Determination of Changes in NaCl Concentration in Aqueous Solutions Using an M-Sequence Based Sensor System

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***Abstract*—In this paper measurements of changes in NaCl concentration in aqueous solutions are presented. For these measurements a simplified pseudo random binary sequence (PRBS) based sensor system, which is based on the binary noise theorem, is used. The pseudo random noise signal is represented by an M-sequence with a bandwidth of 10 GHz. The transfer functions of the sensor with different NaCl concentrations in a fixed tube of a contactless distributed probe are determined and compared to each other. The results show that there is a frequency range with a clear relation between the magnitude of the transfer function and the NaCl concentration. This demonstrates, that it is possible to measure changes in NaCl concentration of aqueous solutions with a PRBS based sensor system.**

I. Introduction

Dehydration is the result of a fluid imbalance in the human body [1]. This can be caused by drinking too little or losing too much water. Especially older people are at risk to get dehydrated because they do not feel thirsty and forget to drink, but also endurance and extreme sportsmen lose much water during their competitions. For those people as well as for people having a long term in-patient stay it is important to know about their hydration status to not jeopardize their health or degrade their performance. The symptoms of dehydration like circulatory collapse, cramp attack and coma can be very dramatic [1].

There are different types of dehydration, depending on the ratio of Na^+ ions relative to the water in the blood [2]. Fig. 1 shows these different types. Sodium (Na^+) ions are important to keep up the voltage gradient over the cell membrane and for the stimulation of nerves and muscle cells. At normal conditions there is enough water as well as enough sodium in the blood. When both is reduced compared to normal conditions there is an isotonic dehydration. If there is enough water but too little sodium a hypotonic state exists and a hypertonic dehydration if it is the other way round. This illustrates that, in terms of health monitoring, besides the measurement of body temperature, pulse and blood pressure measurements of the concentration of certain substances in the human body, like water and Na^+ ions, can be useful. The data can be evaluated and if necessary, a note can be shown on the display of a wrist watch or a smartphone or can be sent to a related person or a doctor.

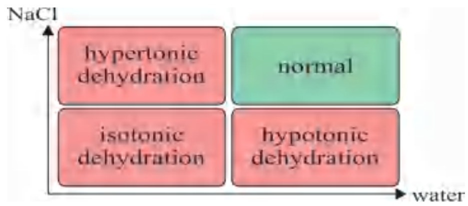

Fig. 1. Different forms of dehydration [2]

This paper is organized in seven sections, section II and III illustrate the basic background of a PRBS based sensor system and the design of the sensor system itself. Section IV describes the used sensor followed by a section describing the measurement system. Section VI summarizes the measurement results and section VII concludes this paper.

II. Random Noise Theory

To measure changes in the concentration of certain substances in liquids, it is conceivable to use a PRBS based sensor system. This concept is an alternative to frequency sweep based techniques and has the advantage of a shorter measurement time because all frequency components are generated at the same time. In [3] the concept of measuring concentrations with pseudo random binary sequences was published and successfully realized. The basic principle of a PRBS based sensor system is the random noise theory.

This theory says that under the condition of white noise excitation the cross-correlation of the input *x(t)* with the output *y(t)* of a linear time invariant (LTI) system is proportional to the system impulse response *h(t)* as shown in Fig. 2 [4]. To get the transfer function *H(f)* of the system the fast Fourier transform FFT is used. As it is not possible to generate ideal white noise, a pseudo random noise is used, which in this work is represented by a Maximum length sequence (M-Sequence). An M-Sequence is the sequence with the longest possible period that can be generated by a linear feedback shift

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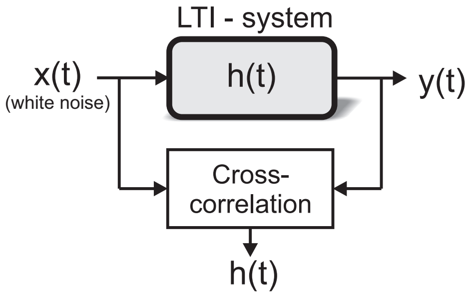

Fig. 2. Principe of pseudo random noise theory [4]

register (LFSR) of a certain length. There are two important characteristics of an M-Sequence. One is its periodicity, which makes it possible to subsample the signal. The other one is that an M-Sequence has the same magnitude for all frequency components, except the DC component [3].

