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Light Fidelity (Li-Fi): Towards All-Optical Networking

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ABSTRACT

Motivated by the looming radio frequency (RF) spectrum crisis, this paper aims at demonstrating that optical wireless communication (OWC) has now reached a state where it can demonstrate that it is a viable and matured solution to this fundamental problem. In particular, for indoor communications where most mobile data traffic is consumed, light fidelity (Li-Fi) which is related to visible light communication (VLC) offers many key advantages, and effective solutions to the issues that have been posed in the last decade. This paper discusses all key component technologies required to realize optical cellular communication systems referred to here as optical attocell networks. Optical attocells are the next step in the progression towards ever smaller cells, a progression which is known to be the most significant contributor to the improvements in network spectral efficiencies in RF wireless networks.

Keywords: Li-Fi, VLC, optical wireless, visible light communications, optical attocell

1. INTRODUCTION

Thirty years after the introduction of the first commercially-available mobile communication systems, wireless connectivity has evolved into a fundamental commodity like gas and electricity. The exponential increase in mobile data traffic during the past two decades has led to the massive deployment of wireless systems. As a consequence, the limited available RF spectrum is subject to an aggressive spatial reuse and co-channel interference has become a major capacity limiting factor. Therefore, there have been many independent warnings of a looming "RF spectrum crisis"[1] as the mobile data demands continue to increase while the network spectral efficiency saturates despite newly-introduced standards and great technological advancements in the field. It is estimated that by 2017, more than 11 exabytes of data traffic will have to be transferred through mobile networks every month.[2] Most recently, VLC has been identified as a potential solution for mitigating the looming RF spectrum crisis.

Over the past decade, significant research efforts have been directed towards exploring alternative parts of the electromagnetic spectrum* that could potentially offload a large portion of the network traffic from the overcrowded RF domain. Very interesting results have recently been reported from the use of millimeter wave (mmWave) communication in the 28 GHz region as well as from the use of infrared and visible light. The latter is particularly enticing as lighting is a commodity that has been integrated in virtually every inhabited environment and sophisticated infrastructures already exist. The use of the visible light spectrum for high speed data communication is enabled by the emergence of the light emitting diode (LED) which at the same time is at the heart of the next wave of energy-efficient illumination. In that sense, the concept of combining the functions of illumination and communication offers the potential for tremendous cost savings and carbon footprint reductions. First, the deployment of VLC access points (APs) becomes straightforward as the existing lighting infrastructure

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*The preferred region of the RF spectrum for use in terrestrial mobile communication is between 0 - 10 GHz due to certain radio propagation characteristics. As wireless communications has changed over the last decade, the authors believe that it is worthwhile to reconsider the importance of these "preferential" propagation characteristics for future wireless systems.

can be reused, and there exist off-the-shelf technologies such as power-line communication (PLC) and power-over-Ethernet (PoE) as viable backhaul solutions for retrofit installations, and new installations respectively. Second, because lighting is on most of the time in indoor environments even during day time, the energy used for communication would practically be zero as a result of the piggy-backing of data on illumination. However, even if illumination is not required energy efficient intensity modulation (IM) techniques exist that would allow data communication even if the lights are visually off.[3] These are already compelling benefits, but the case does not end there. The visible light spectrum includes 100s of THz of license free bandwidth, 10,000 times more than the entire RF spectrum up to 30 GHz, including the mmWave spectrum. Optical radiation, in general, does not interfere with other radio waves or with the operation of sensitive electronic equipment. Therefore, it is ideal for providing wireless coverage in areas which are sensitive to electromagnetic radiation – some examples include: hospitals, airplanes, petrochemical and nuclear power plants, etc. Furthermore, the inability of light to propagate through walls offers an inherent level of network security. The same feature can be exploited to eliminate interference between neighboring cells.

