What is LiFi?

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Abstract *Light-Fidelity (LiFi) takes visible light communication (VLC) further by using light emitting diodes (LEDs) to realise fully networked wireless systems. Synergies are harnessed as lights become LiFi attocells resulting in enhanced wireless capacity for the Internet-of-Things (IoT), 5G and beyond.*

Introduction

Due to the increasing demand for wireless data communication the available radio spectrum below 10 GHz (cm-wave communication) has become insufficient. The wireless communication industry has responded to this challenge by considering the radio spectrum above 10 GHz (mm-wave communication). However, the higher frequencies, f, mean that the path loss, L, increases according to Friis free space equation ($L \propto f^2$). In addition, blockages and shadowing in terrestrial communication are more difficult to overcome at higher frequencies. As a consequence, the systems must be designed to enhance the probability of line-of-sight (LoS), typically by using beamforming techniques and by using very small cell sizes (about 50 m). In fact, the need for small cells sizes are not an issue. This is because reducing cells sizes has notably been the major contributor for enhanced system performance in current cellular communications. This means, contrary to the general belief, using higher frequencies for terrestrial communication is a real option. However, the disadvantage is an increased requirement for infrastructure deployment. LiFi[6,9] is a natural continuation of the trend to move to higher frequencies in the electromagnetic spectrum. Specifically, LiFi could be classified as nm-wave communication. LiFi uses LEDs for high speed communication, and speeds of over 3 Gbps from a single micro LED[13] have been demonstrated using optimised direct current optical orthogonal frequency division multiplexing (DCO-OFDM) modulation[5]. Given that there is a wide-spread deployment of LED lighting in homes, offices and streetlamps because of their energy-efficiency, there is an added benefit for LiFi cellular deployment in that it can build on an existing infrastructure. Moreover, the cell-sizes can be reduced further compared to mm-wave communication leading to the concept of LiFi attocells[10]. LiFi attocells are an additional network layer within the existing heterogeneous wireless networks, and they have zero interference from, and add zero interference to, the radio frequency (RF) counterparts such as femtocell networks. A LiFi attocell network uses the lighting system to provide fully networked (multiuser access and handover) wireless access. This paper provides some initial results of the downlink performance of a DCO-OFDM LiFi attocell network and compares the performance to state-of-the-art RF femtocell networks.

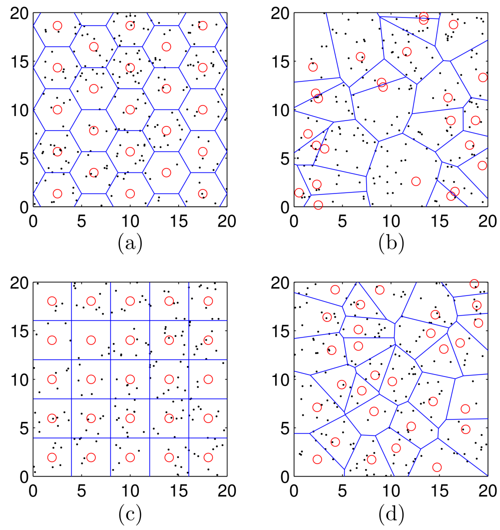

Fig. 1: A room of size 20 m × 20 m is considered. The circles in the figure represent the positions of the optical access points (APs), which are also the room lights, while the dots represent the positions of the terminals which can be smartphones or 'things'. Different deployment scenario studied: (a) Hexagonal network model. (b) PPP network model. (c) square network model. (d) HCPP network model.

Modelling LiFi Networks

In a LiFi attocell network, the placement of the APs affects the system performance. The light signal from a neighbouring AP causes interference which limits the signal-to-interference-plus-noise ratio (SINR). Due to the use of LEDs, coherent transmission is not possible, and data has to be encoded by means of intensity modulation (IM)/direct detection (DD). As a consequence frequencies between zero and typically 20 MHz for

Tab. 1

Parameters	Values
Vertical Separation	2.25 [m]
PD responsivity	0.6 [A/W]
PD physical area	1 [cm^2]
Receiver field of view	$90°$
Receiver noise PSD	10^{-19} [A^2/Hz]

