Modulation Concepts for High-Rate Display-Camera Data Transmission

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***Abstract*— Display-camera data links can be regarded as a massive MIMO visible light communication. They are a research topic since several years. Imperceptible data transmission while simultaneously presenting video sequences for human viewers on the display is an innovative approach allowing for many new applications. Several groups work on this concept. This paper describes a new approach with specific modulation schemes and proposes a system, which combines concepts from digital data transmission and real time video processing while carefully taking the characteristics of the human visual system into account. The modulation parameters are selected as a compromise between picture quality deterioration and decoding performance in terms of data rate and bit error probability. Characterizing a video representation by luminance Y and chrominance U and V as usual in electronic media distribution and video source coding, subjective tests show that data modulation of the chrominance signals is a promising option. An early experimental setup applying modulation of U and V video components already provided data rates of 4.5 Mbit/s at acceptable error rates without significant degradation of perceived video quality.**

Keywords—display-camera communications, screen-camera communications, optical MIMO, free space optical transmission, picture quality, DaViD

I. INTRODUCTION

Visible light communication (VLC) is a concept with attractive features. It does not occupy scarce radio spectrum and thus can be used without any license. Furthermore, VLC provides a well-defined coverage area, directly visible for human beings, and does not give users any reason to be afraid of electromagnetic radiation. Another interesting feature of some VLC concepts is the option to re-use existing devices such as LED lamps as transmitters or cameras as receivers.

Many publications describe VLC systems, and key aspects for specific applications have been standardized in IEEE 802.15.7-2011 [1]. Good overviews on technical aspects of using general-purpose lighting for transmission can be found in [2] and the references therein. Concepts for transmission links supporting high data rates are described e.g. in [3].

A special form of massive MIMO VLC is the data transfer from video displays such as LCDs to cameras. Fundamental considerations have been published by Hranilovic and Kschischang already in 2006 [4]. Hranilovic et al. published further considerations on this topic in [5],[6],[7].

System proposals such as PixNet [8], CoBra [9] and LightSync [10] use LCD screens as transmitters and mobile phones as receiver. The authors of these papers propose several concepts to overcome limitations of existing smart phone hardware or synchronization issues. Considering the performance parameters of advanced video devices, data rates of these proposals are restricted to values well below 1 Gbit/s. Compared to the performance of modern WLAN, such systems are most probably attractive only to a limited range of applications. However, the idea of display-camera communication becomes much more attractive when using displays as transmitters while simultaneously showing video content to human viewers.

This paper describes system aspects of such a transmission concept and presents preliminary results from an experimental testbed. In chapter II, the system concept and its applications are described and compared to the state of the art. Chapter III presents the applied system model, which helps to understand the design issues and suitable data modulation schemes. Chapter IV gives results of subjective tests that have been carried out to define useful modulation parameters. In chapter V, a short description of the testbed at TU Dortmund University and first performance results are given. Chapter VI contains a conclusion and proposals for future work.

II. SYSTEM CONCEPT AND APPLICATIONS

Several proposals for display-camera data transfers running simultaneously with a video presentation have been published since 2014. InFrame [11] proposes the overlay of data patterns based on "superpixels" and pixel blocks. A temporal luminance modulation is used with smooth transitions between different data patterns, thus requiring several video frame pairs per transmission. Due to the large superpixels and slow temporal rate per superpixel, the data rate is limited. A recent publication reports data rates of up to 300 kbit/s when a display frame rate of 120 Hz is applied [12]. Another approach is HiLight [13]. A frequency modulation of the video transparency (α-channel) is applied to achieve data rates of up to 180 kbit/s. This kind of modulation has been selected to allow for a real time implementation on computer graphic cards. However, it limits the options for an efficient modulation scheme, which at the same time achieves high data rates and a high quality video representation. DisCo [14] does not apply a massive MIMO approach. A rolling-shutter camera is used to perform the decoding by translating the temporal sequence to a spatial pattern. The system is very robust concerning camera misalignment and picture occlusions. However, the data rates are limited to about 1 kbit/s [15].

