Implementation and Performance Evaluation of a MIMO-VLC System for Data Transmissions

Fabian Harendran Jesuthasan, Hardik Rohitkumar, Purav Shah, and Ramona Trestian
Design Engineering and Mathematics Department,
Faculty of Science and Technology,
Middlesex University, London, UK
E-mails: {FJ162, HR355}@live.mdx.ac.uk, {p.shah, r.trestian}@mdx.ac.uk

***Abstract*—The ever-increasing streaming culture of large amounts of data and the need for faster and reliable methods of data transfer has created a space and market for new communication technologies such as Visible Light Communication (VLC). However, the integration of VLC into next generation networks is challenging due to the drawbacks of the technology in terms of atmospheric absorption, shadowing, beam dispersion, etc. One way to overcome some of the challenges is to make use of the multiple input multiple output (MIMO) technique which involves the transmission of data in parallel from multiple sources, increasing the data rate. This paper implements and provides a comprehensive evaluation of a MIMO-VLC system for data transmission. A real experimental test-bed is setup to test the performance of the MIMO-VLC system under various conditions such as distance from the source based on luminous flux, ambient lighting, output power, etc. Additionally, subjective tests are carried out to assess the quality of an audio MIMO-VLC link as perceived by the user. The results are compared with the results of a Single Input Single Output (SISO)-VLC system.**

I. Introduction

One of the current challenges that the mobile operators are confronting with at the moment is the massive increase in mobile broadband traffic. Cisco predicts that the global IP traffic will increase threefold by 2021, out of which more than 63% will be exchanged wirelessly and up to 82% will be rich multimedia-based traffic (e.g. live Internet video, virtual reality and augmented reality traffic, 360^o video, etc.) [1]. It is well known that the multimedia traffic is a type of bandwidth-hungry traffic that puts significant pressure not only of the content processing but also on the underlying network technologies [2].

Even though there has been a spectacular evolution of the wireless technologies over the past years, the present trend is to adopt a heterogeneous global network of shared standards which comes to meet users' expectations and applications' requirements [3]. Thus, in order to cope with the ever-increasing users' demands, the next generation of wireless networks is expected to offer 1000 times the system capacity, very high data rates and 10 times increase in spectral and energy efficiency.

In order to increase flexibility, reliability and cost savings one of the adopted solutions by the network operators is network densification where small cells are deployed in an overlapping manner, leading to a Heterogeneous Network (HetNet) small cell environment [4] as illustrated in Fig. 1.

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

The delivery of new rich media traffic with strict Quality of Service (QoS) requirements, especially over a HetNet environment to mobile customers is expected to become one of main economic driving forces in the near future [5]. However, this is not possible without the necessary infrastructure to accommodate the increasing number of mobile users and as well as to cater for their expected high quality of experience levels.

A promising solution for 5G integration is the use of Visible Light Communication (VLC) [6]. The advantages of VLC are high data rates and low energy consumption, high security and no Radio Frequency (RF) interference [7]. A hybrid VLC/RF HetNet environment is illustrated in Fig. 1 where the mobile users can access rich media services anytime and anywhere through ubiquitous connectivity.

Despite its advantages, one of the main problems that VLC faces is the dispersion of light emitted by the LED bulb as well as the impact of parasitic light, thereby causing loss of data.

This paper extends our previous work [8] by implementing a MIMO-VLC system for data transmission. A comprehensive performance evaluation is provided using an experimental test-bed setup. The evaluation is done under various conditions, such as: the distance from the source based on luminous flux, ambient lighting, output power, etc. Moreover, subjective tests are carried out to assess the quality of an audio MIMO-VLC link as perceived by the user. The results are compared with the results from a Single Input Single Output (SISO)-VLC system [8].

II. Related Works

VLC systems have many advantages such as unsaturated bandwidth unlike the RF bands as well as they have also been shown to be highly secure. However, VLC systems tend to have bandwidth limitations depending on the photodiodes being used leading to spectral efficiency decreases [9]. To overcome this, the use of modulation techniques increases the spectral efficiency and thereby the data rates. The IEEE 802.15.7 standard defines dimming mechanisms, using modulation techniques, to ensure that the LEDs do not flicker and also to ensure high data rates [10].

