Wireless Internet Service Providing for 5G with Hybrid TV Broadcast and Visible Light Communications

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Abstract—Visible light communications (VLC) is a potential candidate to be utilized in future 5G networks with energy efficient indoor and outdoor communications with available hardware components such as LED bulbs, TV screens and camera receivers. In this article, a low cost cellular infrastructure is proposed for Internet service providing (ISP). Hybrid TV radio frequency (RF) broadcast and display screen based VLC transmitters are utilized for the downlink while telescopes, camera receivers and LED arrays placed on the roofs of the houses are utilized for the uplink. In the downlink, display screens with quantum dot (QD), organic light emitting diode (OLED) and liquid-crystal display (LCD) technologies are compared in terms of response time, color gamut, spectral color output, contrast ratio and power consumption. Uplink capacity reaches hundreds of Kbit/s data rates for hundreds of houses at tens of kilometer distances with a simple and low cost system with less than hundred watts power consumption at each house while downlink capacity promises several Mbit/s at each house.

Index Terms—Visible light communications, TV broadcast, ISP, display screen, outdoor, cellular network, MIMO.

I. INTRODUCTION

Visible light communications (VLC) systems are future promising for 5G architectures with large and unlicensed bandwidths reaching 400 THz compared with infrared (IR) communications having spectrum and power limitations [1]. In this article, a novel and low cost hybrid RF and VLC outdoor cellular concept is introduced for Internet service providing (ISP). TV multimedia broadcast is combined with display based indoor communications for downlink channels. In the uplink, LED arrays on the roofs of the houses connect with camera receivers combined with high focal length telescopes creating cellular coverage areas. Besides that, the response time, color gamut (CG), static contrast ratio and power consumption are compared for emerging display types, i.e., quantum dot (QD), organic light emitting diode (OLED) and improved liquid crystal displays (LCDs).

Outdoor architectures concentrate on vehicular communications and traffic information systems in [2] with camera based receivers. In [2], receiver diversity is utilized to achieve ranges of hundreds of meters. In [3], 5.7 km range and tens of Kbit/s data rate are achieved. However, telescope based outdoor cellular concept, synchronization with TV broadcast and very long ranges of communication reaching tens of kms combined with coverage for hundreds of houses are not proposed.

VLC indoor wireless architectures based on display transmitters and camera receivers are already designed [4], [5]. Information is modulated through either intensity modulation (IM) or color shift keying (CSK). It is observed that hundreds of Mbit/s data rates are achieved by utilizing high definition (HD) screens and 100 Hz frame rates [6]. However, performance comparison of emerging screen technologies with QD, OLED and LCD displays are not discussed.

In this work, the contributions are listed as follows:

- Wireless ISP with hybrid TV broadcast and cellular VLC.
- VLC cellular uplink capacity and coverage simulations.
- Long range VLC with tens of km ranges and Kbit/s rates, and hundreds of watts power consumption per house.
- Comparison of indoor downlink VLC channels for QD, OLED and LCD displays.

The remainder of the paper is organized as follows. Uplink model is presented in Section II while the downlink in Sections III and IV. In Section V, numerical simulations and comparisons for the channel capacities are performed. In Section VI, the challenges and future research issues are discussed. Finally, in Section VII, the conclusions are given.

II. SYSTEM MODEL FOR UPLINK

The uplink channel includes low cost CCD cameras and telescopes with the novel architecture as shown in Figs. 1(a) and (b). Each telescope with a long focal length of \( f_{eff} \) serves a specific set of LED array transmitters located near a specific region as shown in Figs. 1(b) and 1(c). The angle of view is defined with respect to the effective focal length \( f_{eff} \) as \( \Theta_v = 2 \arctan \frac{w_s}{2f_{eff}} \), where \( w_s \) is the horizontal or vertical size of the camera sensor. Then, for a coverage area of 360°, the number of telescope camera receivers needed for communication with LED panels at a distance \( d \) is given by \( N_T = \frac{360°}{\Theta_v} \) with \( \Theta_v \) defined in terms of degrees. The resolutions with respect to specific focal length and distance are given by \( \Delta_{LED} = d 1.22 \lambda / (A \cos(\phi)) \) and

