

On the Impact of Visible Light Communication for Audio and Video Transmissions

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Abstract—With the massive technological advancements being made every year, the need for better and faster data rates, better and improved security measures is being given high importance in the research community. Therefore, open space communication has become a hot topic in the recent years of which Visible Light Communication (VLC), is one of the highly researched areas. The reason for its high popularity is because of its ability to provide high data rates, high bandwidth and a very secure medium of transmission as it cannot penetrate walls. This paper investigates the impact of visible light communication on audio and video transmissions. A real experimental test-bed is setup to test the performance of audio transmission over VLC under various conditions such as distance from the source, interfering lighting, etc. Subjective tests are carried out to assess the quality of the audio VLC link as perceived by the user. Additionally, a comprehensive study on existing simultaneous video and audio transmission systems over VLC is provided and the challenges and remaining open issues are identified.

I. INTRODUCTION

The increasing consumption of multimedia-based applications along with the mass-market adoption of high-end mobile devices with improved CPU and graphics has led to an outstanding increase in mobile broadband traffic [1]. This puts enormous pressure on the underlying networks and the network operators are trying to adopt various solutions to help them cope with this explosion of data traffic while ensuring high Quality of Service (QoS) levels for the end-users. One promising solution that is being adopted is the deployment of small-cell base stations within the existing macro-cells and offloading the traffic from the macro-cells to the small-cells at key locations [2]. In this way the operators can avail of increased capacity and improved network performance at low cost. Moreover, parallel use of diverse technologies is also employed. For example, the use of Visible Light Communication (VLC) has gained substantial interest especially on its usage as a potential traffic offloading solution in highly crowded Radio Frequency (RF) scenarios. The key advantages of VLC are very high data rates over low energy consumption and low implementation costs making it a promising solution for the future 5G networks [3] and its strict QoS advanced applications, such as 360° multimedia experience [4]. The result is a hybrid VLC/RF heterogeneous network environment (HetNet) as illustrated in Fig. 1 which presents an example

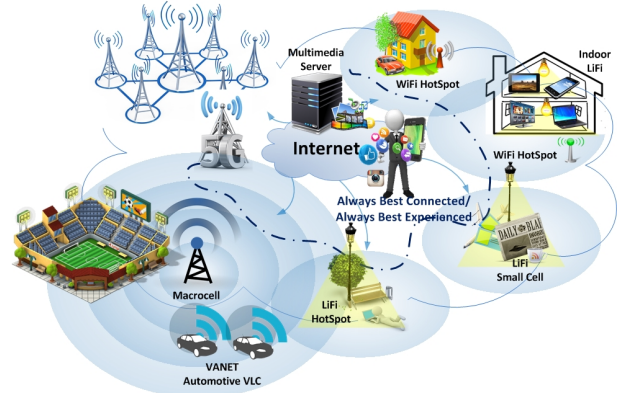


Fig. 1. Hybrid VLC/RF 5G Network Environment - Example Scenario

of ubiquitous connectivity that enables very good quality of various rich media services anytime and anywhere for the mobile users even when on the move. VLC was first proposed by Komine et al. [12] stating that high data rates will be necessary for the day to day life. Although RF is the foremost choice for wireless communications, especially indoors, due to its very overcrowded spectrum it cannot provide an accurate omnipresent high data rate. Therefore, it is suggested that where feasible VLC to be used as a new medium to RF [13].

In the VLC system the use of a white light emitting diodes (LED) is the only way for the system to function accurately. The theory behind VLC is to transfer data by using a visible light source as a transmitter and on the opposite end a photo diode as a receiver. Data is converted from electric signal into a light signal. LEDs are purposely built to switch on and off at extremely high speeds when the light output fluctuates. The data can be represented in the switching ON and OFF of the LED. The photo diode on the receiver has to receive the data as a ON and OFF light pattern. This light pattern then again is converted into an electric signal. VLC will substantially increase the data rate within wireless connections, this means faster uplink and downlink for high end devices.

