VLC: Beyond Point-to-Point Communication

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Abstract

Due to the large growth of mobile communications over the past two decades, cellular systems have resorted to fuller and denser reuse of bandwidth to cope with the growing demand. On the one hand, this approach raises the achievable system capacity. On the other, however, the increased interference caused by the dense spatial reuse inherently limits the achievable network throughput. Therefore, the spectral efficiency gap between users' demand and network capabilities is ever-growing. Most recently, visible light communication (VLC) has been identified as well equipped to provide additional bandwidth and system capacity, without aggregating the interference in the mobile network. Furthermore, energy efficient indoor lighting and the large amount of indoor traffic can be inherently combined. In this article, VLC is examined as a viable and ready complement to radio frequency (RF) indoor communications, and advancement toward future communications. Various application scenarios are discussed, presented with supporting simulation results, and the current technologies and challenges pertaining to VLC implementation are investigated. Finally, an overview of recent VLC commercialisation is presented.

I. INTRODUCTION

Since the introduction of mobile technologies over thirty years ago, wireless communications have evolved into a utility similar to water and electricity, fundamental to the socio-economic growth of the modern society. To support the ever-growing demand for mobile communications, cellular networks have had to evolve from simple local service providers, to massively complex cooperative systems. Indeed, meeting this exponentially growing demand (see Fig. 1) is the main challenge for wireless communications over the next decade(s).

A. *Looming spectrum crisis*

Fig. 1 illustrates the discrepancy between traffic demand and network capacity as a result of the continued proliferation of mobile communications. From Shannon's initial work in information theory, it is clear that the capacity of a wireless link (and, by extension, of a network) is directly proportional to the available bandwidth. On the one hand, the system capacity in previous generations of cellular networks was diminished by limiting the spatial reuse of frequencies in an attempt to minimise interference. On the other hand, the most recent generation of wireless technologies, Long-Term Evolution (LTE) and beyond, rely on full frequency reuse along with advanced interference management algorithms to maximise the system capacity, *i.e.*, each cell may use the entire available bandwidth. Nonetheless, despite employing interference management, there is a trade-off between bandwidth use and link connectivity.

[Fig. 1 about here.]

Future networks are moving towards more heterogeneous architectures where multiple access pointss (APs) (*e.g.*, macro-, pico-, femto-cells, relays and/or remote radio heads) are available in each cell [1]. This will lead to an even denser spatial reuse of resources. These heterogeneous networks (HetNets) provide enhanced coverage in standard cellular networks, and improve the capacity of the system. As an example, Ericsson's recent acquisition of BelAir is specifically aimed at advancing Ericsson networks to heterogeneous deployments, offering "small cell" Wireless fidelity (Wi-Fi) integration into traditional macro-base station (BS) coverage. Unfortunately, the increased frequency reuse introduces both inter- and intra-cell interference, which limits the achievable capacity of the network. To this extent, the conventional methods for capacity-improvement, *i.e.*, enhanced spatial reuse and inter-cell interference coordination (ICIC), will be unable to support the growing demand for mobile communications. Therefore, a new, RF-orthogonal communication medium is required to fill the ever-increasing capacity gap.

B. Closing the Spectral Efficiency Gap with VLC

VLC relies on the visible light (VL) spectrum for communication, rather than the cluttered, scarce and expensive RF spectra used today for wireless communications. In fact, VL is not regulated, and can therefore be used freely for communication purposes, significantly reducing the costs for operators. Thus, VLC presents a viable alternative to traditional communication methods and may be used as a complement to current RF communications [2, 3].

Furthermore, recent studies indicate that a substantial portion ($> 70\%$) of wireless traffic originates indoors [4]. Signal propagation through walls, however, severely inhibits the operation of indoor data services, which is attracting considerable interest into providing wireless communications directly indoors. Indeed, VLC is well suited to fill this function as

- most indoor environments are illuminated;
- VL cannot penetrate solid objects;
- VL can be easily directed through optics; and
- as previously mentioned, it is interference-orthogonal to the cellular network.

