2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

A Novel Wavelength-Division Differential Detection Technique for Microwave Pulse Oximetry

Aaron B. Carman, *Graduate Student Member, IEEE,* Changzhi Li, *Senior Member, IEEE*

***Abstract*— Pulse oximetry is a common measure of patient health due to the correlation between peripheral oxygen saturation and arterial oxygen saturation. Current clinical grade pulse oximeters operate in transmittance mode and therefore must be placed on extremities such as the fingers, restricting patient mobility. Reflectance mode pulse oximeters are widely used in consumer applications, but lack the accuracy and precision required in clinical settings. In this paper, a novel wavelength-division differential detection technique is proposed which allows for a microwave-sensing based approach to reflectance mode pulse oximetry. The theory of microwave wavelength-division differential detection is given, then evaluated using a full-wave simulation of a wearable setup. The theoretical results demonstrate that wavelength-division differential detection produces a signal proportional to changes in the blood's dielectric characteristics but is dependent on the distance from sensor to target. Full-wave results confirm that wavelength-division differential detection may provide an avenue for a more accurate reflectance mode pulse oximetry measurement using microwave near-field sensing.**

I. Introduction

Pulse oximetry facilitates the measurement of peripheral oxygen saturation (SpO_2) and allows physicians to continuously monitor a patient's arterial blood oxygen saturation due to its correlation to SpO_2 [1]. Current state-of-the-art pulse oximeters operate in transmittance mode, utilizing two light-emitting diodes (LEDs) and a photodetector to measure SpO_2 at the extremities of the body [1]. Their principle of operation is that oxygenated and deoxygenated hemoglobin exhibit different optical absorption characteristics at different wavelengths, and therefore the ratio of the received signal strength is proportional to SpO_2 [2]. However, since transmittance pulse oximetry requires light to pass through body tissue, the choices of measurement site are limited to locations such as the fingertips [3]. For applications such as sleep studies where the patient can move unexpectedly, pulse oximeter finger probes are insufficient since they are not securely connected to the measurement site and can easily be removed. In addition, transmittance mode pulse oximeters are inconvenient since they are placed on the finger and do not allow for patient mobility. In order to allow for versatility in the choice of measurement location and provide a secure connection to the measurement site, reflectance pulse oximeters have gained considerable attention as a wearable substitute for traditional transmission pulse oximeters [3]-[4]. Reflectance pulse oximetry works on a similar principle as its transmittance counterpart, except the LED and photodetector are located in the same device [5]. It is popular for personal applications but is currently insufficient for use in a clinical setting due to its relative inaccuracy when compared with transmittance pulse oximetry [4]-[6].

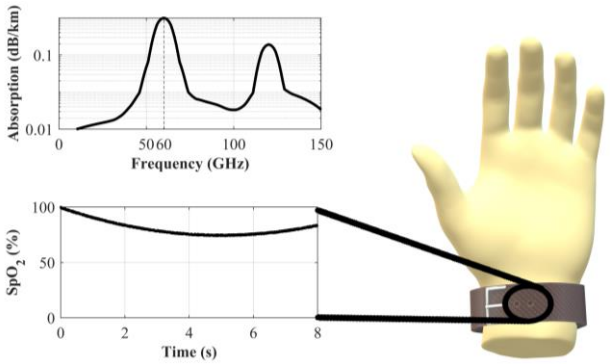

Figure 1: The oxygen absorption spectrum and the proposed reflectance-based microwave pulse oximetry system that provides real-time measurements without restricting patient mobility. The system leverages the enhanced absorption of oxygen at 60 GHz to determine SpO_2.

In this paper, a novel microwave wavelength-division differential detection technique is proposed and examined to determine its effectiveness as a substitute for traditional optical pulse oximetry systems. It is well known that attenuation per unit length increases as frequency increases [7]. The proposed system leverages the increased penetration depth of microwaves compared to visible light and enhanced oxygen absorption to obtain a more accurate measurement of SpO_2.

II. Theoretical Background

Oxygen, although normally modeled as being a lossless medium, does exhibit enhanced absorption in particular frequency bands in the microwave spectrum [8]. This absorption spectrum can be seen in Fig. 1. While meaningful absorption is likely not observable in the short distance between biological tissues, it does stand to reason that the dielectric properties of blood will change based on the presence of oxygen. This change in dielectric changes the near-field interactions between the wearable sensor and body tissues, which can thereby be detected using microwave-sensing techniques. If a simplified example is considered, the received power P_{R1} at any frequency can be modeled as:

$$P_{R1} \propto P_{T1} L_1 \sigma_1 \quad (1)$$

The authors wish to acknowledge National Science Foundation (NSF) for funding support under the Grants ECCS-2030094 and ECCS-1808613.

