ABSTRACT

This work presents the latest simulations and experimental results of an innovative module for functional diffused optical imaging based on double encoding of wavelength and position of the emitting light. A spread spectrum approach to near infrared diffusive optical imaging is implemented: a pseudo-random sequence is used to modulate the light before entering a turbid medium; when the coded sequence propagates through the tissue, it is split into a group of components that have different path lengths. The correlation of the detected signals with the sequence can pick up each component with a specific delay, with the consequence of obtaining time domain information of arriving replicas. We propose to improve that approach, adopting a code division multiple access technology. A module which is expected to enhance the performances in terms of measured time and SNR is presented. We called this technique Wavelength and Space Code Division Multiplexing (WS-CDM).

1. INTRODUCTION

Near Infrared (NIR) diffuse optical technologies have recently emerged as promising tools to monitor important metabolic parameters such as blood oxygenation, volume and flow. These emerging technologies can directly assess tissue composition in terms of the four primary absorbers at NIR wavelengths (water, lipid, oxy- and deoxy-hemoglobin) or tissue microstructure related to the scattering properties [1]. Their utility in a variety of applications for functional imaging of the brain, optical mammography and monitoring of muscle metabolism has been demonstrated [2].

Time-Domain (TD) systems are commonly used to perform NIR spectroscopy, but this technique has some limitations, as the high cost of equipment, the acquisition length and the sensitivity to ambient light. A novel, spread spectrum approach was presented in [3] where Continuous Wave (CW) laser sources were modulated by a Pseudo-Random Bit Sequence (PRBS). This approach can overcome the latter limitations, adding the advantages of CW systems (low cost of components). The use of PRBS coding technique allows improving of the SNR, while the use of Avalanche Photodetector (APD), instead of a conventional Single Photon Counting (SPC), allows lower sensitivity to ambient light. Nonetheless a major limitation is still present, as only one wavelength and one emitting location at a time can be switched on, making the full acquisition from an array of sources and detectors a sequential (thus lengthy) process.

This paper focuses on a novel architecture which exploits the wavelength and code division multiplexing (WDM and CDM) techniques, commonly used in modern telecommunications, to overcome also the last limitation. Indeed this architecture allows to launch simultaneously several signals, at different wavelengths (in order to acquire information about the four primary absorbers mentioned above): thus the acquisition speed is strongly increased. Furthermore, the smart choice of codes allows to improve signal-to-noise ratio (SNR). The architecture of the core element, the encoder, is presented; results of simulations and preliminary laboratory experimental activity aimed at validating the method and assessing the technique performances are discussed and investigated.

2. METHODS

Fig. 1. Functional diagram of the encoder. In the inset: simulation result showing the Temporal Point Spread Function (TPSF) after propagation in a diffusive medium.
Figure 1 contains the functional description of the encoder in the configuration with four wavelengths ($\lambda_1$-$\lambda_4$), three launch sites ($S_1$-$S_3$), and one detector [4]. $\lambda_N$ are cheap CW laser diodes at different wavelengths, whose emission power is dynamically and continuously equalized (this is a general requirement of CDM system); each source is first modulated with a different code word ($C_1$-$C_4$). The fibres enter a coupler such that its output fibres contain the four encoded wavelengths. The obtained signal is split in three replicas, each of these composite signals is then encoded again with a different code by one of $C_5$-$C_7$ modulators. Each light source is thus double-encoded: the first word encodes the wavelength, the second the emission position.

After the optical to electrical conversion, the correlation receiver operates a double decoding to reconstruct the single Temporal Point Spread Function (TPSFs): for instance, by correlating the received signal with $C_5$, light contribution coming from source $S_1$ will be isolated; the subsequent correlation with $C_2$ will isolate the contribution from $\lambda_2$.

For this mechanism to work, the orthogonality of $C_1$-$C_7$ is a must: the ideal code words should have null cross-correlation as well as a Dirac-like auto-correlation function, so that the reconstruction of delayed replicas of each channel is possible (this is essential to build the TPSF functions) without crosstalk. Another requirement is the continuous automatic equalization of the emission power of the four laser diodes.