These characteristics permit very close spacing between VLC nodes, therefore increasing the spatial reuse of resources, providing higher data density and resulting in increased network capacity. In addition, in an attempt to reduce the carbon footprint of the information and communication technology (ICT) industry, there has been a research drive for more energy efficient networks [5]. In this context, another advantage of VLC systems is that the energy used for communication in VLC is essentially free due to the lighting requirement(s) of indoor spaces, *i.e.*, no extra energy is required for information transmission, with minimal additional power to drive the necessary circuitry for communication.

C. Differences between RF and VLC

Although both VL and RF communication employ electromagnetic radiation as the information medium, the two concepts differ significantly in their inherent properties. Waves in the visible region of the spectrum cannot penetrate through most surfaces that are present in everyday surroundings. Radio waves, on the other hand, are particularly apt at providing sufficient connectivity through the majority of commonly-used materials. As previously mentioned, this offers very interesting benefits. Information may be contained within the confined space of the specific premises where a VLC system is deployed. This practically eliminates the possibility for casual eavesdropping. More importantly, it eliminates interference between spatially isolated communication systems, removing one of the biggest challenges in RF communications.

[TABLE 1 about here.]

With the current state of off-the-shelf illumination components and photodetectors, VLC is realisable as an intensity modulation and direct detection (IM/DD) scheme. This means that only the signal intensity is used to convey information, which although more limiting than RF, is also advantageous. The wavelength of VL (380 nm to 750 nm) is much smaller than the typical area of a photodetector, which effectively removes multipath fading (as opposed to RF communication) from the system. In addition, signals in the optical domain do not interfere with the operation of sensitive electronic systems and can be used in a variety of applications where RF is not allowed, *e.g.*, hospitals, aircraft, chemical plants, *etc.* Indeed, the goal of VLC is not to replace RF, but rather to complement it in the context of HetNets where the best of both physical domains and resulting propagation characteristics are employed.

II. POTENTIAL APPLICATIONS FOR VLC

A. Infrastructure

Wireless HetNets are widely seen as the future of mobile communications, as smaller and smaller cells are used to offload and localise traffic. Indeed, the simple concept of cell-size reduction has increased the system spectral efficiency by a factor of 2700 over the last 50 years [6]. To this extent, even smaller VLC atto-cells are just a logical progression to provide the next 1000 times system capacity increase. There are two important aspects to consider with small cells, the first being coordination with the macro-network, while the second aspect is the integration of Wi-Fi capabilities with 3rd Generation Partnership Project (3GPP) technologies. This enables, for example, mobile users to connect to Wi-Fi APs automatically based on authentication information held on a mobile operator's customer database.

In this context, the term "Light fidelity (Li-Fi)" is defined as the subset of VLC that exhibits *high-speed, bidirectional and fully networked* communications; the Li-Fi Consortium has already begun promoting this technology. Li-Fi is envisioned to fill a complementary role along with Wi-Fi to offload traffic from the macro BSs. The key to a high performing system is not merely to increase the link-level spectral efficiency. In fact, the most relevant aspect to a mobile vendor is the area spectral efficiency (ASE), *i.e.*, what mobile data rates can be offered for each user. In this context, Li-Fi is shown to provide at least an order of magnitude improvement in the ASE [7]. In addition, one of the key obstacles to the widespread application and integration of Wi-Fi in modern communication systems is the interoperability of the 3GPP technology with the Wi-Fi standards. Principally, Li-Fi requires adapting only the front-ends and physical layers of typical femto- or pico-cells, while the above-lying protocols, authentication, channels, etc., can remain (fundamentally) unchanged.

However, a VLC standardisation drive would need to account for some of the VL-specific problems such as intra- and inter-frame flicker, dimming, visibility patterns, and others. The new standard, which would be based around orthogonal frequency division multiplexing (OFDM), could stipulate that only sub-carriers above a certain frequency may be used for modulation. In this manner, the system would always avoid flicker issues. Similarly, dimming could be achieved by reducing the average signal power. For example, if direct-current-biased optical OFDM (DCO-OFDM) is used, that would mean a lower biasing point, as well as potentially shallower modulation depth for the signal (of course, this may result in a diminished signal-to-noise ratio (SNR)). This facilitates a rapid development and deployment of Li-Fi technology complementary to the current RF BSs with unique advantages (*i.e.*, high ASE, security, lack of electromagnetic interference, as mentioned in Section I). To this extent, the future implementation of VLC technology should focus on retaining the system architectures outlined in 3GPP and be designed to comply with such standards.

