DaViD: Data Transmission Using Video Devices - An Innovative System for Smart Media Applications

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Abstract: **Visible Light Communication using display-camera pairs is an innovative approach to achieve data transmission while reusing already existing hardware. Due to the increasing performance of the involved key components, data rates up to 100 Mbit/s appear to be feasible, while simultaneously a video presentation for human viewers can be provided on the same screen. Many innovative media applications can be realised using such a system. This paper describes the basic concept of DaVid, a system which is under development at TU Dortmund University. It applies typical real time video processing concepts and algorithms in combination with most recent digital data transmission approaches to achieve a good performance, i.e. allowing for high data rates without significantly reducing the quality of the video presentation. Considering the typical video encoding based on luminance and chrominance components, different options for modulation schemes and the relevant parameters exist. Subjective evaluation of the perceived picture quality during data transmission allows a proper selection. A first testbed implementation, still based on simple algorithms, already provided a data rate of 4.5 Mbit/s at reasonable error probabilities while the overlaid data pattern is nearly invisible to viewers at typical viewing distances. A detailed channel model is currently under development. Evaluation of the system's key characteristics shows that a significant improvement of these figures can be achieved in the near future.**

Keywords: screen-camera data transmission, display-camera communication, visible light communication, DaViD

1 INTRODUCTION

Visible light communication (VLC) is an attractive approach for wireless short-range communication. It does not occupy scarce radio spectrum, provides a visible, well-defined coverage area and does not give a reason for users to be afraid of electromagnetic radiation. Many publications describe VLC systems based on LEDs and photodiodes, and key concepts for different applications have been standardized in IEEE 802.15.7-2011 [1]. 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 [2]. Hranilovic et al. published further considerations on this topic in [3], [4], [5].

System proposals such as PixNet [6], CoBra [7] and LightSync [8] use LCD screens as transmitters and mobile phones as receivers. 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.

Several proposals for display-camera data transfers running simultaneously with a video presentation have been published since 2014. InFrame [9] 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 symbol. The selection of large superpixels and slow temporal rate per superpixel restricts the data rate. A recent publication reports data rates of up to 300 kbit/s when a display frame rate of 120 Hz is applied [10]. Another approach is HiLight [11]. 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 by the authors to support a real time implementation on computer graphic cards. However, this selection limits options for efficient modulation schemes, which is required at the same time to achieve high data rates and a high quality video representation. DisCo [12] does not apply a massive MIMO approach at all. 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 [13].

A very promising approach similar to DaViD was published by Wu and Shu in April 2015 [14]. 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.

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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. The transmission can be modelled as a multi-dimensional sampling at the transmitter as well as at the receiver side, with pre- and post-filters partly defined by the technology of the devices. Sophisticated selection of modulation options allows control of performance, visibility of overlaid data patterns as well as adaptation to different applications scenarios.

The basic concept of DaVid as described for the first time in [15] is shown in Fig. 1. Taking advantage of the ever-increasing performance of video displays and cameras, the intention is to provide a data transmission running simultaneously to a video representation on the same screen. Modulation amplitudes are quite small and can be added to the pixel amplitudes of the video content shown on the screen. While the overlaid data modulation should be invisible for human viewers, a high-resolution camera picking up the scene will be able to demodulate the data. The camera can be a part of a smart phone which also performs the decoding algorithm.

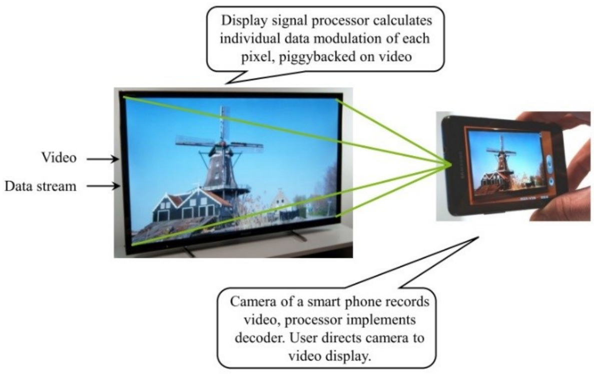


Figure 1: An exemplary implementation of the DaViD system, using a LCD Screen and a mobile phone

The rest of the paper is organized as follows. The subsequent chapter gives an overview on different application areas which might benefit from the DaViD concept. The third paragraph provides information on the transmission concept and applicable modulation schemes. In chapter 4, results of subjective tests of video quality are presented. Chapter 5 comprises a short description of a first transmission testbed which has been set up at TU Dortmund University. The last paragraph concludes the results and gives an outlook on future work.

