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Considerations for Integration of a Physiological Radar Monitoring System with Gold Standard Clinical Sleep Monitoring Systems

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***Abstract*—A design for a physiological radar monitoring system (PRMS) that can be integrated with clinical sleep monitoring systems is presented. The PRMS uses two radar systems at 2.45GHz and 24 GHz to achieve both high sensitivity and high resolution. The system can acquire data, perform digital processing and output appropriate conventional analog outputs with a latency of 130 ms, which can be recorded and displayed by a gold standard sleep monitoring system, along with other standard sensor measurements.**

I. Introduction

Sleep is widely understood to play a key role in physical and mental health. The quality and quantity of sleep that an individual gets can have a significant impact on learning and memory, metabolism and weight, safety, mood, cardiovascular health, disease and immune system function. Research indicates that 40 million Americans suffer from insomnia and chronic sleep disorders [1, 2]. Obstructive Sleep Apnea (OSA) is the most common sleep disorder with an estimated 12 million Americans suffering from it. Patients with OSA usually snore, gasp and choke at night, and awaken unrefreshed. They also suffer from excessive daytime sleepiness and cognitive dysfunction.

If OSA is suspected, confirmation of the diagnosis is accomplished with a sleep study or polysomnogram (PSG). An overnight PSG in an accredited sleep center is the gold standard. This test involves the measurement of a number of physiological parameters including: brain activity (EEG), eye movements (EOG), muscle activity (EMG), cardiac function (ECG), oxygen-hemoglobin saturation, airflow at the nose and mouth, and respiratory effort [3]. These measurements are made through a variety of sensors that come in contact with the patient's skin. These sensors and their associated wiring inevitably impose some discomfort and movement restrictions on the patient, which can adversely affect the quality of the patient's sleep. Sleeping in a foreign environment under the watchful eyes of a technologist also negatively impacts sleep quality.

Non-contact physiological radar monitoring systems (PRMS), based primarily on Doppler radar can be used to produce unique measures of pulmonary, cardiac, and patient movement that potentially can be utilized in the sleep center to augment Type 1 monitoring devices (Fig.1). A PRMS also has the potential to serve as a simple and unique portable monitoring system (PMS). Because it requires no patient contact it may be more bulletproof than current PMS (Type 3 and Type 4), that require contact sensors. This simplicity may also make it the PMS of choice in rural areas such as the islands of the Pacific Basin.

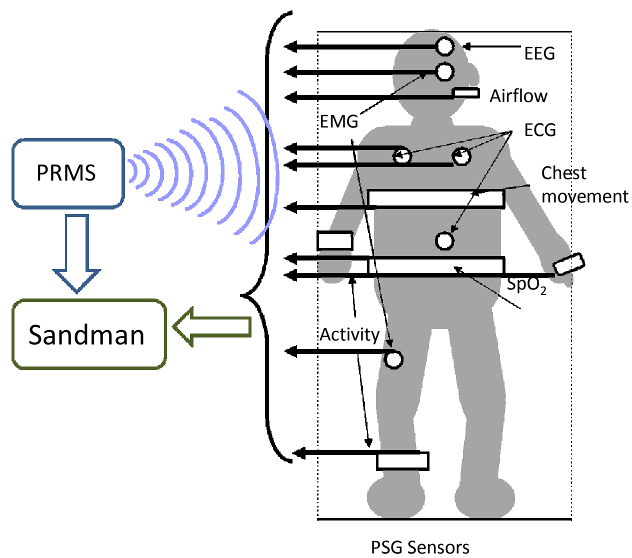

Figure 1. Type 1 monitoring device commonly seen in sleep centers.

Various Doppler radar techniques have been applied for physiological monitoring and performance trade-offs have been associated with different systems, Potentially, a PRMS incorporating multiple radar configurations could offer improved performance over any single system. A dual frequency system is investigated here to optimize sensitivity in

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the measurement of displacement and target size. For practical applications in sleep centers, the PRMS investigated here is also designed to produce output waveforms and data in a format that can be read in real time by an existing sleep assessment system. Challenges include the design of robust data outputs signals, latency small enough for real-time readings, and a practical compact form factor. The system will be used in clinical studies to assess the potential for PRMS use as a compliment to existing contact sensor PSG systems, or as an easily applied stand-alone screening system.