A well-designed HetNet should make use of its elements in an efficient manner. Each link in the network is employed when it is most relevant for the respective task. Just like optical fibers and cables are most appropriate for high-speed backbone functionality and RF communication is suitable for APs with good coverage, VLC communication is best suited for high data rates and a secure interface between a BS and a mobile station (MS). Such a connection is not needed constantly. A lot of the time, a mobile device is simply dormant, waiting for an incoming data transmission or for the user to request one. For these tasks to be negotiated successfully, a constant connection is required. Such a connection can be provided by the existing, well-established, RF connectivity. The heavy load of the high-speed data transfer can then be allocated to the VLC network. If a VLC connection is not possible, the MS may be served with RF until an appropriate optical AP is nearby.

Finally, the discussion regarding the practicality, performance and future of VLC is not constrained by the underlying technology of the physical illumination devices. Currently the most wide-spread devices are traditional light-emitting diodes (LEDs), however other technologies are emerging as well – organic based LEDs, micro-LEDs, as well as resonant cavity LEDs – which are fundamentally all electronics devices, capable of data transmission. Thus, the research community is investing significant effort into manufacturing devices that are capable of simultaneous illumination and communication.

B. Other Applications for VLC

VLC could also enable indoor as well as improve city canyon navigation where Global Positioning System (GPS) signal is weak/non-existent. Due to the simplicity of its front-end hardware, it can play a significant role in enabling the Internet of things and machine-to-machine communication in general. Car-to-car communication [8] could be one of the first implementation scenarios as manufacturers are beginning to make a move towards solid-state lighting solutions.

Other possible areas that stand to benefit from the practical implementation of VLC include museums, hospitals, and underwater communications [9, 10]. Museums could exploit the already present light fixtures to not only illuminate their exposition pieces, but also to continuously transmit information about them. This could redefine the way automated tours are executed. Hospitals could achieve ubiquitous networking without any detriment to equipment that is sensitive to RF radiation. This should improve hospital care and reduce staff workload.

Underwater communications stand likely to benefit most. RF and sound communication are unable to provide fast wireless connectivity under water. Although VLC will also face challenges in that particular propagation environment, it should deliver significant data rate improvements when conditions allow, and otherwise fall back to existing technology, for example sound waves, to provide basic connectivity.

III. CHALLENGES OF VLC PRACTICAL IMPLEMENTATION AND INTEGRATION

A. Modulation

Realisation of VLC as an IM/DD system means that only positive and real signals can be successfully transmitted. This limits the modulation schemes which can be employed. Early work in the field suggested on-off keying (OOK) and pulse-position modulation (PPM) as viable techniques. However, the bandwidth of the front-end elements and the optical channel is limited. This leads to the requirement for multi-level schemes like unipolar pulse-amplitude modulation (PAM) in order to achieve higher throughput. As the communication speeds increase, the limited communication bandwidth leads to inter-symbol interference (ISI). Hence, a more sophisticated scheme like OFDM becomes the prime candidate for VLC.

Conventional OFDM generates complex bipolar signals. Therefore, modifications have to be made before it becomes suitable for VLC. A commonly-accepted method to generate a real time domain OFDM signal is to impose Hermitian symmetry on the carriers in the frequency domain. The resulting waveform, however, is still bipolar and needs to be modified further. A number of different techniques for the creation of unipolar signals exist. A straightforward approach is called DCO-OFDM. It involves the addition of a bias current to the bipolar signal, making it unipolar [11]. However, the addition of the direct current (DC)-bias increases the power dissipation of the time domain signal significantly when compared to the bipolar case.

In order to avoid this DC bias, alternative techniques such as asymmetrically-clipped optical OFDM (ACO-OFDM) exploit the properties of the OFDM frame to generate a signal which does not need biasing. In ACO-OFDM, only the odd subcarriers in the frequency domain are modulated, which leads to a symmetric time domain signal [11]. The symmetry allows negative values to simply be set to zero without affecting the encoded information as all distortion falls on the even subcarriers in the frequency domain. Other similar approaches which exploit different properties of the OFDM frame, but effectively achieve the same result are: pulse-amplitude modulated discrete multitone modulation (PAM-DMT), unipolar OFDM (U-OFDM) and flip-OFDM.