III. PRBS-Based Sensor System

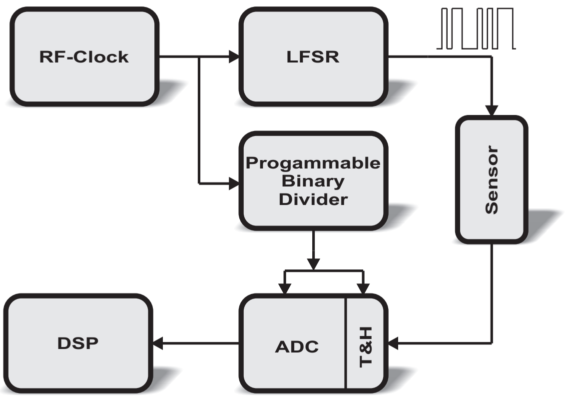

Fig. 3. Block diagram of a PRBS based sensor system [5]

A PRBS based sensor system underlies the pseudo random noise theory (section II) and contains of several components as illustrated in Fig. 3. The clock signal that drives the linear feedback shift register (LFSR) is generated by an RF signal generator. The clock frequency and length of the LFSR determine the bandwidth of the generated M-Sequence and the space between two frequency components, respectively. The sequence is sent to a sensor, which is described in the following section. The output of the sensor is tracked and hold by an track and hold amplifier (THA) and an analog to digital converter (ADC) is used to sample the signal. The signal processing, like the calculation of the cross correlation function or the Fourier transformation, is done by a digital signal processor (DSP). Due to the periodicity of the M-Sequence it is possible to use the subsampling technique [3]. This lowers the requirements to the ADC in the sensor system on cost of a higher measurement time. To realize the subsampling technique a binary divider is used to divide the clock signal.

IV. Contactless Distributed Probe

A photograph of the sensor is shown in Fig. 4. The tube contains the liquid material under test (MUT). The sensor is a contactless distributed probe that has been developed for the contactless spectroscopy of dielectric materials [6].

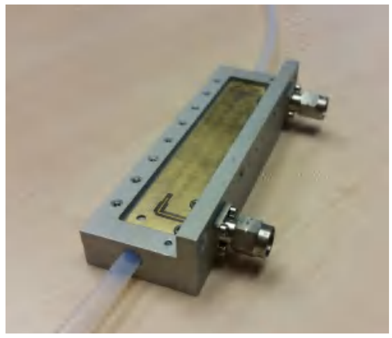

Fig. 4. Photograph of the used contactless distributed probe [6]

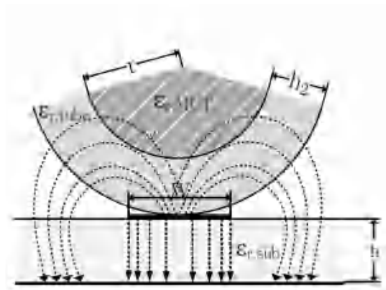

Fig. 5. Cross section of a contactless distributed probe structure [6]

Fig. 5 shows the cross section of a contactless distributed probe. The sensor is build to have a fixed tube with an inner diameter r and an outer diameter $r + h_2$ on top of a transmission line with height h on a dielectric RF substrate [6].

V. Measurement System

The general measurement system described in section IV is simplified by replacing the THA and ADC by a high speed oscilloscope to sample the signals (Fig. 6). The signal generator is used to create an RF clock signal with a power of 0 dBm and a frequency of 5 GHz. The M-Sequence is generated by an LFSR of order $N = 9$ and has a length of $L = 511$ bits (1) [7].

$$L = 2^N - 1 = 511. \qquad (1)$$

The LFSR has a parallel structure. Multiplexing the signals at proper points of the two parallel paths generates the same M-Sequence with a bandwidth BW of twice the clock frequency, resulting in $BW = 10$ GHz. The space Δf between two frequency components is 19.56 MHz (2).

$$\Delta f = \frac{BW}{2^N - 1} = \frac{10\,GHz}{2^9 - 1} = 19.56\,MHz. \qquad (2)$$

