a next step, similar to the enabled multiuser multiple-input and multiple-output (MU-MIMO) in Long-Term Evolution (LTE). In dense environments, cooperative beamforming between adjacent APs is also considered [2].

However, a big standardization effort is needed to define such a new mode of simultaneous transmissions to multiple users that must remain backwards-compatible. Moreover, there are complexity limits with larger numbers of antennas. It is well known that the complexity of linear MIMO equalizers scales with N3, where N is the number of antennas; while optimal scheduling problems, in particular between the beams of multiple adjacent APs, are NP-hard. Recently, a practical solution has been developed, see [3] and references therein. Due to these standardization, scalability, and complexity issues, and due to the increasing demand for WiFi, scalability is limited and there is rationale to consider other wireless media.

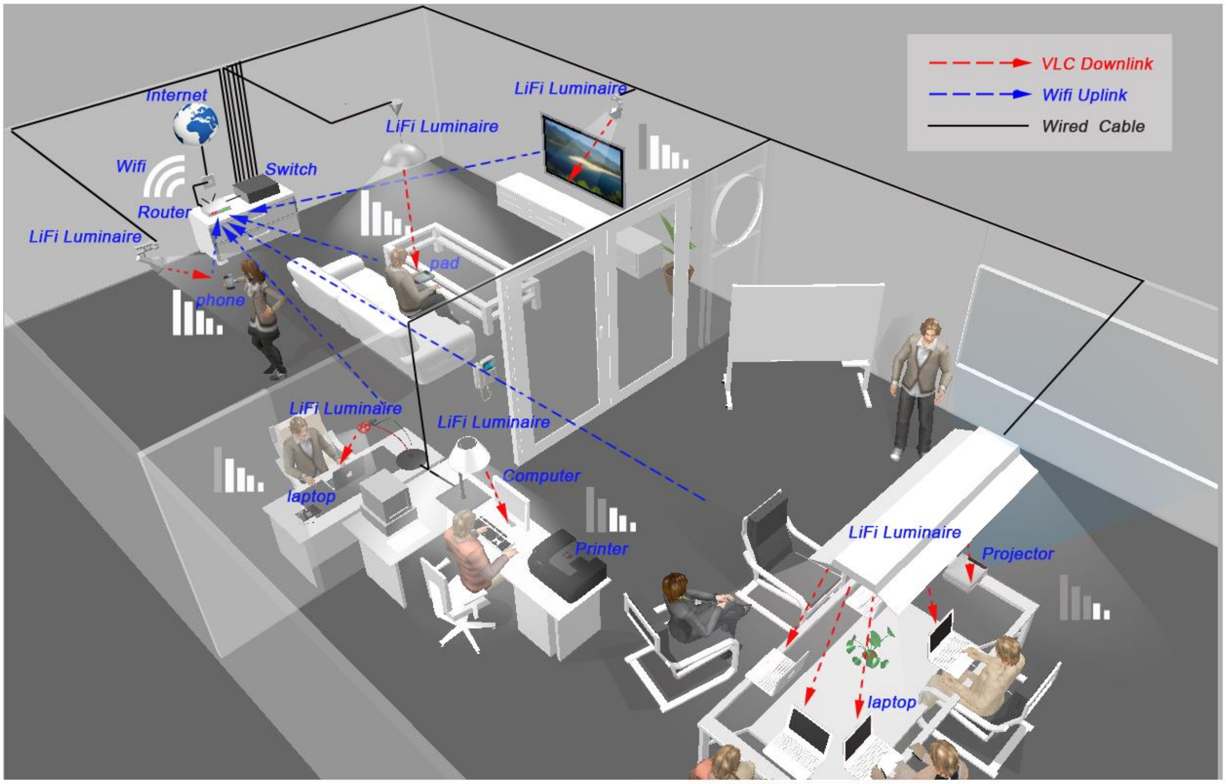

Figure 1 The proposed Li+WiFi HetNet.

b. Getting to high capacity and density

Given the aforementioned challenges, we envision an additional tier in the wireless HetNets comprised of indoor gigabit SCs to offer additional wireless capacity where it is needed the most. LiFi-enabled indoor luminaries (lights) can be modeled as optical SCs (O-SCs) in a HetNet, where a three-layer network formed by RF macrocells, RF-SCs, and O-SCs are deployed. Offloading traffic to the most localized and directional LiFi is expected to enhance the performance of a single WiFi AP or across multiple WiFi APs. Besides high-speed traffic offloading with seamless connectivity, the proposed Li+WiFi system also offers new interesting features, such as enhanced security in O-SC and improved indoor positioning [4]. Security enhancement is an obvious result because visible light doesn't penetrate through walls and improved indoor positioning is a result of a better resolution in a centimeter range compared to other RF based technologies including WiFi.

Operators say that 80% of the mobile traffic occurs indoors; therefore, the combination of LiFi and WiFi has great potential to be breakthrough technologies in future HetNets including the next generation (5G) mobile telecommunications systems [5] [6]. To our knowledge, the state-of-the-art research is currently focused on enhancing the performance of each of the technologies alone while there is a clear need for reliable WiFi and LiFi coexistence solutions [7].

As shown in Figure 1, stationary and quasi-stationary mobile users are provided data access via LiFi-enabled light fixtures, or luminaires, in lighting parlance. This approach can alleviate congestion and free RF resources to serve users being more mobile or outside the LiFi coverage area. More highly mobile users will be able to fall back on the broader coverage of the WiFi network.