Another solution to increase the data rate is the integration of MIMO technique. Various solutions for MIMO-VLC are presented in the literature as summarized in Table I. Dambul et al. [11] built a MIMO VLC system achiving data rates of up to 2 Mbps. Wang et al. [12] showed that by building a MIMO VLC system with a "hemispherical lens" the line of sight (LOS) can be drastically improved and thereby also increase the amount of light being captured by the photodiode. Hong et al. [13] built a MIMO VLC system capable of achieving data rates of up to 100 Mbps and a Bit Error Rate (BER) of 10^{-6}. Moreover, the challenge of eliminating the cross-talk from the multiple LEDs was also addressed. The system corrected this problem by implementing a transmit precoding scheme.

Yeh et al. [14] proposed a bi-directional MIMO VLC-IR system that was used to transmit a 720P MPEG-2 video at a data rate of 28.4 Mbps over a distance of 1.5m. The maximum data rate achieved by this system was 37 Mbps. The TX design included the use of five phosphor LED each with a bandwidth of approximately 1 MHz and was increased to about 12 MHz by implementing a pre-equalization scheme and thereby removing the need for a blue filter. Moreover, an OFDM modulation scheme was used to further increase the data rates.

Jian et al. [15] proposed an indoor MIMO VLC system that has been optimized for video transmission and that has been designed by studying three different transmission schemes. The authors compared Unity Frequency Reuse (UHR), Higher Frequency Reuse Factor based Transmission (HFRT) and Vectored Transmission (VT) schemes in order to find out which of these would optimize the VLC system so that the total distortion of video caused during streaming can be reduced as much as possible. The transmission schemes were compared on the basis of quantified values of any delay caused during transmission, data rates achieved, the amount of energy that was used up and also the Peak Signal to Noise Ratio (PSNR). Based on these findings, VT was the recommended transmission scheme. In addition to minimizing video distortion, the authors also focused on achieving sufficient transmission rates. In order to do so, the authors implemented an ACO-OFDM modulation scheme as well as ensured that the video clips are encoded using H.264 and H.265 video codecs, prior to transmission so that the video being transmitted would require less bandwidth.

In our previous work [8] we investigated the use of SISO-VLC for audio and video transmissions. In this work we implement a MIMO-VLC system in order to study the impact of environmental parasitic light on data transmission.

III. System Design

In VLC systems a transmitter will transmit the data through the use of a light emitting diode (LED). At the receiver side, the receiver will receives the data by capturing the light using a photodiode and then convert the light into the original data. The LED light intensity and the photodiode sensitivity are key parameters that could be used to increase the transmission range of the system. Consequently, the accuracy of the received signal could be increased by using a highly sensitive photodiode.

The circuit design of the proposed MIMO-VLC system is illustrated in Fig. III and represents an extension of our SISO-VLC system proposed in [8]. As seen in Fig. III the circuit consists of a transmitted and a receiver. The transmitter component was fitted with two LEDs while the receiver component was fitted with two solar panels. At the transmitter side, the input audio signal is first amplified and then superimposed on the LEDs using a T-bias circuit. The audio signal is transmitted by the two LEDs in the form of light which is collected at the receiver side by the photodiode. The original signal is recovered by the photodiode and sent to the output after being amplified. The gain of the transmitter and the receiver amplifiers are the same as that of the SISO VLC setup, i.e., 200.

The LM386 microchip, a low power audio amplifier was used to amplify the audio signal. By using a $10\mu F$ capacitor the amplifier gain is boosted to 200. The output of the amplifier is superimposed onto the LEDs through the use of a T-Bias circuit which is obtained by adding the positive voltage to the output through an inductor. In order to be able to control the input voltage level for the microchip, a variable resistor was placed between the audio input and the inverting pin. At the receiver side, a similar circuit is used. However, the input to the amplifier is done through two solar panels and the output is sent to a speaker. The photodiode used in the circuit is a solar panel as it produces an output of 2.4V, compared to an output of only 0.3V as generated by the Hamamatsu S6968. The high output produced by the solar panel is due to the characteristics of avalanche photo diodes.

IV. Experimental Setup

This section presents the experimental test-bed setup and introduces the scenarios used for performance evaluation of the proposed system. The designed MIMO-VLC system was implemented and an experimental test-bed for audio transmission was setup and used for performance evaluation.