A modulation signal can be linearly encoded in the current which flows through an LED. The relationship between the current and the emitted light is not linear as illustrated in Fig. 2. OFDM-based systems are particularly sensitive to the described non-linear effects due to their high peak-to-average power ratio (PAPR). One approach to counter non-linearity is to operate the LED in a small range where its output characteristic is linear enough. However, the dispersive nature of non-coherent light and the resulting high path loss require the use of as much of the device active region as possible. Another approach is to pre-distort the signal such that the output of the LED has the desired shape. This, however, is limited by the accuracy of the digital-to-analog conversion and inconsistencies in the non-linearity of the LED output characteristic. Currently, the question of combating non-linearity is one of the biggest challenges for VLC systems.

[Fig. 2 about here.]

B. Multiple Access

As with any communication system, however, the ability to serve multiple users is crucial. Both time division multiple access (TDMA) and code division multiple access (CDMA) are viable alternatives in addressing the multiple access limitation of Li-Fi. Indeed, TDMA was utilised within the OMEGA project for the optical wireless medium access control (MAC) [12], whereas optical-CDMA uses codes to separate users over the channel. To this extent, the underlying modulation scheme is irrelevant for enabling multiple access in an optical wireless system.

However, since OFDM is widely considered as the most viable modulation technique for VLC, orthogonal frequency division multiple access (OFDMA) is the natural extension to provide multiple access. OFDMA can be employed in VLC in a similar manner to RF communications, where each user is allocated a portion of the total available subcarriers in each time slot. Furthermore, subcarrier allocations may be varied over time, such that users' potentially varying traffic requirements and channel conditions can be accommodated.

It should be noted that, due to the constraints of VLC (see Table 1), not all OFDM subcarriers are available for communication, as discussed in Section III-A. However, this will not retard the multiple access capabilities of the system, but simply limit the number of subcarriers allocatable to each user.

C. Uplink

In general, most demonstrations of VLC technology up until now focused on maximising the communication speed over a point-to-point, *unidirectional* channel [9, 10]. However, in order to realise the envisioned Li-Fi communication systems, it is clear the first logical step is the establishment of bidirectional communication, *i.e.*, uplink transmission. This is not straightforward, as employing the same VL band in both directions would result in large self-interference at a transceiver due to cross-talk, unless physical separation of the photo diode (PD) and LED can be administered. However, just as in RF communications, there are two methods to support this bidirectionality: time division duplexing (TDD) and wavelength division duplexing (WDD) (termed frequency division duplexing (FDD) in RF).

WDD employs separate (non-overlapping) frequency bands for downlink and uplink, such that cross-talk between a transceiver's LED and PD is eliminated. For example, the near-infrared band may be utilised for uplink transmission, avoiding interference to/from the VL band. Although, because this band is outside the visible region, eye safety must be ensured by transmit power limitation. TDD, on the other hand, allows the use of the same VL band, however downlink and uplink are not performed simultaneously. However, a VL transmitter at the device may be uncomfortable from a user perspective, and the power requirements for such a source may make it impractical for device integration.

Finally, another perspective to solve this problem is to make use of the already existing infrastructure, *i.e.*, RF communication. Through the proliferation of Wi-Fi and mobile connectivity, the VLC downlink is maintained while essentially "piggy-backing" the RF networks in order to provide uplink transmission. However, seamless connectivity between networks and fixed mobile convergence are long-standing problems in RF, and thus this must be solved before Li-Fi can be properly integrated in future RF HetNets.

IV. RESULTS

This section present results from previous studies, indicating the enormous potential VLC has for future networks in a multitude of application scenarios.

A. HetNet ASE

In Section I the evolution of wireless networks towards heterogeneous architectures is described, where multiple tiers of communication can be located within the area normally served solely by a macro-cell. The reduced spatial separation when reusing the RF spectra, results in more interference; using Li-Fi indoors can mitigate this interference.

In [7], a comparison of the achievable ASE of RF femto-cells and a VLC network in a two-tier HetNet is examined, yielding the results displayed in Fig. 3.

[Fig. 3 about here.]