A very promising approach similar to DaViD was published by Wu and Shu in April 2015 [16]. A temporal differential modulation of frame pairs is applied as described as one option in chapter III. Pixels are grouped in superpixel blocks to facilitate demodulation. Data rates of up to 1 Mbit/s are reported while achieving reasonable BER performance.

Most published work is based on computer vision paradigms. However, it is advantageous to regard also concepts from real time video processing as used in media distribution and transmission. It is advantageous to describe the transmission as a multi-dimensional sampling on the transmitter as well as on the receiver side, with pre- and post-filters defined by the technology of the devices. Symbol synchronization and detection as well as forward error correction should be defined such as in advanced wireless data transmission schemes. A basic consideration of modulation options allows control of performance, visibility of overlaid data patterns as well as adaptation to different applications scenarios.

The basic arrangement of our proposal for a data transmission using video devices (DaViD) is shown in fig. 1. At a first glance, it is very similar to the mentioned state of the art. However, the modulation amplitudes for data transmission are quite small and are added to the R, G, and B pixel amplitudes of the video content to be shown on the screen. While the additional data modulation is designed to be nearly invisible for human viewers, a high-resolution camera picking up the scene will be able to demodulate the data. This concept and some of its options have been presented for the first time in January 2015 [17].

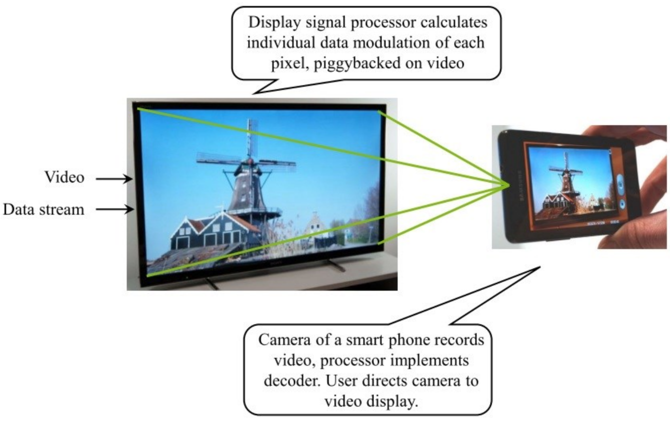

Fig. 1. Basic transmission concept of DaViD [18]

As discussed also in other publications on simultaneous video display and data transmission, many application scenarios of this technology can be considered and appear to be very attractive. These comprise:

1. Indoor individual communication: Short-range links will be based on relatively small displays, e.g. with a size comparable to tablet screens. An application might be the transmission of background information to visitors in the museum or individual data kiosk systems in a media shop.

2. Indoor multicast communication: The link distance is greater than in the first case, and accordingly the displays are larger. Flat screens of 40"-100" size or projectors are suitable. An application example might be a kiosk system, which is showing a video while allowing observers to download application data or media files. The application of such technical concepts can also be attractive in certain factory floors scenarios, e.g. adjustment and final quality inspection in car manufacturing.

3. Outdoor communication: The difference is the display size. Here large screens used for advertising in shopping malls or sport arenas can serve as the transmitter. Applications can be similar to those of the second indoor scenario.

In many cases, enhanced smart phones can be used as the receiver. As soon as services are implemented in public screens, users of modern smart phones, equipped with a suitable camera, could experience innovative offers after installing a new app. At the same time, new business ideas will come up if this kind of communications is introduced in the mass market.

On one hand, it is a great advantage that many application scenarios appear to be attractive. On the other hand, for the development of a suitable system and the selection of the relevant parameters, this causes the challenging problem that many implementation options are available and have to be selected carefully. Size, distance and contrast ratio of the display influence the best parameter choice for the setup. In the following, some basic considerations are given. While the basic principles remain unchanged, the technical details have to be adjusted to the applied hardware setup.