TABLE I
SUMMARY OF THE LITERATURE REVIEW

Reference	Main Findings
Dambul et al. [11]	An indoor MIMO VLC system for receiving images was proposed and data rates of up to 2 Mbps were obtained.
Wang et al. [12]	A MIMO VLC system was built along with hemispherical lens which drastically improved the LOS.
Hong et al. [13]	A MIMO VLC system was built with data rates of up to 100 Mbps and a BER of 10^{-6}. The elimination of cross-talk was carried out using transmit precoding scheme.
Yeh et al. [14]	A bidirectionional VLC-IR system to transmit MPEG-2 video signals was proposed with data rates reaching 28.4 Mbps over a distance of 1.5m. Bandwidth of each LED bulb was increased from 1MHz to 12MHz by implementing a pre-equalization scheme so that blue filters were not required.
Jian et al. [15]	A MIMO system was proposed in order to compare UHR, HFRT and VT schemes and VT was found to be the best as PSNR was highest and had lower energy consumption. ACO-OFDM technique was used to increase data rates while encoding the video signals with H. 264 or H.265 codecs prior to transmission which was recommended to reduce bandwidth usage.

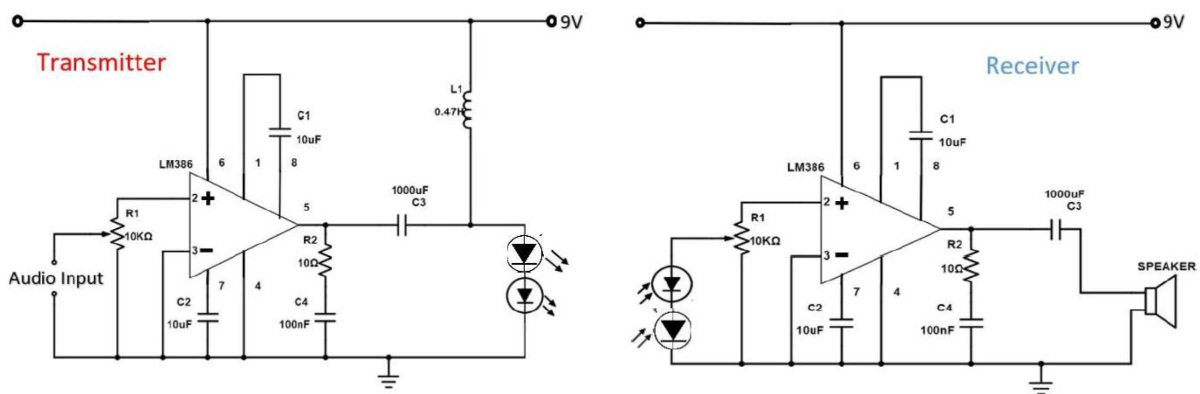


Fig. 2. Audio MIMO VLC System - Circuit Design

A. Test Scenarios

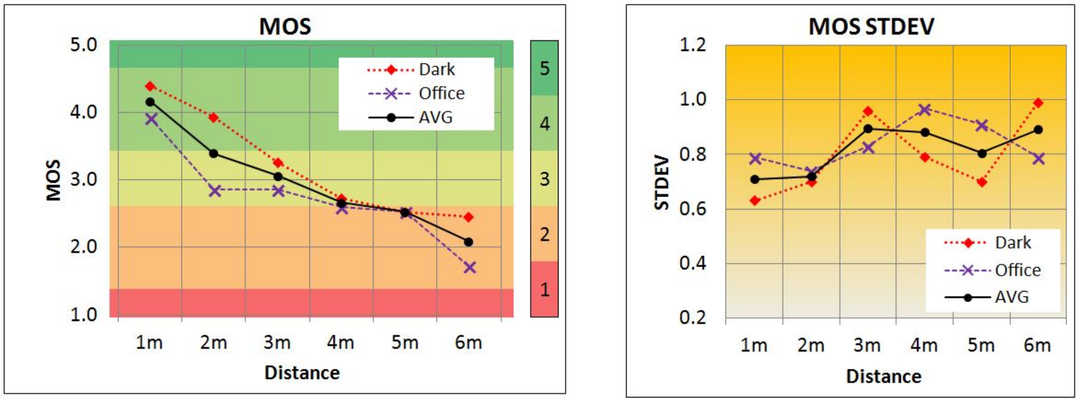
Two scenarios were considered, in order to analyse the impact of different levels of interfering light on the audio link quality of the MIMO-VLC system, such as:

- Normal office Environment - in this scenario the only source of interfering light is the fluorescent light. The aim of this scenario is to analyse the impact of the fluorescent lighting on the audio MIMO-VLC link quality.
- Dark office Environment - in this scenario there is no source of interfering light. The aim of this scenario is to analyse the audio MIMO-VLC link quality under no interfering light source.

