Miller Code Usage in Visible Light Communications under the PHY I layer of the IEEE 802.15.7 standard

Alin-Mihai Cailean[1, 2], Barthélemy Cagneau[1,*], Luc Chassagne[1], Mihai Dimian[2] and Valentin Popa[2]
[1]*Université de Versailles, Laboratoire d'ingénierie des systèmes de Versailles, Vélizy-Villacoublay, France*
[2]*Stefan cel Mare University, Department of Computers, Electronics and Automation, Suceava, Romania*
[*]Corresponding author (E-mail : barthelemy.cagneau@uvsq.fr)

***Abstract*—This paper approaches the issues concerning the usage of the delay modulation as a coding technique used for outdoor Visible Light Communications (VLC) under PHY I layer of the IEEE 802.15.7 standard. We perform a comparative analysis between the Manchester code, as a traditional code, specified by the upper mentioned standard and the Miller code as a possible candidate for outdoor MIMO applications. Simulation and experimental results are provided, offering an overview over the multi-channel, flickering and Bit Error Ratio (BER) performances.**

***Keywords*- delay modulation; IEEE 802.15.7; intensity modulation; light emitting diode; Manchester coding; visible light communication.**

I. INTRODUCTION

LED systems began to be used in several applications because of specific advantages. Besides lighting, LEDs can enable VLC. VLC is safe for the human health unlike radiofrequency waves which are considered as a possible cause of cancer in humans [1] or like infrared communications which can cause thermal damage on the cornea. VLC also offers worldwide unregulated unlimited bandwidth, having the potential for extremely high data rates that can go above 1 Gbps [2].

One particular field of application for VLC is in the Intelligent Transportation System (ITS). VLC allows for Infrastructure-to-Vehicle (I2V) and for Vehicle-to-Vehicle (V2V) communications (see [3, 4] and [5, 6]). Enabling inter-vehicle communication may substantially improve the safety and the efficiency of the transportation system, addressing up to 81% of all-vehicle crashes [7].

In the recent years, LED-based lighting has begun to be integrated in the transportation system. The car manufactures began to replace the halogen lamps by LEDs, whereas city authorities use LEDs systems to replace the classical street lighting systems and integrate them in traffic lights. This enables VLC to be an ubiquitous technology capable of high market penetration, contributing to the success of the ITS.

This paper presents an analysis of the Miller coding technique and of its appropriateness for VLC outdoor usage in ITS application. Simulation results show that in terms of bandwidth and channel coexistence, the Miller code clearly outperforms the Manchester code. Experimental results confirm that in terms of BER, both the codes exhibit same performances. Since the IEEE 802.15.7 [8] standard, choses the usage of the Manchester code taking into consideration its flickering performances, the paper also analyses the flickering performances of the Miller code. As far as we know, this is the first detailed analysis that focuses on the Miller code for VLC usage.

II. MODULATION TECHNIQUES USED IN VLC

Intensity Modulation (IM) is considered to be the most appropriate modulation technique for VLC. IM implies to modulate the desired waveform onto the instantaneous power of the carrier. The receiver extracts the data from the modulated light beam by using Direct Detection (DD). The photodetector generates a current proportional to the incident power. This current is thus transformed into a voltage by a transimpedance circuit and then the signal passes through several filters and amplification stages until the data signal is reconstructed. For short, this is also the working principle of the system we have developed and that is detailed in section IV.

Depending on the application, many modulations techniques were proposed and investigated for VLC usage. Orthogonal Frequency Division Multiplexing (OFDM) [9] and discrete multi-tone modulations (DMT) [10] techniques offer the premises for high data rates and are mainly used for indoor static applications. However, complex modulations may lead to complex transceivers. For applications that require dimming, Pulse Width Modulation (PWM) [11] is considered as an alternative. For low data rates applications meant for outdoor usage, where the Signal-to-Noise Ratio (SNR) is low, simpler modulations techniques are generally used. On-Off-Keying (OOK) is a solution quite efficient. OOK modulation is regularly used with Not Return to Zero (NRZ) or with Manchester coding. The uses of Pulse Position Modulation (PPM) or of Inverted-PPM [12] have also been investigated. Compared with OOK, PPM and I-PPM can achieve higher data rates but require more bandwidth, higher peak power and are more sensitive to noise. In order to reduce the effect of the noise, the use of Direct Sequence Spread Spectrum (DSSS) sequence inverse keying (SIK) has been investigated and implemented [3]. This type of coding has error detecting capabilities and enables multiple transmitters.

