Barcode Modulation Method for Data Transmission in Mobile Devices

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Abstract—The concept of 2-D barcodes is of great relevance for use in wireless data transmission between handheld electronic devices. In a typical setup, any file on a cell phone, for example, can be transferred to a second cell phone through a series of images on the LCD which are then captured and decoded through the camera of the second cell phone. In this study, a new approach for data modulation in 2-D barcodes is introduced, and its performance is evaluated in comparison to other standard methods of barcode modulation. In this new approach, orthogonal frequency-division multiplexing (OFDM) modulation is used together with differential phase shift keying (DPSK) over adjacent frequency domain elements. A specific aim of this study is to establish a system that is proven tolerant to camera movements, picture blur, and light leakage within neighboring pixels of an LCD.

Index Terms—Barcode, data transfer, differential phase shift keying, orthogonal frequency-division multiplexing (OFDM) modulation.

I. INTRODUCTION

Barcodes have played a great role in facilitating numerous identification processes since their invention in 1952 [1]. In fact barcode is a simple and cost-effective method of storing machine readable digital data on paper or product packages. As pressing needs to transfer even more data faster and with high reliability have emerged, there have been many improvements that were made on the original barcode design. Invention of two dimensional (2D) or matrix barcodes opened a new front for these cost-effective codes and their application in more complex data transfer scenarios like storing contact information, URLs among other things, in which QR codes [2] have become increasingly popular. A comparison of 2D barcode performance in camera phone applications can be found in [3].

Much of the efforts in matrix barcode development have been dedicated to barcodes displayed on a piece of paper as that is the way they are normally used. With the replacement of books with tablets and e-Book readers one could contemplate that replacement of the paper with LCD may open another promising front for broader applications of 2D barcodes as a mean of data transfer. Moreover unlike the static paper, the LCD may display time-varying barcodes for the eventual transfer of streams of data to the receiving electronic device(s) as depicted in Fig. 1.

This idea has been implemented in [4] where transmission of data between two cell phones through a series of 2D QR codes is studied, achieving bit rates of under 10 kbps for state of the art mobile devices. Later the idea was further developed in [5] in which a computer monitor and a digital camera are used for transmission and reception with bit rates of more than 14 Mbps achieved in docked transmitter and receiver conditions over distances of up to 4 meters. However, this rate drops to just over 2 Mbps when the distance is increased to 14 meters. The superior performance of the later implementation is achieved using a more effective modulation and coding scheme for mitigation of image blur and pixel to pixel light leakage. The general idea is to use the inverse Fourier transform (IFT) of data like OFDM to modulate LCD pixels. While image blur and light leakage greatly reduce the performance of QR decoders they have a limited effect on OFDM modulation. Furthermore their performance degradation is confined to known portions of the decoded data. This prior knowledge on non-uniform error probability may be used for adaptive error correction coding based on data region as in [5]. There is an increasing interest in design and implementation of LCD-Camera based communication systems as indicated in [6]–[8]. This would require additional investigations in determining optimal modulation and demodulation schemes for this type of innovative communications medium.

The OFDM modulation uses orthogonal frequency subcarriers to transfer data and can confine image blur, which is essentially a low pass filter, to high frequency components such that low frequency data bits are transmitted intact. This method requires high phase coherency to detect the data bits correctly. The

Fig. 1. An illustration of transmission of data between two handheld cameraphones using a sequence of 2D barcodes.
current study extends this idea through additional modifications on the modulation scheme in a way to mitigate LCD-camera relative movements during the capture of a single frame, which results in motion blur distortion on the captured images. This kind of distortion as would be detailed later severely degrades the performance of Quadrature Phase Shift Keying (QPSK) modulated OFDM signals. 

The required movement tolerance is achieved by putting data in phase differences of adjacent frequency components leading to a DPSK-OFDM scheme which would be called simply the DPSK method throughout this study. Observing that any phase distortion due to motion blur would affect neighboring frequency components negligibly, data may be transmitted reliably even in the vicinity of high LCD, camera relative motion. A diagram of the system envisioned is shown in Fig. 2. This method also eliminates the channel estimation requirements resulting in lower processing power. To maximize data transmission rate, one should consider extracting maximum data from a single image shown on an LCD and then increase the rate at which consecutive frames will be decoded. In consideration of this issue, any method that is introduced should efficiently utilize the available bandwidth considering motion distortions. 