The aim of this paper is to investigate the impact of VLC for audio and video transmissions. An experimental test-bed setup is developed to test the performance of audio

TABLE I
RELATED WORK SUMMARY

Ref.	Application	Evaluation	Distance	Main Findings
[5]	transmission of audio and video	Experimental setup under controlled environment	100cm	The use of Pulse Width Modulation of the video signal causes a darker brightness on the image quality. This could be fixed by converting the analog signal to digital prior to transmission.
[6]	real-time audio and video transmission	Experimental setup under controlled environment	2m	The distance can be increased up to 3m by using focusing lenses between transmitter and receiver.
[7]	real-time high-rate multimedia transmission	Experimental setup under controlled environment	0.5m	The proposed VLC system can reach a data rate beyond 500 Mbps in real-time.
[8]	transmission of high-data rates	Experimental setup under controlled environment	1.2m	The proposed system can achieve up to 11.1Gbps making use of OFDM modulation.
[9]	transmission of high definition video at high data rates	Experimental setup under controlled environment	1.2m	The proposed system can reach data rates of up to 84Mb/s using 16-QAM and DMT as modulation techniques.
[10]	video transmission	Experimental setup under controlled environment	2m	The proposed system can achieve a data rate of 1Mbps. The authors propose that modulation techniques such as Pulse-Position Modulation can be used to increase data-rates. As well as the use of RGB lamps real-time video transmissions.
[11]	real-time video transmission	Experimental setup under controlled environment	1.4m	The proposed system can achieve data rates up to 100Mb/s. The authors propose using distributed LED's so that larger coverage area and distances can be achieved.

transmissions over VLC under various conditions: various levels of interfering lighting (ambient lighting), and distance from the transmitter. Subjective tests were carried out to assess the audio quality of the VLC link as perceived by the user. A comprehensive study on existing simultaneous video and audio transmission systems over VLC is also provided. The study will identify the challenges and remaining open issues for multimedia transmission over VLC.

II. RELATED WORKS

The future 5G networks are expected to achieve 1000 times the system capacity, to provide high data rates and 10 times spectral and energy efficiency while maintaining a good end-user quality of experience. To achieve this, one promising solution that some network operators already adopted is the deployment of small cells in an overlapping manner, creating a HetNet small cell environment (see Fig. 1) that significantly increases the system capacity and coverage at low cost.

Recently, there has been much interest regarding using VLC as a possible solution for 5G integration [14]. Studies have shown that VLC offers higher data rates and lower energy consumption, high security, no RF interference while making use of free spectrum when compared to the conventional wireless access systems [15].

Son et al. [5] investigated the transmission of audio and video using VLC. An experimental test-bed setup was built and the results show that compared to the original picture quality, the transmitted picture quality had some issues related to darker brightness, color saturations and some level of distortions. The authors argue that the issues are due to the Pulse Width Modulation (PWM) of the video signal and believe that using an ADC to convert the analog signal to digital signal prior to transmission would fix the problem. Moreover, wavelength division multiplexing could be used to increase the bit rate of transmission.

He et-al. [6] investigates the transmission of real time video and audio over longer distance of VLC and improving the channel capacity by building a prototype to achieve the same. The authors concluded that the transmission distance can be increased further by using a focusing lens and although certain distortions did occur, high quality video and audio transmission is possible over VLC.

Similarly, Li et. al [7] propose a real-time high-speed VLC system for high-speed multimedia signals. The authors demonstrate the system functionality through a real experimental test-bed implementation and show that a transmission data rate higher than 500 Mbps can be reached. The potential of VLC was also demonstrated by Lu et al. in [8] by implementing a vertical-cavity surface-emitting laser (VCSEL)-based OFDM transmission system for VLC achieving a transmission rate of up to 11.1 Gbps.