The impact of the distance from the transmitter combined with the impact of the interfering light is also analysed. Consequently, the measurements were collected at every 1m up to 6m away from the transmitter for each of the two considered scenarios. The results obtained for the MIMO-VLC setup were also compared with the results from the SISO-VLC introduced in [8]. Furthermore, each test was repeated three times and the average results are presented along with the following parameters: the intensity of the interfering light measured in Lux, the internsity 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

From the experimental test-bed setup we only measure the audio sound in dB which cannot indicate the actual audio sound quality. Consequently, a subjective study is conducted to asses how human subjects perceive the quality of the audio clips for each scenario considered and at different distances from the transmitter (e.g., 1m to 6m). A number of 12 20-seconds long audio sequences were used in the subjective tests. Following the standard recommendations for subjective sound quality assessment in [16], the same testing conditions were maintained for all the participants and the audio clips were played in a random order locally on a laptop. A total number of 15 (M=8, F=7) non-experts participants with the ages between 18 and 68 year old (AVG = 28, STDEV = 14) were involved in the subjective tests. All the participants reported that they had normal hearing and no hearing aid was used. The participants were asked to rate the quality of each audio clip using a five Mean Opinion Score (MOS) levels scale as indicated in Table II, starting with level 1 representing *Bad* quality and ending with level 5 representing *Excellent* quality.



Sequence	1m	2m	3m	4m	5m	6m
Dark	4.40	3.93	3.26	2.73	2.53	2.46
Office	3.93	2.86	2.86	2.60	2.53	1.73
AVG	4.17	3.40	3.06	2.67	2.53	2.10

Sequence	1m	2m	3m	4m	5m	6m
Dark	0.63	0.70	0.96	0.79	0.70	0.99
Office	0.79	0.74	0.83	0.97	0.91	0.79
AVG	0.71	0.72	0.90	0.88	0.81	0.89

Fig. 3. Subjective Sound Quality Assessment Results

TABLE II
MEAN OPINION SCORE LEVELS

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly Annoying
2	Poor	Annoying
1	Bad	Very Annoying

TABLE III
IMPACT OF FLUORESCENT LIGHT ON THE MIMO-VLC LINK QUALITY

	Dark	Office
Interfering Light Intensity [Lux]	0.01	33.13
Interfering Light with Transmission Intensity [Lux]	36.83	57.26
Static Noise Level [dB]	60.7	61.83
Audio Sound Level [dB]	39.7	34.33
MOS	4.40	3.93
Perceived Quality	Good	Good

V. RESULTS AND DISCUSSIONS

This section presents the results obtain from the real experimental test-bed setup. All the measurements for all the considered scenarios were repeated three times (a total of 36 tests were carried out) and the average values were computed and used throughout the paper.

A. Subjective Sound Quality Assessment Results

A set of subjective tests were carried out to assess the user perceived sound quality of the audio transmission over the MIMO-VLC setup under the two different scenarios (e.g., Dark and Office) and at different distances from the transmitter (e.g., from 1m up to 6m). For each audio sequence, the participants were asked to rate the overall sound quality on the 1 (Bad) to 5 (Excellent) scale. The mean value represented by the MOS and the standard deviation (STDEV) for each audio sequence were computed and illustrated in Fig. IV-B. The results show that when the Dark scenario is considered the sound quality is perceived as *Good* for the sequences corresponding to 1m and 2m away from the transmitter, dropping to *Fair* at 3m up to 5m and *Poor* at 6m. However, for the Office scenario only the sequence corresponding to 1m scored *Good* while the rest from 2m up to 5m scored *Fair* and *Poor* at 6m. Pearson correlation was used to analyse the relationship between MOS and STDEV. A value of $r = -0.412534071$ was obtained which indicates a negative association. Consequently, this means that the scores across the participants tend to have a higher variation for the audio clips with lower user perceived quality.

B. Impact of the Fluorescent Light on the MIMO-VLC Link Quality

In order to study the impact of the fluorescent light on the MIMO-VLC link, we maintain the same location for the receiver at 1m away from the transmitter and we change the environmental conditions, such as Dark and Office. The obtained results are listed in Table III. The results indicate that as expected, under the impact of the fluorescent light there is a decrease in the audio sound level as well as the MOS. The intensity of the fluorescent light of 33.13 Lux will cause a 10% decrease in MOS when compared to the optimal no interfering light scenario (Dark). However, under both scenarios the sound quality is still perceived as *Good*.