III. System Model

The video display provides a large number of pixels, each consisting of a specific arrangement of subpixels for RGB reproduction. Generally, rendering of moving pictures implies that each frame of a video sequence is represented by a matrix of subpixel values. In DaViD, the video display will carry a modulation for data transmission on top. In order to allow the separation of the overlaid data sequence from the video content, a differential modulation scheme is proposed. Some part of the video information must be repeated, whereas data is modulated as a symmetric Manchester code and added to the video signal components. Generally, modulation schemes can be characterized by their spatial-temporal structure and the modulation amplitude. Fig. 2 shows a simplified block diagram of the proposed modulation system. It should be noted that for high system performance it might be useful to select the modulation parameters depending on the video signal. This allows compensating for nonlinearities of the display-camera link and optimizes the camera SNR which depends on the scene luminance of the video signal.

One modulation option is based on the repetition of video information in temporal domain (frame repetition). In this case, a spatial data pattern is added - with opposite signs - to each pair of frames containing the same video content. This can be considered as a temporal differential modulation, which also allows for different options. The data pattern can be encoded in the luminance component Y only, the chrominance components U and/or V or in the primary colors R, G and/or B.

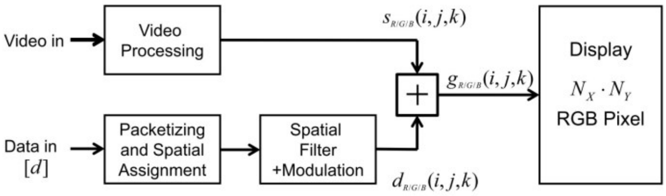

Fig. 2. Block diagram of the signal processing in temporal differential modulation

Another modulation option is a spatial repetition of video pixels (e.g. side by side horizontally) with differential data added per pixel pair. This is a spatial differential modulation. Here, a joint repetition and modulation of a complete color triple can be considered or alternatively a repetition and modulation of the chrominance only. A modulation solely of the chrominance while keeping luminance unmodulated will reduce the visibility of the pattern significantly, while a spatial differential modulation of the luminance requires excellent camera resolution while likely deteriorating perceived picture sharpness and quality.

A broader discussion of all modulation options and their characteristics is beyond the scope of this paper. In the following, the focus will be set on the temporal differential modulation of luminance or chrominance as promising candidates for good system performance. Before describing the proposed modulation parameters, the system concept is described formally for a temporal differential modulation of the luminance signal in order to allow for a deeper understanding of the different options and key parameters discussed later.

We assume a display providing N_y lines, each containing N_x pixels consisting of subpixels for RGB reproduction. The video input signal is processed to provide a display input $s(i,j,k)$ including the frame repetition required for the selected temporal differential modulation scheme:

$$\begin{aligned} &s_{R/G/B}(i,j,k+1) = s_{R/G/B}(i,j,k) \\ &\quad for\ \ 0 \le i < N_X, 0 \le j < N_Y, k = 2m,\ m \in \mathbb{Z} \end{aligned} \tag{1}$$

The indices i and j specify the horizontal and vertical pixel position on the screen, whereas k counts the reproduced number of display frames, each having a duration T. Index m is the counter for the input frames of a video sequence. The amplitude range of the video signal should be limited to allow for the addition of small data amplitudes without severe clipping. If this is not intended, because the full contrast range has to be preserved, a suitable forward error correction scheme must be introduced to provide low bit error rate when presenting arbitrary video content with very dark or bright elements.