II. Doppler radar for sleep monitoring

A. Doppler Radar

A Doppler radar motion sensing transceiver transmits radio wave signals and receives motion-modulated signals reflected from a target. The radio waves reflected from a moving surface undergo a frequency shift proportional to the surface velocity. A quadrature receiver (in-phase and 90° out-of-phase signals) is used to enable detection of the amplitude and direction of motion. If the surface is moving periodically, such as the chest of person breathing, this can be characterized as a phase shift proportional to the surface displacement. If the movement is small compared to the wavelength, a circuit that couples both the transmitted and reflected waves to a mixer can produce an output signal with a low-frequency component that is directly proportional to the movement [4].

Since Doppler radar detects all motion in the radar field of view, one of the main challenges is the separation of fidgeting motion from cardiac and pulmonary motion. An additional challenge is the separation of respiratory and heart signals when breathing is irregular. While these signals may originate from the same spatial coordinates, and have overlapping instantaneous spectra, they each have unique properties that provide a basis for signal separation.

B. Clinical Sleep Monitoring

The output of the sensors used during a PSG is connected to an amplifier for signal conditioning and subsequently to a data acquisition system and monitoring software. The system used for this case study is Sandman Elite® sleep diagnostic software from EMBLA® [5]. The system consists of a digital amplifier with an input box for sensor inputs. The signals are recorded and displayed on the software, which can then be scored by a PSG technologist.

III. Design considerations

There are many design factors that need to be considered when designing a PRMS that could be integrated with a clinical sleep study. While some factors pertain to the physical design of the PRMS itself, others need to consider the interface between PRMS and Sandman.

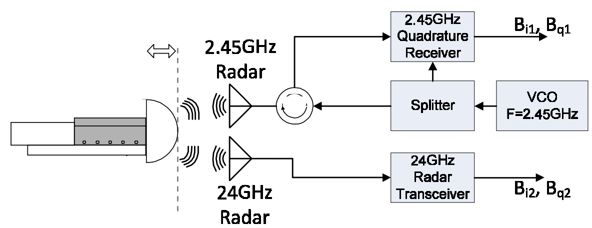
A. Size and orientation

The overnight sleep study will take place in a certified sleep study center at Queen's Medical Center in Hawaii. The size of the room is approximately 5 by 6 m^2.The PRMS has to be placed in the room without obstructing the movement of the subject and hence should be compact. Careful placement of radar is essential as Doppler radar would give most sensitivity for motion that is orthogonal to the plane of the antenna. A sturdy physical structure would be needed to hold the radar and associated equipment in place.

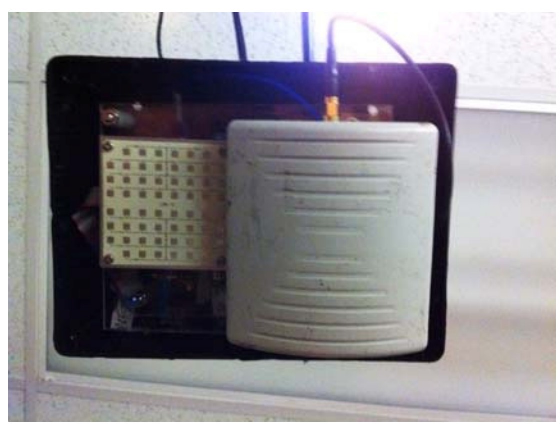
B. Frequency

In addition to monitoring respiration and heart activity, clinical sleep monitoring also monitors the activity or wakefulness of the patient. The nature and magnitude of physiological motion and during any activity (such as turning) is quite different. The use of one radar system for detecting every motion may not be sufficient. Moreover, for a Doppler radar, motion sensitivity is a function of the frequency of operation. The use of higher frequency (smaller wavelength) gives finer resolution. The choice of frequency also affects the Radar cross section of the target. It was shown in [6] that detection of physiological motion using 2.4 GHz provided a higher sensitivity to orientation whereas using 5.8 GHz provided higher displacement resolution. The use of radar systems with different frequencies allows more flexibility in determining and verifying the appropriate signal content.