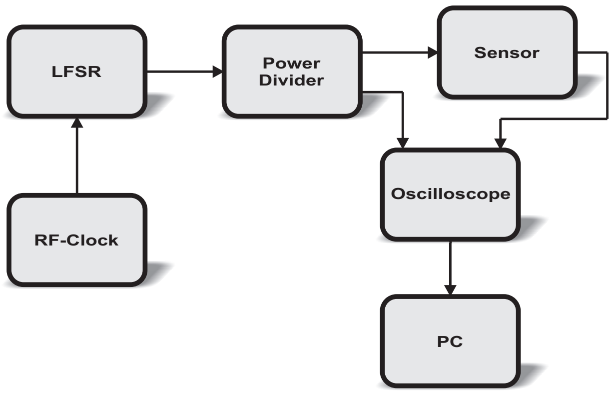

Fig. 6. Block diagram of the simplified PRBS based sensor system

A wideband power divider generates two identical M-Sequences. One sequence is directly sampled by the oscilloscope (TDS6154C digital storage oscilloscope from Tektronix). The other one is sent to the sensor and its output signal is sampled. The sampling rate for both signals is chosen to be 20 GSa/s to meet the Nyquist criterion. One measurement can capture several periods of the sequence what can be used for averaging to increase the signal to noise ratio SNR. Further averaging is achieved by repeating the measurements.

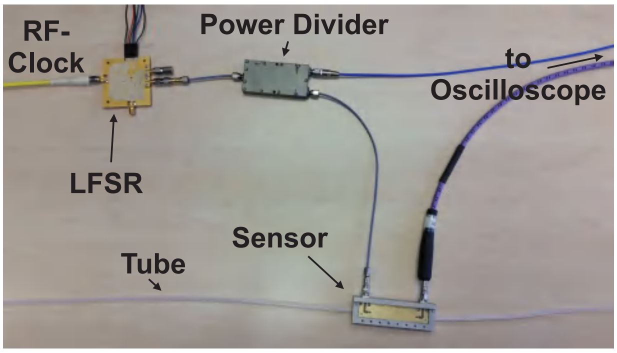

Fig. 7. Photograph of the simplified PRBS based sensor system

The averaging of the captured data is done in Matlab as well as the calculation of the cross correlation function between the generated signal and the output of the sensor to get the impulse response of the sensor with a certain aqueous solution in the tube. The Fourier transformation yields the transfer function. Fig. 7 is a photograph of the realized simplified sensor system. The power supply, the signal generator and the oscilloscope are not shown.

VI. Results

The aqueous solutions with different NaCl concentrations are made by mixing a certain amount of NaCl with distilled water to get 100 g solution. For example 1 g NaCl is mixed with 99 g of water, resulting in a concentration of 1.01 g NaCl per deciliter water. The used amounts of NaCl are 1 g, 2 g, 3 g, 5 g and 8 g resulting in concentrations of 1.01 g/dl, 2.04 g/dl, 3.09 g/dl, 5.26 g/dl and 8.70 g/dl.

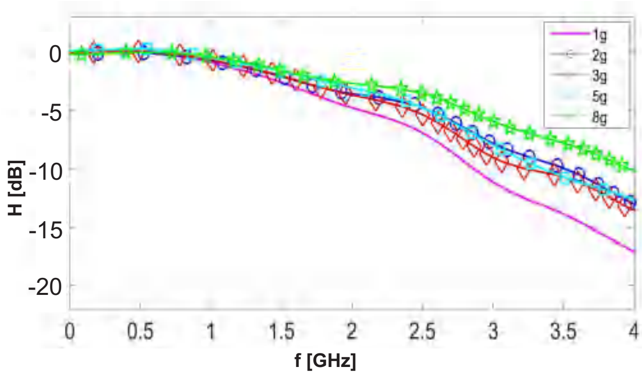

Fig. 8. Magnitude of the calculated transfer function of the sensor with different amounts of NaCl to get 100 g solution, normalized to the maximum occurring magnitude

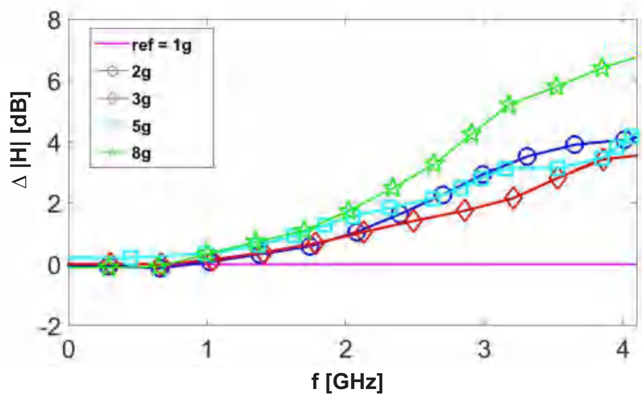

Fig. 9. Magnitude of the transfer function of the sensor with different amounts of NaCl to get 100 g solution referred to a NaCl amount of 1 g