The authors are with the Electrical and Computer Engineering Department at Texas Tech University, Lubbock, TX, USA 79409.

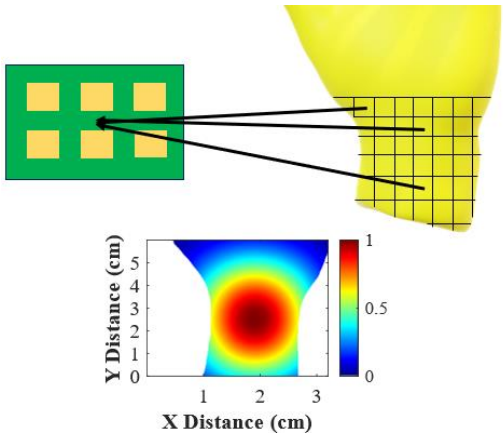

Figure 2: A graphical representation of ray-tracing. The target is parsed into cells, and each cell's response to the incident wave is used to calculate the total response.

where P_{T1} is the transmitted power, σ_1 is the scattering coefficient of the target (i.e. the ratio of backscattered power to incident power density), and L_1 is a loss factor due to attenuation through body tissue. From the equation, a change in the scattering coefficient caused by a change in blood dielectric properties will proportionally modify the received power. However, since the wave must travel through other biological tissues such as skin and fat, the attenuation due to body tissue loss will simultaneously impact received power. Using a single frequency, it is impossible to determine if a change in received power is due to a change in blood oxygen concentration or a change in attenuation of the transmitted wave (e.g. a patient with more subcutaneous fat). To circumvent this limitation, a second frequency is used which does not exhibit this change in dielectric properties dependent on oxygen concentration. Therefore, since the received power at the secondary frequency is independent of blood oxygen saturation, the loss factor due to body tissue attenuation is fixed and can be modeled as:

$$L_2 \propto \frac{P_{R2}}{P_{T2}\sigma_2} \tag{2}$$

where P_{R2} and P_{T2} are the received and transmitted power at the secondary frequency. Since L_2 and L_1 are proportional, determining L_2 simultaneously determines L_1. This effectively negates the effects of path attenuation and isolates the effect of SpO_2 on the received signal. Furthermore, since there will exist periodic dilation/constriction of blood vessels caused by the pulse, the received signal will have both a DC component and an AC component with the same frequency as the heartbeat. By performing a fast-Fourier transform (FFT) on the received signal, the effects of the AC and DC components can be isolated. Lastly, the modulation ratio R can be calculated using (3), which is proportional to SpO_2 [4].

$$R = \frac{P_{AC1}/P_{DC1}}{P_{AC2}/P_{DC2}} \tag{3}$$

To demonstrate this, a far-field ray-tracing simulation is first implemented in MATLAB to show that the received signal is proportional to a change in blood dielectric properties. However, since the proposed device would be placed directly on the measurement location, far-field models and equations will not effectively describe the near-field responses. To provide a more robust justification of the feasibility of wavelength-division differential detection, a numerical full-wave simulation is also implemented to determine if it is feasible to detect small changes in the dielectric properties of peripheral blood using a wearable device.

III. Methods

A. Selection of Frequencies

Due to the enhanced oxygen absorption window present at 60 GHz, the primary frequency is selected to be 61.2 GHz since it is expected that a change in SpO_2 will have a profound effect. In addition, 61.2 GHz lies in an Industrial, Scientific, and Medical (ISM) band, and therefore would not require any licensure for any future systems. For similar reasoning, the secondary frequency is chosen to be 24 GHz for all initial simulation purposes. If future works demonstrate that another frequency exhibits a greater/lesser change in dielectric properties of blood, then this frequency should be used for the primary/secondary frequency, respectively.