Previous studies have demonstrated the feasibility of such systems and have addressed the effects of single distortions like linear misalignment [9], defocus blur [10] and vignetting [11] on the modulation methods under consideration, but they have not provided a comparative assessment of these systems in a controlled environment. Moreover, no comparisons were made考虑 motion distortions. 

Although in practice, it might be challenging to obtain a fair assessment of the system’s performance, it is important to know what affects the transfer rate and what can be done about each limiting factor in this data transmission medium. The data capacity of an LCD may be calculated by considering for instance the maximum number of bits in a raw image as shown on the LCD. A display having the \( M_D \) rows and \( N_D \) columns, showing a color image in \( L_D \) channels (typically \( L_D = 3 \) for red, green and blue) and color bit depth of \( B_D \) bits per channel, would have the maximum information of: 

\[
C_I = M_D \times N_D \times L_D \times B_D \text{ bits per image} \tag{1}
\]

This is the maximum information that can be shown on the LCD on a single image due to the discrete nature of the data shown. 

A digital camera could be considered as a device which digitally samples a 2D signal. For correct sampling of consecutive frames in time, camera capture rate should be 2 times the display refresh rate \((R_D)\) unless there is a synchronization system in place to activate the camera shutter when the image is stabilized on the display (exactly between frame changes). As it is not normally the case, if the camera capture rate is for example \( R_C = 8 \text{ Hz} \) then the display refresh rate could not exceed 4 Hz. 

To satisfy the Nyquist criteria for image resolution, each pixel of the image shown on the LCD should be sampled by 2 or more pixels in the camera [12]. The image sensor uses limited number of bits per channel for conversion of each color pixel, resulting into quantization noise. To limit the effect of this noise on the overall detection performance it should be maintained well below signal power level, depending on the modulation method used, in order to have acceptable bit error rates (BER) [14]. 

### A. Camera Limitations

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### B. Power Limitations

The capacity of every communication channel depends on the power of the signal sent through that medium as predicted by Shannon theorem [15], and in this case the power would
be limited by the intensity of light an LCD can generate. Increasing this intensity would improve signal to interference and noise ratio (SINR) in the receiver. Like RF power transmitters, LCD displays are limited in terms of the maximum power leading to the Peak to Average Power Ratio (PAPR) limitation, which is a common challenge for OFDM signals. When maximum available intensity is fixed, higher PAPR yields lower average intensity and thus lower SINR. Therefore transmission of OFDM signals over an LCD requires a trade-off between the average power transmitted and the resulting distortion due to clipping of the peaks, another issue that is addressed in this study. Although various PAPR reduction methods are available, they would affect QPSK-OFDM and DPSK-OFDM methods in a same manner, and DPSK modulation would still be superior when the same method of PAPR reduction is used. Further discussions on clipping OFDM signals can be found in [16] and [17].

C. Inter-Symbol Interference (ISI)

When a barcode is printed on paper, a white pixel does not affect its neighboring black pixels provided that the print quality is good and the resolution is high enough. On the other hand, when data is shown on an LCD, light that is passing through white pixels may leak into neighboring black pixels making them look gray. The straightforward solution to this problem is to increase the size of the pixels so that they have minimal effects on each other. This is called barcode granularity in QR coding [2]. On a lower level this is exactly the way a printed barcode is generated, where each printed dot is not corresponding to a data symbol but rather many printer dots contribute to a single black symbol. In the case of LCD, each $k \times k$ pixel set is assigned the same color to generate just one symbol, isolating the center pixel from bordering pixels that may be affected by neighbors. Unfortunately this method greatly decreases the transfer rate because the $M \times N$ independent data symbols reduce to $\frac{M}{k} \times \frac{N}{k}$ which leads to a $k^2$ to 1 rate decrease. The inter-symbol interference could happen in the receiver camera as well becoming a major obstacle for increasing the pixel density of barcodes.

