Spread Spectrum EIT by Code Division Multiplexing

A McEwan, J Tapson, A van Schaik and D Holder

1 School of Electrical and Information Engineering, CARLAB
The University of Sydney, Australia, NSW 2006
2 Department of Electrical Engineering, University of Cape Town,
Cape Town, South Africa.
3 Department of Medical Physics and Bioengineering, University College London,
Gower St, London, UK.
alistair.mcewan@sydney.edu.au

Abstract Code division multiplexing is proposed as a new EIT method that can provide simultaneous impedance measurements of the multiple channels. Code division provides clear advantages of a wide frequency range at reduced cost and reduced complexity of sources. A potential drawback is the lack of perfectly orthogonal code sets. The method described provides images and spectra which are equivalent to the conventional time multiplexed method, with increases in frequency resolution and measurement speed which may be of benefit in some applications of EITS.

1. Introduction

The purpose of this manuscript is to describe a new method of EITS called Code Division Multiplexing (CDM) EITS, and to demonstrate that CDM-EITS is an inexpensive method with higher frequency resolution than current systems. Furthermore, CDM-EITS may be used measure the impedance spectrum from multiple channels simultaneously to form EITS images at a faster rate. The principle of CDM is that a signal through a particular channel is modulated using a unique binary digital code. A receiver which is receiving several channels simultaneously can separate the data for each channel by demodulating the measured signal using a copy of each of the modulation codes. There are a number of different codes which may be used. The basic requirements are that there should be at least one code per channel; that the codes should be orthogonal, or nearly so; and that the autocorrelation functions of the codes should be flat with a single sharp peak (in the ideal case, approximating a delta function) [1]. The codes which we have used in this work are called Gold codes, which are also used in the Global Positioning System (GPS) to encode the signals from the GPS satellite constellation. The codes are bit sequences which appear to be random, but in fact are deterministically generated, usually by means of a modulo-addition of bits in a shift register. Codes of this type are generally referred to as pseudorandom noise (PRN) sequences, as they appear to be random and have the characteristics of noise, including a broad spectral content. For EIT the use of CDM allows us to take measurements over all the channels simultaneously. In addition, for EITS the spectral characteristics of the CDM input signal effectively interrogate the sample over a wide range of frequencies and the output signals can be transformed to produce a spectrum, giving us simultaneous wide-band spectroscopy on all channels. A similar technique has been used previously in a single channel where a maximum length sequence (MLS) was used to detect changes in impedance spectrum in single cell analysis [2]. The use of MLS, but not PRN, in EIT has been proposed in [3], but no working system has been reported. Only a single non-zero MLS exists for any given code length, so for simultaneous measurement we are forced to use larger sets of PRN sequences, such as
the Gold codes. These have similar properties to a MLS, but their autocorrelation deviates more from the ideal Kronecker delta function, i.e., they are sets of nearly orthogonal codes. The size of the PRN code set and the orthogonality increases with code length [1], so longer codes are preferred. Longer codes also conveniently increase the resolution and bandwidth of the demodulated spectrum at the cost of a longer acquisition time.

2. Methods

2.1 Serial Imaging of a 16 electrode saline tank
A serial EITS system, the UCL Mk2.5 [4], was reprogrammed with the 1st 1023-chip-length code of a set of eight Gold codes. Only one code was used as the UCL Mk2.5 is based on a single channel of the Sheffield Mk3.5 system multiplexed to 32 electrodes. In normal operation the UCL Mk2.5 system measures the spectrum using a 2048 samples long composite waveform of 10 frequencies of equal amplitude, logarithmically spaced between 2kHz and 1MHz [4,5]. The waveform is normally repeated in 3 epochs with a shift of 1 octave to give 30 frequencies; however to compare with our new method we only use one 10 frequency epoch. The Gold code was sampled at 2 samples/chip to meet the Nyquist criterion. As the lengths of both test waveforms are the same, and the timing of the system clock (2MHz) was unchanged, they span the same frequency range of 2kHz-1MHz. For simplicity, and so that the instrumentation did not saturate, the amplitude of the Gold code waveform was set to the maximum of the composite waveform. Firstly a reference data set is collected with only saline in the tank, by sequentially injecting a current modulated by the Gold code from each electrode while measuring the voltages at the other electrodes. The observed signals were correlated with the Gold code to obtain the transfer functions from each electrode to all other electrodes and the magnitude of the Fourier transform was taken as a measure of the impedance between electrodes as a function of frequency. In a second step, the object is introduced and another data set taken. These two data sets are subtracted which removes small yet significant errors due to geometry and electrode positions. The difference data, which ideally should only represent the impedance changes, is then used in the image reconstruction algorithm to create a 'time difference' image. In keeping with previous EITS measurements we chose to use a piece of banana 2 cm long and 1 cm in diameter located at 8 o’clock and 1cm from the edge of the tank as our object. A piece of banana changes the local impedance in the tank by over 100% between 2kHz and 1MHz. The saline solution’s impedance will remain relatively unchanged over the same frequency range and hence it is possible to determine the spectrum of the object inside the tank from a sequence of images at the measured frequencies. The tank was cylindrical with a diameter of 10cm and filled with 0.1% saline solution. It had 16 stainless steel electrodes on its perimeter. We used polar (opposite) current injection and time-difference image reconstruction was done using a linear solver (EIDORS, [6]) and a 15,000 element FEM mesh of the tank.