B. Far-Field Simulation Setup

To verify the working principle of wavelength-division differential detection, a far-field ray-tracing simulation is implemented using MATLAB. The simulation uses a 2D mesh simulating the wrist, a 2D antenna array function, and the radar equation to determine the backscattered power that is received from the mesh. At each cell of the mesh, the antenna array gain, incident power density, distance, and scattering coefficient are used to determine the received power. The sum of the effects of each cell determines the final response that is seen in the baseband spectrum. A graphical representation of ray-tracing is shown in Fig. 2. The target's scattering coefficient changes as a function of time for one frequency and stays static at the other to simulate the change in dielectric properties. Quadrature demodulation is used at each frequency, and the magnitude of the quadrature data is taken to determine the absolute power that is received at each frequency. Since the received signal is proportional to the square of the wavelength according to the radar range equation, the magnitude data is normalized to the square of its respective wavelength to decouple the effects of frequency from the differential signal. The results from this simulation do not consider the near-field interactions but provide a relatively easy to understand example of wavelength-division differential detection.

C. Far-Field Simulation Results

The results from the ray-tracing simulation demonstrate that wavelength-division differential detection produces a signal proportional to the change in dielectric properties of the target. Because this change occurs only at a single frequency, the differential signal changes proportional to the change in scattering coefficient. Note that, as the scattering coefficient increases, the differential signal decreases. This inverse relationship is due to the fact that, as the scattering coefficient at the primary frequency increases, the high frequency signal that is received increases as well, which decreases the magnitude of the differential signal. In this case, a decrease in oxygen concentration corresponds to an increase in scattering

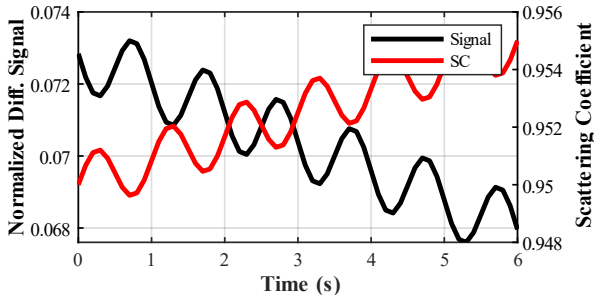

Figure 3: Differential signal vs time with a fixed distance to target. The corresponding scattering coefficient vs time is shown as well. As the scattering coefficient changes due to blood oxygen concentration and vessel width, the signal exhibits a proportional change.

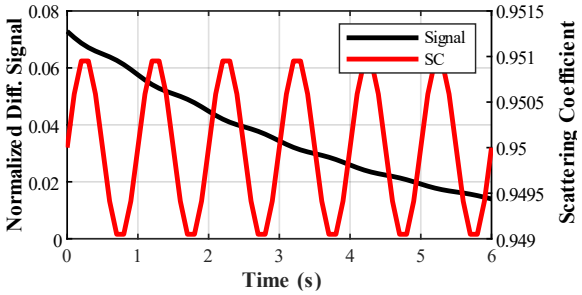

Figure 4: The effects of finite antenna directivity on wavelength-division differential detection. Although scattering coefficient varies only with the heartbeat, a change in distance greatly modifies the differential signal.

coefficient due to the decreased absorption and enhanced reflection. Therefore, the differential signal seen in Fig. 3 is directly proportional to blood oxygen concentration.

It is important to note that, even in an ideal far-field simulation, the effects of finite antenna directivity impact the received signal. This can be seen by modifying the distance from the sensor to the target as time passes. In an ideal case using an antenna with infinite directivity, the differential signal will not be dependent on distance. However, since infinite directivity is not realizable, distance impacts the received signal. To examine the effects of distance, the distance from sensor to target is swept while the scattering coefficient is kept constant. Fig. 4 shows the results of this simulation illustrating that distance does impact the received signal and must be addressed in a system where distance to target is not constant. If the effects of range are decoupled from the differential signal, then wavelength-division differential detection could potentially offer a noncontact method of measuring SpO_2 in the far-field.

IV. Results

A. Full-Wave Simulation Setup

To determine the precise effects of blood oxygen concentration and blood vessel thickness on the received signal, a simple near-field sensor is designed and simulated using COMSOL Multiphysics. The simulation utilizes the RF Module in a full-wave simulation to accurately determine the change in response due to a change in dielectric properties of the blood and blood vessel diameter. The first step in modeling the system is to design an antenna that can effectively radiate power when in contact with the skin. For simplicity, this simulation uses two microstrip patch antennas: one for

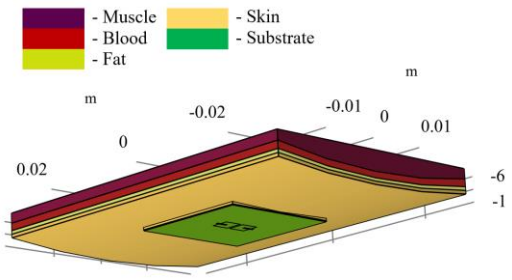

Figure 5: The COMSOL simulation setup. The antennae and substrate are in direct contact with the outermost skin layer. The incident energy travels through the skin and fat layers to reach the blood, and the received power is measured at the receiving antenna.