During the last ten years, there have been continuous reports of improved point-to-point link data rates using off-the-shelf white LEDs under experimental lab conditions. Recently, data rates in excess of 1 Gbps has been reported using off-the-shelf phosphor-coated white LEDs,[4] and 3.4 Gbps has been demonstrated with an off-the-shelf red-green-blue (RGB) LED.[5] Another similar Gigabit/s wireless system with phosphor-coated white LEDs has been demonstrated[6] using a 4×4 multiple-input-multiple-output (MIMO) configuration. To the best of the authors' knowledge, the highest speed that has ever been reported from a *single* color incoherent LED is 3.5 Gbps.[7] The experiment was led by researchers of the University of Edinburgh. A theoretical framework for the achievable capacity of a intensity modulation and direct detection (IM/DD) systems using orthogonal frequency division multiplexing (OFDM) has been established in,[8] and a closed-form solution on the impact of non-linearties on the achievable signal-to-noise ratio in practical OFDM based VLC systems is reported in.[9] To date, research in the field of OWC has been focused on successful implementations of physical-link connections and proofs of the concept.[10] For the realization of a mobile communication system, however, a full networking solution is required. This is what we refer to as Li-Fi: the *networked*, *mobile*, *high-speed* VLC solution for wireless communication.[11] The vision is that a Li-Fi wireless network would complement existing heterogenous RF wireless networks, and would provide significant spectrum relief by allowing cellular and wireless-fidelity (Wi-Fi) systems to off-load a significant portion of wireless data traffic. The current paper summarizes some of the research conducted so far and looks at the different aspects of the communication system with a particular focus on wireless networking. The rest of this paper is structured as follows: Section 2 looks at the modulation scheme requirements of Li-Fi which is based on IM/DD; Section 3 discusses the different possibilities for achieving multiple access; Section 4 summarizes the uplink concepts; Section 5 introduces the optical "attocell" concept; Section 6 summarizes interference mitigation techniques for optical attocell networks; and finally, Section 7 provides concluding remarks.

2. SIGNAL MODULATION IN OWC

A seamless all-optical wireless network would require ubiquitous coverage provided by the optical front-end elements. This necessitates the usage of a large amount of Li-Fi enabled lighting units. The most likely candidates for front-end devices in VLC are incoherent solid-state lighting LEDs due to their low cost. Due to the physical properties of these components, information can only be encoded in the intensity of the emitted light, while the actual phase and amplitude of the light wave cannot be modulated. This significantly differentiates VLC from RF communications.

VLC can only be realized as an IM/DD system, which means that the modulation signal has to be both *real valued* and *unipolar*. This limits the application of the well-researched and developed modulation schemes from the field of RF communications. Techniques such as on-off keying (OOK), pulse-position modulation (PPM), pulse-width modulation (PWM) and unipolar M-ary pulse-amplitude modulation (M-PAM) can be applied in a relatively straightforward fashion. As the modulation speeds are increased, however, these particular modulation schemes begin to suffer from the undesired effects of intersymbol interference (ISI) due to the non-flat frequency response of the OWC channel. Hence, a more resilient technique such as OFDM is required. OFDM allows adaptive bit and energy loading of different frequency sub-bands according to the communication channel

properties.[12] This leads to optimal utilization of the available resources. OFDM achieves the throughput capacity in a non-flat communication channel even in the presence of nonlinear distortion.[8] Such channel conditions are introduced by the transfer characteristic of an off-the-shelf LED that has a maximum 3 dB modulation bandwidth in the order of 20 MHz.[4,5] In fact, the record-breaking results presented in[4–6] have all been achieved using OFDM with, to the best of the authors' knowledge, the first experimental OFDM results for VLC reported in.[13] Further benefits of this modulation scheme include simple equalization with single-tap equalizers in the frequency domain as well as the ability to avoid low-frequency distortion caused by flickering background radiation and the baseline wander effect in electrical circuits.