Similarly, Bouchet et. al [9] propose adding a MAC layer in the VLC system so that it can manage VLC communication to control the coverage area of the broadcast and enable the support for full duplex high data rate communication using infra-red communication. This was successfully demonstrated experimentally by setting up a test bed that achieved data rates of 84 Mb/s for the broadcast of three high definition video signals. The authors mention that different modulation techniques such as discrete multi-tone (DMT) and multi-level quadrature amplitude modulation (M-QAM, specifically, 16-QAM), were used to improve the bandwidth-limitations on the transmitter. The authors conclude that higher rates of up to 100 Mb/s can be achieved by modulating multiple LED bulbs which are to be setup using the lock step model.

Rufo et. al [10] discuss how video can be broadcast at data rates of up to 1 Mb/s using a low-cost visible light communication transceiver and different modulation techniques such as pulse-position modulation (PPM) in order to make up for the bandwidth limitation and avoid the symbol

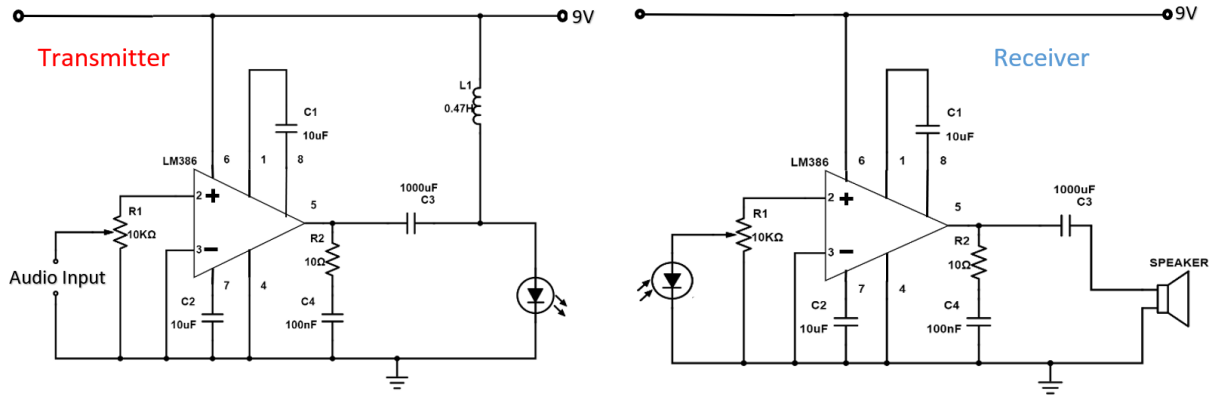


Fig. 2. The Circuit Design of the Audio VLC System

interference caused phosphor LED's. The proposed system could achieve data rates of up to 1 Mb/s. The author finally hypothesizes that different types of LED's such as RGB lamps can be used to carry out real-time video transmission and also be used for achieving higher data rates.

Vučić et. al [11] proposes the implementation of video transmission over VLC, at data rates of 100 Mb/s with an application of real time discrete multi-tone modulation technique. Moreover, the test bed and the experiments are conducted in the lighting range that is typical for an office environment. The performance of the physical layer was evaluated and a video signal was streamed without any errors at a data rate of 100 Mbps, over a distance of 1.4m. Finally the authors recommend using multiple LED bulbs to achieve larger distance and coverage area.

A summary of the related works is listed in Table I. Most of the studies have looked into using VLC for real-time video transmissions and used an experimental test-bed setup to validate the solution. Looking at the distance between the transmitter and receiver, the authors in [6] were able to obtain a better distance of 2m whereas [5] was only able to obtain a transmission distance of 50cm. The works in [7] and [8] are very similar in terms of demonstrating that high data rates can be achieved over VLC. However, [8] uses OFDM modulation technique to achieve this and similarly [16] also uses OFDM in addition to WDM,

Despite the amount of research done in the transmission of audio and video applications over VLC not many works have looked into the impact of interfering light (ambient light) and distance from the transmitter on the application quality perceived by the user.

