Comparison of Coding Techniques for Photoacoustic Coded Excitation

Martin P. Mienkina[1], Annika Eder[1], Claus-Stefan Friedrich[2], Nils C. Gerhardt[2], Martin R. Hofmann[2], Georg Schmitz[1]

[1] *Institute of Medical Engineering, Ruhr-Universität Bochum, Germany, Email: martin.mienkina@rub.de*
[2] *Photonics and Terahertz-Technology, Ruhr-Universität Bochum, Germany*

Introduction

Photoacoustics deals with the electromagnetic excitation of sound and ultrasound in matter [1]. In particular, by irradiating biological tissue with laser pulses in the nanoseconds range ultrasound is generated, which can be received by conventional medical ultrasound systems [2]. This allows the imaging of the optical properties of biological tissue with the resolution of clinical ultrasound systems. For example, photoacoustic imaging has been used, for imaging of vascular morphology [3], for breast cancer imaging [4], and for molecular imaging [5].

Commonly, Q-switched Nd:YAG lasers in combination with optical parametric oscillators (OPOs) are used as multispectral photoacoustic laser sources. Recently, pulsed laser diodes have been proposed as alternative radiation sources for photoacoustic imaging [6, 7]. Combinations of Nd:YAG lasers and OPOs usually exhibit a much higher pulse energy than laser diodes, while the maximum pulse repetition frequency (PRF) of the laser diodes exceeds the PRF of the Nd:YAG lasers. Consequently, averaging schemes can be employed to improve the signal-to-noise ratio (SNR) of photoacoustic imaging using laser diodes, while maintaining a high frame rate. In order to obtain a maximum SNR gain per time unit, a maximum PRF of the laser diodes should be used. However, range ambiguities occur if the PRF exceeds the inverse of the acoustical time-of-flight. Consequently, we introduced the usage of photoacoustic coded excitation (PACE) [8, 9] to increase the PRF beyond this limit, i.e. further increasing the SNR. So far, unipolar Golay codes (UGC) and Simplex codes (SC) were proposed separately for PACE. Therefore, within the scope of this paper, we compare the performance of UGC and SC based on the estimated coding gain for realistic sets of simulation parameters. The remainder of this paper is structured as follows: first, we present the concept of PACE based on UGC and SC and derive the SNR gain for UGC and SC, respectively. Then, the coding gain normalized to time equivalent averaging is calculated and evaluated as a function of frame rate of a hypothetic imaging system for both coding procedures.

Materials and Methods

Physical Properties and Geometry

We assume the following geometry and physical properties for the subsequent calculations: an ultrasound detector is positioned in a distance z_a from an ideal optical absorber. The surrounding medium exhibits a speed of sound c_0 and is assumed to be optically and acoustically linear and non-absorbing. Subsequent to each trigger event, the laser diode irradiates the absorber and generates an ultrasonic wave. The acoustical time of flight, i.e. the echo time, is defined by

$$\tau_E = \frac{z_a}{c_0}. \qquad \text{[s]} \qquad (1)$$

The time between the emission of two consecutive light pulses is defined by τ_L. $h_{PA}(k)$ is a time discrete impulse response, which models the ultrasonic response of the total set-up to a light pulse. The ideal impulse response is superimposed with additive white noise $n(k)$ exhibiting a variance of σ^2.

Unipolar Golay Codes

Unipolar Golay codes have recently been proposed for photoacoustic coded excitation [9]. They are derived from Golay codes, which find wide spread application in medical ultrasound imaging. Golay codes comprise a complementary pair of sequences A and B

$$\begin{aligned} A(t) &= \sum_{k=1}^{N_{UGC}} a_k \delta\left(t-(k-1)\tau_L\right) \\ B(t) &= \sum_{k=1}^{N_{UGC}} b_k \delta\left(t-(k-1)\tau_L\right) \end{aligned}. \qquad (2)$$