Conventional OFDM signals are complex-valued and bipolar in nature. Therefore, the standard RF OFDM technique has to be modified in order to become suitable for IM/DD systems. A straightforward way to obtain a real-valued OFDM signal is to impose a Hermitian symmetry constraint on the sub-carriers in the frequency domain as illustrated in Fig. 1. However, the resulting time-domain signal is still bipolar. One way for obtaining a unipolar signal is to introduce a positive direct current (DC) bias around which the amplitude of the OFDM signal can vary as shown in Fig. 2. The resulting unipolar modulation scheme is known as DC-biased optical OFDM (DCO-OFDM). The addition of the constant biasing level leads to a significant increase in electrical energy consumption. This can be easily visualized when Fig. 2(a) and Fig. 2(b) are juxtaposed. However, if the light sources are used for illumination at the same time, the light output as a result of the DC bias is not wasted as it is used to fulfil the illumination function. Only if illumination is not required, such as in the uplink of a Li-Fi system, the DC bias can significantly compromise energy efficiency. Therefore, researchers have devoted significant efforts to designing an OFDM-based modulation scheme which is purely unipolar. Some well-known solutions include: asymmetrically clipped optical OFDM (ACO-OFDM),[14] pulse-amplitude-modulated discrete multitone modulation (PAM-DMT),[15] unipolar OFDM (U-OFDM),[3] Flip-OFDM,[16] spectrally-factorized optical OFDM (SFO-OFDM),[17] etc.. The general disadvantage of all these techniques is a 50% loss in spectral efficiency, i.e., the data rates are halved. This limitation has recently been overcome by researchers at the University of Edinburgh and a patent application is pending.
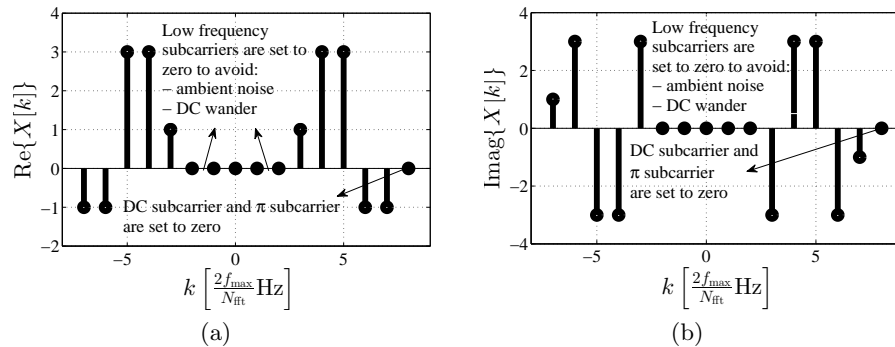

Figure 1. Hermitian symmetry ensures a positive signal in the time domain: (a) real parts of the corresponding positive and negative frequency components are equal; (b) imaginary parts of the corresponding positive and negative frequency components are equal in absolute value, but have opposite signs.

From a networking perspective, OFDM offers a straightforward multiple access implementation as subcarriers can be allocated to different users resulting in orthogonal frequency division multiple access (OFDMA). The merits of OFDM have already been recognized, and OFDM is used in IEEE 802.11 Wi-Fi systems. The multiuser access version of OFDM, i.e., OFDMA, is used in the 4th generation (4G) Long Term Evolution (LTE) cellular standard. Therefore, the application of OFDM in optical mobile networks would allow the use of the already-established higher level communication protocols used in LTE and IEEE 802.11, which constitutes a major advantage.
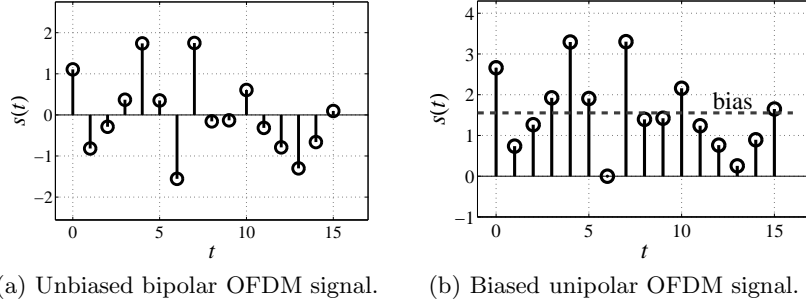
(a) Unbiased bipolar OFDM signal.

(b) Biased unipolar OFDM signal.

Figure 2. Real OFDM signal made bipolar through the addition of a DC bias – DCO-OFDM.