A stream of data $d(l)$ that has to be transmitted first should be split up to slices of length L. Each slice contains the amount of data that can be transmitted in one pair of frames, counted by m. The data slice is assigned to the two dimensional display array. A straightforward approach is a direct mapping of data bits to subpixel triples line by line. In this case, slices of N_x bits from each transmission block are taken and assigned successively to the pixels of each line in one frame pair:

$$\begin{aligned} &d(l) \to d(i,j,m) \qquad 0 \le l < L,\ L = N_X \cdot N_Y \\ &i = l \bmod N_x \\ &j = \lfloor l / N_x \rfloor \end{aligned} \tag{2}$$

An important parameter is the modulation amplitude A for data transmission. On principle, the amplitude can be selected independently for the three display primaries to optimize the system performance. In case of a temporal differential modulation of the luminance, the amplitudes for R, G and B are equal:

$$A_R = A_G = A_B = A \tag{3}$$

In case of a chrominance modulation, the amplitudes U and V are specified according to the color matrix as used in TV transmission. The differential modulation method assigns a sequence of {-A,A} to $d=0$ and {A,-A} to $d=1$, respectively. Modulated data symbols and processed video amplitudes are added to provide the display input $g(i,j,k)$:

$$\begin{aligned} g_{R/G/B}(i,j,k) &= s_{R/G/B}(i,j,m) + A \cdot (2 \cdot d(i,j,m) - 1) \\ g_{R/G/B}(i,j,k+1) &= s_{R/G/B}(i,j,m) - A \cdot (2 \cdot d(i,j,m) - 1) \end{aligned} \tag{4}$$

An example of a sequence of four modulated frames (i.e. two video content frames) is shown in Fig. 3. Adding the modulated data (here luminance modulation with $A=4$) to the video input yields the display signal amplitudes in the right column.

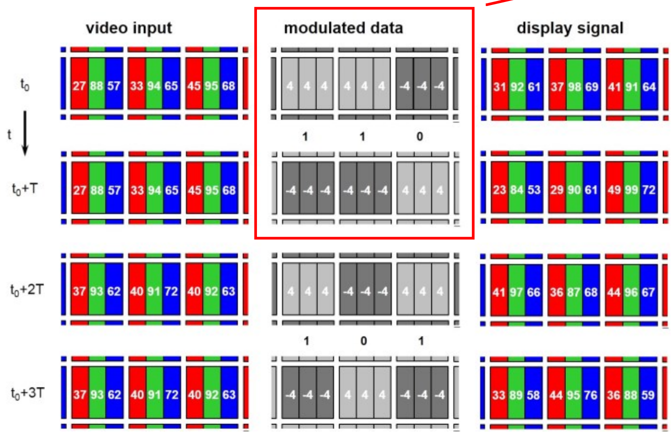

Fig. 3. Example of display amplitudes in temporal differential modulation

Direct assignment of one bit to one single screen pixel provides a high data rate, as a simple calculation shows.

Assuming a display frame rate of 100 Hz and a full HD display, the resulting gross data rate, i.e. without overhead for synchronization and error correction, can be as high as

$$1920 \cdot 1080 \cdot 50 b/s = 103{,}68 Mb/s. \quad (5)$$

Certainly, this kind of modulation requires a high camera resolution. Due to the sampling theorem, even under ideal conditions the camera has to provide more than 8.3 Megapixels for luminance recording. In order to relax the camera requirements, modulation can be restricted to a part of the screen. Another approach is a spatial resampling and filtering of the overlaid data, as sketched by the signal processing blocks in Fig. 2.

A simple and straightforward (however not optimal) concept is the assignment of each data bit to a block of B_X x B_Y display pixels. In this case, equation (2) for data assignment is replaced by:

$$\begin{aligned} & d(l) \rightarrow d(i,j,m) \qquad 0 \le l < L \\ & L = \lfloor N_X / B_X \rfloor \cdot \lfloor N_Y / B_Y \rfloor \\ & i = \left(l \cdot B_X\right) \bmod N_x + r_X, \;\; r_X = 0...(B_X - 1) \\ & j = \lfloor l / \lfloor N_X / B_X \rfloor \rfloor \cdot B_Y + r_Y, \; r_Y = 0...(B_Y - 1) \end{aligned} \quad (6)$$

As there is no principle reason to select different block sizes for both dimensions, the evaluations in section IV of this paper have been done for square blocks:

$$B_x = B_y = B. \quad (7)$$

If a slice of data for transmission does contain less than L bits, bit stuffing should be performed. As mentioned, this simple scheme is neither optimal concerning signal to noise ratio nor regarding visibility of the pattern.