phosphor-coded commercial white LEDs assuming a blue filter at the receiver, and between 60 MHz – 100 MHz for micro LEDs are used. The bandwidth can be shared among different optical APs according to the well-known frequency reuse concept[7] in order to mitigate co-channel interference, but this is at the expense of available bandwidth at each AP. Frequency reuse is modelled with a parameter Δ. For example, $\Delta = 3$ means that the available modulation bandwidth is divided into three equal parts and each part is assigned to an AP in a way that the geometric re-use distance of the same part of the bandwidth is maximised. Since lighting and wireless data communication are combined the placement of the optical APs is mainly determined by the lighting design. The effect of the location of APs is evaluated for four different scenarios as shown in Fig. 1. The models developed for cellular RF networks are used because the principal optimisation objectives are similar, namely complete and uniform signal coverage. Similarly, lighting in home and office environments is designed to be able to illuminate the entire space in a uniform manner[8]. Fig. 1 a) shows the traditional hexagonal topology as has been used to analyse RF cellular networks. Fig. 1 b) shows a random AP deployment following a Poisson point process (PPP) model which reflects practical cellular network deployments. However, there is a possibility that the distance between two AP is zero, which is unrealistic. Also, APs can be close to each other leading to high interference. Frequency re-use of $\Delta > 1$ will reduce interference. Fig. 1 c) shows a square lattice topology to model a regular lighting placement used in large offices and public places. Fig. 1 d) shows the Matérn type I hardcore point process (HCPP) deployment scenario which includes an additional parameter c that controls the minimum separation distance between any two APs in order to address the limitation of the PPP model in Fig. 1 b)[12]. These four models represent many specific lighting deployment scenarios. Experimental validation of this is being undertaken. Random user locations are considered in this work. Fig. 2 shows the cumulative density function (CDF) of the SINR for the different network topologies in Fig. 1. For all scenarios an AP density of 0.0353 APs/m^2 is considered. The optical output power of the LiFi AP is set so that the average illuminance in the room is at least 500 lx for reading purposes[8]. The rest of the system parameters are listed in Tab. 1. From Fig. 2, it can be seen that the SINR of an APs deployment on a hexagonal lattice gives the best performance, followed by the deployment on a square lattice. Similar to the conclusions in[1], the SINR performance of a random PPP network results in worst performance. If a minimum distance between APs is enforced by using the HCPP model, the SINR performance improves as is expected. The results show that the performance of a LiFi optical attocell network can vary significantly. Assuming a minimum SINR of 3 dB for data transmission with acceptable bit error ratio (BER), the probability that this would be achieved can vary between 50 % and 75 %.

The data rate performance is also evaluated and compared with state-of-the-art RF femtocell networks. Optical attocell networks exploit the ability of LiFi to achieve a massive spatial reuse because the typical cell radii, R, are 1 m to 4 m enabling a room to have multiple independent LiFi APs. In contrast, femtocells typically have an order of magnitude larger cell radius[3]. To demonstrate the high data density achieved by an optical attocell system, the area data rate, s_{area}, is used, and this is defined as:

$$s_{\mathrm{area}} = \frac{s}{A_{\mathrm{cell}}}, \tag{1}$$

where A_{cell} is the cell area defined as the coverage area of a single AP, and s is the throughput of a single cell. The throughput is obtained from the SINR using adaptive modulation and coding tables[14]. The division by the cell area allows for a normalisation for different cell areas, and is related to area spectral efficiency (ASE). Fig. 3 shows the area data rate performance of optical attocell networks and femtocell networks against channel bandwidth, as LEDs provide freely available spectrum. Also, Fig. 3 shows the potential if the future LED devices are improved in terms of their bandwidth. The results of the femtocell network are taken from[2–4,11]. The indoor ASE achieved by the femtocell network is generally in the range from 0.03 to 0.0012 bps/Hz/m^2. Therefore, this ASE range is used to calculate a minimum and maximum area data rate for the benchmark femtocell network. From Fig. 3 it can be

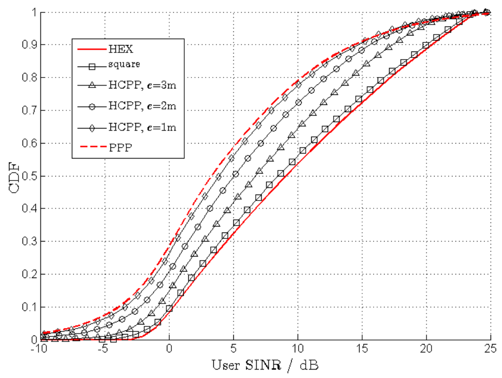

Fig. 2: Compare the SINR CDF by systems with different network deployments. The BS density of each system is 0.0353 APs/m^2, and full frequency re-use is assumed, i.e., $\Delta = 1$. Other parameters are listed in Tab. 1.