3. MULTIPLE ACCESS

A networking solution cannot be realized without a suitable multiple access scheme that allows multiple users to share the communication resources without any mutual cross-talk. Multiple access schemes used in RF communications can be adapted for OWC as long as the necessary modifications related to the IM/DD nature of the modulation signals are performed. OFDM comes with a natural extension for multiple access – OFDMA. Single-carrier modulation schemes such as M-PAM, OOK and PWM require an additional multiple access technique such as frequency division multiple access (FDMA), time division multiple access (TDMA) and/or code division multiple access (CDMA). The results of an investigation regarding the performance of OFDMA versus TDMA and CDMA are presented in Fig. 3.[18] FDMA has not been considered due to its close similarity
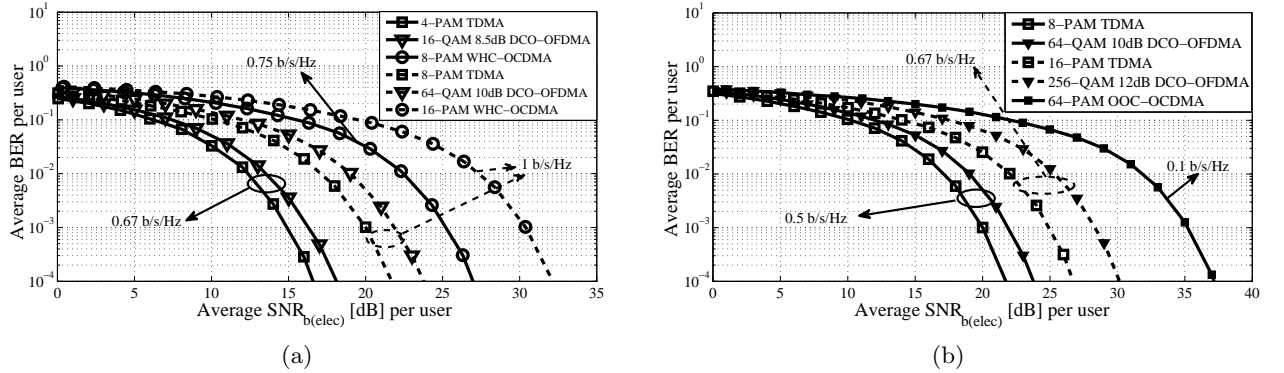

Figure 3. Comparison between different multiple access schemes:[18] (a) TDMA vs. OFDMA vs. CDMA (with Walsh-Hadamard code) in a three-user scenario; (b) TDMA vs. OFDMA vs. CDMA (with optical orthogonal code) in a six-user scenario.

to OFDMA, and the fact that OWC does not use superheterodyning. In addition, due to the limited modulation bandwidth of the front-end elements, this scheme would not present a very efficient use of the LED modulation bandwidth. As shown in Fig. 3, CDMA is very inefficient as the use of unipolar signals creates significant interchannel interference (ICI) and a substantial increase in the power requirements compared to its application in RF communications. At the same time, the performance of TDMA barely surpasses that of OFDMA for the different scenarios. The higher power requirement of OFDMA compared to TDMA is caused by its wider time-domain signal distribution. This leads to the need for higher DC biasing levels and as a consequence to a higher power consumption which is reflected in the shown signal-to-noise ratio (SNR). In a practical scenario where the functions of communication and illumination are combined, the difference in power consumption between the different schemes would diminish as the excess power due to the DC bias would be used for illumination purposes. It should be pointed out that this investigation has been performed for a flat linear additive white Gaussian noise (AWGN) channel where only clipping effects from below, applicable only to OFDMA, have been considered. This is due to the fact that nonlinear effects such as clipping from above as well as the

nonlinear relationship between the modulating current signal and the emitted optical signal are device-specific, while clipping from below is inherent to any IM/DD system. Furthermore, low-frequency distortion effects from the DC-wander in electrical components as well as from the flickering of background light sources are also not considered. In a practical scenario, these effects would not be an issue for OFDMA, but are expected to decrease the performance of TDMA and CDMA. Therefore, the design complexity of a TDMA or CDMA system increases as suitable techniques to deal with these problems need to be implemented. It is also worth noting that the non-flatness of the channel in a practical scenario would further degrade the performances of CDMA and TDMA compared to OFDMA.