III. SYSTEM DESCRIPTION

The concept behind visible light communication (VLC) is that a transmitter transmits data through a light emitting diode (LED), which the receiver receives by capturing the light with the use of a photodiode. The photodiode then converts the light into the original data. The light intensity of the LED and the sensitivity of the photodiode play an important role in increasing the transmission range of

the system. By using a highly sensitive photodiode it can increase the accuracy of the recovered transmitted signal.

In order to select the photodiode to be used in the circuit, we have tested the output power generated by the Hamamatsu S6968 (used in [6]) and a solar panel. The results showed that the solar panel produces an output of 2.4V, whereas the Hamamatsu can only produce 0.3V. This is because the solar panel produces such a high output due to the characteristics of avalanche photo diodes.

The circuit design of the audio VLC system is illustrated in Fig. 2. The circuit consists of a transmitter and a receiver and it was designed so that the input audio signal is amplified and then superimposed on the LED using a T-Bias circuit. The LED transmits the audio signal in the form of light which is collected by the photodiode. The photodiode recovers the original signal which goes to the output after being amplified.

In order to amplify the audio input, a LM386 microchip has been used, which is a low power audio amplifier. The initial gain of the amplifier is 20, however by adding a $10\mu F$ capacitor, the gain is boosted to 200. The output from the amplifier is then superimposed onto the LED. This is achieved by creating a T-Bias circuit by adding the positive voltage to the output through an inductor. The variable resistor is placed in between the audio input and the inverting pin. This is done so that the input voltage can be controlled to an optimum voltage level for the microchip. A similar circuit is used for the receiver, with the difference that the input to the amplifier is done through a solar panel and the output goes to a speaker.

IV. EXPERIMENTAL SETUP AND SCENARIOS

This section presents the measurement environment setup and the scenarios considered. The designed VLC system for audio transmission, was implemented and an experimental test-bed was setup.

A. Test Scenarios

In order to study the impact of different levels of interfering light from the transmitter on the link quality of the

experimental VLC system, three scenarios were considered as described below:

- Office - an office environment is considered where the only source of interfering light is the fluorescent light. The aim is to study the impact of the fluorescent lighting on the VLC link quality.
- Ambient - an office environment is considered where the only source of interfering light is the natural light (e.g., sunlight reflected through the window). The aim is to study the impact of the natural light on the VLC link quality.
- Dark - an office environment is considered where there is no source of interfering light, the room being completely dark. The aim is to study the VLC link quality under no interfering light source.

In order to study the impact of the distance from the transmitter combined with the impact of the interfering light the measurements were collected at every 1m up to 6m away from the transmitter for each of the three considered scenarios. For each test, the following parameters were measured: the intensity of the interfering light measured in Lux, the intensity of the interfering light plus the transmission in Lux, the level of static noise measured in dB, and the level of the audio sound in dB.

B. Subjective Audio Quality Assessment

Since the measured audio sound level in dB does not correlate with the actual audio sound quality, a subjective study was also conducted in order to assess how the human subjects perceive the quality of the audio clips for each considered scenario and for each distance (e.g., 1 to 6m) from the transmitter. Consequently, a number of 17 audio sequences, 20 seconds long each were used in the subjective tests. The audio sequences were played locally on a laptop, in a random order maintaining similar testing conditions for all the participants. Standard recommendations for the subjective assessment of sound quality were followed as in [17]. The subjects were asked to individually rate the quality of each audio sequence on a 5-point scale (e.g., 1 - Bad, 2 - Poor, 3 - Fair, 4 - Good, 5 - Excellent). A number of 15 (M = 7, F = 8) non-experts subjects with ages between 20 and 45 years old (AVG = 26, STDEV = 7) participated in the study. All subjects have reported that they had normal hearing and nobody was wearing a hearing aid.

V. RESULTS AND DISCUSSIONS

For each considered scenario and for each distance from the transmitter we repeated each test three times (a total of 54 tests were carried out) and computed the average values. These values are further used throughout the paper for analysis of the results and discussions.