Depending on the size of the apartments emulating the indoor environment (proportional to the number of walls) and the number of femto-APs allocated in the building, a Li-Fi system can achieve over 900 times the ASE of a corresponding femto-cell network. Of course, this gain diminishes for larger rooms and additional femto-cells, however, Fig. 3 shows that this gain is always positive, indicating a unanimous benefit when utilising non-interfering VL spectrum rather than RF.

B. Multi-band Coverage

In the early days of mobile communications, a cellular network was generally separated into clusters, within which the system bandwidth was split and divided amongst neighbouring cells to mitigate co-channel interference (CCI). The latest generation of wireless technologies, however, employ full frequency reuse, using intelligent ICIC to control interference.

One of the core advantages of VLC is the vast available spectrum in comparison to RF. Instead of having to divide a set system bandwidth into multiple orthogonal bands, it is now possible to simply add a non-overlapping section of VL spectrum, and thus not only enhance the system bandwidth, but also curtail CCI caused by dense spatial reuse.

[Fig. 4 about here.]

Such a process is described in [13], with the results shown in Fig. 4. By adding additional wavelengths, it is evident from Fig. 4 that

a) the dead zones in the coverage area are substantially reduced, and
b) the achievable signal quality and, consequently, rate have been significantly augmented.

Moreover, the utilisation of multiple VL spectra allows for enhanced data density, as physically overlapping cells can transmit on different frequencies and increase the available bandwidth per unit area, and thus the ASE.

C. *Initial multiple-input multiple-output (MIMO) Investigation*

The finite bandwidth of front-end devices limits the speed of a communication system. Different lab experiments have shown communication capability of a single link up to 3 Gbit/s [10]. However, in order to go well beyond the Gbit/s rate, it is likely that MIMO would need to be employed in VLC.

Currently, there exist two possible implementations of MIMO receiver systems – one based on PDs and another on imaging type sensors. Utilising PDs has the advantage that the hardware implementation is relatively simple. On the other hand, imaging sensors facilitate easy separation of MIMO channels. However, the speed and accuracy of their present hardware implementations considerably limit their application in VLC-MIMO.

Recent studies of MIMO have shown that for a well-distributed configuration of transmitters, receiver elements with angle diversity have the potential to reach very high communication capacity which scales almost linearly with the MIMO order employed [14]. Fig. 5 illustrates two possible MIMO configurations and the corresponding capacity distributions across an empty $5\mathrm{m} \times 5\mathrm{m} \times 3\mathrm{m}$ room for three different heights of the receiver. As apparent from the results, the capacity is distributed quite uniformly and grows about linearly with the number of MIMO elements. This stems from the possibility to isolate information streams in space.

[Fig. 5 about here.]

The concept of Spatial Modulation (SM) and Spatial Shift Keying (SSK) are shown to be particularly applicable in an optical wireless system [15], where a low complexity, multiple transmitter generalised space shift keying (GSSK) signaling technique for short range indoor VLC is presented. In a transmitter with N_t number of transmit elements, this signaling technique is capable of achieving a spectral efficiency of N_t bits/s/Hz. GSSK supplies a higher spectral efficiency than the conventional OOK and PPM techniques. Moreover, the GSSK transmitter is much simpler than that of an equivalent regular PAM system with a similar spectral efficiency, avoiding challenges such as the LED non-linearity.

V. CHALLENGES OF VLC COMMERCIALISATION

If VLC is to become widespread, a number of challenges pertaining to its commercialisation must be addressed. In particular, the drive toward an industry standard, possible market penetration and applications must be considered. A number of suitable application scenarios are identified in Section II. However, these applications must offer a sufficient incentive for potential companies and the standard must look ahead of the current technology.

A. Standardisation

Some consideration has already been given to VLC standardisation. Most notably, the IEEE 802.15.7 standard has been established in 2009 for short range optical wireless communications using visible light where the physical (PHY), MAC and logical link control (LLC) layers are specified with very high associated LED bandwidths. Furthermore, the Visible Light Communications Consortium (VLCC) has developed several standards for VLC, published by the Japanese electronics standards body. In addition, the Infrared Data Association (IrDA) has created standards for point-to-point short range optical communications, with data rates from 1 Gbps.