2 APPLICATION AREAS

The DaViD concept is expected to achieve data rates of up to 100 Mbit/s. It is a line-of-sight transmission for short links. Suitable coverage ranges depend on the size of the display and the camera optics. Compared to the performance of recent WLAN versions of IEEE 802.11, this does not sound very attractive. However, the specific advantages of this kind of data transfer make it a candidate for many particular applications. Besides the principal advantages of VLC, the option to reuse existing hardware which has been installed to present video information to observers is an interesting aspect. However, the key feature is the presentation of video material to human viewers while simultaneously transmitting different kinds of data. A preferred application of the proposed concept will be the broadcast of data files in public areas. Without registration in a network, users can pick up data at high rates by simply directing their smart phone camera to the display. An App can provide signal processing and synchronization support. As an example, a real time HD music video might be reproduced on a public screen, while the audio file of the music is transmitted to viewers simultaneously. Software updates for handheld devices might be distributed in a data carousel on a screen showing advertisements while people wait for their subway. Interesting applications can also be found in industrial environments. Here, graphic displays are often used to inform workers about the status of a manufacturing process or deliver instructions for manual interaction. Using the same display, data can be transmitted to products like cars which are in the test and adjustment area of the factory.

With respect to the technical setup, three application areas can be distinguished:

1) Indoor personal communication: Short-range links will be based on relatively small (tablet-size) displays. A possible application is the transmission of background information to visitors in a museum or individual data kiosk systems.
2) Indoor broadcast communication: The link distance is longer than in the first case, and accordingly the displays are larger. Flat screens of 40”-100” size or projectors are suitable. One example application is a kiosk system showing a video while allowing observers to download application data or media files.
3) Outdoor communication: The difference is the display size. Furthermore, the system has to be much more robust with respect to ambient light. In this scenario, digital signage screens can serve as the transmitter. Applications can be similar to those of the second indoor scenario.

In all 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 enjoy 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. However, in the area of professional applications like on factory floors, dedicated cameras can also be introduced as receivers.

Generally, it is a great advantage that many application scenarios appear to be attractive. However, for the development of a suitable system and the selection of the relevant parameters, this causes the big challenge that many implementation options are available and have to be selected carefully. Size, distance and contrast ratio of the display as well as the expected performance of cameras of a changing user group influence the best parameter choice for the setup.

3 DATA MODULATION

3.1 Basic Considerations

A suitable choice of modulation scheme is very important when designing a video device based data transmission system, which operates reliably without reducing the perceived video quality in an inacceptable way. The rapid development of cameras in the market will help to find a compromise, because the performance gap between the human visual system and the video devices will grow, making the cameras see much more information than human observers do.

Simultaneous data transmission is implemented by individual modulation of display pixel amplitudes originally defined by the video signal. In order to achieve an unambiguous and reliable demodulation without significant crosstalk from arbitrary video content, a robust multiplex scheme must be defined. In the DaViD concept, this is accomplished by doubling of video content and adding differential data patterns to pairs of pixels. This means that in temporal or spatial direction a pair of picture elements of the video content has to be kept constant. On principle, this repetition introduces a degradation of picture quality. However, this kind of transmission benefits from the rapid progress of display technology, which achieves spatial resolutions or frame rates beyond the requirements of a good video reproduction for human viewers. Concepts of frame repetition for movie reproduction or enhanced display performance in case of high frame rate displays have been commonplace for many years.

Different versions of the modulation scheme are possible:

- Temporal differential modulation of the luminance
- Temporal differential modulation of the chrominance
- Spatial differential modulation of the luminance
- Spatial differential modulation of the chrominance

Temporal modulation schemes for data transmission, as considered in the following, require that pairs of consecutive frames contain the same luminance resp. chrominance video content. Therefore, the frame rate should be doubled to maintain the motion portrayal quality as much as possible. Of course, the required frame repetition scheme may reduce the perceived quality in critical scenes, as well known by all experts. In contrast, spatial differential modulation demands neighboured pixels with the same video amplitudes. This can also lead to reduced video reproduction quality, but may be acceptable in very high-resolution displays. The display quality degradation is significantly lower when repeating and modulating chrominance information, i.e. U and V components, instead of luminance Y. This could be clearly seen in subjective evaluation of perceived picture quality as described in Chapter 4.

3.2 Temporal Differential Modulation

For the sake of simplicity and better visibility in the pictures, only the concept of temporal differential modulation is described in the rest of this chapter. Fig. 2 gives a block diagram of a typical transmitter implementation.