with $a_k, b_k \in \{-1,1\}$ and $N_{UGC} = 2^L$, $L \in \mathbb{N}$ being the code length of the Golay code, and exhibiting the following property:

$$A(t) * A(-t) + B(t) * B(-t) = 2N\delta(t). \qquad (3)$$

They can be converted into unipolar sequences by the following calculation:

$$\begin{aligned} A_p(t) &= \left(A(t)+1\right)/2 \\ A_n(t) &= \left(-A(t)+1\right)/2 \\ B_p(t) &= \left(B(t)+1\right)/2 \\ B_n(t) &= \left(-B(t)+1\right)/2 \end{aligned}. \qquad (4)$$

Photoacoustic coded excitation requires unipolar sequences for coding since it is not possible to emit negative light intensities. Thus, every '1' of the sequence corresponds to 'laser on' and every '0' corresponds to 'laser off'. Consequently, the coding sequences can be translated into a laser trigger timing scheme for the laser diode, as displayed in Figure 1.

According to [9], the mean square error (MSE) of the resulting decoded signal of UGC can be given by

$$\sqrt{\mathrm{MSE}_{UGC}} = \frac{\sigma}{\sqrt{N_{UGC}}}, \tag{5}$$

assuming that each received ultrasonic response to the coding sequence is superimposed with additive white noise with equal variance σ^2. The total sending time of one unipolar Golay code is given by $T_{UGC} = 4\left(\left(N_{UGC}-1\right)\tau_L + \tau_E\right)$. During this period, instead of sending the code, averaging procedures could be conducted in order to improve the SNR. Thus, the coding gain can be defined as the ratio of the MSE based on unipolar Golay codes and the possible MSE of averaging during the code sending time. The coding gain is given by

$$G_{UGC} = 10 \bullet \log 10 \left(\frac{N_{UGC}}{4\left(\left(N_{UGC}-1\right)\tau_L \frac{c_0}{z_a} + 1\right)} \right) \tag{6}$$

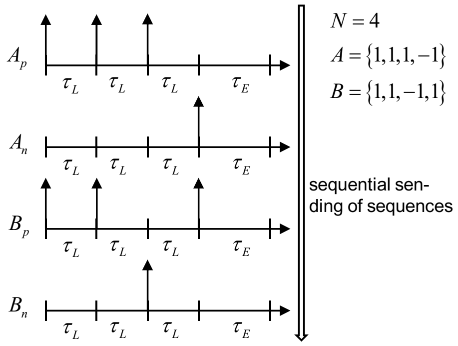

Figure 1: Laser trigger timing scheme for 4 bit unipolar Golay codes.

Simplex Codes

Simplex codes [10] are applied to many problems in optics due to their unipolar nature. They are derived from the Hadamard transform and are based on a matrix **S** composed of 1´s and 0´s. For a 3rd ($N_{SC} = 3$) order Simplex code the matrix has the following structure:

$$\mathbf{S} = \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \end{pmatrix}. \tag{7}$$

In the time domain, each row can be interpreted as one coding sequence [11]. The original photoacoustic impulse response can be retrieved by applying the inverse of the matrix **S** to the acquired signals. The MSE for this coding scheme can be derived as

$$\sqrt{\mathrm{MSE}_{SC}} = \frac{2\sigma}{\left(N+1\right)}. \tag{8}$$

For SC the code sending time is given by $T_{SC} = N_{SC}\left(\left(N_{SC}-1\right)\tau_L + \tau_E\right)$. Consequently, the coding gain compared to time equivalent averaging can be calculated as [8]

$$G_{SC} = 10 \bullet \log 10 \left(\frac{\left(N_{SC}+1\right)^2}{4N\left(\left(N_{SC}-1\right)\tau_L \frac{c_0}{z_a} + 1\right)} \right). \tag{9}$$

Results

The validity of (5) and (9) has been shown in [8] and [9], respectively, by a comparison of analytically derived results and simulations based on experimental data. Consequently, within the scope of this paper, the evaluation of the UGC and the SC is performed solely based on (5) and (9).