However, recent research showing the successful use of OFDM for VLC may drive the need for new standardisation. By considering optical OFDM (O-OFDM), chiefly enabled through the use of variable current drivers and first demonstrated as a viable transmission technique at TED Global in 2011, a VLC system can achieve significant improvements in spectral efficiency and simplify both multiple-access and mobility considerations. Because the PHY layer of an O-OFDM system is so different relative to the existing VLC standards, the MAC and associated higher layers are also different. Therefore, if O-OFDM is to be at the heart of the latest evolution of VLC, then a new standardisation drive is required. The nature of O-OFDM means that only the optical front-end and the lower level PHY would require changes to seamlessly integrate a VLC system with the existing higher layer definitions of either LTE or 802.11. However, the potential of VLC is in the PHY layer with the same features as cellular communication, where it can replace the standard RF front-end with an optical alternative. This consideration means that VLC can rely on readily available IEEE 802.11 or LTE protocol stacks. By removing the need to standardise the entire communication system, VLC may be employed in a large scale network with minimal infrastructure and coordination efforts. Such a combination narrows the focus of any standardisation effort. In addition, since the publication of the IEEE 802.15.7 standard, research in the area of VLC has increased. Among the key findings are the increased system performance resulting from the application of both OFDM and the MIMO concept, which emphasizes the need for a new, industry driven, standard.

B. Market Conditions

Despite the need for standardisation, companies are actively working on commercialising VLC technology. The VLC market is projected to grow as LED lighting becomes more prolific. The VLC market applications have been outlined in Section II. In addition, VLC is particularly well suited to provide last mile connectivity and indeed projects such as the Reasonable Optical Near Joint Access (RONJA) initiative are deployed to service this demand. Furthermore, the US Department of Energy estimates that a faster adoption rate of LED lighting in the US over the next 20 years can deliver energy savings of about \$265 billion and reduce the demand for lighting electricity by 33$\%$ in 2027. This highlights the inevitable growth and proliferation of LED devices along with the associated VLC market potential [9].

The VLC link is untethered in the sense that a user is independent of any one AP, and can acquire the same information from other optical APs, providing for mobility and seamless handover. Moreover, each communication link can serve multiple, distinct, user devices. This is the future of indoor Li-Fi applications, which at present are providing data connectivity in point-to-point scenarios. Nonetheless, indoor networking applications account for the largest overall market share. This market for VLC is expected to grow further from around \$83 million in 2012 to around \$4,500 million in 2018, increasing at a rate of around 84$\%$ annually from 2013 to 2018. To this extent, indoor network applications compose around 70$\%$ of the global VLC market and the growth of indoor commercial connectivity will be the major driver of this market [10].

VI. CONCLUSION

In this paper, VLC has been introduced as a unique and viable alternative to RF indoor communication strategies, and furthermore presented a plethora of application scenarios for future systems. VLC furthers the concept of ever smaller cells to deliver wireless data at exponentially increasing rates, now and in the future. It is clear that wherever there is man-made light, there is an opportunity for high-speed wireless connectivity that is complementary to RF networks and thus interference-free. Furthermore, the vast, unused VL spectrum can provide the necessary bandwidth to meet the ever-growing demands for mobile traffic. The fact that more secure indoor networks can be established through VLC is a further advantage. VLC, it seems, is destined to provide ubiquitous wireless access in the next generation(s) of mobile communication.

Being a relatively modern technology, there are, of course, many challenges that VLC systems are currently facing. Apart from the inherent non-linearity of the LEDs and limits of LED bandwidth, aspects such as signal modulation, power delivery to the transceiver, and multiple access pose difficulties for the immediate proliferation of VLC. However, since such technical challenges have already been conquered in RF through decades of research, VLC is well equipped to go along a similar, only much-accelerated, path. Furthermore, while the current abundance and maturity of RF communications may impede the commercialisation and standardisation of VLC technologies, there is no doubt that VLC will be needed in future communications generations. Thus, its proliferation has already begun.