Moreover, any movements between camera and LCD during the capture of an image for barcode processing results in motion blur which is translated into ISI as neighboring pixels affect each other in the captured image. At first this effect might not be evident based on common experiments with 2D barcodes like QR codes. These codes are decoded successfully without major efforts in terms of stability of code or camera. While performance of some QR code detection algorithms are studied in [18] and first read rate performances of some 2D barcodes have been studied in [19], the research is rather focused on user experience as an important factor, which is to determine if the user is able to decode the barcode at first try. In fact, performance of 2D barcode decoders are measured by the frames processed per second, thus when a barcode scanner tries to decode a stationary 2D barcode, multiple frames are processed within a second and a successful decode will be reported if only one frame is captured in good conditions.

To investigate if a relative barcode camera motion affects the performance of the decoder, the following experiment was conducted. Alphanumeric strings of various lengths of number $\pi$ were encoded into QR Codes of increasing dimensions, in a way to fill the barcode capacity as shown in Fig. 3. Error correction level is set to medium (M) which is capable of correcting roughly 15% error rate. Consecutive frames were captured using a hand-held camera phone, first by fixing the camera and then by holding it in one hand by a non-experienced user. Camera focus was locked the same way in both cases and normal office lighting and a distance of 12 cm were maintained. Moreover, the width of rectangular QR code pixels was 312 mm regardless of the code capacity. As a result the largest QR code which had $121 \times 121$ pixels was 37.7 mm in width which is double the density of ordinary QR barcode. Encoding and decoding of the QR codes were accomplished using ZXing open-source libraries.\footnote{ZXing project, http://github.com/zxing.}

In order to limit the effect of perspective distortion, camera and barcode are held parallel in the docked case, and although this angle cannot be guaranteed in the handheld scenario, the performance drop would be negligible as reported in [20]. The captured images taken at 10 frames per second where processed to detect the QR code, and the percentage of decodable images are shown in Table I. As can be seen from these results, for smaller QR codes it does not make any difference if the camera is held by hand or fixed as all the frames would be detected successfully. However, as the size of the QR code increases, more and more frames are dropped in the moving case compared to the fixed camera setup. In any setup studied, user experience would not be a problem as there was at least one detectable frame within one second of recording onset.

D. Interference, Distortion, and Noise

When a camera is used to take a picture of a 2D barcode, certain image artifacts could impact the result of data extraction method. These artifacts are mainly due to the following:
III. DPSK-OFDM

While LCD technology is improving on pixel to pixel isolation, some of the image capture distortions still remain, causing neighboring pixels of the barcode mix up in the image and resulting in some kind of Inter Symbol Interference. The main idea in resolving this problem is to interpret the barcode image as a wireless radio signal for which ISI reduction techniques have already been proven successful. One of the best and most feasible modulation methods capable of coping with severe conditions in band limited communication channels is the so-called Orthogonal Frequency Division Multiplexing or OFDM [22]. The general idea is that when dealing with band-limited, power-constrained, multipath channels, it is more efficient to transfer a bunch of narrow-band signals in parallel instead of a single high bandwidth signal.

A. Similarities of Barcode and Wireless RF Channel

For simplicity each 2D image is reformulated into a 1D row vector containing all pixels in the 2D image. Each row can be considered as a time domain signal which has Pulse Amplitude Modulation (zeros are black and ones are white pixels). Consider taking a picture of this single row, in a band limited communication channel which has a combination of camera focus problems, resolution limitations, light leakage from white to black pixels, among other things. Moreover in a multipath channel in which the camera moves during image capture and mixes up the image of several neighboring pixels, the resulting image will suffer from high ISI. To solve these problems in a time domain radio signal, OFDM method is used to essentially divide the channel into multiple orthogonal low bandwidth channels and the low rate data is sent into these channels in parallel. So in case of the 1D data the inverse Fourier transform is used for displaying the data instead of using the PAM modulated process, where Hermitian symmetry conditions should be met to have real-valued components leaving low frequency components intact for data transmission.