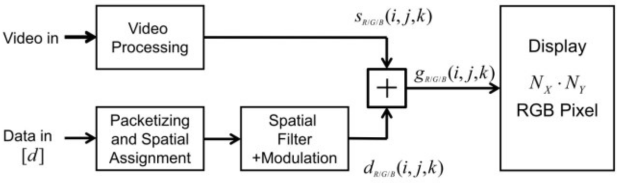


Figure 2: Block diagram of the signal processing in temporal differential modulation

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 modulation scheme:

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

The indices *i* and *j* specify the horizontal and vertical pixel position on the screen, whereas *k* is the number of the reproduced frame. Index m is the counter for the input frames of a video sequence. The amplitude range of the video signal can be limited to allow for the addition of small data amplitudes without clipping. If this is not possible due to picture quality requirements, measures like forward error correction can be introduced to prevent data transmission from being corrupted. The optimum compromise between these two methods to support a low bit error probability when displaying high contrast video content is a topic of future research.

To transmit a stream of data, it first has to be split up into slices of length *L*. Each slice contains the amount of data that can be transmitted in one pair of frames, counted by *m*. It is assigned to the two-dimensional pixel array. A straightforward approach is a direct mapping of data bits to pixel 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:

$$\begin{aligned} &d(l) \to d(i,j,m) \qquad d(l) \in \{-1,1\} \\ &0 \le l < L, L = N_X \cdot N_Y \\ &i = l \bmod N_x \qquad j = \lfloor l / N_x \rfloor \end{aligned} \quad (2)$$

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. If a temporal differential modulation of the luminance is intended, equal amplitudes for R, G and B need to be selected:

$$A_R = A_G = A_B = A \quad (3)$$

The differential modulation method assigns a sequence of {*-A,A*} to *d=-1* 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)*:

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

The human eye is much less sensitive to color contrasts than it is to luminance contrasts. In order to reduce the visibility of the data pattern to the viewer, an interesting option is the modulation of the colour difference signals U and V instead of the luminance component Y. This way the overall luminance of a pixel triple will not be influenced by the data modulation. The conversion between (R,G,B) and (Y,U,V) can be based on a standard conversion matrix. For HDTV displays, the elements of such a matrix are specified by ITU-R BT.709 [16]:

$$T = \begin{pmatrix} 0,213 & 0,715 & 0,072 \\ -0,115 & -0,385 & 0,5 \\ 0,5 & -0,454 & -0,0458 \end{pmatrix} \tag{5}$$

Before applying the modulation, the video signal s*(i,j,k)* needs to be converted into Y, U, and V components. A subsequent inverse conversion provides the display input signal:

$$\begin{pmatrix} g_R(i,j,k) \\ g_G(i,j,k) \\ g_B(i,j,k) \end{pmatrix} = T^{-1} \cdot \left(T \cdot \begin{pmatrix} s_R(i,j,m) \\ s_G(i,j,m) \\ s_B(i,j,m) \end{pmatrix} + \begin{pmatrix} 0 \\ A_U \cdot d(i,j,m) \\ A_V \cdot d(i,j,m) \end{pmatrix} \right) \tag{6}$$

$$\begin{pmatrix} g_R(i,j,k+1) \\ g_G(i,j,k+1) \\ g_B(i,j,k+1) \end{pmatrix} = T^{-1} \cdot \left(T \cdot \begin{pmatrix} s_R(i,j,m) \\ s_G(i,j,m) \\ s_B(i,j,m) \end{pmatrix} - \begin{pmatrix} 0 \\ A_U \cdot d(i,j,m) \\ A_V \cdot d(i,j,m) \end{pmatrix} \right)$$

This type of modulation can be considered as a modulation of the red and the blue subpixel, while the green subpixel is used to compensate for the change in luminance of the pixel triple. Modulation amplitudes of $A_U = A_V = 8$ for example result in higher red and blue amplitudes, as shown in (7). By definition A_U correlates with A_B, and A_V with A_R. The transmitter rounds the resulting pixel amplitudes due to the 8 bit representation in the typical display signal processing.

$$\begin{pmatrix} A_R \\ A_G \\ A_B \end{pmatrix} = T^{-1} \cdot \begin{pmatrix} A_Y \\ A_U \\ A_V \end{pmatrix} = T^{-1} \cdot \begin{pmatrix} 0 \\ 8 \\ 8 \end{pmatrix} = \begin{pmatrix} 12.6 \\ -5.24 \\ 14.85 \end{pmatrix} \tag{7}$$

Furthermore, it is possible to double the number of data bits per frame pair L by modulating the U and the V channels separately with different data $d_U(i,j,m)$ and $d_V(i,j,m)$. Subjective tests presented in section 4 demonstrate a significant reduction of the visibility of the overlaid data in comparison with the luminance modulation. Thus, this is a very attractive way of hiding the data pattern. Conversely, a higher modulation amplitude can be selected to improve the robustness of the modulated data at the decoder, while the video signal degradation for the viewer does not increase. Of course crosstalk between the colour channels needs to be considered, especially when modulating U and V separately.