The IEEE 802.15.7 standard for wireless optical communications using visible light defines for the PHY I outdoor usage, the utilization of OOK and of Variable Pulse

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Position Modulation (VPPM) as possible modulation techniques. VPPM is an improved modulation technique that combines the characteristics of pulse position modulation (2-PPM) for non-flicker and of PWM for dimming control and brightness control. VPPM is similar to 2-PPM but it allows the pulse width to be controlled for light dimming. All VPPM PHY I modes use 4B6B encoding. VPPM is intended mostly for applications which require dimming. For OOK, the standard mentions the usage of the Manchester code, with five different data rates: 11.67, 24.44, 48.89, 73.3 and 100 kb/s.

III. SIMULATION RESULTS

A. *Considerations on the multi-channel capabilities for Manchester and Miller codes*

The Manchester code, also called the biphase code, is a classical code, in which '0' is encoded as '01' and '1' becomes '10'. The main advantages of this code are DC balance, easy clock and data recovery, decent BER performances. However, even if it has plenty of advantages, the Manchester code requires high bandwidth compared to other common codes. For example, it requires twice the bandwidth of NRZ. On the other hand, the Miller code [13], also known as delay modulation, appears to be more convenient for Multiple Input Multiple Output (MIMO) applications, since it uses the bandwidth more efficiently. The Miller code can be easily constructed using the Manchester code. In Miller code, a '1' is encoded as a transition on the mid-bit position, a '0' following a '1' is encoded as no transition on the entire bit period, whereas a '0' following a '0' is encoded as a transition on the beginning of the second bit period. The Miller code has very good timing content, and carrier tracking is easier than Manchester coding. The Power Spectral Densities S_f (PSD) for these three codes are given by 1, 2 and 3.

$$S_{NRZ}(f) = \frac{V^2T}{4}\left(\frac{\sin \pi fT}{\pi fT}\right)^2 + \frac{V^2}{4}\delta(f) \quad (1)$$

$$S_{Man}(f) = V^2T \times \left[\frac{\sin^2(\pi fT/2)}{\pi fT/2}\right]^2 \quad (2)$$

$$S_{Mil}(f) = \frac{V^2T}{2(\pi fT)^2[17 + 8\cos(2\pi fT)]} \times [23 - 2\cos(\pi fT) - 22\cos(2\pi fT) - 12\cos(3\pi fT) + 5\cos(4\pi fT) + 12\cos(5\pi fT) + 2\cos(6\pi fT) - 8\cos(7\pi fT) + 2\cos(8\pi fT)] \quad (3)$$

where V is the signal amplitude and T the modulation period. f is the frequency for which the PSD is calculated.

Even if the performances of the NRZ code are not addressed by this paper, we introduce it as a reference. The corresponding curves for a modulation frequency of 11.67 kHz are plotted in figure 1.

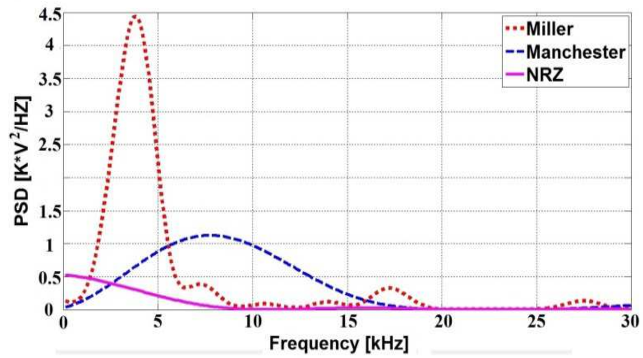

Figure 1. PSD for NRZ, Manchester and Miller code at 11.67 kHz.