In OWC there exists an additional alternative dimension for achieving multiple access. This is *color*, and the corresponding technique is wavelength division multiple access (WDMA). WDMA harnesses the different light wavelengths to facilitate multiple-user access. This scheme could reduce the complexity in terms of signal processing, however, it would lead to increased hardware complexity as well as to the need at each access point for multiple transmitter elements with narrow wavelength emission. This immediately puts strict requirements on the optical front-end elements, and compromises SNR and, hence, capacity. In addition, WDMA excludes the usage of a large variety of off-the-shelf LEDs as most of them are not optimized for WDMA. The typical emission profile of an off-the-shelf white LED is illustrated in Fig. 4(a). At the same time, light sources with different narrow wavelength emission spectra have different modulation frequency profiles as well as different optical efficiencies. When combined with the varying responsivity of photodetectors at different wavelengths, as shown in Fig. 4(b), these differences complicate immensely the fair distribution of communication resources between multiple users.
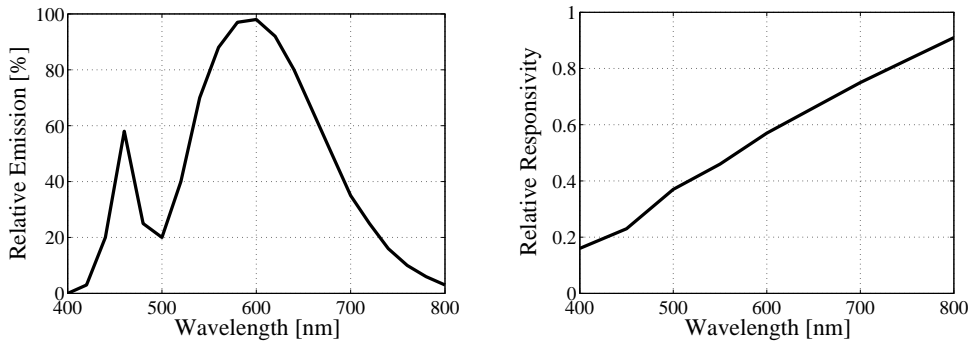
(a) Typical spectrum of a white-phosphor LED.[19]

(b) Typical responsivity of a photodetector.[20]

Figure 4. Data provided by device data-sheets.

4. UPLINK

Up until now, research has primarily focused on maximizing the transmission speeds over a single unidirectional link.[4–6] However, for a complete Li-Fi communication system, full duplex communication is required, *i.e.*, an uplink connection from the mobile terminals to the optical AP has to be provided. Existing duplex techniques used in RF such time division duplexing (TDD) and frequency division duplexing (FDD) could be considered, where the downlink and the uplink are separated by different time slots, or different frequency bands respectively. However, FDD is more difficult to realize due to the limited bandwidth of the front-end devices, and because superheterodyning is not used in IM/DD systems. TDD provides a viable option, but imposes precise timing and synchronization constraints which is needed for data decoding, anyway. However, plain TDD assumes that both the uplink and the downlink transmissions are performed over the same physical wavelength. This could often be impractical as visible light emitted by the user terminal may not be desirable.[21] Therefore, the most suitable duplex technique in Li-Fi is wavelength division duplexing (WDD), where the two communication channels are established over different electromagnetic wavelengths. Using infrared (IR) transmission is one viable option for establishing an uplink communication channel.[21] A first commercially-available full duplex Li-Fi modem using

IR light for the uplink channel has recently been announced by pureLiFi.[22] There is also the option to use RF communication for the uplink.[21] In this configuration, Li-Fi may be used to do the "heavy lifting" and off-load data traffic from the RF network, and thereby providing significant RF spectrum relief. This is particularly relevant since there is a traffic imbalance in favor of the downlink in current wireless communication systems.

5. THE LI-FI ATTOCELL

In the past, wireless cellular communications has significantly benefited from reducing the inter-site distance of cellular base stations. By reducing the cell size, the network spectral efficiency has been increased by two orders of magnitude in the last 25 years. More recently, different cell layers composed of microcells, picocells and femto cells have been introduced. These networks are referred to as heterogeneous networks.[23, 24] Femtocells are short range, low transmission power, low cost, plug-and-play base stations (BSs) that are targeted at indoor deployment in order to enhance coverage. They use either cable Internet or broadband digital subscriber line (DSL) to backhaul to the core network of the operator. The deployment of femtocells increases the frequency reuse, and hence throughput per unit area within the system since they usually share the same bandwidth with the macrocellular network. However, the uncoordinated and random deployment of small cells also causes additional inter- and intra-cell interference which imposes a limit on how dense these small RF can be deployed before interference starts offsetting all frequency reuse gains.