In the Li+WiFi network, user devices (UDs) must be LiFi-enabled. To evaluate the development of LiFi-enabled devices, the evolution of cellular network can be used for reference. Evolving from 1G to 4G, the mobile technologies blaze the trail for marketing more advanced and more expensive user devices. By delivering richer mobile broadband experiences, LiFi-enabled smartphones offer manufactures considerable profitability. Actually, most modern smartphones already support multiple radios and protocols. Even though the Li+WiFi network is likely to be asymmetric with LiFi as the downlink; this should free up WiFi system capacity to accommodate any future growth in traffic-uploading. This is due to challenges to overcoming upwards link alignment, glare, and energy consumption factors in the handset. But despite the asymmetry, the benefits of the added VLC channel are significant. Our work, and this article, are motivated by promising preliminary results using high-throughput LiFi transceivers utilized in a proof-of-concept hybrid Li+WiFi demonstration [8][9].

2. A HetNet Vision Incorporating VLC and Current Research Activities

Central issues in designing and managing a Li+WiFi network include dealing with how a UD attaches to the network, how mobility is supported as a device moves from cell to cell and between networks, and how multiple users are accommodated. Ultimately, the combined performance of the LiFi and WiFi networks aggregate to match available capacity to where devices need it. In this section, we describe the proposed Li+WiFi network with a goal to provide seamless connectivity and to optimally distribute resources among users. Also, we consider some of the most relevant recent works addressing present challenges.

a. Multiple Links and Aggregation:

Because luminaires are distributed throughout our living spaces, it is often possible to "see" more than one at a time. This fact can be exploited using a multichannel receiver. Imagine that the lighting infrastructure is potentially enabling MIMO transmission using a multi-detector UD. However, reconciling the optimal link or links involving one or more luminaires in the presence of multiple UDs is challenging. This is more difficult with mobility and changing UD orientation. Therefore, reliable sensing of the optical link quality between individual luminaires within the UD receiver's field-of-view is critical and requires careful investigation. Previous work assumes that the transmitter exactly knows the channel state information (CSI) from each UD in the room. Accurate CSI may be relatively easier to obtain in a static condition, however, and from a practical perspective in the case of user mobility, obtaining the CSI is an estimation problem which cannot be error free. Therefore, it is important to understand the effect of the channel estimation error on the system throughput in a multiuser environment for time-varying single-input single-output (SISO) and MIMO wireless channels.

On the other hand, connecting a user on multiple optical channels might be an advantage, whenever the application needs high throughput. Since multiple LiFi-enabled luminaires are in each room, both, modulation frequency sub-bands and wavelengths can be reused at some distance to achieve a higher throughput. Carrier and channel aggregation, similar to LTE-Advanced, is one key approach to increase the overall transmission bandwidth. Performing aggregation in the Li+WiFi network needs efficient methods to split the overall traffic between the RF and optical links, to handle packet drops on the individual links, and to reorder the packets, accordingly. These issues clearly affect higher layer protocols such as the transmission control protocol (TCP). In scenarios, in which a user can be attached to a single luminaire (SISO configuration) or simultaneously to multiple luminaires (MIMO configuration), three possible access scenarios can be considered. Initially, the user is served by a single luminaire providing the highest link quality. Multiple luminaires serving a single user are allowed to satisfy the user's requirements. However, and to insure fairness and minimum QoS among multiple users, especially in a dense user scenario, the number of luminaires serving a single user can be managed depending on resource availability.

MIMO research activities on LiFi typically consider the single-user MIMO (SU-MIMO) scenario where a single multi-detector UD is communicating with a single multi-chip LED based luminaire or multiple distributed luminaires. The limited spatial separation between the different detectors on a single UD suggests pointing them to different directions to maximize receiver diversity. As shown in Figure 2, for a SU-MIMO, the singular value decomposition (SVD) based MIMO transmission can ideally support parallel links and maximize the capacity while satisfying illumination constraints [10]. However, SU-MIMO LiFi channels can be highly correlated [10], which needs a joint rank- and rate-adaptation to the channel similar to RF wireless links.

As already mentioned, optical beamforming, for example, through a spatial light modulator (SLM), can provide enhanced spatial separation and channel quality [11]. In a MU-MIMO, the rank of the MIMO channel can be improved depending on the selected user locations. Multiple luminaires can send signals to multi-detector UDs to serve these multiple users in parallel. Note that such parallel transmission are common in RF communications, while multiple-source, multiple-access schemes, also including multi-color luminaires are only just emerging from early lab prototypes. In a practical indoor VLC deployment, target illumination and color quality must be maintained while maximizing the system throughput and supporting each user's mobility.