It can be noticed that the Manchester code requires twice the bandwidth of the NRZ code. For the Miller code's PSD, the maximum energy is reached for a frequency around 2/5 of the modulation frequency.

Figures 2 and 3 illustrate the coexistence of five adjacent channels for the data rates specified by the 802.11.7 standard for OOK, for Manchester and Miller codes respectively. It can be seen that for the Manchester code, the five carriers overlap, making the separation quite difficult and introducing decoding errors. Regarding the Miller code, the five channels can be well distinguished. This allows for the five sub-carriers to be more easily processed by bandpass filters, either analog or digital.

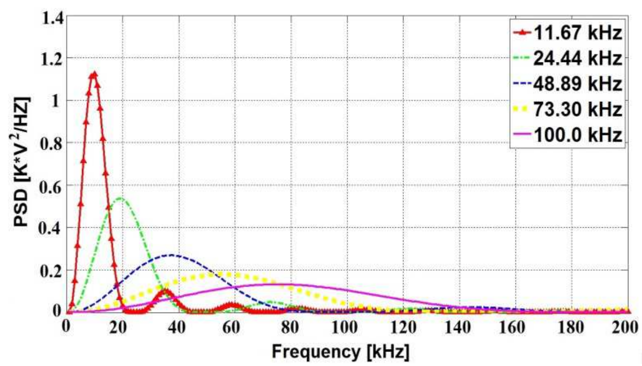

Figure 2. Simulation for five channels configuration, using the Manchester code.

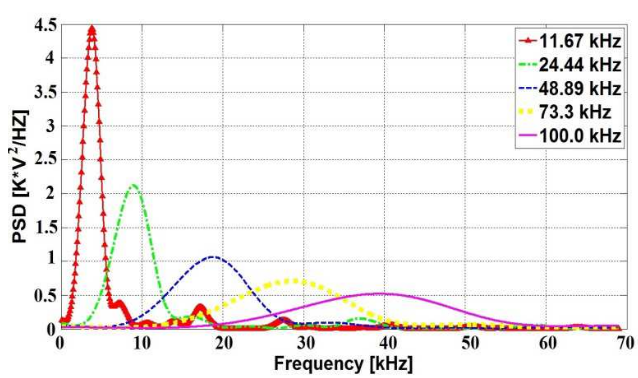

Figure 3. Simulation for five channels configuration, using the Miller code.

B. Flickering issues concerning the Manchester and the Miller code

The VLC technology adds communication capabilities to the classical lighting. However, VLC must not affect in either way the primary role of the appliance, which is lighting or signaling. Flickering mitigation is one of the main concerns regarding the VLC. Flickering represents the light intensity fluctuation caused by the modulation technique. It is classified as inter-frame flickering and as intra-frame flickering. Flickering is prevented when the light intensity changes within the Maximum Flickering Time Period (MFTP). In this case the human eye does not notice the light intensity changes. Even if an optimal flicker frequency is not widely accepted, it is considered that a MFTP smaller than 5ms (200 Hz) is safe [8, 14]. The IEEE 802.15.7 standard specifies the usage of Run Length Limiting (RLL) line coding as a technique for preventing perceivable flickering. Manchester, 4B6B or 8B10B codes are some examples. The RLL codes prevent long runs of 1s and 0s that can cause flickering and also ensure better clock and data recovery. For outdoor usage, the IEEE 802.15.7 standard specifies for the OOK, the usage of Manchester coding as a technique for preventing perceivable flickering, whereas for VPPM, it specifies the usage of the 4B6B code. For both modulations, the non-flickering characteristic is achieved by having the same brightness for bits '1' and '0'.