Up to this point, the key elements of the transmission scheme have been described in a pragmatic way. First experiments using a PC as display signal generator, a standard computer LCD screen as transmitter display and high quality cameras have shown that the concept is feasible if filter design and synchronization procedures are well designed.

In order to support this design process and evaluate the influence of all components and parameters, a more systematic description is required. On principle, the system is a massive parallel transmission of temporal data sequences that might be impaired by noise, spatial crosstalk of data, interference from overlaid video reproduction as well as temporal inter-symbol-interference. In temporal differential modulation, each pixel or pixel block is a data channel, modulated by a Manchester code. As well-known from transmission theory, the spectral power density is dc-free, but contains significant components at frequencies much lower than the bit clock. This means that a high frame rate of e.g. 100 Hz does not completely suppress flicker components at e.g. 10 Hz when considering arbitrary data sequences. Practical observation of modulated video material confirms this theory. This aspect is not considered in most existing publications. Visibility of data patterns must be kept at an acceptable level. This is achieved by selecting small data block structures and low modulation amplitudes.

Concerning temporal ISI, a temporal synchronization and suitable selection of shutter time can help to avoid any problems. We postulate the option to synchronize the camera frame clock to the transceiver frame frequency. Measurements of recent displays have shown that typical response times are sufficient to avoid problems of temporal ISI, as long as no further display internal processing is involved. This means that the calculated display input $g(i,j,k)$ has to be fed to the display panel directly.

In the following, perfect synchronization is assumed. In practice, the scanning schemes of display and camera have must be taken into account. E.g., a rolling-shutter camera performs different from a global shutter device. Similarly, in many display technologies the picture on the screen is refreshed line by line. Selection of synchronization schemes have to consider this.

The spatial multiplex in this massive parallel transmission system is much more complex to model, as described in the following. While in the preceding sections pixels have been considered as discrete elements which are addressed by indices i and j, respectively, continuous spatial coordinates x and y are now introduced in the description. For simplification, the same symbols are used for the coordinate system of the transmitter as well as that of the receiver. In reality, the camera lens performs a transformation between both coordinate systems. As this paper focusses on principle aspects of this complex transmission system, the transformation process is neglected in the formal description. Fig. 4 sketches the transmitter side for transmission of one frame. By Fourier transformation, the system can also be analyzed in the frequency domain.

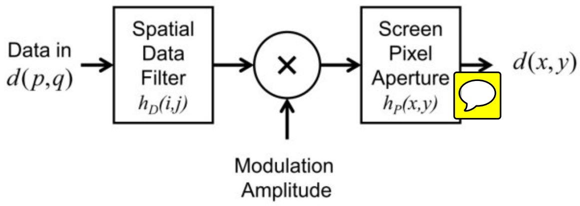

Fig. 4. Spatial system model of a display as data transmitter

Input data is assigned to the two-dimensional plane of the frame on the screen. As the sampling pattern of the data can be different to the pixel pattern (like in the data transmission in blocks of pixels as described above), indices p and q are introduced here. The spatial data filter, characterized by its impulse response $h_D(i,j)$, performs resampling to the display pixel pattern and spectral filtering. The resulting data amplitudes are multiplied by the modulation amplitude, which is selected as a compromise of visibility of the data pattern and system robustness. Due to the nonlinearity of typical displays, which is defined by the gradation function, there will be a certain amount of crosstalk coming from the video signal, influencing the modulation amplitude. The resulting amplitudes of the pixel samples are transferred to a spatially continuous luminance density by the subpixels for R, G and B.

This process is described by the display's spatial aperture in form of an impulse response $h_P(x,y)$, which is given by the pixel geometry of the involved display. As modulation of the different primaries is done, and the pixel positions for R, G, and B usually differ due to the spatial color multiplex in flat screens, the system model has to represent the exact geometry of the display for the colors.