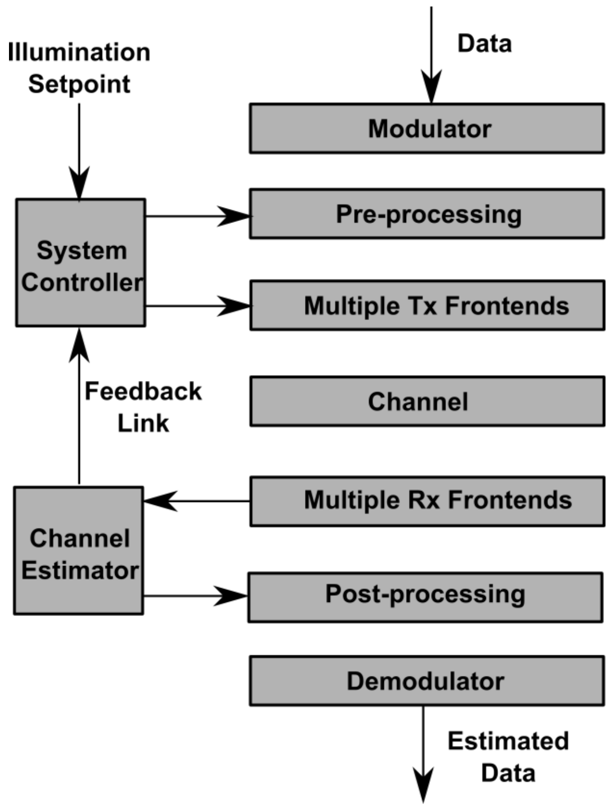

Figure 2 The SU-SVD-MIMO concept can be used to avoid interference and maintain target illumination. The SVD is used to decompose the MIMO channel into parallel SISO sub-channels, enabling interference-free spatial multiplexing. At the receiver, and after estimating the channel, the information needed to pre- and post-process the signals at the transmitter and receiver, respectively, and the illumination set point (room brightness) is available on the feedback channel, to extract the parallel SISO channels.

b. Mobility and Medium Access:

The issue of overlapping and non-overlapping coverage of the distributed luminaires needs careful examination. It has a major impact on the handover not only between WiFi and LiFi-enabled luminaires but also among the distributed luminaires themselves [9]. The handover mechanism may also involve information about UD location, which can be realized using both technologies, while LiFi is probably more precise.

Resource allocation and scheduling are important aspects of QoS support in wireless networks. In order to support mobility, they need adaptation to changing channel on both, slow and fast time scales. While the LiFi link changes more slowly, as the instantaneous signal power is proportional to the integral of the optical power over the detector surface, the WiFi link is subject to fast fading where the radio channel can fade randomly over few centimeters passed during few milliseconds.

Moreover and as discussed earlier, the drawback of CSMA/CA in WiFi is particularly notable in scenarios where low latency is required for multiple users in parallel [12]. Moreover, WiFi standards are backwards compatible and typical environments with mix clients and protocols do not achieve the peak performance specified in standards. These WiFi issues are solved using MU-MIMO and coordinated beamforming, see [2]. By offloading the data of users with high-quality channels on optical links, WiFi CSMA/CA fairness of resources allocation issue can be improved. Also, offloading removes congestion and interference within the same the WLAN and other networks in the area.

Maintaining continuous connectivity for mobile users is the first challenge. Handover on the same wireless access technology is needed due to the small coverage area created by each luminaire as well as the limited number of luminaires per room. Hence, user mobility triggers frequent switching among the O-SCs resulting in connectivity losses and/or undesired latency. This handover may thus be complemented by a second handover mechanism, where the traffic from a UD is rerouted from O-SCs to RF-SCs and vice versa [6]. Handover in RF cellular networks is an important research area, where the signal-to-interference and noise ratio (SINR) is commonly the optimal metric for decisions regarding channel selection between cells within a tier. In multi-tier and/or HetNets, a preference to connect is often given to SCs. This is due to the aggregate performance improvement that dense networks provide. The sensitivity of LiFi to occlusions and vulnerability due to sudden losses in the LOS path also requires additional metrics. Specifically, a history of previous losses should be considered in the decision process because large overhead due to frequent handover may make the LiFi connection less desirable than the RF macrocell or SC.

A new protocol considering the mobility combined with access is presented in [13]. The handover between the SCs of the same technology and between SCs of the different technology (O-SCs to RF-SCs and vice versa) are combined using orthogonal frequency-division multiple access (OFDMA). . In OFDMA, data is transmitted on orthogonal narrow-band subcarriers, where users are allocated subcarrier-groups to enable concurrent transmissions. In this OFDMA scheme, the system complexity is relatively increased compared to CSMA/CA, because transmission needs a tight coordination of the resource assignment in the entire network. Alternatively, and while targeting fairness among users, parallel transmission MAC (PT-MAC) protocol containing both, CSMA/CA algorithm and parallel transmission is proposed in reference [4]. This PT-MAC protocol improves the throughput and efficiency of the hybrid (IEEE 802.11n and VLC) network.

Motion information can also be considered as an important and distinctive metric in the utility function for the traffic routing and handover in Li+WiFi systems. For example, a predictive handoff scheme is proposed in reference [14] using real-time user tracking information (e.g., user location, moving direction and velocity). This approach minimizes the number of luminaires involved in the handoff mechanism while maintaining a seamless transition. The mobility models of users and several performance metrics, such as file size, average connectivity and system throughput, are considered in [14]. The results in [14] show that the hybrid WLAN-VLC is always better than VLC- or WLAN when individually implemented for both single and multi-user cases.

A VLC network coordinator is introduced in reference [7] to provide a bi-directional interface between WiFi uplink and optical downlink. While first steps are already made, these problems need to be further investigated.