The small cell concept, however, can easily be extended to VLC in order to overcome the high interference generated by the close reuse of radio frequency spectrum in heterogeneous networks. The optical AP is referred to as an attocell.[25] Since it operates in the visible light spectrum, the optical attocell does not interfere with the macrocellular network. The optical attocell not only improves indoor coverage, but since it does not generate any additional interference, it is able to enhance the capacity of the RF wireless networks. Li-Fi attocells allow
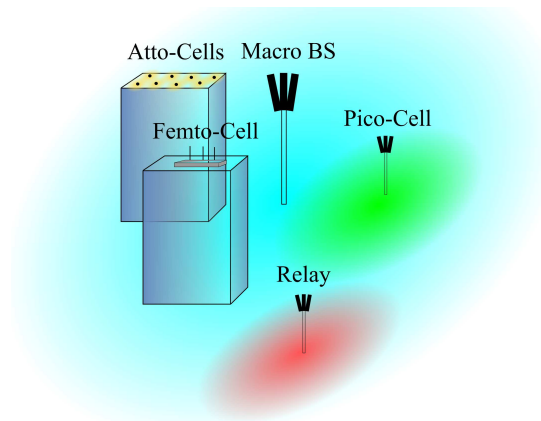

Figure 5. The attocell in the context of the heterogeneous network.

for extremely dense bandwidth reuse due to the inherent properties of light waves. The coverage of each single attocell is very limited, and walls prevent the system from suffering from co-channel interference between rooms. This precipitates in the need to deploy multiple access points to cover a given space. However, due to the requirement for illumination indoors, the infrastructure already exists, and this type of cell deployment results in the aforementioned very high, practically interference-free bandwidth reuse. A byproduct of this is also a reduction in bandwidth dilution over the area of each access point, which leads to an increase in the capacity available per user. The user data rate in attocell networks can be improved by up to three orders of magnitude.[26]

Moreover, Li-Fi attocells can be deployed as part of a heterogeneous VLC-RF network as illustrated in Fig. 5. They do not cause any additional interference to RF macro- and picocells, and can, hence, be deployed within RF macro-, pico- and even femtocell environments. This allows the system to vertically hand-off users between the RF and Li-Fi sub-networks, which enables both free user mobility and high data throughput. Such network structure is capable of providing truly ubiquitous wireless network access.

6. THE CELLULAR NETWORK

The deployment of multiple Li-Fi attocells provides ubiquitous data coverage in a room in addition to providing nearly uniform illuminance. This means that a room contains many attocells forming a very dense cellular attocell network. A network of such density, however, requires methods for intra-room interference mitigation while there is no inter-room interference if the rooms are separated by concrete walls. Interference mitigation techniques used in RF cellular networks such as the busy burst[27] technique, static resource partitioning,[28] or fractional frequency reuse[29] have been considered. The unique properties of optical radiation, however, offer specific opportunities for enhanced interference mitigation in optical attocell networks. Particularly important is the inability of light to penetrate solid objects, which allows interference to be managed in a more effective manner than in RF communication. According to,[26] for example, the VLC interference mitigation caused by solid objects in a typical indoor environment leads to a tremendous increase in area spectral efficiency (ASE) over an RF femtocell network deployment in same LTE indoor office environment. The presented results highlight that the improvement with respect to ASE can reach a factor of up to 1000 in certain scenarios.

Essential techniques for increasing wireless system capacity such as beamforming are relatively straightforward to use in VLC as the beamforming characteristic is an inherent, device specific property related to the field of view (FOV), and no computationally complex algorithms and multiple transmitting elements are required. A simple example is provided with the technique of joint transmission in indoor VLC downlink cellular networks proposed by Chen *et al.*[30] and illustrated in Fig. 6. The application of multiple simple narrow-emission-pattern transmitters at each attocellular AP results in significant co-channel interference reduction. The technique allows the cellular coverage area to be broken down further into areas of low interference and areas that are subject to higher interference – typically at the cell edges. The frequency allocation can then be performed in a more optimal way which allows the overall throughput distribution over the coverage area to increase significantly as indicated by the results in Fig. 7. A similar concept realized at the receiver side is illustrated in Fig. 8(a) where multiple receiver elements with a narrow FOV provide a means for enhanced interference mitigation capabilities. The narrow FOV causes each photodetector to scan only a fraction of the available space. The overall combination of all photodetectors provides a wide FOV. This discretization of the receiver eyesight allows interference to be avoided by careful recombination of the output signals from each receiver element. These are only some examples of the cellular network research that is being conducted in the field of OWC.