A. Results of Subjective Audio Quality Assessment

To assess the user perceived quality of the audio transmission over VLC under the three different scenarios and distance from the transmitter, the subjects were asked to

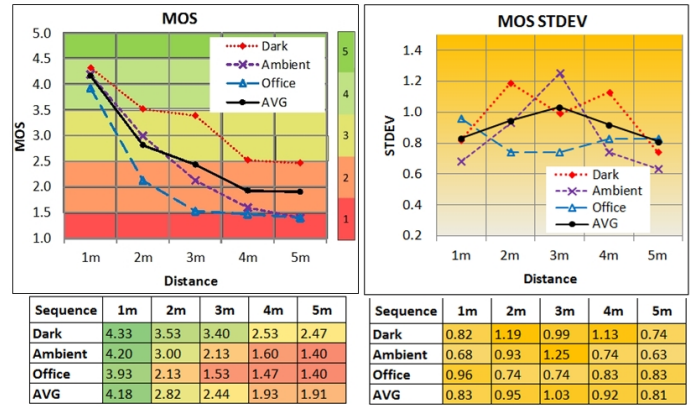


Fig. 3. Subjective Quality Assessment Results

rate the overall quality on a 1 to 5 scale (Bad to Excellent) for each audio sequence. Consequently, the mean value represented by the Mean Opinion Score (MOS) and the standard deviation (STDEV) of the statical distribution of the assessment rates for each audio sequence were computed. The results of the subjective test are illustrated in Fig. 3. It can be noticed that in case of the Dark scenario, the sequences corresponding to 1m and 2m scored 4 (Good), whereas for Ambient and Office scenarios, only the sequences corresponding to 1m scored 4 (Good). The sequences corresponding to 3m and 4m for Dark and 2m for Ambient scored 3 (Fair), while the sequences corresponding to 2m and 3m for Office scored 2 (Poor). A score of 1 (Bad) was received by the sequences corresponding to 4m and 5m Office scenario, and 5m for the Ambient scenario. Considering the relationship between the MOS and STDEV we calculate the Pearson correlation ($r = 0.234$) which indicates a positive association. This means that the ratings across participants tend to have a higher variation for the audio clips with higher perceived quality. Because at 6m away from the transmitter there was no audio sound perceived for the Ambient and Office scenario, these results were not illustrated. However, for the Dark scenario and 6m away from the transmitter the MOS registered was of 1.80 (Poor).

B. Impact of the Interfering Light on the VLC Link Quality

In this section we want to study the impact of the interfering light level on the VLC audio link quality. For this purpose, we maintain the same location for the receiver at 1m away from the transmitter and we study the impact on the audio link quality under the three different scenarios: Dark, Ambient and Office. The results are listed in Table II.

As expected, we can notice that as the interfering light intensity is increasing, there is a decrease in the audio sound level as well as the MOS. Additionally it can be noticed that the fluorescent lighting (Office scenario) with a light intensity of 40.97 Lux has the strongest impact on the MOS, presenting a 9.2% decrease when compared to the optimal no interfering light scenario (Dark). The static noise

TABLE II
IMPACT OF INTERFERING LIGHT LEVEL ON THE VLC LINK QUALITY

	Dark	Ambient	Office
Interfering Light Intensity [Lux]	0.01	13.89	40.97
Interfering Light with Transmission Intensity [Lux]	5.86	29.00	59.17
Static Noise Level [dB]	48.47	64.15	72.77
Audio Sound Level [dB]	47.10	18.60	12.76
MOS	4.33	4.20	3.93
Impairment	Good	Good	Good

TABLE III
IMPACT OF THE DISTANCE ON THE VLC LINK QUALITY - DARK SCENARIO

	1m	2m	3m	4m	5m	6m
Interfering Light with Transmission Intensity [Lux]	5.85	1.34	0.64	0.36	0.21	0.15
Static Noise Level [dB]	48.47	41.63	35.80	34.66	34.36	29.90
Audio Sound Level [dB]	47.10	41.53	38.20	33.93	32.70	31.86
MOS	4.33	3.53	3.40	2.53	2.47	1.80
Impairment	Good	Good	Fair	Fair	Poor	Poor

level in case of the Office scenario also presents an increase of 50% when compared to the Dark scenario. However, under all three considered scenarios the audio quality is still perceived as Good.