3. A Prototype System – Proof of Concept and Results

Through a partnership among researchers from the Fraunhofer Heinrich Hertz Institute, the New Jersey Institute of Technology, Chicago State University, and Boston University, we have implemented a proof-of-concept Li+WiFi HetNet prototype system. In this section, we describe the various components of the system and show performance results from experimental data gained from the prototype.

a. Capabilities of the LiFi Transceivers:

The proposed Li+WiFi HetNet is tested using bidirectional high-speed LiFi transceiver devices that satisfy real-time data delivery and achieve layers 1 and 2 of the OSI protocol stack. The device, the principle of which is shown in Figure 3, uses a conventional lighting-grade high-power phosphorus-converted LED (PC-LED) and it realizes both functionalities in parallel, illumination and data transmission. A proprietary LED driver is used to enable an analog modulation bandwidth of up to 180 MHz. At the receiver, a large-area high-speed silicon PIN photodiode is used together with a trans-impedance amplifier (TIA). A plano-convex 1” lens is used at both the LED and the photodiode to concentrate the beam and to enlarge the receiving area, respectively.

Behind the analog transmitter and receiver circuits, a digital baseband unit (BBU) is used to convert Ethernet packets into DC-biased orthogonal frequency division multiplexing (OFDM) signals and vice versa. The OFDM signals have a bandwidth of 70 MHz. The BBU performs pilot-assisted channel estimation and frequency-domain equalization to reconstruct the received symbol constellations. From the received pilot sequence, the error vector magnitude (EVM) is measured and this information is fed back to the transmitter. Depending on the channel quality as a function of frequency, the bit loading is adapted. The data rate is increased as much as possible so that no errors occur after forward error correction. Thanks to the techniques used in link adaptation, implemented in real-time as a closed-loop, the achievable data rate is realized while avoiding outages due to changing channel conditions such as varying illumination levels. The relation between the data rate and the illumination level is explicitly given in [15]. Each transceiver is equipped with an external power supply and a standard RJ45 1 Gb/s Ethernet connector. Altogether, a gross and net data rate of 500 and 270 Mbps are possible, respectively with one-way latency of around 10 ms independent of the data rate [15].

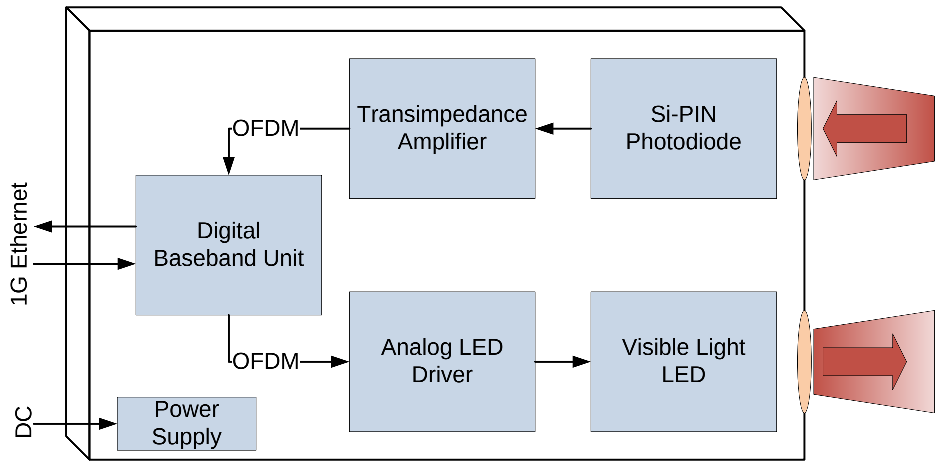

Figure 3 The LiFi transceivers.

b. Performance of indoor and outdoor LiFi links:

Indoor and outdoor experiments are conducted to measure the achievable throughput of the LiFi frontends. The distance between the transmitter and receiver is varied in the range of 2-15 meters and 2-10 meters for the indoor and outdoor experiments, respectively. In an indoor deployment, distance represents the vertical range of the O-SC. The throughput is also measured at different points away from the center of the light beam representing the horizontal distance within the coverage area of the O-SC.

Figure 4 (left) shows that the achieved throughput is 74 and 25 Mbps at a vertical distance of 2 m and 5 m, respectively. Note that the vertical distance will be in this range for most of the indoor applications. The data rate offered by our LiFi devices is already reduced at such distance due to the wide transmitter beam formed by the 1 inch aperture lens. Results are further reduced by using a white LED and measuring the throughput at the application layer. In reference [15], monochromatic LEDs were used with a 2 inch lens so that a higher throughput was measured at the physical layer. Despite those practical limitations, the single-user throughput achieved with LiFi is higher than what can be achieved using current WiFi devices based on “up to 54 Mbps” mode, see also Figure 6. Due to the small coverage area for the O-SC, the total throughput can be significantly increased by spatial reuse of the optical spectrum if multiple O-SCs are deployed serving multiple users in parallel. The results for the outdoor setting obtained during a sunny day are very close to these for the indoor setting. The results indicate that the optical frontends are robust even in outdoor conditions. While direct sunlight was avoided as it would probably disconnect the link, scattered sunlight, e.g. from back-illuminated clouds, only degrades the signal-to-interference-and-noise ratio (SINR) due to increased shot noise. In this case, the VLC transceivers adapt the data rate according to the reduced SINR.