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LIST OF FIGURES

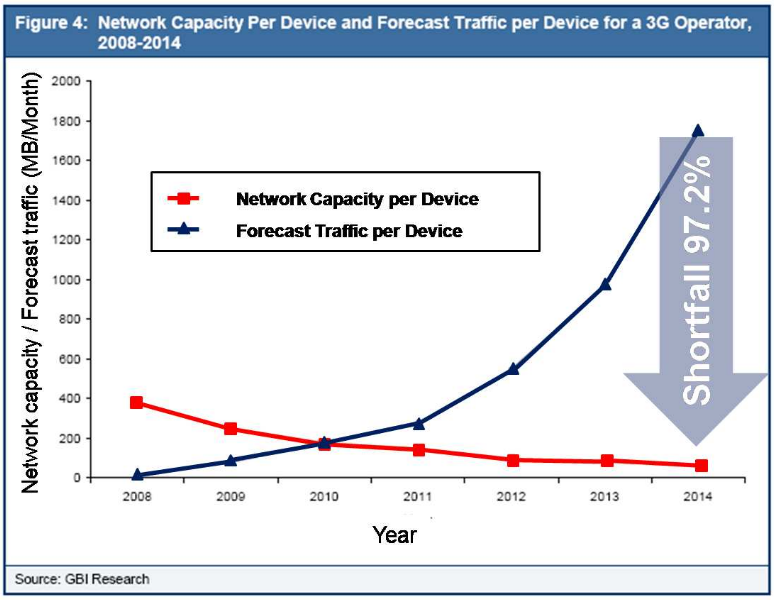


Fig. 1: The predicted, almost exponential, increase in demand of mobile communications services over the next years [9], and the corresponding network capacity evolution.

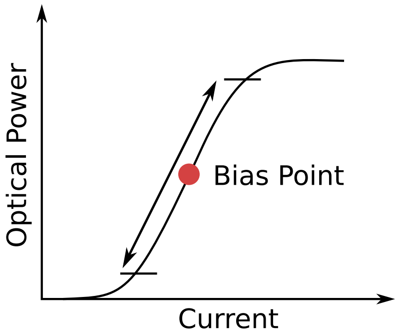


Fig. 2: Typical LED output characteristic is non-linear in three aspects: *i)* a minimum current is required for photon emission to occur; *ii)* light emission saturates after a certain current level; and *iii)* the relationship between current and light output intensity is non-linear even within the range between minimum and maximum allowed current.

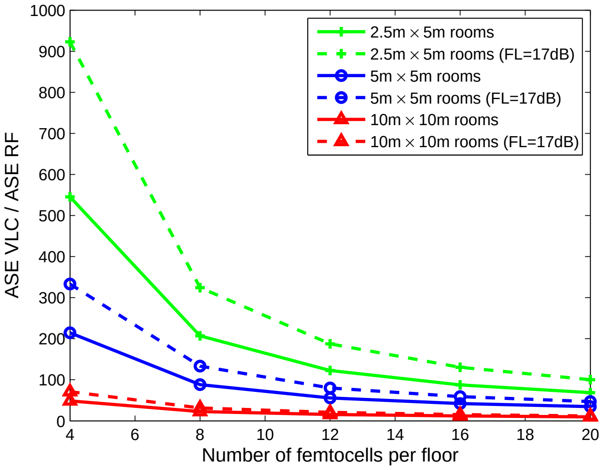
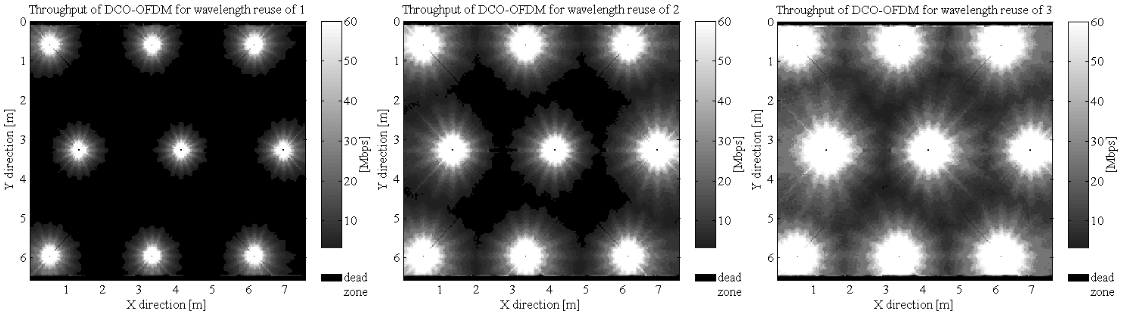


Fig. 3: The ratio of VLC ASE and RF ASE for different floor layouts.