C. Impact of the Distance on the VLC Link Quality

In order to study the impact of the distance from the transmitter on the VLC audio link quality, we maintain the optimal conditions with no interfering light (Dark) and vary the distance from the transmitter. The results are collected at every 1m away from the transmitter up to 6m (the room length). The results are listed in Table III. As expected, as the distance from the transmitter is increasing the transmission light intensity is decreasing and consequently the audio sound level is reduced as well as the MOS. For example, when the receiver is located at 2m away from the transmitter the sound quality is perceived as Good. However, when the receiver moves even further, at 3m and 4m away from the transmitter the perceived quality drops to Fair. When the receiver is located at 5m and 6m away from the transmitter there is a 41.5% and 58.4%, respectively, decrease in MOS as compared to the 1m location, and the sound quality is perceived as Poor.

D. Impact of both, Distance and Interfering Light on the VLC Link Quality

This section studies the impact of both, the distance and the interfering light level on the VLC audio link quality. Consequently, we vary the distance from the transmitter under all three scenarios. The results are illustrated in Table IV and Figs. 4 and 5. It can be noticed that the fluorescent lighting (Office scenario) has the strongest impact on the audio sound level and MOS, especially as the distance from the transmitter is increasing. For example, at an interfering light intensity level above 50 Lux and distance greater than 4m the audio sound level becomes inaudible (< 0.50 dB). Similarly, for the Ambient scenario with an interfering

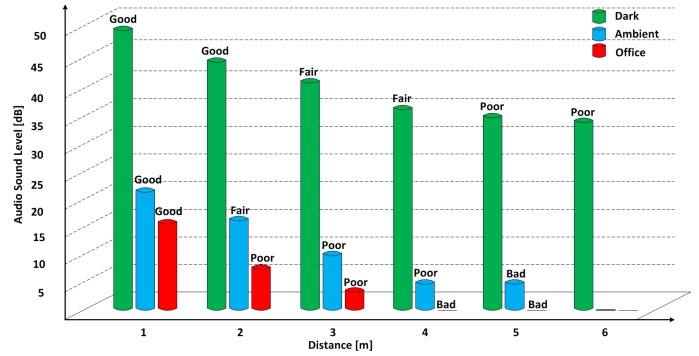


Fig. 4. Audio Sound Level and MOS vs. Distance

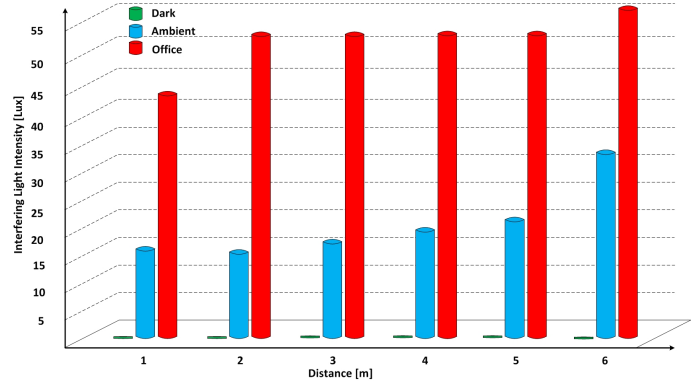


Fig. 5. Interfering Light Intensity vs. Distance

light intensity of 30 Lux and 6m distance the audio sound level becomes inaudible, However, comparing to the Office scenario, when we have natural light (Ambient scenario) we can still perceive the sound as Fair at a distance of 2m, Poor for 3m and 4m and Bad for distances above 5m, whereas for the Office scenario the sound quality is perceived as Poor at a distance of 2m and 3m and Bad starting from 4m.

