Area Spectral Efficiency Performance Comparison between VLC and RF Femtocell Networks

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***Abstract*—In this paper the average area spectral efficiency (ASE) of indoor visible light communication (VLC) wireless network is investigated for various room geometries (2.5 m×5 m×3 m, 5 m×5 m×3 m and 10 m×10 m×3 m). A comparison is made against state-of-the-art radio frequency (RF) systems employing femtocells indoors. A modified version of the wireless world initiative new radio (WINNER) indoor deployment scenario (office building) is used as the common setup where femtocell access points (APs) and VLC APs are installed alternatively. For the RF system the minimum number of femtocell APs per floor area is four as specified in [1]. The requirement for the VLC system is to fulfill the lighting conditions inside the room, characterized by the illuminance distribution in rooms with several possible dimensions. The ASE gains of the VLC system compared to the femtocell network range between 12 and 924 (depending on the number of femtocell APs and floor geometry).**

***Index Terms*—Visible light communication, area spectral efficiency, LED, femtocell.**

I. Introduction

RF communication networks are confronted with a growing demand of high data rate mobile services and applications, especially indoors where most of mobile voice and data usage occurs. A practical solution to this problem is to employ radio femtocells [2] which are low-power, low-cost, user-deployed cellular base stations (BSs) overlayed on the existing cellular network. Femtocells provide wireless connection to subscribers within a coverage range limited to tens of meters. This improves the indoor coverage and the capacity for user traffic due to an increased reuse of radio resources.

An alternative solution which has the potential of delivering greater data rate densities (b/s/Hz/m^2) compared to radio-based systems is VLC technology [3]. VLC can be used as a complementary technology to radio technology, being able to provide high speed communication and to off-load data traffic from congested RF systems. A proposal for an indoor hybrid system that integrates wireless-fidelity (Wi-Fi) and VLC luminaries can be found in [4] where the broadcast VLC channels are used to supplement RF communications. Another attractive feature of VLC is the free and unregulated bandwidth and the fact that it can be safely used in environments where RF technology is prohibited, *e.g.* hospitals, airplanes, petrochemical plants, power plants, mines *etc.*

VLC is a data communication technology that uses the visible light spectrum with wavelengths between 375 nm and 780 nm. This technology primarily uses commercially available light emitting diode (LED) sources that can be modulated up to 500 Mbit/s [5], and are incorporated in indoor and outdoor lighting sources, commercial display, illuminated signs, computer screens, digital cameras and on mobile phone cameras for communication purposes. Therefore, the LED has a dual functionality: illumination and data transmission. As the energy efficient white LEDs are replacing the incandescent and fluorescent lamps, applications of VLC technology are expected to become widespread. Studies show that by broadcasting the light in a wide field of view (FOV), an even signal coverage and lighting for an entire room [6–8] can be achieved. Taking advantage of the fact that light waves do not propagate through walls, multiple non-interfering cells (channels) can be created in a building. This improves security and allows easy bandwidth reuse which leads to increased data rate densities. The data transmission is achieved by intensity modulation and direct detection (IM/DD). Suitable digital modulation techniques are the single-carrier pulse modulation techniques, such as multi-level pulse position modulation (M-PPM) and multi-level pulse amplitude modulation (M-PAM). Multi-carrier modulation such as orthogonal frequency division multiplexing (OFDM) in combination with multi-level quadrature amplitude modulation (M-QAM) can also be used to achieve high data rates [9].

In this paper we investigate the gains obtained in terms of b/s/Hz/m^2 by VLC systems compared to RF femtocell networks. The performance of the two systems is evaluated in terms of ASE through system-level simulations. VLC access points are installed in every room in the building and each room constitutes a cell. We also consider different femtocell deployment densities ranging from 4 to 20 femtocell APs per floor area to determine how the benefits of using femtocells scale as the number of femtocells increases.

The remainder of the paper is organized as follows: the simulation model for both RF and VLC systems is presented in Section II. In Section III, the ASE is introduced. Simulation results including the illuminance and the signal to noise ratio (SNR) distributions for the VLC system in the room, and a comparison of achieved ASE in the deployment scenario using RF and VLC systems are discussed in Section IV. Finally, Section V concludes the paper.