Due to its characteristics, the Miller code cannot ensure the same brightness for bits '1' and '0'. For bit '1', every bit has the same brightness. But, for '0', the brightness can be either twice the brightness of '1' or it can be zero. Under these considerations, instead of determining the brightness of Miller coded messages on an individual bit level, we determine it on a byte level. It seems that as long as the modulation period is at least eight of the MFTP, if each byte's brightness is equal, no noticeable flickering is induced.

To determine the flickering characteristic of the Miller code, we have performed several simulations. A number of 10^5 messages, containing 64 random ASCI characters (512 bits) were generated. The messages were encoded using the Miller code. The brightness of each byte is determined by measuring the 'lights on' time as a percentage of the total byte time. We consider that 100% brightness is achieved when the light is on for half of the byte time (as for the Manchester code).

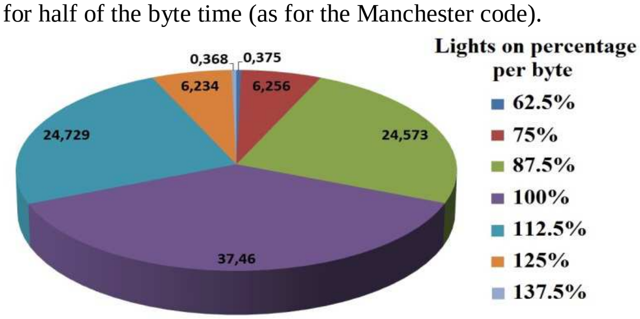

Figure 4. Simulation results showing the bytes percentage for different brightness intensities.

The figure 4 shows that the brightness of the bytes is 100% for 37.46% of the cases, varies in 49% of the cases by ±12.5%, in 12.5% of the cases by ±25%, whereas in 0.7% of the cases by ±37.5%. Regarding these results, we can conclude that unlike the Manchester code, the Miller code exhibits some brightness variations from one byte to another. However, since the byte period is significantly shorter than the MFTP, flickering at the byte level cannot be perceived.

In figure 5, we determine the brightness of each MFTP, for the five data rates mentioned by the standard.

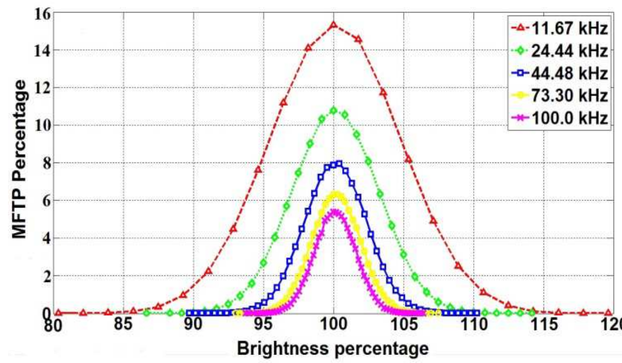

Figure 5. Simulation results showing the percentage of MFTP for different brightness percentages.

As showed in figure 5, the MFTP's brightness is a Gaussian distribution, centered on the 100% brightness intensity, which gets narrower as the modulation frequency increases. The results show that even at the lowest data rate, more than 96% of the MFTPs have an oscillation bellow ±10%. Furthermore, the human eye does not have a linear response to changes in light intensity. According to [15], the relation between the perceived light and the measured light is given by eq. 4.

$$Perceived\ light(\%) = 100 \times \sqrt{\frac{Measured\ light\ (\%)}{100}} \quad (4)$$

Considering this relation, it can be appreciated that the brightness variation sensation is even more reduced, and that the flickering effect perceived by the human eye is limited.

IV. Hardware implementation and experimental results

For the final tests, we determine the BER performances of the two codes. These tests are performed using a VLC communication system that we have developed (see figure 6). The system is meant to be used for traffic safety information. It broadcasts data between a traffic light based on LED to a vehicle (information about the color of the traffic light and the countdown before the next color change). The emitter was developed based on a commercial LED traffic light on which we have added a controller unit that performs data encoding and LEDs switching. The receiver consists of a photodiode-based light detection module, several filtering and amplification stages, and a signal processing unit.