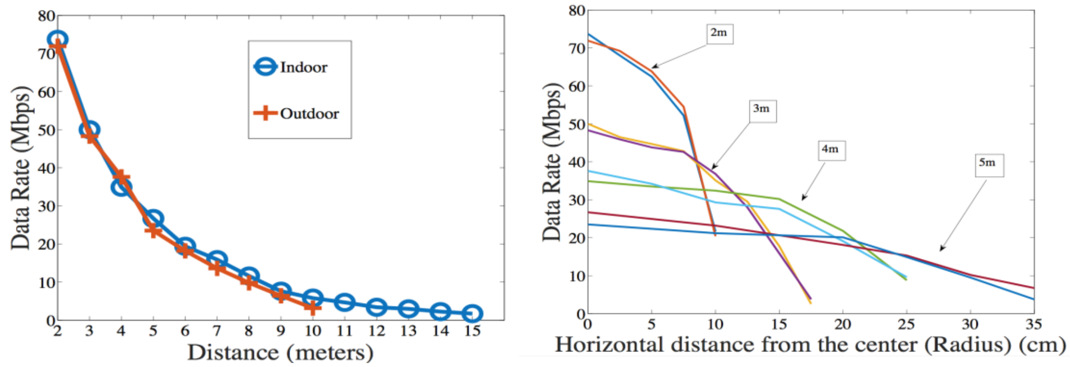

Figure 4 Vertical and horizontal distance between LiFi transceivers

c. Proof-of-concept experiment:

A proof-of-concept hybrid Li+WiFi setup in which there is a single WiFi AP and a single LiFi AP is implemented [8][9]. Here, three systems are compared. In the first system, the WiFi is only used to connect to the Internet. The second system, referred to as hybrid system, is the same as the first one, but the downlink of one of the users is connected through a LiFi link. In the third system, referred to as aggregated system, one user is connected to both WiFi and LiFi in parallel. Figure 5 depicts the configurations of the hybrid system (a) and the aggregated system (b). In the hybrid system, the unidirectional LiFi link is exploited to supplement the conventional WiFi downlink. While in the aggregation system, both bi-directional WiFi and LiFi links are fully utilized to improve the achievable throughput and provide robust network connectivity.

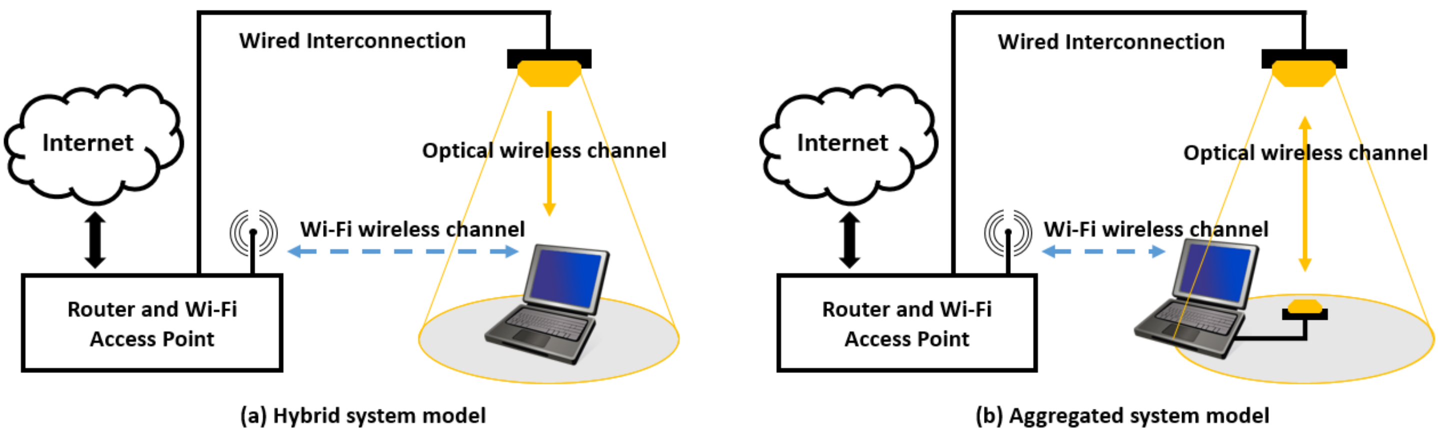

Figure 5 Configurations of the hybrid system (a) and the aggregated system (b)

Figure 6(a) shows the average throughput of the three systems measured at different distance between the WiFi and LiFi frontends. In this setup, the LiFi frontends are strictly aligned (i.e., zero off-axis displacement). The mode of the WiFi router is selected as the "up to 54 Mbps" to provide robust connectivity in crowded environment. Although the signaling scheme of WiFi depends on the received SNR in principle, the WiFi-only throughput shown in Figure 6(a) is almost constant in the coverage area of the LiFi AP because the throughput degrading of WiFi will manifest when the distance increases up to 25 meters, where the connectivity of VLC already becomes unavailable.

The hybrid system more than doubles the throughput near the LiFi AP, while degrading quickly, as the distance increases. The throughput of WiFi-only surpasses that of the hybrid system when the distance is increased to around 4.1 m. This is because as the distance increases, the downlink capacity of LiFi decreases with distance, eventually becoming insignificant. Note that the throughput results of the hybrid VLC system only depend on the capacity of the LiFi downlink.

The aggregated system triples the achievable average throughput and its lowest bound is higher than the average throughput of WiFi-only. Therefore, the aggregation technique not only enhances the available integrated bandwidth, but also provides reliable network communication. Due the inherent short-range property of LiFi, much better performance can be reached close to the LiFi AP for individual users. Note also that LiFi and WiFi users can be served in parallel in- and outside this limited coverage area.

Considering that mobile devices can have irregular movements, LiFi channel blockage can be a significant aspect that is mitigated by the hybrid solution. Figure 6 – (b) shows the average throughput achieved by the three systems with the variation of periods in which the LiFi link was blocked from 5 s to 30 s per minute. The distances between the WiFi and LiFi frontends are both set to 2 meters. It is observed that even if the LiFi link is blocked 50% of the time, while the user is moving, the hybrid system outperforms the WiFi-only system.