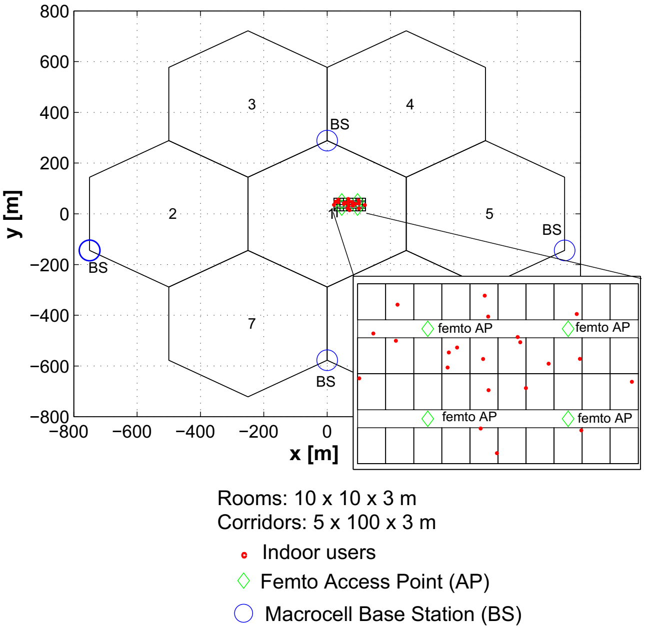


Fig. 1: The macro-cellular simulation environment. Layout of the office floor building.

II. System model/Simulation setup

Fig. 1 illustrates the simulated RF network layout consisting of 7 hexagonal macrocells with 4 sectored BSs. The area of interest is an office building where femtocell BSs and VLC APs are installed alternatively. The office building is randomly placed in the central macrocell. The simulation setup considers two cases: i) a one floor building and ii) a building with three floors for which the floor penetration loss (FL) must also be included in the computation of ASE. There is no interference between the RF system and the VLC system. It is assumed that the femtocell network operates in the same bandwidth (co-channel deployment) as the macrocell (*e.g.* 10 MHz for LTE). The worst case interference scenario is modeled (full frequency reuse). We focus on downlink transmission, and compute capacity and hence ASE based on path loss, shadowing, and interference.

The WINNER II channel model [1] for indoor office propagation scenario (A1) is used for system level simulations of the femtocell system.
The path loss models are typically of the form:

$$\mathrm{PL[dB]} = A\log_{10}(d[\mathrm{m}]) + B + C\log_{10}\left(\frac{f_c[\mathrm{GHz}]}{5}\right) + X \quad (1)$$

where d is the distance between the transmitter and the receiver in [m], f_c is the carrier frequency in [GHz], A, B and C are constants depending on the model used, and X is an environment-specific term (*e.g.*, wall attenuation in the indoor office non line-of-sight (NLOS) scenario). For the A1 path loss model, the line-of-sight (LOS) scenario $A = 18.7$, $B = 46.8$, $C = 20$ and standard deviation of the shadowing component is $\sigma = 3\,$dB. For the NLOS scenario $A = 36.8$, $B = 43.8$, $C = 20$ and $X = 5(n_w - 1)$ (light walls) or $X = 12(n_w - 1)$ (heavy walls) where n_w is the number of walls between the femtocell BS and the user, and standard deviation of the shadowing component is $\sigma = 4\,$dB.

It is assumed that users are independently and randomly distributed in their respective cells and that the femtocell BSs are randomly distributed inside the office building. The average number of users considered per femtocell BS is two. The signal-to-interference and noise ratio (SINR) at the intended user assuming a femtocell network deployment is calculated as:

$$\gamma_{\mathrm{fem}} = \frac{P_{\mathrm{fem}} G_{\mathrm{des}}}{\sum_m P_{\mathrm{macro}} G_{m,\mathrm{I}} + \sum_l P_{\mathrm{fem}} G_{l,\mathrm{I}} + P_n} \quad (2)$$

where P_{fem} is the femtocell transmit power, G_{des} is the path gain of the desired link (transmitter femtocell to the desired user), P_{macro} is the macrocell BS transmit power, $G_{m,\mathrm{I}}$ is the path gain of the m^{th} interfering macrocell BS to the desired user, $G_{l,\mathrm{I}}$ is the path gain of the l^{th} interfering femtocell BS to the desired user. Moreover, P_n is thermal noise power given by $P_n = k_B T W_u$ where k_B is the Boltzmann constant, T is the ambient temperature and W_u is the user bandwidth which is obtained by dividing the available bandwidth, W_{fem} by the total number of users served by the femtocell BS.
The path gain, G, is defined as