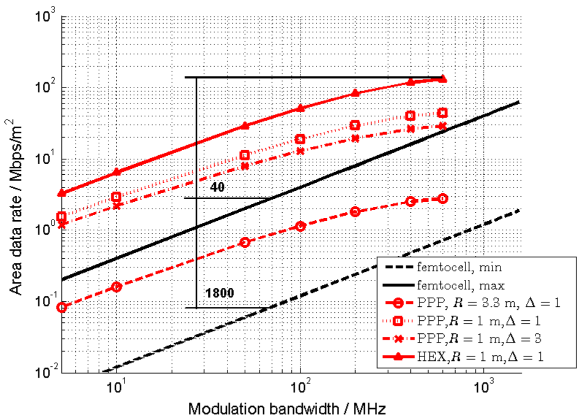

Fig. 3: Area data rate of LiFi attocell network assuming different deployment scenarios, and comparison with state-of-the-art RF femtocell networks. The micro LED as used in [13] is considered; its 3-dB bandwidth is 60 MHz. Note, bit- and power loading are used in DCO-OFDM, and the modulation bandwidth is significantly larger than the device bandwidth as there are no bandwidth limitations. This is because LiFi is using free and unlicensed spectrum.

concluded that i) the LiFi attocell network could achieve 40 – 1800 higher area data rate compared to femtocell networks; ii) the best femtocell performance would require a total channel bandwidth of 600 MHz to achieve the same performance of an LiFi attocell with PPP random AP deployment, frequency reuse of 3 and cell radius of 1 m; iii) when the LiFi AP cell coverage is large (R=3.3 m, A_{cell}=34.2 m^2), the AP deployment is PPP random, and full frequency reuse, Δ=1, the LiFi attocell area data rate performance is within the reported range of femtocell networks, and also closer to the maximum reported performance; iv) in all cases, the LiFi attocell network enhances the wireless performance significantly, and for the considered office of 400 m^2, the additional maximum throughput is in the range 12 – 48 Gbps.

Conclusions

More than 15 years of research in physical layer techniques for LED-based VLC has provided the fundamental solutions to develop LiFi attocell networks that are capable of achieving magnitudes of higher data rates per unit area compared to state-of-the-art RF small cell solutions. A key factor enabling this is the radical reduction of cell sizes, and this is possible by using the existing infrastructures through the combination of LED lighting and wireless data networking. The new wireless LiFi networking paradigm offers performance enhancements that are sought from the 5$^{\mathrm{th}}$ Generation (5G), and at the same time due to the ubiquitous use of LEDs, this will provide an infrastructure for the emerging IoT.

Acknowledgements

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References

[1] J. Andrews, F. Baccelli, and R. Ganti. A tractable approach to coverage and rate in cellular networks. IEEE Trans. on Commun., 59(11):3122–3134, Nov. 2011.
[2] P. Chandhar and S. Das. Area Spectral Efficiency of Co-Channel Deployed OFDMA Femtocell Networks. IEEE Trans. Wireless Commun., 13(7):3524–3538, July 2014.
[3] V. Chandrasekhar, J. Andrews, and A. Gatherer. Femtocell Networks: A Survey. IEEE Commun. Mag., 46(9):59–67, 2008.
[4] W. C. Cheung, T. Quek, and M. Kountouris. Throughput Optimization, Spectrum Allocation, and Access Control in Two-Tier Femtocell Networks. IEEE J. Sel. Areas Commun., 30(3):561–574, Apr. 2012.
[5] S. Dimitrov and H. Haas. Information Rate of OFDM-Based Optical Wireless Communication Systems With Nonlinear Distortion. J. Lightw. Technol., 31(6):918–929, March 2013.
[6] S. Dimitrov and H. Haas. Principles of LED Light Communications – Towards Networked Li-Fi. Cambridge University Press, Mar. 2015.
[7] V. Donald. Advanced mobile phone service: The cellular concept. The Bell System Technical Journal, 58(1):15–41, Jan 1979.
[8] European Standard EN 12464-1. Lighting of Indoor Work Places, Jan. 2009.
[9] H. Haas. Wireless Data from Every Light Bulb. TED Website, Aug. 2011.
[10] H. Haas. High-speed Wireless Networking Using Visible Light. SPIE Newsroom, Apr. 19 2013.
[11] H.-S. Jo, P. Xia, and J. Andrews. Downlink Femtocell Networks: Open or Closed? In Proc. of IEEE Int. Commun. Conf. (ICC), pages 1–5, June 2011.
[12] D. Stoyan, W. S. Kendall, and J. Mecke. Stochastic Geometry and its Applications. John Wiley and Sons, 2nd edition, 1995.
[13] D. Tsonev et al. A 3-Gb/s Single-LED OFDM-Based Wireless VLC Link Using a Gallium Nitride μLED. IEEE Photon. Technol. Lett., 26(7):637–640, Apr. 2014.
[14] F. Xiong. Digital Modulation Techniques. Artech House Publishers, 2nd edition, 2006.