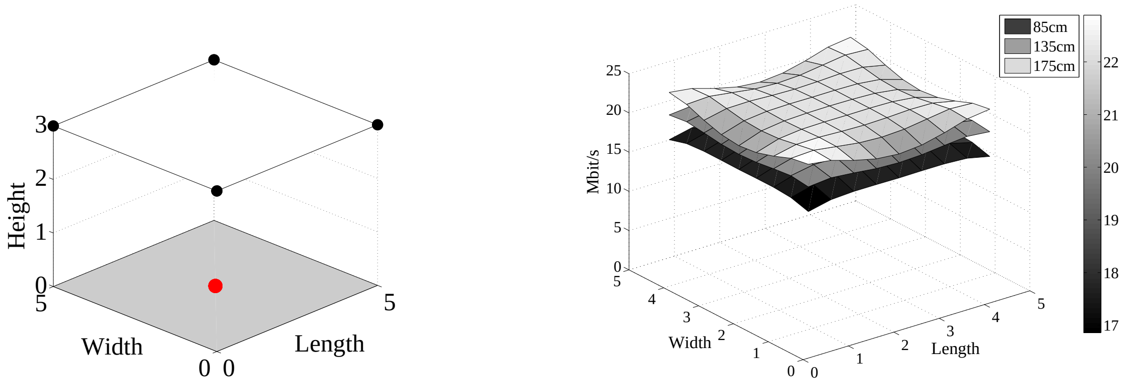


(a) Wavelength reuse of 1.

(b) Wavelength reuse of 2.

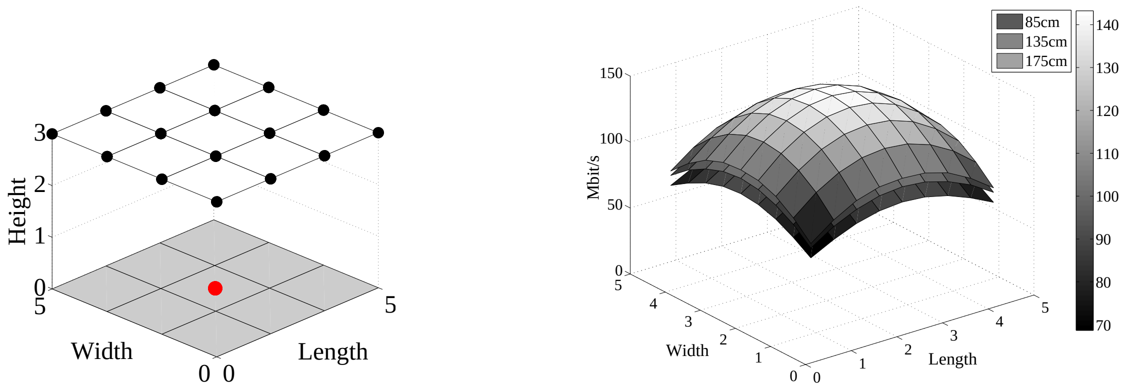
(c) Wavelength reuse of 3.

Fig. 4: Throughput of DCO-OFDM estimated via a Monte Carlo ray-tracing global irradiation simulation in a computer-aided design airplane cabin model. Signal contributions from both line-of-sight and non-line-of-sight propagation paths are considered. Wavelength sets of [940 nm], [940 nm, 870 nm], and [940nm, 870nm, 840nm] are employed in the different scenarios with wavelength reuse factor of 1, 2, and 3, respectively.



(a) 4×4 MIMO configuration.

(b) Capacity distribution for 4×4 MIMO.



(c) 16×16 MIMO configuration.

(d) Capacity distribution for 16×16 MIMO.

Fig. 5: Transmitter layout and room capacity for different MIMO configurations. Black dots indicate transmitter positions, the red dot on the floor their directions. Emission pattern is Lambertian. High-power off-the-shelf illumination devices are assumed, limiting the capacity to well below the values reported in lab experiments.

LIST OF TABLES

TABLE 1: RF vs. VLC

System	**Information**	**Signal**	
RF	carried on electric field	complex valued	bipolar
VL	carried on optical intensity	real valued	unipolar