4. Future Research Opportunities

Based on our experience with the proof-of-concept system, there are considerable opportunities in future work in this area. In this section we outline an agenda for the combined Li+WiFi approach proposed in this article.

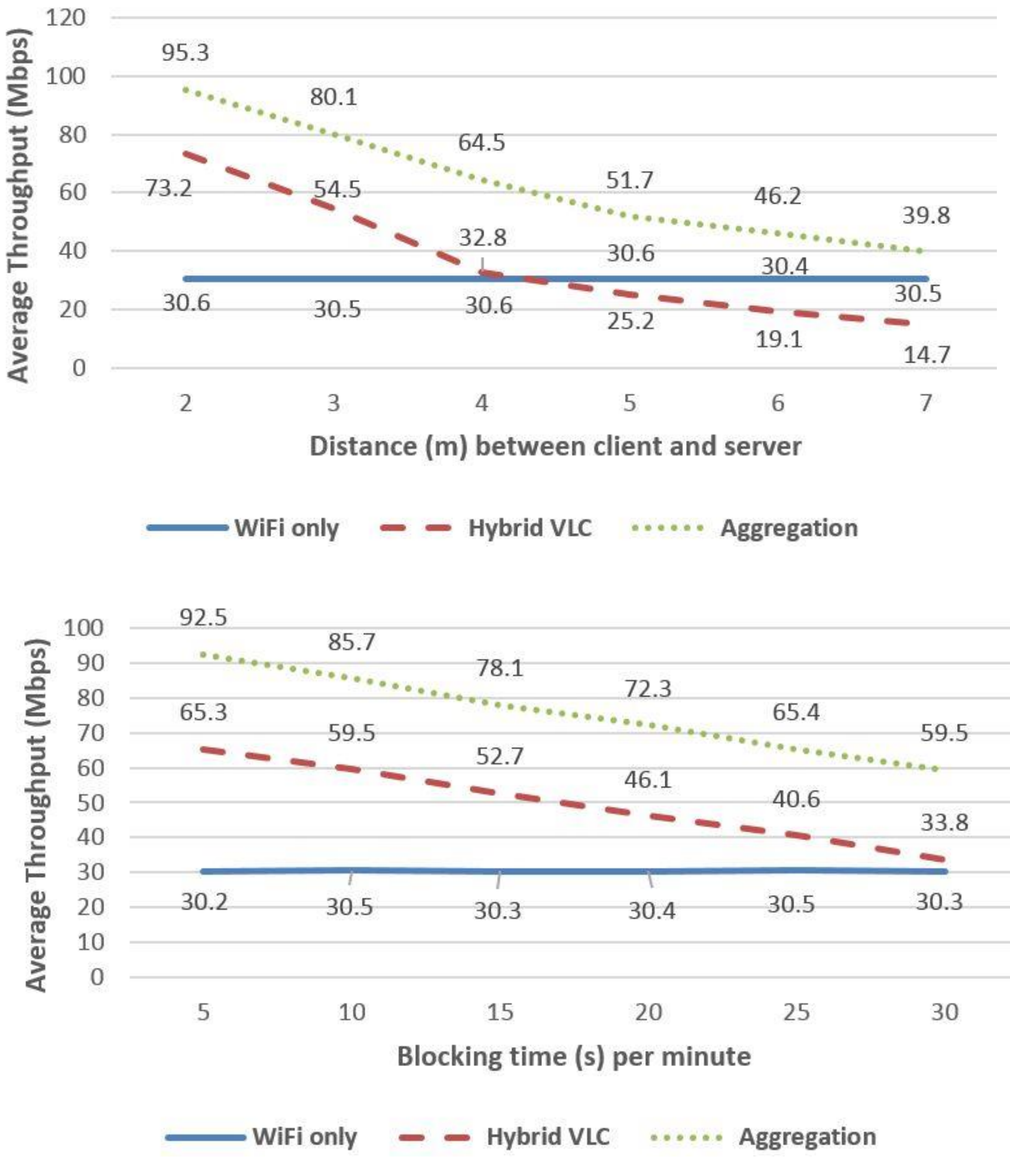

Figure 6 Throughput vs. distance (a) and throughput vs. blockage duration (b)

First, both technologies will experience further evolution to higher data rates. LiFi allows Gbit/s throughput using higher bandwidth, monochromatic LEDs or lasers together with wavelength-division multiplexing as well as MIMO. WiFi is currently also upgraded by using more antennas and more bandwidth.

Besides unlicensed WiFi APs, research is needed to explore potential effects of LiFi data offloading when licensed indoor femtocells and outdoor macrocells are included in the system. The obtained results will yield a complete picture and offer first insights into a practical multi-tiered HetNet under practical illumination constraints (*e.g.*, meeting lighting standards for office lighting) [6]. A proper system design must carefully consider the unique illumination qualities and services of individual spaces and applications to achieve the best compromise between VLC performance and illumination needs.

Another opportunity is to study the coexistence and further evolution of CSMA/CA and OFDMA in the proposed HetNet including closed-loop link adaptation envisioned for both LiFi and enhanced WiFi networks. It is important to manage proportional fairness among the users, meaning that each of N users would get a constant fraction of the bandwidth when being alone in a combination of both LiFi and WiFi channels [13].