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\[ \Delta_d = f_{eff} \frac{1.22 \lambda}{(A \cos(\varphi))} \] where \( \Delta_{LED} \) and \( \Delta_d \) are the minimum distances between perimeters of LEDs in real and image planes, respectively, \( d \) is the distance between the LED array and the camera, \( \varphi \) is the angle between the camera image plane and LED array, \( A \) is the diameter of the aperture and \( \lambda \) is the wavelength. For simplicity, the planes of LEDs and the camera are parallel, and the panels and the telescope at the plane and LED array, \( A \) is the diameter of the aperture and \( \lambda \) is the wavelength. The panels have the distance \( d_h \) between houses. Then, the number of served houses, i.e., \( N_h \), in a single cell becomes the following:

\[ N_h = \frac{d w_s}{(f_{eff} d_h)} - 1 \]  

and the number of pixels where each LED covers is \( P_{LED} = f_{eff} D_{LED} / (d s) \) where \( s \) is the physical size of the pixel. The VLC channel experiences various detrimental effects, e.g., fog, rain, snow and wind reducing the received power or change the position of the panels. The empirical model including the effects of the severe fog is modeled in [7], [8] as \( \gamma_\lambda = (17.35 / V)(\lambda / 550)^{-\alpha} \) where \( \gamma_\lambda \) is the attenuation coefficient (dB/km), \( V \) is the visibility range in kms, \( \lambda \) is the wavelength in nm and the parameter \( \alpha \) is a function of the visibility range \( V \) for various air conditions from clear sky to heavy fog. The effect of sun light ambient noise is reduced by specific placement and design of the receiver units [3], [8]. Scintillation is neglected for ranges of several kms communications. Furthermore, under heavy fog conditions, a delay tolerant network (DTN) approach can be utilized to provide the communication infrastructure modeled for exotic media networks in [9]. The theoretical model proposed in this article should be verified with experimental studies or realistic simulations modeling the effects of the channel variations. Then, the received current at a pixel with index \( (i,j) \) due to a LED at a view angle of \( \Theta = \psi < \Theta_v \) as shown in Fig. 1(b) is given by the following [8]:

\[ I_{R}^{\Theta}(i,j) = P_{n} 10^{-\gamma d / 10} g(\psi) T_{s}(\psi) \cos(\psi) \times A_{ij} R_{n} D_{LED}^{2} \cos^{m}(\Theta) (m + 1) / (8 d^{2}) \]  

where \( A_{ij} = 4 s^{2} / (\pi P_{LED} s + \sigma_{i,j})^{2} \) is the proportional area of the pixel compared with the total image area of LED as defined in [5], \( \sigma_{i,j} \) is the lens Gaussian blur standard deviation defined as the ratio of minimum distance between image circumferences on the image plane to \( 2 \sqrt{2 \ln 2} \) in [5] or \( \Delta_s / (2 \sqrt{2 \ln 2}) \) in our model, \( R_{n} \) is the responsivity of a sensor pixel in \( (A/W) \), \( m = -\ln 2 / \ln(\cos(\Phi_{1/2}) \) / \( T_{s}(\psi) \) is the signal transmission coefficient of an optical filter, \( g(\psi) = n^{2} / \sin^{2}(\Theta_v) \), \( n \) is the internal refractive index of the optical concentrator and \( \Phi_{1/2} \) is the transmitter semi-angle at half power. The focal length and the number of telescope cameras are adjusted to discriminate all the single LEDs then, the capacity for a single color LED at the angle \( \Theta \) in the IM framework is given as follows [5]:

\[ C_{LED,\Theta} \approx K^{2} W_{r} \log_{2} \left( 1 + \sum_{i,j \in S_{\Theta}} \frac{(i,j)^{2}}{(\sigma_{i,j})^{2}} \right) \]  

where \( \sigma_{i,j} = \sqrt{2 q R_{n} P_{n} s^{2} W_{r}} \) is the noise current at the pixel \( (i,j) \), \( P_{n} \) is the shot noise power per unit area, \( q \) is the electron charge, \( W_{r} \) is the frame rate of the camera and \( S_{\Theta} \) includes the index of the pixels covered in the image area of the LED on the camera, i.e., \( \pi P_{LED} s + \sigma_{i,j}^{2} \) / 4.

Indoor uplink unit is connected with TV (as a monitor) through a low cost device including VLC transmitter circuit (Tx) driving LEDs, VLC decoder circuit (Rx) extracting the data embedded in TV broadcast image and input devices, e.g., a keyboard and a mouse, as shown in Fig. 1(a). The device can be realized by combining low cost hardware, e.g., Raspberry Pi, as a personal computer and simple LED driving circuits.