$$G = 10^{-\mathrm{PL[dB]}/10} \quad (3)$$

For the VLC system, we consider uniform lighting implementation (wide field LEDs) where each room constitutes a cell. A certain number of downwards pointing illumination modules provide the required illumination and are placed at 0.5 m below the ceiling. The system performance is evaluated at desktop height at 0.85 m above the floor in a horizonal plane containing the user's optical receiver. The minimum required illuminance for reading is 400 lx according to the European lighting standard [10]. This is achieved by using 576 high luminous intensity (28 cd) [11] OSRAM white-LEDs in the large room of 10 m×10 m×3 m dimension. A number of 144 LEDs are sufficient in the 5 m×5 m×3 m rooms and 72 LEDs are used for the 2.5 m×5 m×3 m rooms. Each LED is biased at the recommended bias point in the datasheet (*i.e.* 350 mA) and has an optical output power, P_{LED} of 189 mW.

The illuminance is the most significant parameter when characterizing white-LEDs for illumination purposes. Assuming a Lambertian radiation pattern, the horizontal illuminance can be calculated as [7]:

$$\mathrm{E_h} = I_0 \cos^n(\phi)\cos\theta / R^2 \quad (4)$$

where ϕ is the angle of irradiance, θ is the angle of incidence, R is the distance to the illuminated surface, and I_0 is the maximal luminous intensity. The illuminance at any point of the receiving surface is evaluated by considering only the LOS signal path from each chip.

The channel DC gain from the i^{th} LED is given by [12]:

$$h_{\mathrm{LOS},i} \approx \frac{(n+1)A_d}{2\pi R_i^2}\cos^n(\phi_i)\cos(\theta_i)\mathrm{rect}(\theta_i/\beta) \quad (5)$$

TABLE I: Simulation parameters

VLC system	
LED half intensity viewing angle, $\phi_{1/2}$	60°
LED maximum luminous intensity, I_0	28 cd
Average emitted optical power, P_{LED}	189 mW
Modulation bandwidth, W	20 MHz
Responsivity of SI-PD in the blue region, γ	0.28 A/W
Noise power spectral density, N_0	10^{-21} A^2/Hz
Receiver field of view, β	85°
Detector physical area, A_d	1 cm^2
RF system	
System bandwidth, W_{fem}	10 MHz
Macro-cell BS transmit power, P_{macro}	46 dBm
Macro-cell radius	500 m
Femtocell transmit power, P_{fem}	10 dBm

where A_d is the detector physical area, β is the receiver field of view, the Lambertian index n depends on the viewing angle ($\phi_{1/2}$) of the LED as $n = -1/\log_2(\cos\phi_{1/2})$, and

$$\text{rect}(x) = \begin{cases} 1 & \text{for } |x| \leq 1 \\ 0 & \text{for } |x| > 1 \end{cases} \tag{6}$$

It is assumed that all LEDs in one room are driven by the same signal (single source), therefore for a flat fading channel the received optical signal power is the sum of powers coming from all LED chips

$$P_R = \sum_i P_{\text{LED}} h_{\text{LOS},i} = P_{\text{LED}} \sum_i h_{\text{LOS},i} \tag{7}$$

The electrical SNR at the intended optical receiver is

$$\text{SNR}_{\text{VLC}} = \frac{(\rho P_{\text{R}})^2}{N_0 W} \tag{8}$$

where ρ is the responsivity of SI-based photodiodes (PDs) in the blue region, W is the LED modulation bandwidth and N_0 is the noise power spectral density of shot noise. The shot noise stemming from ambient light is assumed to be the dominant noise contribution. Table I, outlines the relevant simulation parameters.