This idea may be generalized to 2D signals to meet the requirement for transferring the entire image at once. Instead of 1D inverse Fourier transform, the 2D version is used such that the effect of artifacts acting on two axes would be confined to high frequency components. The exact modulation scheme will be discussed later in this study.

In general each sub-carrier in an OFDM signal is modulated using M-quadrature amplitude modulation (M-QAM). Thus proper phase shift of each element should be estimated and compensated for before demodulation. This generally requires specific conditions on the channel characteristics like fast fading where pilot tones are used for channel estimation or slow fading where most methods would require multiple symbols in seeking similar channel responses (i.e., similar transfer functions) [23] and [24].

When using OFDM for transmission of data as images, all the channel equalization computations should be based on a single OFDM frame due to the independent channel response between subsequent frames, unless the frame rate is very high. In fact each frame is distorted by LCD-Camera relative motion during its own capture time. To mitigate this problem the phase difference between adjacent elements is used to convey data. Using DPSK modulation prior to applying the inverse Fourier transform in OFDM modulation, data would not have to be stored in the absolute phase of the received elements but rather in its phase difference to the neighboring element, which eliminates the requirement for channel estimation and equalization if the channel response does not vary abruptly between adjacent subcarriers.

B. Transmitter

One of the advantages of using OFDM is its effective computation method which uses the Inverse Fast Fourier Transform (IFFT) to modulate input data into orthogonal frequencies. The modulated signal should be real-valued in order to be shown on an LCD, so the input to the IFFT algorithm should have Hermitian symmetry. This requirement is shown in the following equation:

\[ T(M - m, N - n) = T(m, n) \dagger \quad (2) \]

where \( 0 \leq m < M \) and \( 0 \leq n < N \), and \( \dagger \) denotes the complex conjugate operator. Fig. 4 shows the elements relationship in order to have a real-valued IFFT for \( T \) matrix. In this configuration, only regions 1 and 2 are used for data transmission independently, and regions 3 and 4 are calculated accordingly to have a real-valued IFFT. Moreover, the symmetry requirements for elements that have been deliberately set to zero would be automatically satisfied.

**Constellation Mapping:** The input data is decomposed into 2-bit symbols. Each symbol is converted to a complex phase by the following rules:

- \( 0 \rightarrow e^{j\frac{2\pi}{4}}, 1 \rightarrow e^{j\frac{2\pi}{4}}, 00 \rightarrow e^{j\frac{2\pi}{4}}, 01 \rightarrow e^{j\frac{2\pi}{4}} \)

Therefore the first bit modulates the real component and the second bit modulates the imaginary component of the phase for
Differential PSK: Matrix $\mathbf{S}$ is transferred into a differential matrix $\mathbf{D}$ using the following method:

- $\mathbf{D}(0, 0) = \mathbf{S}(0, 0)$;
- $\mathbf{D}(0, n) = \mathbf{D}(0, n-1) \times \mathbf{S}(0, n) \mid 1 \leq n < N - 2$;
- $\mathbf{D}(m, n) = \mathbf{D}(m-1, n) \times \mathbf{S}(m, n) \mid 1 \leq m < \frac{M}{2} - 1, 0 < n < N - 2$.

Subsequently, the DPSK modulated $\mathbf{D}$ matrix is divided into two matrices:

- $\mathbf{D}^1(m, n) = \mathbf{D}(m, n)$;
- $\mathbf{D}^2(m, n) = \mathbf{D}(m, n + \frac{N-2}{2})$;

where $0 \leq m < \frac{M}{2} - 1, 0 < n < \frac{N}{2} - 1$. These two matrices are used to fill regions 1 and 2 of the matrix $\mathbf{T}$. Regions 3 and 4 of $\mathbf{T}$ are generated based on the Hermitian symmetry requirement, and all the remaining strips on $\mathbf{T}$ are set to zero. These small regions, especially around region 1 (left top corner), may be used for special data transmission such as frame rate or type of error correction coding used.