III. SYSTEM MODEL FOR DOWNLINK

The downlink channel is formed in a hybrid mechanism as shown in Fig. 1(a) synchronizing TV RF broadcast of multime-
dia data and the transmission of the information embedded in the multimedia to either mobile phone through wireless VLC channel or the receiver device through wired connection with the TV. A multi-user encoding architecture is required for TV RF broadcast channels. TV station should be synchronized with the uplink camera receivers connected with high speed wired line to achieve two-way communication. Hybrid data link and MAC layer protocols should be designed. Hundreds of Mbit/s multimedia data is possible to be distributed to the cellular service area with tens of broadcast channels of several MHz UHF band enough to provide several Mbit/s the cellular service area with tens of broadcast channels of each house. Capacity for each house extends from hundreds of bits to thousands of Kbit/s for coverage distance reaching $d = 50$ km. Focal length increases the total capacity due to the increased resolution allowing to detect more individual LEDs on the arrays of each house as shown in Fig. 2(d). Each LED experiences higher capacity with short focal length until $d \approx 10$ km while different focal lengths result in the same performance for $d \approx 100$ km as shown in Fig. 2(b). In higher ranges, $f_{eff} = 1000$ nm provides better capacity for each individual LED unit. On the other hand, the number of served houses by each telescope increases with shorter focal length and higher distance as shown in Fig. 2(c). Therefore, there is a trade-off among capacity per house, $N_h$ and $d$ as shown in Figs. 2(a) and (d). The uplink channel range is compatible with the range of TV broadcast reaching tens of km by promising a scalable ISP infrastructure.

In Fig. 3(a), higher power above 100 W allows data rates reaching Kbit/s at tens of kilometers distance for each LED unit. LED diameter of 20 mm provides good performance at both short and long ranges as shown in Fig. 3(b). The fog significantly reduces the capacity as shown in Fig. 3(c) as a challenging issue for long range VLC communications.

### V. NUMERICAL CALCULATIONS

#### A. Uplink Performance

Uplink performance is simulated for the parameters defined in Table II which are based on the available outdoor and indoor VLC architectures and channel models in [5], [7], [8] while providing telescope based image reception, large LED array transmitters and a simple model for premises and the locations of the houses. $f_{eff}$ is chosen in the interval (100 mm - 2000 mm). Total area of the LED array, i.e., $W_{LED}$, is chosen as one square meter. The color is chosen as red with wavelength 650 nm, however, other colors can also be experimented. Aperture size is chosen as $f_{eff} / 10$ as a medium level ratio reaching both short and long range capabilities. The distance between homes is $d_h = 10$ m. Furthermore, sensor pixel ($s$) and array size ($w_s$) are chosen similar to practical camera based receiver architectures, e.g., [5]. Noise power spectral density is taken as the same with experimental results of machine vision based cameras in [5]. The semielongitude $\Phi_{1/2} = 60^\circ$, $\varphi = 0$, $n = 1.5$, $T_s(\phi) = 1$ and $R_p$ as 0.5 A/W in accordance with [5].

In Figs. 2(a), (b), (c) and (d), capacity (denoted by $C$) per house, capacity per single LED unit in each house, $N_h$, and $K$, are shown, respectively, for clear sky with $V = 20$ km, $D_{LED} = 20$ mm and the total transmit power of $P_{tot}^T = 100$ W chosen less than the power consumption of a high power commercial LED bulb. The performances are calculated for varying focal lengths of the telescope. In Fig. 2(a), the uplink capacity for each house extends from hundreds of bits to thousands of Kbit/s for coverage distance reaching $d = 50$ km. Focal length increases the total capacity due to the increased resolution allowing to detect more individual LEDs on the arrays of each house as shown in Fig. 2(d).

### VI. CHALLENGES AND FUTURE WORK

There is a set of challenges and future research issues making the system more practical summarized as follows:

- Multi-user encoding architecture storing data of multiple users in the form of TV broadcast images and the assignment of unique TV channels for ISP purposes.
- Synchronization between broadcast downlink and uplink camera receiver with reasonable latency and delay, and
hybrid data link and MAC layer protocols including the utilization of DTNs under heavy fog conditions.

- Experimental studies modeling the effects of fog and flying insects on the overall system performance.
- Design of a low cost indoor VLC TX-RX unit, and low cost combinations of multiple camera and telescope units in a highly fixed positioning and orientation.
- Mobile phone high frame rate camera receiver design to fully utilize OLED TV display transmitters.
- Analysis of the effects of spectral distribution of RGB colors on CSK performance for each display type.
- Constellation design with OLED infinite contrast ratio.

VII. CONCLUSION

A hybrid TV RF broadcast and VLC cellular communications model is proposed for ISP infrastructures. The performances of QD, OLED and LCD display screens are compared in terms of response time, spectral color output, contrast ratio and power consumption. Uplink capacity with a single high focal length telescope and ordinary digital camera receiver reaches hundreds of Kbit/s data rates at tens of kms distances and with coverage areas including hundreds of houses by using a LED array of one square meter area and less than hundred watts power consumption at each house. Indoor downlink synchronized with TV broadcast promises several Mbit/s data rate for each house.

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