As the first step of the evaluation the asymptotic coding gain for infinite code duration is determined. It is given by

$$\lim_{N_{UGC}\to\infty} G_{UGC} = \lim_{N_{SC}\to\infty} G_{SC} = \frac{1}{2}\sqrt{\frac{z_a}{\tau_L c_0}} = \frac{1}{2}\sqrt{\frac{\tau_E}{\tau_L}}. \tag{10}$$

The coding gain limit for both codes is determined by the ratio of the acoustical time of flight and the period between sending two light pulses. Consequently, the minimum PRF of the laser diode in order to achieve a positive coding gain is given by

$$\mathrm{PRF}_{0\,\mathrm{dB}} = \frac{4c_0}{z_a}. \tag{11}$$

Since the code order is defined differently for both coding schemes, it is necessary to assess the coding performance as a function of the code sending time.

In Figure 2 the SNR gain is shown as a function of code sending time. For the chosen simulation parameters averaging yields a lower SNR gain than both coding procedures. UGC outperform SC for code sending times higher than 0.3 ms. By increasing the code length the difference between both coding schemes decreases.

A crucial parameter for imaging systems is the frame rate. For imaging applications using photoacoustic coded excitation the frame rate can be defined as the inverse of the code sending time. In Figure 3 the coding gain is displayed as a function of the frame rate. For high frame rates SC outperform UGC, while at lower frame rates the UGC yield higher coding gains than SC.

The intercept frame rate, i.e. the frame rate where $G_{UGC} - G_{SC} \overset{!}{=} 0$, is further investigated by varying the PRF of the laser diodes and the depth of the absorber. Figure 4 displays the results of the evaluation. SC outperform UGC for frame rates higher than 2500 Hz, assuming realistic simulation parameters. For these frame rates SNR gains of less than 15 dB are achievable. Due to the low pulse energy of laser diodes a SNR gain of 40-60 dB is needed in order to achieve a SNR, which is comparable to photoacoustic imaging using Nd:YAG lasers. This requires long coding sequences, leading to frame rates below the intercept frame rate. Within this regime the UGC yield a higher coding gain than SC. Thus, UGC seem to be more suitable for PACE using laser diodes than SC. Since the coding gain of both coding procedures converges to the same limit for infinite code sequences, the difference between the codes for long code sending times is small. Still, both coding procedures offer substantial benefits compared to averaging, as can be seen in Figure 5. The parameters used for this simulation (PRF: 1000 kHz, z_a : 3 cm) are realistic, because state of the art laser diode drivers exhibit PRFs up to 1 MHz and a photoacoustic imaging depth of 3 cm has already been demonstrated [4]. For this scenario, assuming that a minimal SNR gain of 40 dB is needed for photoacoustic imaging, a code sending time of 40 ms and averaging time of 200 ms are needed. Thus, a fivefold increase in frame rate of the photoacoustic imaging system can be achieved using PACE.

Conclusion

Photoacoustic coded excitation (PACE) is introduced as a new concept for photoacoustic imaging. Unipolar Golay codes (UGC) and Simplex codes (SC) are proposed as coding schemes and the coding gain with respect to time equivalent averaging is derived for both codes. Based on these analytic expressions the codes are compared to each other. It is shown that for realistic simulation parameters, employed for photoacoustic imaging using laser diodes, UGC outperform SC. Both coding schemes exhibit a positive coding gain compared to time equivalent averaging for these simulation parameters. These findings show that PACE is potentially a promising acquisition concept for photoacoustic imaging using pulsed laser diodes.