III. Area Spectral Efficiency

The ASE [13] defined for cellular data systems as a suitable measure of spectral efficiency is used as a performance metric for the VLC system investigated in this paper. For the RF system, the ASE of a cell is defined as the sum of the maximum bit rates per Hz per unit area supported within a cell. The ASE, A_e, [b/s/Hz/m^2], is therefore approximated by

$$A_e = \frac{\sum\limits_{k=1}^{N_s} C_k}{W A_r} \tag{9}$$

where N_s is the total number of active serviced channels per cell, C_k [bits/s] is the maximum data rate of the k^{th} user, W [Hz] is the total allocated bandwidth per cell and A_r [m^2] is the area served by a BS. The maximum rate, C_k is defined to be the Shannon capacity of the k^{th} user in the cell, which depends on γ_k, the received SINR of that user, and W_k, the bandwidth allocated to that user.

Given γ_k, C_k is calculated as:

$$C_k = W_k \log_2(1 + \gamma_k). \tag{10}$$

The ASE for the VLC system is defined in a similar fashion, except that femtocell BSs are replaced by VLC access points.

IV. Simulation Results

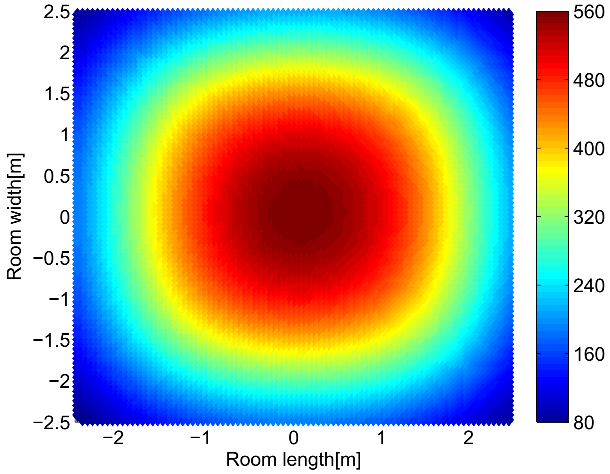
Monte Carlo simulations are used to calculate the ASE for both RF and VLC systems, involving the following basic steps:

1) The position of the desired users is randomly picked inside the office floor area.
2) The distance from the serving AP and the distance from each interfering AP to the desired users is calculated.
3) The path losses are calculated based on the previously determined distances.
4) The SINR for RF and the SNR for VLC is calculated according to (2) and (8) respectively.
5) The ASE is then calculated using (9).

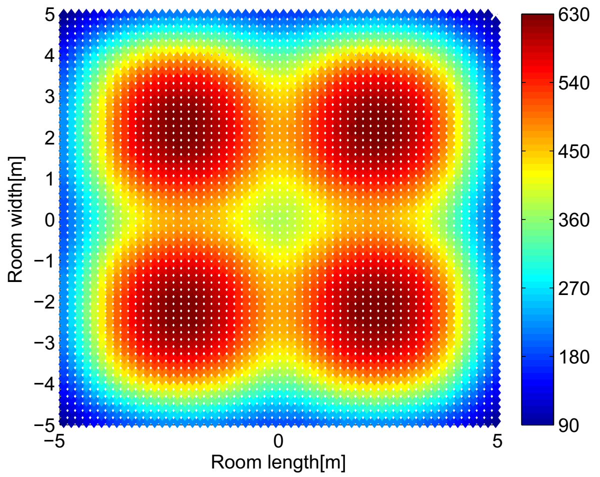
The above steps are repeated 10000 times and the ASE is expressed as the mathematical expectation from the obtained distribution.

All possible attempts have been undertaken to arrive at a fair comparison, but it should be highlighted that fundamental differences exist between RF and VLC, among which we mention the following: the VLC system provides two functions: 1) illumination and, therefore, the VLC system uses more transmit power to achieve the required reading levels and 2) high speed wireless data communication. In VLC, there is no interference from one room to another since light does not propagate through walls unlike RF signals. Therefore we consider RF co-channel femtocell indoor deployments with a given density of femtocell BSs per floor area and VLC APs installed in every room. In the experiment we will vary the density of femtocell BS per floor. We also assume an office building with heavy walls separating the rooms *e.g.* 12 dB wall attenuation and the exterior walls with a 20 dB attenuation. The original WINNER indoor scenario consists of 10 m×10 m×3 m rooms. In the simulations we consider several room geometries derived from the original scenario. A regular office size of 5 m×5 m×3 m can be created by adding two walls in the 10 m×10 m×3 m rooms resulting in four rooms. The same procedure is used to derive rooms with a size of 2.5 m×5 m×3 m.