3.3 Data Blocks

In order to relax the requirements on camera resolution, it is helpful to reduce the spatial density of the data pattern. Of course, this reduces the achievable data rate. A simple approach is the assignment of one data bit to a block of $B_X \times B_Y$ display pixels:

$$\begin{aligned} & d(l) \to d(x,y,k) \qquad 0 \le l < L \\ & L = \lfloor N_X / B_X \rfloor \cdot \lfloor N_Y / B_Y \rfloor \\ & x = (l \cdot B_X) \bmod N_x + r_X, \;\; r_X = 0...(B_X - 1) \\ & y = \lfloor l / \lfloor N_X / B_X \rfloor \rfloor \cdot B_Y + r_Y, \;\; r_Y = 0...(B_Y - 1) \end{aligned} \tag{8}$$

If the number of pixels per line is not a multiple of B_X, or if the number of lines is not a multiple of B_Y, the number of pixels and lines used for modulation in (8) must be replaced by:

$$\begin{aligned} N_X &= \lfloor N_X / B_X \rfloor \cdot B_X \\ N_Y &= \lfloor N_Y / B_Y \rfloor \cdot B_Y \end{aligned} \tag{9}$$

The remaining display elements can be left unmodulated. Utilizing data blocks of 2×2 or 3×3 pixels can reduce requirements on camera resolution and signal processing significantly. Unfortunately, the resulting coarse structure of the overlaid data increases the visibility of the modulation with given modulation amplitudes.

3.4 Example of a Modulated Video Frame

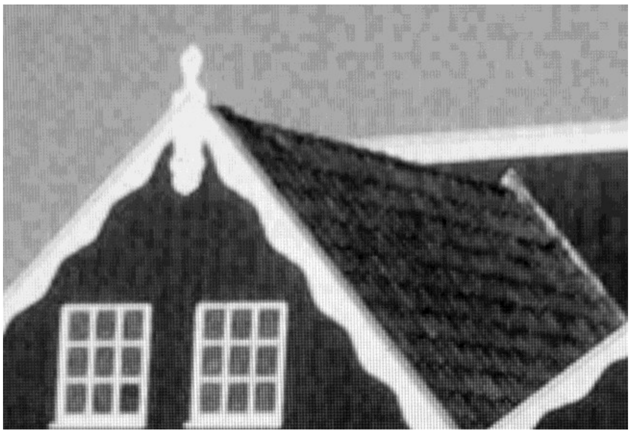
The result of a temporal differential modulation of luminance can be seen in fig.3. The photos show details of two consecutive frames (frame repetition) on an LCD screen reproducing a modulated video sequence, as well as the difference of these frames. The data pattern was calculated by assigning each bit to a 3×3 block of pixels. The temporal differential modulation was performed, using A=4 for an 8-bit representation of RGB. While in real life such a modulation scheme would result in a visible reduction of perceived picture quality, it has been used here to make the modulation concept visible.

4 SUBJECTIVE TESTS

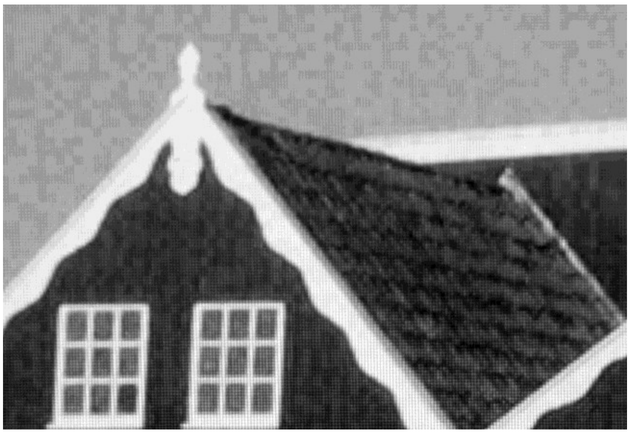
The visibility of the overlaid data pattern depends on the selected scheme, the modulation amplitude and the data block size. High modulation amplitudes for the luminance in combination with large blocks will provide the easiest and most robust demodulation, but at the same time the worst visual perception and the lowest data rate. A compromise has to be found for each intended application. Unfortunately, an elaborate discussion of all pros and cons is beyond the scope of this paper.