C. Impact of Distance on the MIMO-VLC Link Quality

In this section we want to study the impact of the distance from the transmitter on the MIMO-VLC audio link quality . For this purpose, we maintain the optimal conditions without any interfering light as in the Dark scenario and we vary the distance from the transmitter from 1m up to 6m. The obtained results are listed in Table IV. As expected, it can be noticed that as the distance

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

	1m	2m	3m	4m	5m	6m
Interfering Light with Transmission Intensity [Lux]	36.83	6.16	2.58	1.89	1.47	1.10
Static Noise Level [dB]	60.70	60.13	56.73	56.30	54.76	53.13
Audio Sound Level [dB]	39.73	24.70	19.00	19.00	18.43	16.93
MOS	4.40	3.93	3.26	2.73	2.53	2.46
Perceived Quality	Good	Good	Fair	Fair	Fair	Poor

from the transmitter is increasing, the transmission light intensity is decreasing and consequently the audio sound level is reduced. This has a direct impact on the MOS. For example, when the receiver is located within 2m from the transmitter, the sound quality is perceived as *Good*. As the receiver moves away from the transmitter at 3m up to 5m the perceived quality is dropping to *Fair* and further to *Poor* at 6m away from the transmitter. Thus, there is a 44% decrease in MOS when the receiver is located at 6m away from the transmitter compared to the case when the receiver is located at just 1m away.

D. Impact of Distance and Fluorescent Light on the MIMO-VLC Link Quality

In order to study the impact of both, distance and fluorescent light on the MIMO-VLC audio link quality, we vary the distance between the receiver and the transmitter from 1m up to 6m and compare the results under the two environmental conditions, no interfering light (Dark scenario) and with interfering fluorescent light (Office scenario). The results are listed in Table V and it can be noticed that the fluorescent light together with the distance have a strong impact on the audio sound level. For example, in the case of the Office scenario, at a distance of 6m away from the transmitter the audio sound level dropped by 96% when compared to the receiver being located at 1m away. This translates into a 56% decrease in MOS, the sound quality being perceived as *Poor*. When compared to the Dark scenario, at the same distance of 6m away from the transmitter there is a 92% drop in the audio sound level caused by the impact of the fluorescent light (Office scenario). This is also reflected into 30% decrease in MOS and the sound quality being perceived as *Poor*. Additionally, under the Dark scenario the audio sound is still perceived as *Good* when the receiver is located at 2m away from the transmitter, whereas under the Office scenario at 2m distance the user perceived sound quality drops to *Fair*.

E. SISO-VLC vs. MIMO-VLC

This section compares the results obtained from the SISO-VLC setup introduced in our previous work in [8] with the results obtained from the MIMO-VLC setup. Figure V-E illustrates the MOS results for SISO-VLC and MIMO-VLC under the two scenarios, Dark and Office. It can be noticed that in the case of Dark scenario, both SISO-VLC and MIMO-VLC received similar scores, with a noticeable different at a distance of 6m away from transmitter when

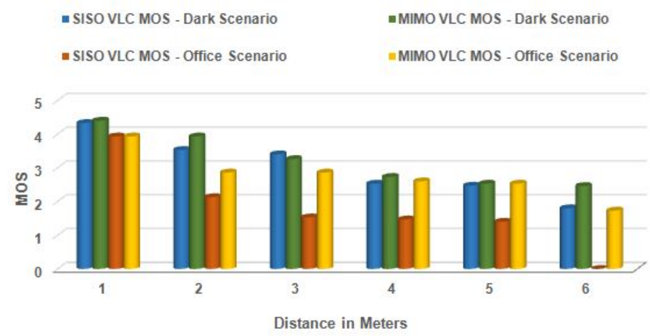


Fig. 4. MOS Comparison of SISO VLC vs. MIMO VLC for Dark and Office Scenarios

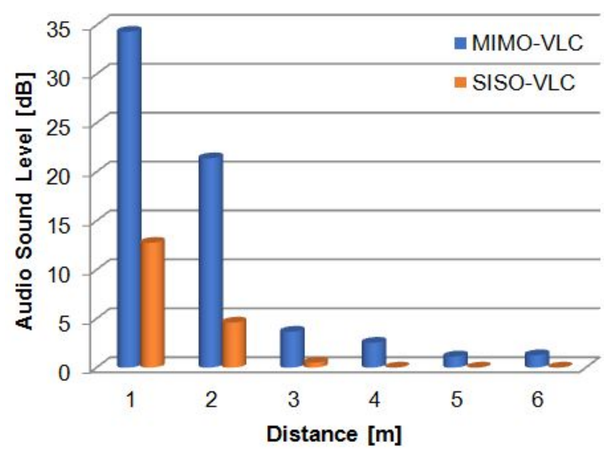


Fig. 5. Audio Sound Level Comparison of SISO VLC vs. MIMO VLC for Office Scenario