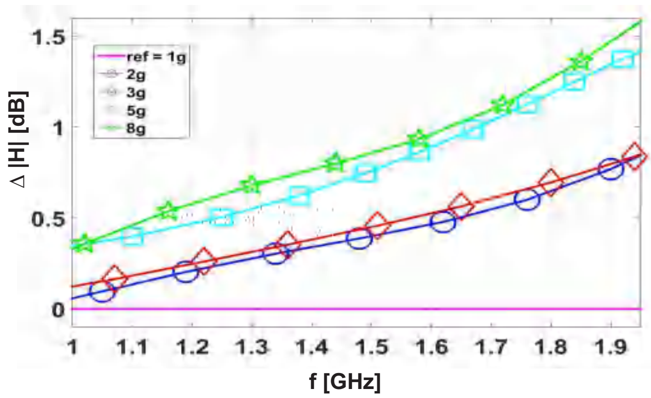

Fig. 10. Part of the magnitude of the transfer function of the sensor with different amounts of NaCl to get 100 g solution referred to a NaCl amount of 1 g

Fig. 8 shows the magnitude of calculated transfer functions of the sensor with different NaCl concentrations in the aqueous solution in the sensor tube. Basically, the magnitude of the transfer function, especially at higher frequencies increases with a higher NaCl concentration.

For an appropriate comparison of the different transfer functions they are all referred to the transfer function of the solution with a NaCl concentration of 1.01 g/dl in Fig. 9.

Fig. 10 displays the part of Fig. 9 in the frequency range of 1 to 1.9 GHz. In this area there is a clear relation between the magnitude of the transfer function and the NaCl concentration. An increased concentration comes with a higher magnitude. This shows that it is possible to use a PRBS based sensor system for the measurement of NaCl concentrations in aqueous solutions.

VII. Conclusion

In this paper the determination of changes in NaCl concentrations in aqueous solutions is presented. The measurement system is a PRBS based sensor system using a contactless distributed probe. Aqueous solutions with different NaCl concentrations are filled into the tube and the generated M-Sequence as well as the signal after the sensor are sampled by an oscilloscope followed by signal processing in Matlab. The measurements show that there is a frequency range in which a higher NaCl concentration correlates with a higher magnitude of the transfer function. Thus changes in the concentration of aqueous solutions can be determined.

Future work has to show if this sensor system is suitable for measurements of lower changes in Na^{+} concentration as occurring in the human blood. Furthermore, it has to be examined how other ions in the blood effect the sensor efficacy.

Acknowledgment

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References

[1] R. I. Popkin BM, DAnci KE, "Water, hydration and health," *Nutrition reviews*, vol. 68, no. 8, pp. 439–458, April 2010.

[2] F. Trenz, V. Kalpen, R. Weigel, and D. Kissinger, "Modeling and measurement of a tissue-equivalent liquid for noninvasive dehydration sensing in the 2.45 GHz ISM-band," in *RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO), 2015 IEEE MTT-S 2015 International Microwave Workshop Series on*, Sept 2015, pp. 32–33.

[3] G. Guarin, M. Hofmann, R. Weigel, G. Fischer, and D. Kissinger, "Determination of sugar concentration in aqueous solutions using ultra-wideband microwave impedance spectroscopy," in *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International*, June 2013, pp. 1–4.

[4] M. R. Schroeder, "Integrated impulse method measuring sound decay without using impulses," vol. 66, no. 2, 1979, pp. 497–500. [Online]. Available: http://scitation.aip.org/content/asa/journal/jasa/66/2/10.1121/1.383103

[5] J. Sachs, "M-sequence ultra-wideband-radar: State of development and applications," in *Radar Conference, 2003. Proceedings of the International*, Sept 2003, pp. 224–229.

[6] M. Hofmann, "Six-port-based microwave spectroscopy of dielectric materials for non-invasive ISM applications," Ph.D. dissertation, 2015.

[7] B. Sewiolo, B. Laemmle, and R. Weigel, "Ultra-wideband transmitters based on m-sequences for high resolution radar and sensing applications," in *6th Conference on Ph.D. Research in Microelectronics Electronics*, July 2010, pp. 1–4.