In the following, experimental results on the visibility of the modulation are given for temporal modulation of the luminance and the chrominance for different suitable block sizes as described in chapter 3. The test material – three different HD video sequences – was presented on a 24-inch LCD screen.

(1)



(2)



(3)

Figure 3: Temporal differential luminance modulation with *B_X=B_Y=3, A=4*. (1) and (2) show the repeated video frame +/- modulated data pattern, (3) shows the difference pattern

Fifteen expert viewers assessed the perceived video quality for different modulation amplitudes and three block sizes. The setup of this double stimulus test was defined according to recommendation ITU-R BT.500-13 [17]. Viewing distance was selected to be three times picture height. The display frame rate was 60 Hz, leading to a data rate of 30 b/s per pixel block. These parameters - close viewing distance and low frame rate - are more critical than expected in most applications. Fig. 4 shows the test results. In this setup, *A=4* will be acceptable for most applications when using 1×1 blocks and luminance modulation. Larger blocks reduce the perceived quality significantly, limiting the acceptable modulation amplitude to *A=2* in case of 3×3 blocks.

In [18], results of a similar test for pure luminance modulation were given. Now we also evaluated chrominance modulation for several useful parameter sets. 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.

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 seen clearly. If we intend to use a block size of 3×3 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.

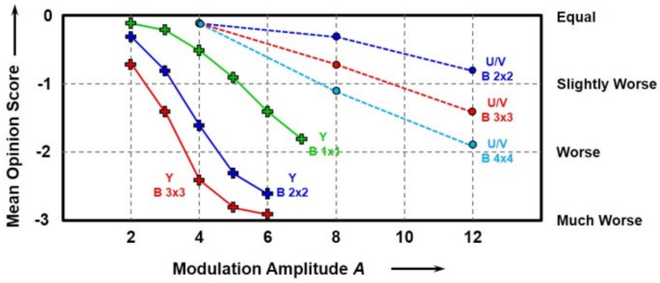


Figure 4: Results of subjective tests of the degradation of the picture quality due to overlaid data pattern

5 TRANSMISSION TESTBED

The subjective tests described in chapter 4 have shown that a modulation of colour differential signals reduces visibility of the data pattern while still allowing for robust decoding. 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. 5 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 the frames without any source coding to a PC running the decoding software. Due to the use of MATLAB standard algorithms, data files are not yet decoded in real time. Depending on the selected parameters, our system decodes approximately 20 times slower than real time. Applying modulation of the U and V channels and large data blocks (4×4 samples, for relaxed requirements on spatial synchronisation and filtering), a data transmission with a rate of 4.5 Mbit/s with BER<0.5×10^{-3} (without any FEC) has been achieved. The data pattern in this configuration is almost invisible for viewers at a typical viewing distance.

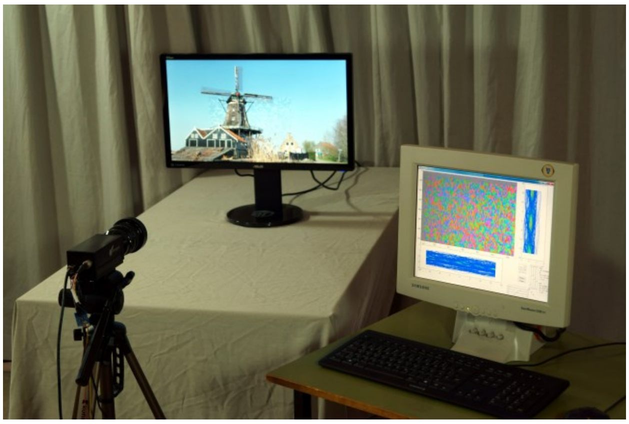


Figure 5: Testbed for a transmission path at TU Dortmund University

6 OUTLOOK

While the first results are very encouraging, a lot of work still has to be done on filter and synchronisation algorithms as well as forward error correction and adaptive modulation. It appears to be certain that the system works. However, in order to provide an attractive system for many applications, fine-tuning will be needed to support high data rates and high quality of user experience at the same time. Our goal is to achieve 100 Mbit/s data rate when using off-the-shelf displays and cameras. The rapid progress in display and camera technology as well as processing power in mobile devices will help us to reach this target.

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 for 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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