Inverse FFT: Considering $\mathbf{T}$ is the frequency domain representation of the signal, the IFFT is applied on it to have the time domain signal referred to as $\mathbf{D}_t$. This signal would have zero mean because $\mathbf{T}(0, 0') = 0$, so it should be adjusted in order to use the full dynamic range of pixels.

PAKR Adjustment: $\mathbf{D}_t$ is a real-valued 2D signal with high peak to average ratios. In fact, the probability of having a high PAPR increases as the number of frequency components increases as can be seen in Fig. 5. There are several methods to limit the PAPR of OFDM signals which might be applied here with slight modifications for 2D signals. One of the most practical methods would be soft clipping of the signal in which a threshold level of $A_{\text{max}}$ based on signal average power level is set such that:

$$\text{ClippRatio} = \frac{A_{\text{max}}}{\sqrt{P_{\text{avg}}}}$$

where $P_{\text{avg}}$ is average power per element in the OFDM signal before clipping. Any components with higher amplitude than $A_{\text{max}}$ are consequently clipped to $A_{\text{max}}$ resulting in a 2D matrix $\mathbf{D}_c$.

Amplitude Adjustment: The pixel levels in the PAPR adjusted image need to be transformed into LCD dynamic range levels for efficient utilization of transmission power. Normally the intensity levels on the LCD goes from 0 to $I_{\text{max}}$. So $\mathbf{D}_c$ values are transformed linearly to this range using the following equation:

$$\mathbf{D}_a(i, j) = \frac{\mathbf{D}_c(i, j) - \text{Min}(\mathbf{D}_c)}{\text{Max}(\mathbf{D}_c) - \text{Min}(\mathbf{D}_c)} I_{\text{max}}$$

Thus the average power of $\mathbf{D}_a$ is maximized for LCD projection.

Finder Patterns: Proper demodulation of data requires precise extraction of the modulated data from captured image and compensating for any perspective distortions. General finder patterns used with 2D barcodes may be used here like the 1, 1, 3, 1, 1 pattern used in QR-codes, for which fast and efficient detection algorithms have already been developed in [25] and [26]. A sample $128 \times 128$ image generated by the preceding method is shown in Fig. 6 as it would be shown on the LCD of the transmitting device.
C. Cyclic Extension

OFDM systems require cyclic extension to prevent inter carrier interference (ICI) [27]. To be sufficient, the length of the added cyclic extension must be more than the time spread of the channel. In case of the 2D barcode, periodic extension of the image generated by 2D-IFFT is required to prevent ICI. The length of this extension is determined by the impulse response of the channel, which in turn depends on the image blur and the amount of movement anticipated between LCD and camera. However, since in this study the channel response is modeled in the frequency domain, frequency domain filtering [12] is applied on the barcode, and effective cyclic extension is achieved by frequency domain multiplication which results in time domain cyclic convolution. Hence in all the following simulations the length of the cyclic extension is the same for DPSK-OFDM and QPSK-OFDM ensuring ICI elimination in the longest channel responses simulated.

D. Receiver

After displaying the generated image of Fig. 6, the receiver uses its camera for sampling and registering the acquired image so that a fairly acceptable copy of \( D_i \) is created at the receiver end. The effects of interference, noise and distortions encountered in this step are addressed in the simulation section. To obtain the transmitted data successfully, the following steps should be taken into consideration at the receiver end:

Image Capture: Digital camera and display systems have a limited refresh rate which tends to be more than 23 Hz for different standards. In a synchronous system the camera can capture each displayed frame at the exact moment when it is fully stable. However if the receiver does not know when a new frame is ready on the display, the sampling rate should be at least twice the display rate to ensure capture of at least one acceptable frame. Moreover the relative distance and angle between camera and display is bounded by the Nyquist criteria where each pixel on the display frame should map into a minimum of \( 2 \times 2 \) block in the camera.

Image Registration: The first step in processing the captured image is to extract the displayed image from background which depends on predefined finder patterns put into the image. For example, data matrix guidance lines are used in [5]. Because measurement errors in finder pattern location and perspective correction errors are not part of this study, the simulated images and their distorted received signals are ideally registered isolating the effects of blur and camera movement on error rate of different schemes.