(a) Illustration of signal contributions to cell-center regions and to conflicting regions.

(b) Different frequency allocation schemes. Joint transmission 1 (JT1) allocates the same frequency to all conflicting regions. Joint transmission 2 (JT2) allocates non-overlapping frequency bands to neighboring conflicting regions.
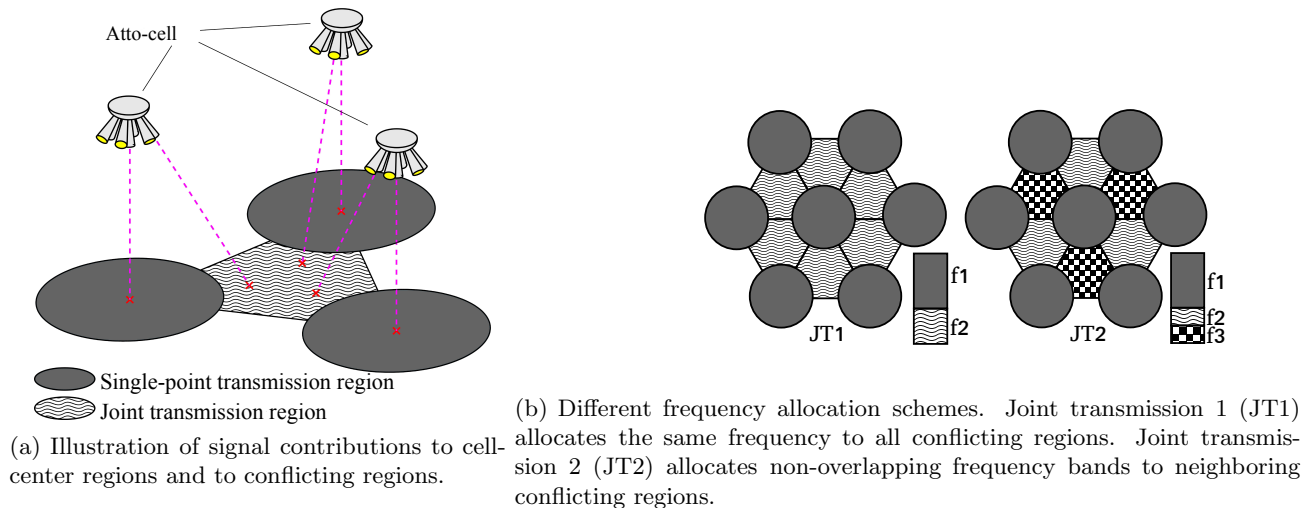
Figure 6. Resource allocation by using joint transmission. The adjacent APs transmit the same data at the cell-edge regions by coordinated transmissions. Note, in Li-Fi signals only add constructively which is a specific property that is exploited here. Frequency bands allocated to the high interference regions are different than frequency bands allocated to the cell-center regions.[30]

(a) CDF of the overall system throughput.[30]

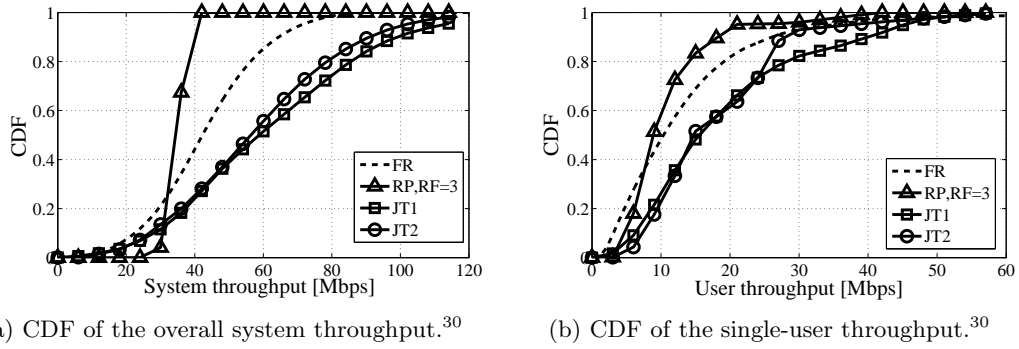(b) CDF of the single-user throughput.[30]

Figure 7. Performance comparison between four resource allocation schemes: full frequency reuse (FR), static resource partitioning (RP). joint transmission 1 (JT1), and joint transmission 2 (JT2).[30]

(a) Angle-diversity receiver and a conventional receiver.