Thus, as expected and as illustrated in Figures 4 and 5, as the interfering light intensity and the distance are increasing, the audio sound level and its corresponding MOS are decreasing.

VI. CHALLENGES AND OPEN ISSUES

Lately, VLC is receiving significant attention in the research community, being studied by experts to make it a viable solution and enable its integration in the heterogeneous 5G networks environment. Even though VLC offers promising advantages in terms of energy efficiency and high data rates, it also faces a lot of challenges and open issues. Some of the main limitations of the VLC technology are summarized in this section.

One of the major issues is the data loss caused by the characteristics of the VLC link as the light from the LED is dispersing. Another important limitation that VLC is facing is its inability of offering duplex communication. VLC has a broadcast characteristic and unlike WiFi, it can only be used for one-way communication. However, to rectify this limitation VLC could be used in combination with a

TABLE IV
IMPACT OF BOTH, DISTANCE AND INTERFERING LIGHT ON THE VLC LINK QUALITY

	Dark						Ambient						Office					
	1m	2m	3m	4m	5m	6m	1m	2m	3m	4m	5m	6m	1m	2m	3m	4m	5m	6m
Interfering Light Intensity [Lux]	0.01	0.01	0.01	0.01	0.01	0.01	13.89	12.51	14.46	16.40	18.35	30.35	40.96	50.06	50.80	50.73	50.63	54.03
Interfering Light with Transmission Intensity [Lux]	5.85	1.34	0.64	0.36	0.21	0.15	29.00	14.82	15.27	17.92	19.92	30.30	59.16	55.03	52.73	50.70	51.46	54.03
Static Noise Level [dB]	48.47	41.63	35.80	34.66	34.36	29.90	64.15	62.30	62.55	65.55	63.70	67.25	72.76	73.33	74.03	73.43	74.16	73.7
Audio Sound Level [dB]	47.10	41.53	38.20	33.93	32.70	31.86	18.60	13.05	7.05	1.55	1.55	NA	12.76	4.60	0.50	NA	NA	NA
MOS	4.33	3.53	3.40	2.53	2.47	1.80	4.20	3.00	2.13	1.60	1.40	NA	3.93	2.13	1.53	1.47	1.40	NA
Impairment	Good	Good	Fair	Fair	Poor	Poor	Good	Fair	Poor	Poor	Bad	NA	Good	Poor	Poor	Bad	Bad	NA

different medium of communication such as infrared [9]. In this case, the transmitter of the VLC system would need to also act as a receiver for infrared communication and the receiver of the VLC system would need to act as a transmitter for IR, which might prove to be a costly solution.

Due to the LED Driver being bandwidth limited it limits the bandwidth of the VLC system. However, this limitation can be overcome by using modulation techniques such as OFDM and DMT, and thus increasing the data rates exponentially [16]. Another problem faced by the VLC system is to ensure that its coverage area and the distance between the transmitter and receiver are at their optimum. A possible solution is increasing the number of LEDs and arranging them in a lock step model that would increase coverage area and distance [9]. As we have seen in this study, the impact of interfering light from other artificial or natural sources represents another major problem for VLC and remains an open issue, An important aspect is that VLC is not regulated by a particular body yet. However, VLC is currently under study to becoming a ratified form of communication, specifically, IEEE 802.15c [18].

VII. CONCLUSIONS

The use of Visible Light Communication has gained substantial interest lately especially for its potential of offering high data rates, high security, no RF interference and lower energy consumption. This paper provides a comprehensive study on the impact of visible light communication on audio and video transmissions and identifies the challenges and remaining open issues. Additionally, a real experimental test-bed is setup to test the performance of audio transmission over VLC under various conditions such as distance from the source, impact of interfering lighting, etc. Moreover, subjective tests have been carried out to assess the quality of the audio transmission over the VLC system under varying conditions, as perceived by the user. The results show that within an office environment, the artificial light has the greatest impact on the user perceived audio quality when compared to the impact of the natural light.

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