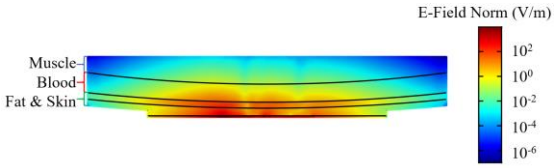

Figure 6: Electric field distribution in wrist. The electric field magnitude is still at an appreciable level within the blood vessels and is not heavily attenuated by body tissue.

transmission and one for reception. The simulation is carried out on 0.127 mm RT/Duroid 5880 high frequency laminate with a dielectric constant of 2.20 and a loss tangent of 0.0009 [9]. To model body tissue, the simulation platform requires the relative permeability, relative permittivity, and electric conductivity at the frequency of interest. This information is obtained using a parametric model developed by C. Gabriel and provides an accurate baseline for the dielectric properties of body tissues [10]. Unfortunately, no research has been published that conclusively determines the effect of blood oxygen concentration on the blood's dielectric properties, especially at the frequencies of interest. To circumvent this limitation, a range of values are simulated to prove that a change in dielectric properties can in fact be detected by a wearable device. A second sweep is used to vary blood vessel thickness.

The simulation setup utilizes a 2cm x 2cm substrate in direct contact with a 4cm x 6cm cylindrical section of wrist with layers of various depths. The wrist was chosen as the simulated measurement location due to its relatively small distance from epidermis to blood vessels and its potential usage in a wearable configuration. A summary of the dimensions of the simulated layers, as well as their dielectric properties is provided in Table I, and a graphical representation is offered in Fig. 5. Since the simulation setup uses a truncated cylinder, the thickness of the muscle layer is nonuniform. It is worthy of mention that, since the radiating antenna is directly in contact with the outermost layer of skin, traditional design equations for patch antennas are insufficient since the medium in which the antenna is radiating is electrically dissimilar to air. Modifications are necessary in order to create a match between the antenna and the feedline and ensure sufficient energy is transferred into the wrist. However, since the antenna design is not a direct concern of this study, a simple parametric sweep is used to find antenna dimensions with an acceptable return loss and radiation pattern. The final simulated antenna dimensions were 3mm x 3mm. Lastly, since the target of interest is extremely close to

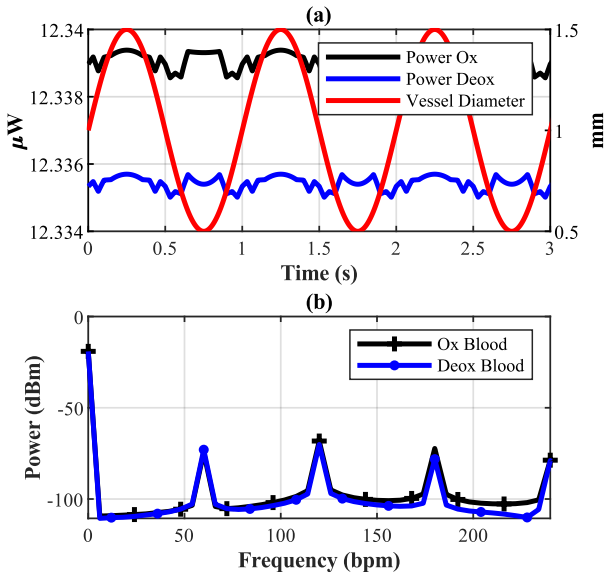

Figure 7: (a) The periodic nature of the received signal. Although this signal is not sinusoidal, the frequency domain results in (b) demonstrate that there exists a clear AC component that can be detected.

the antennae, near-field effects are present in the system. As such, the spacing between the two antennae is swept in order to find the dimensions that provide the greatest change in received power when the dielectric properties of the blood are modified. This optimal spacing was found to be 0.5 mm.