Channel aggregation of Li+WiFi is another interesting challenge. Two models are of interest: (1) aggregating channels from one access technology and (2) aggregating channels from different access technologies. These can include multiple channels within either RF or optical spectrum [8]. Both approaches can be implemented on different layers of the OSI reference model ranging from the data link to the application layer. Relying on higher layers requires modifying both the client and server sides. Aggregation at lower layers must remain compatible with higher layer protocols such as TCP, otherwise cross-layer aggregation must be achieved.

User mobility is also an important consideration for the provision of seamless connectivity and is required in order to properly evaluate the performance of the proposed Li+WiFi network. Physical layer (PHY) techniques can be used to enhance the performance of Li+WiFi in multi-user scenarios. For example, user separation can be performed by assigning separate color clusters to the users analogous to frequency reuse or subcarrier isolation in RF-cellular systems. One strategy is to leverage difference color shift keying (CSK) triplets in neighboring cells under the IEEE 802.15.7 model. A multi-color enabled VLC receiver allows separation of the individual channels in the color domain using a filtering technology. Optimized multi-color multi-user MIMO solutions based on the hybrid nature of the Li+WiFi network are not well investigated. The UD battery drain and the impact of the user population and density on the performance, while maintaining target illumination, are important research problems.

Finally, there is further need for experimental measurements to provide insights into the practical deployment of Li+WiFi networks and to attract the industry interest in the most promising solutions. Therefore, a testbed is needed to investigate and realize Li+WiFi networks using different configurations and to evaluate the most promising solutions and algorithms for the integration. The fact that high-speed VLC frontends using existing baseband processing solution are already available allows for early experiments also at the higher protocol layers that combine WiFi and LiFi with increasing sophistication [8][9]. Of course, the available optical frontends need further development. Investigating the use of multiple colors and of fully software-defined digital signal processing will allow intervention at all protocol layers. There is a great deal of research opportunity for heterogeneous Li+WiFi networks.

5. Conclusion

The coexistence between WiFi and LiFi is a new promising research area. We have discussed the primary characteristics of both technologies and the possibility for them to coexist. We have demonstrated that a close integration of both technologies enables off-loading opportunities for the WiFi network to free resources for more mobile users because stationary users will preferably be served by LiFi. In this way, LiFi and WiFi can efficiently collaborate. We have implemented several ways of channel aggregation for the suggested coexistence and demonstrated by proof-of-concept results, using state-of-the-art LiFi and WiFi frontends, that both technologies together can more than triple the throughput for individual users and offer significant synergies, yielding a combined solution that can adequately address the need for enhanced indoor coverage with highest data rates needed in the 5^{th} generation of mobile networks (5G). Finally, we have outlined a roadmap for future research opportunities towards the integration of both technologies.

6. Acknowledgements

The authors are grateful for partial support by the NSF grant ECCS-1331018, the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056 and the German Ministry for Education and Research (BMBF) for the support of the collaborative project OWICELLS grant 16KIS0199K.

7. References

[1] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan and M. C. Reed, "Femtocells: Past, Present, and Future," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, p. 497–508, 2012.

[2] J. Kim and I. Lee, "802.11 WLAN: History, and Enabling MIMO Techniques for Next Generation Standards," *IEEE Communications Magazine,* vol. 53, no. 3, pp. 134-140, 2015.

[3] V. Jungnickel, K. Manolakis, W. Zirwas, B. Panzner, V. Braun, M. Lossow, M. Sternad, R. Apelfröjd and T. Svensson, "The role of small cells, coordinated multipoint, and massive MIMO in 5G," *Communications Magazine, IEEE,* vol. 52, no. 5, pp. 44-51, 2014.

[4] W. Guo, Q. Li, H. Yu and J. Liu, "A Parallel Transmission MAC Protocol in Hybrid VLC-RF Network," *Journal of Communications,* vol. 10, no. 1, 2015.

[5] S. Wu, H. Wang and C.-H. Youn, "Visible light communications for 5G wireless networking systems: from fixed to mobile communications," *IEEE Network*, vol. 28, no. 6, pp. 41-45, 2014.

[6] M. Rahaim, A. Vegni and T. Little, "A Hybrid Radio Frequency and Broadcast Visible Light," in *GLOBECOM Workshops* , 2011.

[7] Z. Huang and Y. Ji, "Design and demonstration of room division multiplexing-based hybrid VLC network," *Chinese Optics Letters*, vol. 11, no. 6, pp. 1671-7694, 2013.

[8] S. Shao, A. Khreishah, M. Rahaim, H. Elgala, M. Ayyash, T. Little and J. Wu, "An Indoor Hybrid WiFi-VLC Internet Access System," in *Workshop on CellulAR Traffic Offloading to Opportunistic Networks (CARTOON),* Philadelphia, 2014.

[9] S. Shao, A. Khreishah, M. Ayyash, M. Rahaim, H. Elgala, V. Jungnickel, D. Schulz, T. Little, J. Hilt and R. Freund, "Design and Analysis of a Visible-Light-Communication Enhanced WiFi System," *OSA/IEEE Journal of Optical Communications and Networking (JOCN),* vol. 7, no. 10, pp. 960-973, 2015.

[10] P. M. Butala, H. Elgala and T. Little, "SVD-VLC: A novel capacity maximizing VLC MIMO system architecture under illumination constraints," in *4th IEEE Workshop on Optical Wireless Communications*, Atlanta, 2013.

[11] K. Kim and S. Kim, "Wireless visible light communication technology using optical beamforming," *Lasers, Fiber Optics, and Communications,* vol. 52, no. 10, pp. 1-6, 2013.