FFT: Applying Fast Fourier Transform on the registered image results in frequency domain data which is comprised of the differential phase modulated elements stored in \( R_f \) matrix.

DPSK Demodulation: The original constellation mapped data can be extracted using phase differences between respective elements, but first data corresponding to regions 1 and 2 should be concatenated together to form matrix \( R \) corresponding to the transmitted matrix \( T \).

\[
\begin{align*}
R_d(0,0) &= R(0,0), \\
R_d(n,0) &= R(0,n) \times R^*\{0, n - 1\} 0 < n < N - 2, \\
R_d(m, n) &= R(m,n) \times R^*(m - 1, n) 0 < n < N - 2, 0 < m < \frac{M}{2} - 1.
\end{align*}
\]

The resulting \( R_d \) would be a distorted copy of \( S \) in transmitter path.

Detection: Now that the phase differences have been extracted, each input bit may be calculated using the constellation map of the transmitter. Each element is evaluated using its real and imaginary components. The sign of the real component determines the first bit and the sign of the imaginary component determines the second bit.

E. Error Correction

Error correction coding is often used in communication systems to correct for the different number of bits lost in the transmission process. For example, Reed-Solomon (RS) coding is used in QR codes, where depending on the level of error correction used, error rates of 7% up to 30% can be corrected at the receiver end [2]. While the selection of error correction coding has a great influence on the overall performance of the communication system, they are generally used on top of the modulation-demodulation scheme and after source coding. Therefore, based on the achievable error rates without error correction coding, one can select an appropriate coding scheme to create a reliable communication channel. As a result, when considering the BER performance plots provided in the simulation section (IV), it should be noted that error rates in excess of 30% are not correctable even with the most redundant RS codes defined in [2] and would consequently be considered a non-reliable channel for this kind of transmission.

F. Computational Complexity

An important issue regarding the applicability of such a system would be the computational power required to implement the system. Although a thorough investigation of such requirements and any optimization process can be subject to further study, it should be noted that the proposed DQPSK-OFDM system has a limited processing overhead compared to the equivalent QPSK-OFDM system which is already implemented and tested. More specifically, on the transmitter side, although the differential modulation is described by complex multiplications, it can be easily implemented using a small look-up table taking current phase and data to be modulated as inputs. However, in the receiver side about \( M \times N \) multiplications are required to extract phase differences before detection which is not prohibitive compared to the complexity of the 2D FFT preceding it which is in the order of \( M \times N \times \log(M \times N) \).

IV. Simulation

Current 2D barcodes use PAM as the preferred modulation method [2]. To compare them with the proposed modulator and demodulator, both systems are implemented in MATLAB. A Simple PAM modulator which translates bits into light and dark pixels of an image is compared to the proposed DPSK-OFDM method which uses the described algorithm for modulation and demodulation. Furthermore, the performance of QPSK-OFDM [28], which is essentially the same as 4-QAM (Quadrature Amplitude Modulation) OFDM used in PixNet [5], is compared to the proposed DPSK-OFDM system. The main parameters that are considered include:

- noise and clip ratio;
To study the effect of each of these parameters, first a random data stream is modulated to the displayed image using the algorithm under test. Then a controlled distortion is applied to the image before passing it to the receiver. The bit stream at the output of the decoder is compared to the input random stream to count for erroneous bits. This process is repeated several times using various random data streams and the same amount of distortion. The average result would be the bit error rate corresponding to that particular situation and assumed distortion. The process is then repeated for another distortion amount resulting in a plot for bit error rate against distortion.