Fig. 2 shows the spatial illuminance distribution at desktop height for two room dimensions: (a) 5 m×5 m×3 m room, (b) 10 m×10 m×3 m room. The lighting conditions are fulfilled for more than 70% of the room area for both room scenarios. For the 10 m×10 m×3 m rooms four coordinated light sources, each consisting of 144 LEDs, that act as a single source are considered. Since the LOS signal path gain from each light module adds up at the receiver, slightly larger illuminance/SNR values are obtained compared with the case when rooms of size 5 m×5 m×3 m are analyzed.

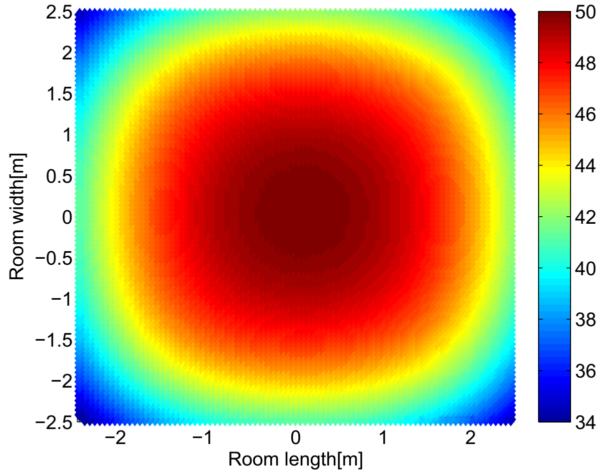


(a)

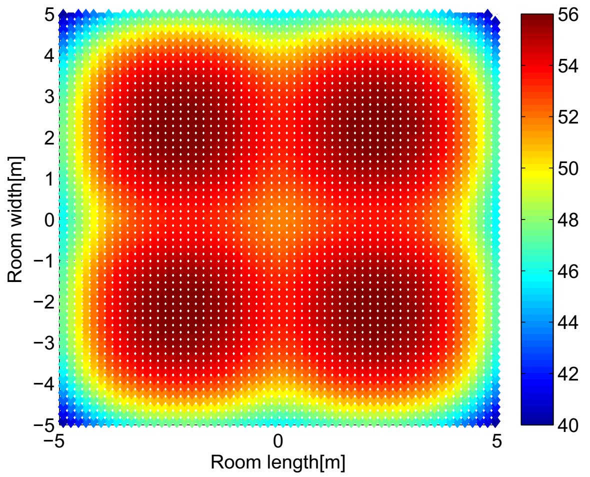


(b)

Fig. 2: The distribution of illuminance [lx] at desktop height for (a) 5 m×5 m×3 m rooms, (b) 10 m×10 m×3 m rooms.



(a)



(b)

Fig. 3: The distribution of SNR [dB] at desktop height for (a) 5 m×5 m×3 m rooms, (b) 10 m×10 m×3 m rooms.

TABLE II: Area spectral efficiency for VLC

Room size	Avg. ASE per floor
2.5 m×5 m×3 m	1.2 b/s/Hz/m^2
5 m×5 m×3 m	0.6 b/s/Hz/m^2
10 m×10 m×3 m	0.176 b/s/Hz/m^2

Fig. 3 shows the SNR distribution at desktop height for the illumination conditions illustrated in Fig 2. Due to the high number of lighting modules employed, the SNR values are relatively high throughout the room with an average SNR of 45 dB and 53 dB in the 5 m×5 m×3 m room and 10 m×10 m×3 m room respectively. The capacity in the room for the considered VLC system where the minimum lighting conditions are fulfilled is approximately uniform. Due to the considered uniform lighting conditions throughout the floor area, the average ASE per floor is approximately the same as the average ASE per room. The average ASE per floor/room of the VLC system is listed in Table II.