The system model for the receiver side is shown in Fig. 5. For the sake of simplicity, the same symbols are used for indices and coordinates, although in practice transmitter and receiver will apply different geometry and sampling patterns.

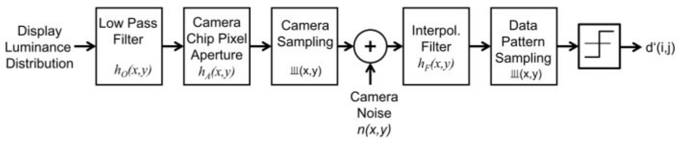

Fig. 5. Spatial system model of a camera as data receiver

The luminance distribution of the screen is picked up by the lens and projected onto the camera chip. The camera lens acts as a spatial low pass filter which is described by its spatial impulse response $h_O(x,y)$. As the conversion between luminance and the electrical signal is almost linear, this process does not influence the abstract model. Therefore, no functional block is introduced here. The aperture of the pixel elements in the camera chip, characterized by the aperture function $h_A(x,y)$, reflects the geometry of the camera. When considering single chip cameras, the mosaic pattern also has to be considered when modelling the characteristics. The camera chip performs a two dimensional spatial sampling of the signal, represented by the following functional block in the figure, that may cause aliasing. Camera noise is added to the signal of each pixel individually. As the generated noise, mainly generated by dark current and shot noise, depends on the total exposure time of the pixel, the overlaid video signal influences the noise power of each pixel.

In the next processing step, the camera signal will be processed by an interpolation filter specified by the impulse response $h_F(x,y)$. This filter is a key element in the processing chain. It has to be developed such that the following two-dimensional sampling delivers optimum signal amplitudes for the decider.

This model contains many simplifications. If color modulation schemes are applied, crosstalk between the RGB signal components also has to be considered.

Considering this model, it is obvious that fine data patterns require higher camera resolution, more precise filtering and lower noise, compared to coarser spatial data patterns. Certainly, visibility of the overlaid modulation in the video presentation increases with higher data amplitudes A or coarser data patterns. In order to evaluate a set of suitable operational parameters, subjective tests of perceived picture quality have been carried out.

IV. Picture Quality Evaluation

The perceived quality of video scenes with overlaid data transmission based on temporal differential modulation has been evaluated in subjective tests, which have been designed in accordance with recommendation ITU-R BT. 500-13 [19]. In [18] results of a similar test for pure luminance modulation were given. Now we also evaluated the impairment caused by chrominance modulation in a double-stimulus continuous quality scale test. Each parameter set was evaluated in four different full HD video scenes. Three scenes were motion videos, while one scene was generated by repeating a still picture. The total duration of one test run with all parameters was 27 minutes, and evaluation was done by a total number of 15 expert viewers. Viewing distance was 3 H. A frame rate of 60 Hz was applied in this test. This is a good choice if standard cameras with limited frame rates have to be used, but with respect to the visibility of the pattern, it is still very critical. When using 120 Hz, the quality deterioration is significantly lower, although not negligible, due to the power density function of Manchester coding, as mentioned in chapter IV.

Therefore, the results gained by this subjective test with 60 Hz frame frequency and 3 H viewing distance can be regarded as a worst case for practical system design. Three different high definition video scenes with overlaid modulation were evaluated by 15 expert viewers. Fig. 6 shows the results for practical modulation parameter sets. It can be clearly noted that pure luminance modulation is much more critical than modulation of the chrominance signals. The influence of the block size and the modulation amplitude can be clearly seen. If we intend to use a block size of 3x3 pixels to allow for simple and robust demodulation, only a modulation amplitude A=2 is acceptable for luminance modulation, whereas very high amplitudes of about A=8 may be applied for modulation of the U and V components. Obviously, the picture quality degrades much less when selecting smaller blocks.