3. CODING TECHNIQUES

The choice of the code family for $C_1$-$C_4$ and $C_5$-$C_7$ and their lengths is a central aspect. A Matlab-based simulator was developed to study the effects of different coding words families, words length and spectrum spreading factor on the performances of the whole system in terms of SNR. Speed of acquisition and reconstruction, robustness to non perfect channel equalization, depending on various diffusive and absorbing characteristics of the tissue is also a mandatory investigation.

The correlation properties of generated sequences have been studied by finding the auto-correlation of each sequence as well as the cross-correlation among all possible pairs of sequences for a particular length $L$. The process has been repeated for the length $L$ in the range $64$ – $512$. These data have been used for calculation of two quality factors, namely the processing gain $A$, defined as the difference between the maximum value of auto-correlation and that of cross-correlation, and the ratio $B$ between the peak magnitude of the cross-correlation between two sequences and the peak magnitude of the auto-correlation. High value of $A$ and low value of $B$ assure better performances in CDMA codes.[5] $A(L)$ and $B(L)$ for the three coding families are shown in figure 2 and figure 3 respectively. The processing gain $A$ linearly increases with $L$, while $B$ follows a nonlinear decreasing path. Figure 2 and figure 3 are in good agreement with the desired correlation properties of CDMA.

4. ACTIVITIES AND RESULTS

The proposed system has been studied and validated by means of both numerical and experimental tools.

4.1. Simulation activity

Simulations have been performed setting 2 channels per each coding level, so that the received signal is the sum
of four contribution (one for each path on the two coding levels).

Moreover, those simulations have been performed tuning several parameters, i.e. length of input signals (from 32 to 1024 bits), coding type (PRBS, Gold, Kasami) and frequencies of signals, to obtain the set of parameters leading to better performances in terms of signal to noise (SNR) and signal to interference ratio (SNRi).

Two kinds of filter have been implemented, namely a deterministic multipath and a diffusive-absorptive filter.

**Deterministic multipath**

Deterministic multipath is a channel in which several replicas of input signals are subjected to 4 different (fixed) delays, then summed together. In this architecture with two coding levels and two signals per level, expected simulation results are 4 peaks in each TPSF corresponding to delay values set. Different delay values have been set for the two channels on the second coding stage, in order to distinguish and associate each TPSF to the corresponding path. An example of simulation with deterministic multipath is shown in figure 4, where there are four peaks, corresponding to the four delay values of each path. That simulation has been performed using two PRBS codes with length \( L_1 = L_2 = 512 \) bits, with frequencies \( f_1 = 1 \) MHz and \( f_2 = 512 \) MHz respectively. The expected delay values were \( \Delta = (2.55, 15.33, 28.10, 40.88) \) ms.

**Medium with diffusion and absorption**

A more realistic channel takes into account both diffusion and absorption phenomena. It has been implemented a simple model of diffusion, in which delays are extracted from a Gaussian distribution (as one can expect using a probabilistic approach to solve the diffusion equation). Then, the signals are subjected to a variable attenuation (to model the absorption) according to the conventional Lambert-Beer law, that can be expressed as follows:

\[
A = cCl \quad A(t) = \log_{10} \left( \frac{I_0}{I_t} \right) = cCvt.
\]  

where \( l \) is the optical pathlength, \( A(t) \) is the absorbance at a certain time \( t \), \( I_0 \) is the amplitude of the signal before entering the channel, \( I_t \) is that with an absorber; \( c \), \( C \) and \( v \) respectively represent the molecular absorption coefficient of absorber, concentration of absorber and constant velocity of light in the solvent, 0.23, mm/ps, the solvent being water in the simulations. It is worth to stress that the Lambert-Beer law does not work for turbid (i.e. highly scattering) media. In this case, scattering is predominant on absorption and other kind of physical models are required. Our future activity will also focus on the study of the propagation of the light in highly scattering media. An example of simulation with diffusion and absorption is shown in figure 5.

4.2. Experimental activity

The experimental setup is shown in figure 6. It is focused on the detection of an optical signals and related replicas generated by a fading-affected channel, in a double stage coded system. In order to validate our approach, experimental activities have been carried on using devices operating at wavelengths in C-band range (all the components are commercial devices).