Fig. 4 shows the ASE of the indoor femtocell network as a function of the number of femtocells per floor area (5000 m^2). The indoor femtocell network is placed in a realistic macro-cellular environment (see Fig. 1). As the density of femtocells per floor increases the ASE improves since the number of simultaneous data links increases. The highest values of ASE are noticed for the setup consisting of 10 m×10 m×3 m rooms and the lowest values of ASE are observed for the setup consisting of 2.5 m×5 m×3 m rooms independent of the femtocell AP density on the floor. The amount of interference originating from surrounding femtocells is reduced as the number of walls increases. This is the case when 2.5 m×5 m×3 m rooms are considered, although the received desired power also decreases. The interference in the simulated RF system is significant since both the macrocell and the femtocells transmit on the same downlink channel. For a three-floor-building setup the floor penetration loss is also taken into account. Hence, the ASE diminishes compared to the case where a one floor office

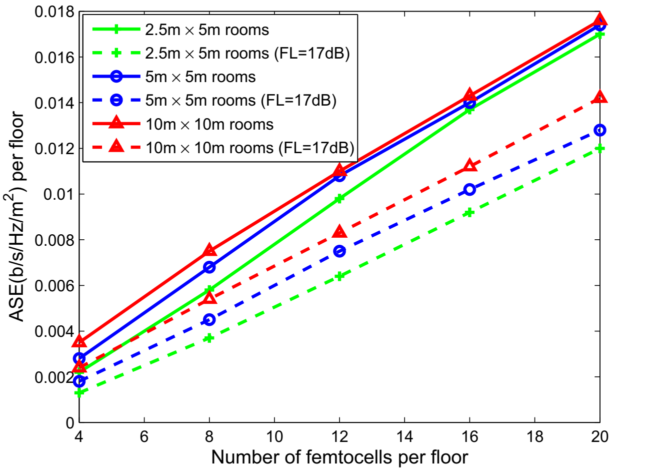


Fig. 4: RF ASE as a function of femtocell density per floor for a three-floor-building with the given FL and for a single floor building.

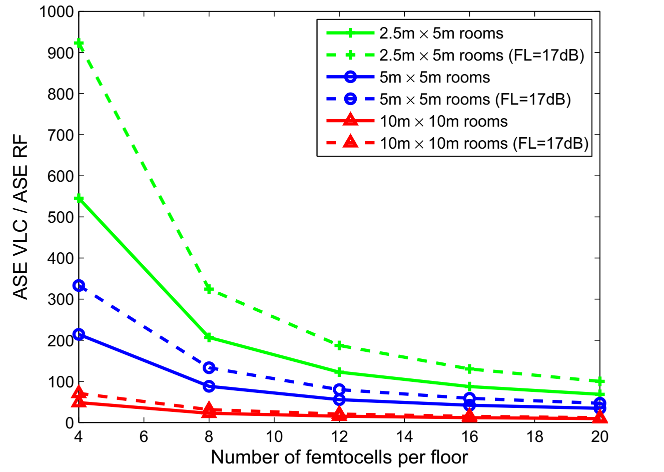


Fig. 5: The ratio of VLC ASE and RF ASE for different floor layouts.

building is assumed. This is a result of the extra interference caused by femtocell BSs situated in different floors.

Fig. 5 shows the improvement in ASE by considering a VLC system over the RF system in the same floor area. These results show the possible gains in ASE of the VLC network. The ASE improvements range between 12 and 924 depending on the number of femtocells installed per floor and the room layout. The VLC system can achieve almost three orders of magnitude higher data density compared with the RF system when a three-floor office building with $2.5\,\text{m}\times5\,\text{m}\times3\,\text{m}$ rooms and 4 femtocells per floor is considered. The lowest ASE improvement by a factor of 12 is achieved for a setup consisting of $10\,\text{m}\times10\,\text{m}\times3\,\text{m}$ rooms and 20 femtocells per floor. It is evident that the gains in ASE of the VLC system decrease as the number of femtocells increases. This is due to the continuous improvement of the ASE in the femtocell network as more femtocells are deployed.

V. CONCLUSIONS

This paper investigates the gains in ASE achieved indoors in a heterogeneous network when using a VLC network as opposed to an RF femtocell network. The highest ASE gain of 924 is obtained in a three-floor-building with rooms of size $2.5\,\text{m}\times5\,\text{m}\times3\,\text{m}$ and a single source optical AP per room, as compared to an RF system with 4 femtocell BSs per floor. For all the considered simulation scenarios, the VLC network always achieved an ASE performance gain. This highlights the potential of VLC systems to act as a powerful complementary technology to RF indoors. This also translates into a significant data rate improvement experienced by the end-user. By adding the LED data transmission functionality to the LED lighting infrastructure, significant performance gains can be achieved. Taking also into consideration the fact that optical components and modulation methods continue to improve for VLC, all this contributes towards a rapid establishment of VLC commercially.

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