B. Full-Wave Simulation Results

The results from the full-wave simulation reveal that there is an appreciable EM interaction within the blood vessels. Fig. 6 shows that at 61.2 GHz, a considerable amount of energy reaches the blood vessels in the wrist. Using the received power results from the full-wave simulation, it is possible to determine the combined effects of SpO_2 and heartrate on the received signal power. Two instances are simulated. In the first, it is assumed that SpO_2 is at a maximum, while for the second, there is a 10% increase in blood dielectric constant and conductivity to simulate deoxygenated blood. Both the time and frequency domain results are shown in Fig. 7. In the time-domain, the periodicity of the received signal is quite evident, although the received signal power does not have a direct linear relation to the vessel diameter. When examining the signal in the frequency domain, both the fundamental heartbeat frequency is seen at 60 BPM, as well as harmonics that are present at multiples of the fundamental. Finally, since the ultimate goal is determining the modulation ratio, the power at the heartbeat frequency is compared to the DC power for both instances. By performing this calculation, it is determined that a 10% increase in blood dielectric properties induces a 37% increase in the ratio of heartbeat power to DC power. Using a calibration curve, the SpO_2 of the wearer can be determined.

V. Conclusion

In this paper, a novel wavelength-division differential detection technique is proposed and evaluated as a substitute for optical reflectance mode pulse oximeters. Current state-of-the-art pulse oximeters either limit patient mobility due to the restricted choices of measurement location, or do not provide the accuracy required for use at the clinical level. A microwave-sensing based approach could potentially solve these issues by leveraging the increased penetration of EM waves in the microwave spectrum compared to the optical spectrum. The proposed system would provide a more accurate reflectance mode pulse oximetry method that can be used in a variety of settings ranging from personal to clinical use. Utilizing two separate frequencies allows for the measurement to be decoupled from a change in path attenuation such as an increase in subcutaneous fat or skin thickness. Results from the far-field simulation show that wavelength-division differential detection can be used to detect a change in scattering coefficient. Near-field full-wave results show that a change in blood dielectric properties can be detected using a wearable device. The combined results from this study have shown that, so long as there exists a change in dielectric properties, it is possible to detect changes in blood oxygen concentration. This technique could also be leveraged to provide noninvasive and convenient measurements of important body fluid metrics such as blood glucose for diabetic patients. To verify the practical effectiveness of this method, future work should focus on conclusively verifying the effect of oxygen concentration on blood dielectric properties and testing the proposed technique in a practical system. Synthetic blood samples could be used to provide a controlled testing environment prior to clinical deployment to conclusively verify the effectiveness of wavelength-division differential detection.

References

[1] R. Ortega, C. Hansen, K. Elterman and A. Woo, "Pulse Oximetry", New England Journal of Medicine, vol. 364, no. 16, p. e33, 2011.

[2] A. Jubran, Applied Physiology in Intensive Care Medicine, 1st ed. Berlin: Springer, 2012, pp. 51-54.

[3] J. Wan, Y. Zou, Y. Li and J. Wang, "Reflective type blood oxygen saturation detection system based on MAX30100," 2017 International Conference on Security, Pattern Analysis, and Cybernetics (SPAC), Shenzhen, 2017, pp. 615-619.

[4] H. Lee, H. Ko and J. Lee, "Reflectance pulse oximetry: Practical issues and limitations", *ICT Express*, vol. 2, no. 4, pp. 195-198, 2016.

[5] K. A. et al., "Reflectance Pulse Oximetry for Blood Oxygen Saturation Measurement from Diverse Locations-A Preliminary Analysis," 2018 *IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, Rome, 2018, pp. 1-6.

[6] J. Collins, A. Rudenski, J. Gibson, L. Howard and R. O'Driscoll, "Relating oxygen partial pressure, saturation and content: the haemoglobin–oxygen dissociation curve", *Breathe*, vol. 11, no. 3, pp. 194-201, 2015.

[7] U. Inan and A. Inan, Engineering Electromagnetics, 1st ed. Menlo Park, Calif.: Addison-Wesley, 1999, pp. 672.

[8] M. Miacci and C. Angelis, "Ground-Based Microwave Radiometer Calibration: an Overview", *Journal of Aerospace Technology and Management*, vol. 10, 2018.

[9] "RT/Duroid 5870/5880 High Frequency Laminates", Rogers Corportation, 2021.

[10] S. Gabriel, R. Lau and C. Gabriel, "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues", *Physics in Medicine and Biology*, vol. 41, no. 11, pp. 2271-2293, 1996.