the MOS increased by 37% for the MIMO-VLC setup. The advantage of the MIMO-VLC system is visible under the Office scenario where we can notice the impact of the fluorescent light on the VLC link quality. It can be noticed that when using a SISO-VLC setup, the sound quality drops to *Poor* when the distance increase to 2m and 3m and to *Bad* for a distance of 4m and 5m, while at 6m the sound is imperceptible. However, when the MIMO-VLC setup is used, the sound quality is perceived as *Fair* for a distance of 2m up to 5m and drops to *Poor* at 6m away from the transmitter. This is noticeable in Figure V-E as well, which illustrates the audio sound level for SISO-VLC vs. MIMO-VLC under the Office scenario. It can be noticed that with MIMO-VLC the audio sound level increases significantly when the receiver is located near the transmitter as well as the range is increased. The detailed results under the impact of the fluorescent light are listed in Table VI for both cases. With the SISO-VLC setup the audio sound level becomes imperceptible starting at a distance of 4m while with the MIMO-VLC setup the sound quality is still perceived as *Fair* at a distance of 6m.

TABLE V
IMPACT OF BOTH, DISTANCE AND FLUORESCENT LIGHT ON THE MIMO-VLC LINK QUALITY

	Dark						Office					
	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	33.13	43.26	45.50	42.36	43.83	45.16
Interfering Light with Transmission Intensity [Lux]	36.83	6.16	2.58	1.89	1.47	1.1	57.26	46.16	46.93	43.36	44.36	45.76
Static Noise Level [dB]	60.70	60.13	56.73	56.30	54.76	53.13	61.83	62.80	62.60	65.80	66.43	66.96
Audio Sound Level [dB]	39.73	24.70	19.00	19.00	18.43	16.93	34.33	21.40	3.66	2.53	1.13	1.26
MOS	4.40	3.93	3.26	2.73	2.53	2.46	3.93	2.86	2.86	2.60	2.53	1.73
Perceived Quality	Good	Good	Fair	Fair	Fair	Poor	Good	Fair	Fair	Fair	Fair	Poor

TABLE VI
SISO-VLC VS. MIMO-VLC LINK QUALITY

	SISO-VLC						MIMO-VLC					
	1m	**2m**	**3m**	**4m**	**5m**	**6m**	**1m**	**2m**	**3m**	**4m**	**5m**	**6m**
Interfering Light Intensity [Lux]	40.96	50.06	50.80	50.73	50.63	54.03	33.13	43.26	45.50	42.36	43.83	45.16
Interfering Light with Transmission Intensity [Lux]	59.16	55.03	52.73	50.70	51.46	54.03	57.26	46.16	46.93	43.36	44.36	45.76
Static Noise Level [dB]	72.76	73.33	74.03	73.43	74.16	73.70	61.83	62.80	62.60	65.80	66.43	66.96
Audio Sound Level [dB]	12.76	4.60	0.50	NA	NA	NA	34.33	21.4	3.66	2.53	1.13	1.26
MOS	3.93	2.13	1.53	1.47	1.40	NA	3.93	2.86	2.86	2.60	2.53	1.73
Perceived Quality	Good	Poor	Poor	Bad	Bad	NA	Good	Fair	Fair	Fair	Fair	Poor

VI. CONCLUSIONS

VLC is one of the new technologies that presents increased interest from the research community to study its capabilities and the possibilities of integrating it within the next generation of wireless networks, like 5G. However, one of the critical disadvantages that VLc is facing is how it copes under parasitic light. When using VLC, the light from other sources, artificial or natural hinder the VLC channel link and create a lot of noise. In this context, this paper provides the implementation details of a MIMO-VLC system for data transmission. A study on the impact of environmental parasitic light (e.g., fluorescent light) on data transmission within the MIMO-VLC system is presented. Moreover, a real experimental test-bed is setup to test the performance of the MIMO-VLC system under various conditions such as distance from the source based on luminous flux, ambient lighting, etc. Subjective tests were carried out to assess the quality of an audio MIMO-VLC link as perceived by the user. Additionally, the obtained results from the MIMO-VLC setup were compared to the ones from a SISO-VLC setup. The results indicate that even by using a 2x2 MIMO setup, the perceived quality of the audio sound as well as the receiving range are significantly improved when compared to the SISO-VLC case.

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