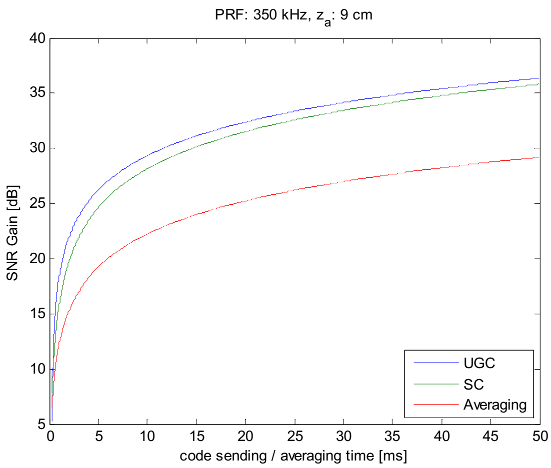

Figure 2: The SNR gain is displayed as function of the code sending time for unipolar Golay codes, Simplex codes, and averaging. It is assumed that the absorber is located 9 cm in front of the ultrasound detector and the PRF of the laser diode is set to 350 kHz.

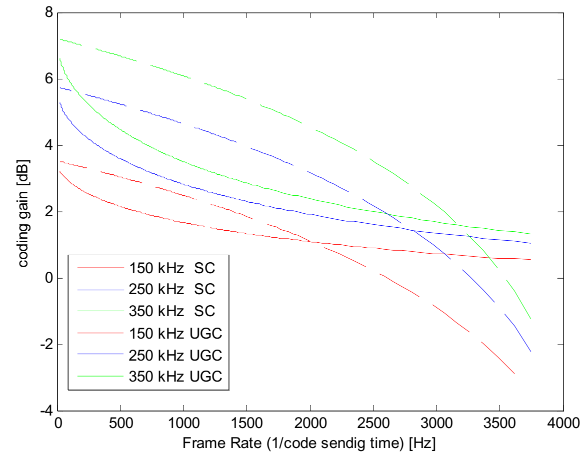

Figure 3: The coding gain with respect to averaging is evaluated as a function of the frame rate. The absorber depth is set to 9 cm.

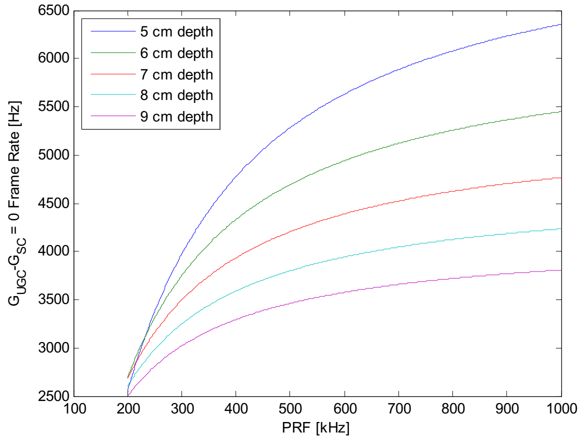

Figure 4: The intercept frame rate is evaluated as a function of the PRF and absorber depth.

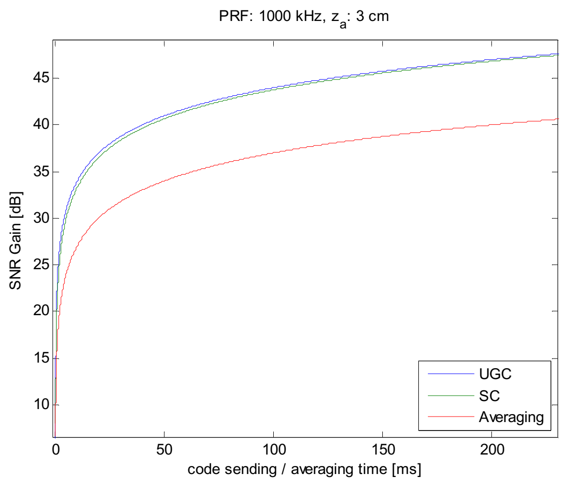

Figure 5: The SNR gain is displayed as function of the code sending time for UGC, SC and averaging, respectively, assuming realistic simulation parameters.

Acknowledgments

This research was sponsored by the German Federal Ministry of Education and Research (bmb+f grant no. 01 EZ 0707).

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