2.2 Simultaneous Imaging of an 8 electrode saline tank
To investigate if the technique could be used to successfully acquire simultaneous images, a multichannel, time multiplexed, Sheffield Mk3.5 EIT system [5] was reprogrammed to activate two sources simultaneously, either with orthogonal frequencies, or the 1023 chip Gold codes. Three voltmeter channels measured the impedance change from introducing a cylindrical piece of banana, 2cm diameter at 2 o’clock, and 4cm from the edge of a cylindrical tank (of 10cm diameter) which was filled with 0.2% NaCl. The resulting signal was demodulated with each orthogonal frequency, or Gold code, and an impedance image formed at 10kHz and 50kHz.

3. Results
Boundary voltages (figure 1), Serial images (figure 2) and extracted spectra (figure 3a) were obtained with the composite waveform and Gold codes, and simultaneous images were obtained with FDM and CDM (figure 3b).
Fig. 1. Comparison of boundary voltage measurements in a single frame. Each line is a different electrode combination measurement. Combinations more sensitive to the perturbation show a greater change over frequency. Figure (a) shows a composite representation of the output of the standard 10 frequency system. Figure (b) shows the output of the new system, using PRN codes for excitation and demodulation.

Fig. 2. Serial imaging on a 16 electrode tank. Time difference images collected at three frequencies using the two waveforms. As the frequency increases, the contrast (impedance difference) between perturbation and background decreases.

Fig. 3 Left: Spectra obtained from the images in Figure 2. The spectra for the banana object were constructed by plotting the value of a pixel at the known position of the object at 10 different frequencies. These spectra are similar to those that have been previously obtained from the Mk2.5 system [4]. The new method produces a spectrum which is very similar to the standard method. Both EITS spectra deviate from a direct measurement at frequencies above 128kHz, for reasons explained below. Right: imaging on an 8 electrode tank. Left column: 10kHz, right column: 50kHz. Row 1: FDM, Row 2: CDM.

4. Discussion

Using CDM the frequency resolution was increased to 1023 points from the 10 points available in the system before modification. Parameters of interest such as corner frequencies can be correctly derived. Imaging could be performed twice as fast as TDM or FDM as two sources could be used.
simultaneously. Future systems might be able to use many more codes simultaneously. FDM does offer truly orthogonal signals by using exact harmonics of the data acquisition period [15]. However there are a limited number of exact harmonics for any given bandwidth, so unlike CDM, FDM could not be extended to high electrode count systems. In addition FDM is not able to measure the spectrum at each electrode simultaneously. The boundary voltages measurements obtained using the Gold codes are similar to those obtained with a 10 frequency composite waveform, as shown in Figure 1. The Gold code voltage measurements are 1 mV lower, due to the lower current per frequency component. As this is constant between the perturbation and reference frames, it is cancelled out in the subtraction process and is not apparent in the images. The Gold code boundary voltages appear to be noisier, particularly at higher frequencies. In practice these spectra would be smoothed, thus reducing the noise. The 1023 point CDM waveform and 10 point TDM waveform were formed from the same number of points and driven at the same clock frequency leading to an equal acquisition time. Therefore the CDM waveform was able to measure the same 96 combinations in the 16 channel tank with over 10x the frequency resolution in the same acquisition time. The Mk2.5 EIT system has limited performance at frequencies above 128kHz (figure 3a) due to the effect of 0.5m long unscreened cables [4]. These are likely to be the cause of the increased noise seen in the Gold code spectra. This is not seen with the 10 frequency composite waveform, due to the lower spectral resolution of this method. High frequencies are difficult to apply in EITS systems due to the effects of stray capacitance, cables and contact impedances. In this design we lessened the effect by measuring the injected current and using this signal to demodulate the recorded voltages. However this is not only an issue for CDM-EITS; the upper bandwidth requirements are exactly the same for the maximum frequency of TDM and FDM systems. The simultaneous images (figure 3b) were qualitatively similar, but the spatial resolution was constrained in our experiments with the currently available system, since only five effective channels were available, i.e., two sources and three differential measurement channels. In this experiment we chose to use separate electrodes for current injection and voltage measurement in a similar way to that used to demonstrate the FDM approach [7-8]. However a recent conference paper on electrode circuits for FDM and CDM EITS show that the same electrodes may be used [9]. Additionally when moving to multiple current sources, the sources must be well matched adding circuit complexity which may impact the advantages of CDM depending on the application.

5. Conclusion

Code division multiplexing using pseudo-random noise sequences can be used to measure high resolution impedance spectra on multiple channels simultaneously, thereby increasing the acquisition speed of electrical impedance spectroscopy measurements. However, the quality of the spectra produced is slightly degraded due to the lack of completely orthogonal code sets. This will increase as the number of simultaneous channels goes up. From a commercial perspective, the codes are cheaper and easier to generate than sinusoidal waveforms as they are binary sequences that may be generated with digital hardware, usually by modulo-addition of bits in a shift register. Therefore, the CDM method should be pursued for biomedical and industrial EITS in some applications where spectral information is required in a short time frame. This potentially powerful technique might also be applicable to rapid measurement of the transfer functions of any multichannel network.

6. References

[1] D.V. Sarwate, and M.B. Pursley, Proc. IEEE, 68, 593-619, 1980.
[2] S. Gawad et al, Rev. Sci. Instrum., 78, 2007.
[3] I. Schneider, IEEE EMBS Conference, 1996, Vol. 5, pp.1934–1935.
[4] A. McEwan et al 2006 J. Physiol. Meas. 27 S199-S210
[5] A.J. Wilson et al, Physiol. Meas., 22, 49-54, 2001.
[6] N Polydorides, WRB Lionheart, Measurement science and technology, 13,12, 1871-1883, 2002.
[7] G. Teague, PhD thesis, University of Cape Town, 2002.
[8] Y. Granot, Int J Biomed Imaging. 2007.
[9] A. McEwan, et al, BIOCAS, 2007. IEEE pp 130 – 133.