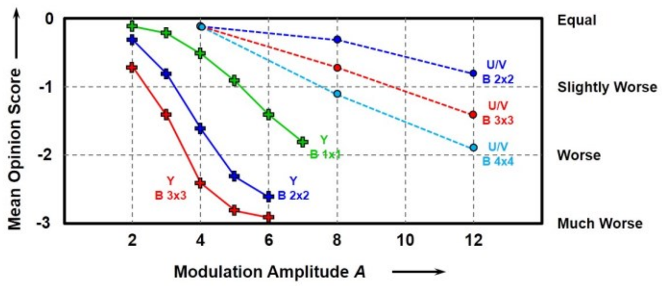

Fig. 6. Subjective evaluation of perceived video quality for different modulation parameters in temporal differential modulation

V. Testbed

In order to evaluate practical system performance for different modulation schemes and to support the design of the filter and synchronization algorithms, a testbed has been set up. Fig. 7 shows the experimental setup. In this picture, a chrominance modulation is used for data transmission. The modulation amplitude is selected very high to visualize the pattern which occupies only a part of the screen.

In practical data transmission, the system has been used with parameters, which cause only a slight degradation of the perceived picture quality. A PC replays HD video sequences and adds data patterns in real time. The combined signal is fed to a 24" computer monitor (ASUS VG248QE) via DisplayPort. For demonstration purposes, a simple data packet format has been defined which allows to transmit arbitrary data files in a carousel mode. An industrial camera (Emergent Vision Technologies HS-12000C) is used to record the video and transfer without any source coding to a PC running the decoding software. Due to the use of MATLAB standard algorithms, the decoding of data files is not possible in real time until now. Depending on the selected parameters, our system decodes 20 times slower than real time.

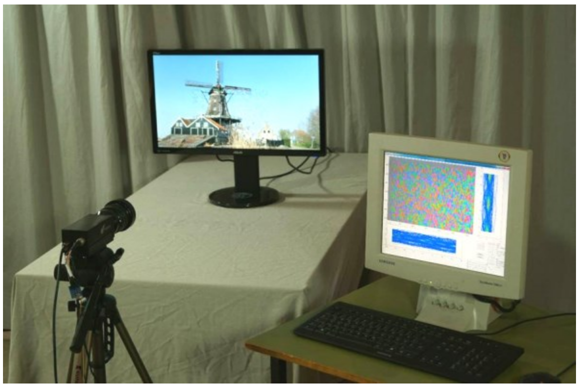

Fig. 7. Photo of experimental transmission testbed, using a PC monitor as transmitter and industrial camera as receiver

First experiments with temporal differential chrominance modulation (modulation amplitude 8, block size 4x4) in the medium part of the screen provided a gross data rate of 4.5 Mbit/s. The bit error rate (without any FEC) was between 0.3 and 2.8 x 10^{-3}, depending on the presented video material. When introducing a simple FEC scheme based on RS Codes, audio files and pictures could be transmitted almost without any errors.

Certainly, the introduction of powerful FEC schemes - preferably based on LDPC-codes - in combination with soft decision will significantly enhance the performance.

VI. Conclusion and Future Work

Visible light communication using video displays and cameras is a promising approach for a variety of applications where data transmission is provided parallel to a video reproduction. Data rates of 100 Mb/s appear to be feasible for technologies available today. Subjective tests have shown that modulation parameters can be selected such that a reliable transmission is possible while perceived video quality is degraded at most very slightly.

The design of a suitable demodulation process still needs further research. Temporal and spatial synchronization as well as high quality interpolation filters are key aspects of future work. These filters should also compensate misalignments of the camera. Furthermore, the selection of suitable forward error correction schemes as well as video adaptive modulation schemes are key elements for system improvement. The adaption of the modulation and decoding schemes to different application scenarios - from personal communication with small distances between transmitter and receiver to large multicast scenarios in public areas - is another demanding task. Future work should also provide input to standardization initiatives.

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