[12] R. Nishioka, T. Nishio, M. Morikura and K. Yamamoto, "A Camera and LED-Based Medium Access Control Scheme for Wireless LANs," *IEICE Transactions on Communications,* Vols. E98-B, no. 5, pp. 917-92, 2015.

[13] X. Bao, X. Zhu, S. T. and Y. Ou, "Protocol Design and Capacity Analysis in Hybrid Network of Visible Light Communication and OFDMA Systems," *IEEE Transactions on Vehicular Technology,* vol. 63, no. 4, pp. 1770 - 1778, 2014.

[14] H. Chowdhury and M. Katz, "Cooperative Data Download on the move in Indoor Hybrid (Radio-Optical) WLAN-VLC Hotspot Coverage," *Transactions on Emerging Telecommunications Technologies,* vol. 25, no. 6, pp. 666-677, 2014.

[15] L. Grobe, A. Paraskevopoulos, J. Hilt, D. Schulz, F. Lassak, F. Hartlieb, C. Kottke, V. Jungnickel and K.-D. Langer, "High-speed visible light communication systems," *IEEE Communications Magazine*, vol. 51, no. 12, 2013.

8. Biographies

Moussa Ayyash (mayyash@csu.edu) is an associate professor in the Department of Information Studies at Chicago State University. He is the Director of the Center of Information and National Security Education and Research. He received his BSc in electrical and computer engineering (ECE) from Mu'tah University, his MSc in ECE from University of Jordan, and PhD in ECE from IIT/Chicago. He is a Senior Member of the IEEE and a member of the ACM.

Hany Elgala (helgala@albany.edu**)** is an Assistant Professor in the Computer Engineering Department, at University at Albany - State University of New York (SUNY). Before moving to SUNY, he was a Research Professor at Boston University and the Communications Testbed leader at the National Science Foundation Smart Lighting Engineering Research Center. His research focuses on visible light communications (VLC) or LiFi, wireless networking and embedded systems. He is a member of the IEEE and IEEE Communications society.

Abdallah Khreishah (abdallah@njit.edu) is an assistant professor in the Department of ECE at NJIT. His research interests fall in the areas of visible light communications, green networking, network coding, wireless networks, and network security. He received his BS degree in computer engineering from Jordan University of Science and Technology in 2004, and his MS and PhD degrees in ECE from Purdue University in 2006 and 2010. He is the chair of North Jersey IEEE EMBS chapter.

Volker Jungnickel (volker.jungnickel@hhi.fraunhofer.de**)** received doctorate and habilitation degrees from Humboldt University in 1995 and Technical University in 2015, respectively, both in Berlin. He joined Fraunhofer Heinrich Hertz Institute in 1997 where he is leading the metro, access, and in-house systems group. Volker contributed to high-speed optical wireless links, a first 1 Gb/s mobile radio link, first real-time trials of LTE and first coordinated multipoint trials. He contributed to 180 papers, 10 books and 25 patents.

Thomas DC Little (tdcl@bu.edu) is a professor of Electrical and Computer Engineering in the College of Engineering at Boston University. He is also an Associate Director and principal investigator of the National Science Foundation Smart Lighting Engineering Research Center. Little received his BS degree in biomedical engineering from RPI in 1983, and his MS degree in electrical engineering and Ph.D. degree in computer engineering from Syracuse University in 1989 and 1991, respectively.

Sihua Shao (ss2536@njit.edu**)** is a PhD student in the Department of Electrical and Computer Engineering at New Jersey Institute of Technology. His current research interests include wireless communication, visible light communication and heterogeneous network. Mr. Shao received his BS degree in electrical and information engineering from South China University of Technology in 2011, and his MS degree in electrical and information engineering from Hong Kong Polytechnic University in 2012. He is an IEEE student member.

Michael Rahaim (mrahaim@bu.edu**)** is a postdoctoral researcher in the department of Electrical and Computer Engineering at Boston University, working with the NSF funded Smart lighting Engineering Research Center. His research focuses on Software Defined Radio, Visible Light Communication, HetNets, and Smart Lighting. Dr. Rahaim received his BS in electrical and computer systems engineering from Rensselaer Polytechnic Institute in 2007 and his MS and PhD in computer engineering from Boston University in 2011 and 2015, respectively.

Dominic Schulz (dominic.schulz@hhi.fraunhofer.de) received his MS in communications engineering from Berlin University of Applied Sciences in 2012. In 2013 he joined the department of Photonic Networks and Systems at Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute. He recently is working towards his PhD in the field of optical wireless communications. His current activities include the development of high data rate systems for wireless access as well as on research towards long-range links

Jonas Hilt (jonas.hilt@hhi.fraunhofer.de**)** received his Diploma in Electrical Engineering from Berlin University of Applied Sciences in 2009. In 2009 he joined the Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, where he acts as an electrical engineer in the department of Photonic Networks and Systems. His current activities are in the area of design and realization of embedded systems and visible light communication systems (VLC).

Ronald Freund (ronald.freund@hhi.fraunhofer.de) received the Dipl.-Ing. degree and the Dr.-Ing. degree in Electrical Engineering from Technical University of Ilmenau (TUI), in 1993 and in 2002, respectively. In 2013, he received a MBA degree from RWTH Aachen. Since 1995, he is with Heinrich Hertz Institute in Berlin, where he is currently leading the department Photonic Network and Systems.