(b) Performance conventional receiver (CR) vs angle-diversity receiver with three possible signal recombination techniques: equal-gain combining (EGC), select best (SB), and maximum-ratio combining (MRC).
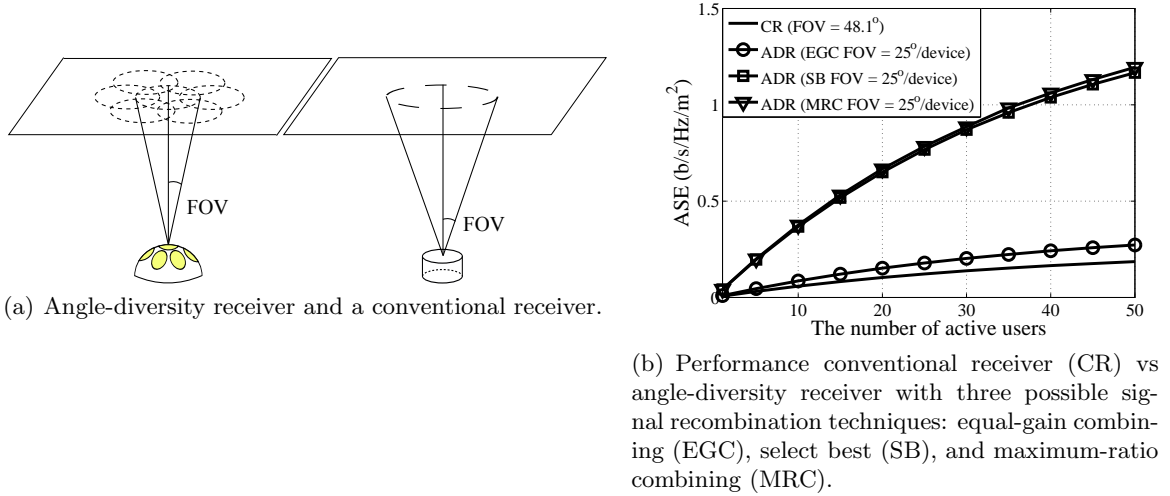
Figure 8. Performance of an angle-diversity receiver (ADR) vs. performance of a conventional receiver (CR). Parameters have been selected such that the effective area and the coverage of the two receivers are equivalent.

7. CONCLUSION

Research in VLC over the past ten years has primarily been focussed on finding an optimum modulation scheme for IM/DD assuming point-to-point VLC links by taking into account that VLC may serve two simultaneous functions: (a) illumination, and (b) gigabit wireless communication. The predominate sources for signal distortion are frequency dependent in such systems. This constitutes one key reason why there is now a general understanding that OFDM is the most suitable choice as a digital modulation scheme for Li-Fi, and there are good technical reasons to reconsider the IEEE 802.15.7 VLC standard. The straightforward multiple access technique that OFDMA provides at almost no additional complexity and its compatibility to state-of-the art wireless standards like LTE and IEEE 802.11 further favor the selection of this modulation/multiple access scheme.

The realization of a bidirectional connection also seems to have been addressed successfully to an extent that the first commercial bidirectional point-to-point Li-Fi systems are available. The most practical solutions to the uplink channel realization is to consider the IR or RF spectrum. The confidence brought by encouraging recent research results and by the successful VLC link-level demonstrations, has now shifted the focus towards an entire Li-Fi attocell networking solution. The unique physical properties of light promise to deliver very densely-packed high-speed network connections resulting in orders of magnitude improved user data rates. Based on these very promising results, it seems that Li-Fi is rapidly emerging as a powerful wireless networking solution to the looming RF spectrum crisis, and an enabling technology for the future Internet-of-Everything. Based on past experience that the number of wireless applications increases by the square of the number of available physical

connections, Li-Fi could be at the heart of an entire new industry for the next wave of wireless communications.

ACKNOWLEDGMENTS

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