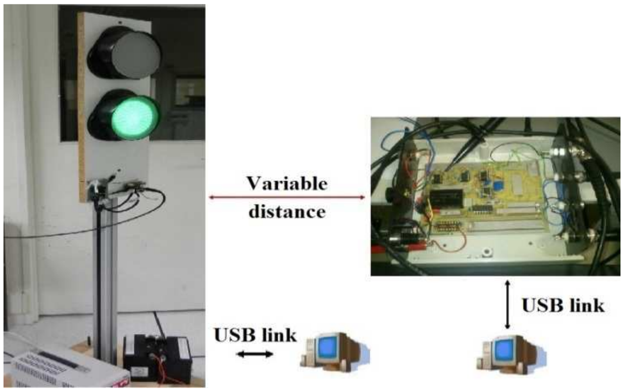

Figure 6. Visible light communications system consisting of a traffic light (red or green) emitter and a receiver.

Information treatment and decision taking are performed by a low-cost 8-bit microcontroller. In our prototype, the microcontroller can be switched either on the Manchester or Miller code in order to test different configurations.

Tests were performed under various conditions, to determine the BER for the two codes. The data transmission was made at a 15 kHz modulation frequency. The results are detailed in [16] and summarized in Table I.

Table I Bit Error Ratio performances at 15 kHz

Data coding	**Emitter-Receiver Distance**	**BER**	**Testing conditions**
Manchester	1 – 50 m	$<10^{-7}$	Outdoor with daylight
Miller		$<10^{-7}$	
Manchester	1 – 20 m	$<10^{-7}$	Indoor with neon lights
Miller		$<10^{-7}$	

We demonstrate that the both codes exhibit the same BER performances, at least at the 10^{-7} level. The developed system is able to maintain the BER lower than 10^{-7} for distances that increase up to 50 meters and in different testing conditions for both codes. Even in the presence of light perturbations, represented by moderate sun or by indoor neon lights, the BER performances are the same for the two codes. We mention that no error correction techniques were used for these experiments.

V. Conclusions

This paper presented a comparative analysis over the coding techniques used in VLC, focusing on the Manchester and on the Miller codes. The results showed that in terms of BER, up to the 10^{-7} level, Manchester and Miller code have similar results, which was experimentally verified. However, in terms of spectral distribution, the Miller code clearly outperforms the Manchester code offering the premises for MIMO applications. Since the IEEE 802.15.7 standard, choses the usage of the Manchester taking into account its flickering performances, the paper also analyzed the flickering performances of the Miller code. The results showed that even at modulation frequencies as low as 11.67 kHz, the flickering effect is very limited. However, the effects of this limited flickering must be further investigated, to determine if there is any negative effect.

Acknowledgment

This paper was supported by the project "Sustainable performance in doctoral and post-doctoral research PERFORM - Contract no. POSDRU/159/1.5/S/138963", project co-funded from European Social Fund through Sectorial Operational Program Human Resources 2007-2013. This work was also supported by the competitiveness cluster in automobile and public transport Mov'eo and the Co-Drive project.

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17^{20}	**Sorin ZOICAN** **Marius VOCHIN** Politehnica University of Bucharest, *Romania*	*On Implementing Packet Inspection using CUDA Enabled Graphical Processing Units*
17^{40}	**Alin-Mihai CAILEAN** **Barthélemy CAGNEAU** **Luc CHASSAGNE** Université de Versailles, *France* **Mihai DIMIAN** **Valentin POPA** Ştefan cel Mare University of Suceava, *Romania*	*Miller Code Usage in Visible Light Communications under the PHY I layer of the IEEE 802.15.7 standard*
18^{00}	**Adelina OCHIAN** **George SUCIU** Beia Consult International, *Romania* **Octavian FRATU** **Carmen VOICU** Politehnica University of Bucharest, *Romania* **Victor SUCIU** Beia Consult International, *Romania*	*An Overview of Cloud Middleware Services for Interconnection of Healthcare Platforms*
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The last sentence of section 3 should be revised. A mathematical relationship cannot determine human sensation.