In the specific case, the two signals are 1540.5 nm and 1542.1 nm CWs generated by Distributed Feedback (DFB) lasers. The first coding stage is obtained directly modulating the light sources by two waveform generators, with \( C_1 \) and \( C_2 \), that are \((2^6 - 1)\)-long PRBSs at 156.160 KHz, generated by different polynomials. The two signals are coupled together and the derived signal is split again to the second coding stage and coded by \( C_3 \) and \( C_4 \), that are still \((2^6 - 1)\)-long PRBSs at 9.99424 MHz, but generated by diverse polynomials. Nevertheless the numerical activity about coding families and words length (discussed in section 3) suggests to transmit signals coded with longer sequences, we ex-
exploited $2^6 - 1$-long sequences because of devices bandwidth limitations. In order to investigate the principle effectiveness, in this preliminary activity the multipath is obtained in a deterministic way by a split and delay architecture. In particular, the same optical signal is delayed by using a 5000 m, 10000 m and 12600 m-long SMF spools, as shown in the inset of figure 6, introducing 29.5 µs, 50µs and 63 µs delays.

4.3. Results

Preliminary simulation results stated the ability of the decoder to correctly reconstruct the transmitted double coded signals.

![Figure 7](image)

**Fig. 7.** SNR in the physiological scenario against the length of the words $L_1$ and $L_2$ (both belonging to the GOLD family). Better SNR is achieved with longer words on both levels.

![Figure 8](image)

**Fig. 8.** SNRi in the physiological scenario against the length of the words $L_1$ and $L_2$ (both belonging to the GOLD family). Better SNRi is achieved with longer words on both levels.

The simulations showed that SNR and SNRi are dependent on length and frequencies of the words, while the type of coding families used has minor effects. Figures 7 and 8 are the SNR and SNRi respectively, versus the logarithm of the length of words on two coding stages, in the framework of the realistic diffusive condition (the so-called diffusive-absorptive filter described in section 4.1). This analysis shows that longer are the sequences, higher are SNR and SNRi (as previously seen in section 3): in particular, sequences with $L_1 = L_2 = 512$ bits are the best combination that allows to achieve maximum SNR and SNRi. For this reason, the TPSF showed in figure 5 has been obtained choosing 512 bits sequences on both coding stages. The performance of the system is not heavily affected by the type of coding families in this range of length. For the sake of shortness, only results about Gold family are shown (the same study about other coding families gives very similar results in terms of SNR and SNRi versus codes length).

Figure 9 contains the simulation results for $C_1$-$C_3$ and $C_1$-$C_4$ double decoding, while figure 10 is the corresponding experimental result (for the sake of shortness, only results about the first branch are shown).

![Figure 9](image)

**Fig. 9.** Real TPSF relative to signals passing through the first branch of each coding stage.

![Figure 10](image)

**Fig. 10.** Simulated TPSF relative to signals passing through the first branch of each coding stage.
5. CONCLUSION

In this work the applicability of a novel architecture which exploits the wavelength and code division multiplexing (WDM and CDM) techniques to overcome the limitations of time domain diffuse optical systems has been investigated.

The approach aims to reduce the measured acquisition time and to improve the decorrelated SNR, as well.

A preliminary numerical activity, supported by a Matlab simulator, has been carried out in order to investigate the impact of different coding family, words length and signal frequency to the signal decorrelation at the receiver stage. PRBS, Gold and Kasami codes have been compared in terms of cross-correlation and auto-correlation properties. For their features, these three family of codes are inputed as candidate in the coding approach in channel with fading.

A deterministic and a Gaussian channels have been modelled in order to evaluate the simulator in presence of multipath.

As a proof of concept, a preliminary experimental activity has been carried out, with signal in the telecom band and for deterministic channel. First results provide a good agreement between numerical and experimental approach. The promising outcome and the potential improvement to diffuse optical imaging strongly motivate the continuation in WS-CDM research in the near infrared range of interest in medicine.

6. REFERENCES