A. Noise and Clip Ratio

In a barcode setup where PAM is used to modulate data onto image pixels, the average power is maximized. Consider the maximum amplitude driving a fully “on” pixel is $A_p$ leading to a transmitted energy of $P_p$. In QR coding which uses binary-PAM, amplitude of each pixel may be either 0 or $A_p$. Considering that the DC offset is removed, each element would then have an amplitude of $\pm \frac{A_p}{2}$, yielding the following average power per pixel:

$$P_{ave} = \frac{P_p}{A_p^2} \frac{1}{M \times N} \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}^2$$

(5)

where $A_{mn}$ is the amplitude of element $(m, n)$. Thus $P_{ave} = \frac{P_p}{A_p^2}$ too. The fact that peak to average power ratio in binary-PAM signal is always 1 no matter what the data is, makes it suitable for situations where there is a limit on peak available power like LCD transmission. On the other hand, OFDM modulation has the intrinsic problem of PAPR which increases with increasing number of elements. In Fig. 5 PAPR for different image sizes is calculated. The figure shows the probability of PAPR being greater than a certain value.

High PAPR and limited peak power enforces a reduction in average power for the signal if it is going to be transmitted as is. Low average power means higher error rate in the presence of noise. To mitigate this problem, PAPR should be decreased as the maximum power is limited by physical constraints of LCD. Here soft clipping method is used as described before and the output after clipping is mapped linearly to the $[0 \ 255]$ interval for a grey scale image. In Fig. 7 the effect of various clipping levels is shown along with additive white Gaussian noise. As the clipping increases, the average power also increases due to fixed maximum power and lower PAPR. However this increased average power is at the expense of a more distorted signal which translates into more BER. In this figure BER approaches 18% as clipping ratio decreases. Moreover, increasing noise level forces the BER approach 50%. It can also be observed that increased noise level requires a lower clipping threshold to obtain optimal error rate, but the induced distortion causes the benefit of increased average power to be limited and at some point BER actually starts to increase while average power is also increasing.

B. Low Pass Filtering

Inter symbol interference and out of focus lens may be modeled by applying low pass filtering on the captured image. To simulate this out of focus effect, the Butterworth low pass filter in the frequency domain is used with various cutoff frequencies and the resulting BER is measured. Equation (6) defines the applied filter.

$$L(u, v) = \frac{1}{1 + (u^2 + v^2)^n / d_0^2}$$

(6)

The resulting BER-based performance plots using different modulation methods are shown in Fig. 8. It can be observed in these plots that the BER increases with lower cutoff frequencies. Here $D_0 = d_0 / N$ defines the cutoff frequency as a percentage of image width ($N$). It can be seen that unless the cutoff frequency is less than 20%, frequency domain modulations have better error performance than the PAM method.
Fig. 9(a) shows the effect of 20% filtering on the $128 \times 128$ DPSK modulated image of Fig. 6. Consider the raw data which was mapped to matrix $S$ described in 3.2. After decoding the signal at the receiver and comparing it to $S$, matrix $E$ may be generated to show the location of each detected bit that differs from its corresponding bit in $S$. To show the errors both in real and imaginary parts of $S$, the lower half of $E$ provides errors in the imaginary part of $S$ while the upper part indicates errors in the real part of $S$. The generated $E$ is shown in Fig. 9(b). An interesting point that can be seen here is that unlike PAM modulation, the location of error bits are not distributed randomly. In fact error bits are more concentrated in the high frequency areas of the OFDM based modulation methods.

C. Camera Movement

Assuming linear image motion in $x$ and $y$ directions and instantaneous shutter opening and closing, the motion may be modeled by the following transfer function as described in [12]:

$$H(u, v) = \frac{T}{\pi (ua + vb)} \sin[\pi (ua + vb)] e^{-j\pi (ua + vb)}$$  \hspace{1cm} \text{(7)}$$

where $T$ is the exposure time, the $a$ and $b$ elements are the assumed image movements in the $x$ and $y$ direction respectively during the exposure time. As can be observed, this transfer function consists of a sinc function which is in fact blurring the image due to motion and a translation function which shifts the image. To asses only the effect of camera motion it is supposed that the received image is ideally located and registered at the receiver end. So by shifting the image half the induced camera motion, the processed image would be at the exact same location of the transmitted image but is blurred due to motion. Fig. 10 shows the effect of linear motion with and without the translation portion. Thus the following centralized transfer function is used to simulate the camera motion effect:

$$H_e(u, v) = \frac{T}{\pi (ua + vb)} \sin[\pi (ua + vb)]$$  \hspace{1cm} \text{(8)}$$

