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Coexistence of Wi-Fi and LiFi toward 5G: Concepts, Opportunities and Challenges

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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 HetNets will play an important role toward the goal of using a diverse spectrum to provide high quality-of-service, especially in indoor environments where most data are consumed. An additional tier in the wireless HetNets concept is envisioned using indoor gigabit small-cells 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 Wi-Fi and 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.

I. 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 macro cells providing broad lower-rate services, RF small-cells (RF-SCs) providing improved coverage at locations occupied by users, and Li-Fi small cells that provide additional capacity through the use of the optical spectrum. Indoor RF-SCs, including licensed femto cells and/or unlicensed Wi-Fi access points (APs), deployed under coverage of macro cells, can take over the connection when moving indoors. In this manner, Wi-Fi enables traffic offloading from these capacity-stressed licensed macro cells or RF-SCs [1].

The Wi-Fi evolution considers higher frequencies with new spectrum to reach multi-Gb/s peak data rates (Wi-Gig (www.wigig.com) at 60 GHz) indoors and to serve multiple users in parallel. While the IEEE 802.11ad (Wi-Gig) 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, specifically based on visible light communications (VLC) technology, also called Li-Fi, offer dual-functionality to transmit data on the intensity of optical sources (lighting concurrent with data communication) [2]. The authors in [3] describe an integrated architecture for 5G mobile networks that includes SCs and enhanced Wi-Fi as the main scaling factor for wireless capacity. For example, the first user detecting an unused channel is allowed to start transmission,

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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 increases both data utilization and the need for continuous gap-free data delivery.

Therefore, concurrent multiuser transmission is used in Wi-Fi 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 beam forming 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 backward-compatible. Moreover, there are complexity limits with larger numbers of antennas. It is well known that the complexity of linear MIMO equalizers scales with N^3 , 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. Due to these standardization, scalability, and complexity issues, and due to the increasing demand for Wi-Fi, scalability is limited and there is a rationale to consider other wireless media.

II. GETTING TO HIGH CAPACITY AND DENSITY

Given the aforementioned challenges, we add an additional tier in wireless HetNets comprised of indoor gigabit SCs to offer additional wireless capacity where it is needed the most.



Figure 1 : VLC downlink, Wi-Fi uplink

LiFi-enabled indoor luminaires (lights) can be modeled as optical SCs (O-SCs) in a HetNet, where a three-layer network formed by RF macro cells, 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 Wi-Fi AP or across multiple Wi-Fi 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 does not 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 Wi-Fi. Operators say that 80 percent of mobile traffic occurs indoors; therefore, the combination of LiFi and Wi-Fi has great potential to be a break-through technology in future HetNets, including 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 Wi-Fi and LiFi coexistence solutions [7].

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III. 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 Wi-Fi 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.

III. 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. However, accurate CSI may be relatively easier to obtain in a static condition, and from a practical perspective in the case of user mobility, obtaining the CSI is an estimation problem that 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, modulation frequency sub-bands and wavelengths can both be reused at some distance to achieve a higher throughput.

IV. 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 Wi-Fi 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.

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 dense networks providing. The sensitivity of LiFi to occlusions and vulnerability due to sudden losses in the LOS path also requires additional metrics.

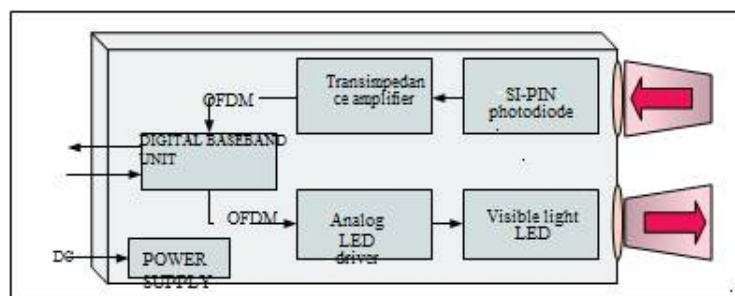


Figure 2: Transmission Module

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V. 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 Fig. 3, uses a conventional lighting-grade high-power phosphorus-converted LED (PC-LED), and it realizes both illumination and data transmission in parallel. 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 (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.

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.

The achieved throughput is 74 Mb/s and 25 Mb/s 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 [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 Wi-Fi devices based on "up to 54 Mb/s" mode.

VI. FUTURE RESEARCH OPPORTUNITIES

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

First, both technologies will experience further evolution to higher data rates. LiFi allows Gb/s throughput using higher bandwidth, mono-chromatic LEDs or lasers together with wave-length-division multiplexing as well as MIMO. Wi-Fi is currently also upgraded by using more antennas and more bandwidth.

Besides unlicensed Wi-Fi APs, research is needed to explore potential effects of LiFi data offloading when licensed indoor femtocells and outdoor macro cells 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 Wi-Fi 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 Wi-Fi channels [13].

Channel aggregation of Li+WiFi is another interesting challenge. Two models are of interest:

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- Aggregating channels from one access technology
- 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 multiuser MIMO solutions based on the hybrid nature of the Li+WiFi network are not well investigated. UD battery drain and the impact of the user population and density on 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 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 solutions are already available allows for early experiments also at the higher protocol layers that combine Wi-Fi 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.

VII. 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 Wi-Fi network to free resources for more mobile users because stationary users will preferably be served by LiFi. In this way, LiFi and Wi-Fi 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 Wi-Fi 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 the highest data rates needed in the 5th generation of mobile networks (5G). Finally, we have outlined a roadmap for future research opportunities toward the integration of both technologies.

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