It was already shown that OFDM based modulations have a great advantage over PAM modulation in dealing with image blur. The QPSK-OFDM had a slight advantage over DPSK-OFDM in that case. However, when the camera motion effect is considered, DPSK-OFDM shows its superiority. When $H_e$ is applied to the received image in the frequency domain it may attenuate some elements resulting in SINR decrease or it may reverse the phase of the original elements resulting in constellation rotation and hence in error bits. Frequency attenuation in sub channels is something that affects both OFDM methods. On the other hand, constellation rotation does not affect DPSK-OFDM decisively because the sign of $H_e$ would be the same for adjacent sub channels unless $H_e$ is near zero where attenuation would dominate the capability of the system in detecting the modulated data.

The linear motion described by (7) can be considered as a motion of magnitude $r = \sqrt{a^2 + b^2}$ and angle $\theta = \arctan(\frac{b}{a})$. The $H_e$ transfer function for each magnitude and angle is calculated using Eq. (8). Two dimensional plots of BER for different $r$ and $\theta$ are shown in Figs. 11, 12 and 13.

BER for OFDM and PAM modulations introduces oscillations as a function of motion’s magnitude and angle due to the sampling point residing between transmitted pixels. In order to eliminate these oscillations, sub-pixel registration measures are required as described in [29].

In the proposed DPSK-OFDM method BER is maximized as $\theta$ reaches about $\pi/2$. This is the case where the motion is perpendicular to the differential phase modulation path. Because vertical phase difference of the elements is what transfers data,
if the movement is in the vertical direction, then errors may emerge. On the other hand, if the movement is horizontal it is not going to change the phase differences of elements in two consecutive rows, thus no error is generated (the errors, if any, in that case will be due to amplitude attenuation). Exact vertical movement has slightly less error rate in Fig. 13 due to the fact that the first row is modulated horizontally and vertical movement has minimal effect on it.

Because in practical data transmission scenarios frame to frame relative movement of camera and LCD may be considered uniformly distributed over different angles, it is safe to average the BER over $\theta$ where $0 < \theta < \pi$. This result is shown in Fig. 14 for $128 \times 128$ image.

This is where DPSK modulated OFDM shows its promising capabilities in mitigating aggressive relative movements between transmitter and receiver. Moreover it should be noted that in Fig. 14, PAM modulation is using about 5 dB more average power than OFDM and DPSK methods. This is due to the fact that the peak and average power of PAM are the same, and the full intensity range of LCD is utilized. As any practical system would use full power of the LCD, this type of comparison between the three methods is meaningful. Should the SNR for all three methods be the same, BER performance for PAM would be worse than what is shown in Fig. 14.

V. CONCLUSION AND FUTURE WORK

In this paper Differential Phase Shift Keying was combined with Orthogonal Frequency Division Multiplexing in order to modulate data stream into visual two dimensional barcodes. It was shown that QPSK-OFDM modulation has serious shortcomings in the mitigation of camera LCD movements where the phase of each element changes continuously. On the other hand, addition of a differential phase modulator before OFDM to modulate the data stream into phase differences of adjacent elements (DPSK-OFDM) causes the motion effect to increasingly weaken because of its gradual change from element to element, contributing to a small deviation from the ideal phase in the received signal.

It was observed that under relative LCD-camera motions that generate error rates in excess of 30% in PAM and QPSK-OFDM, the proposed system of DPSK-OFDM will maintain an error rate less than 8% which is practically correctable using error correction coding. Future inquiries in a resolution to this problem have to address the best choice of differential pattern to optimize performance for various motion scenarios. Moreover, extension of the current two-bit per symbol constellations increases data transfer capacity, and its BER performance evaluation would be required. Nevertheless, a study on the effect of perspective correction errors on the BER performance of this algorithm compared to the other ones could augment our understanding of its applicability to real world scenarios.

REFERENCES


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