However, the use of a multiple Doppler radar system should not come at the cost of a significant increase in size. As such, for this PRMS, two quadrature Doppler radar systems, one at 2.45 GHz and the other at 24 GHz were used in a single integrated package of 20cm*15cm*8cm, shown in Fig. 3.



Block diagram of two quadrature Doppler radar systems.



Physiological Radar Monitoring System (PRMS)

C. Signal Processing

The results from a PSG study are observed and marked by a certified polysomnographic technologist to indicate the periods of Rapid Eye Movement (REM) sleep, apnea and activity. Most of the sensors in sleep study are associated with one signal. The output of a quadrature Doppler radar include in-phase (I) and quadrature (Q) signals that need to be either selected carefully or combined to yield information. With two frequency radar systems, there will be four baseband outputs that need to be digitally processed to produce robust meaningful traces such as sedentary chest displacement, respiration rate, and periods of activity.

There are different ways of combining I/Q data such as eigen demodulation [7], arc tangent demodulation [8], and complex demodulation [9]. Activity monitoring for small animals using multi-transceiver Doppler radar has been shown in [10]. A similar signal combining algorithm could be used to detect the different levels of activity for human subjects as well.

D. Integration with Sandman

From the description of the Sandman system in II (B), it can be seen that the most conventional way to integrate the PRMS with the Sandman system is to connect the processed outputs as analog signals into the standard Sandman inputs. This adds complexity, as the radar outputs must go first through an analog to digital (A/D) conversion, then through a processing stage, and the resulting outputs must then be converted from digital to analog (D/A) signals the be read by Sandman. The foremost problem introduced is that of real time implementation and latency. The signal processing and D/A conversion would introduce a time offset between the sensor data from Sandman and the PRMS. Another consideration is the impedance match between the two systems. Most of the sensors used with Sandman are connected to the isolated head box shown in Fig. 1. Sandman also provides another box for connecting unconventional signals or signals that contain dc. After initial experimenting, it was found that dc box provided a more stable interface between the PRMS and Sandman.

IV. MEASUREMENTS

To evaluate the flexibility and performance of dual Doppler radar system, preliminary motion detection measurement was made on a programmable linear mover. The 2.45GHz Doppler radar and 24GHz Doppler radar were placed together for comparison, aiming at a target on the line of sight. The 2.45 GHz radar was assembled from carefully chosen coaxial parts and a commercial off the shelf 24 GHz module K-MC1 from RF beam was used.

The target was designed to move back and forth in a small periodic motion within 8mm range, emulating the surface movement of a human body. The four radar outputs were pre-processed by Stanford research low noise amplifiers (SR-560). The gain for 24GHz and 2.45GHz radar outputs were set at 200 each. Both pairs of signals were ac-coupled and went through a low pass filter with the corner frequency at 30Hz. Shown in Fig. 4 are the I/Q plots on the complex plane of signals at two frequencies. Fig. 4(a) shows the I/Q plot of the 24GHz radar, in which all the sample points form a full circle, while the 2.45GHz radar output only forms a portion of a circle. This is due to the fact that the arc length is inversely proportional to the radar wavelength. With higher carrier frequency, longer arcs can be obtained.

As seen in Fig. 4(a), the multiple arcs formed by the 24-GHz motion-modulated signal overlap to create a complete circle. These arcs can be measured using an arctangent demodulation algorithm and the 24GHz radar thus provides a higher displacement resolution over the 2.45 GHz radar. However, due to dc drift of the I/Q channel signals, the circular traces inevitably overlap with one another, creating complexity for demodulation. In Fig. 4(b) with the 2.45GHz radar, a simple arc is formed due to the periodic motion. Analysis of the IQ signals in this case can be performed using a simple linear demodulation technique, and the measurement has higher sensitivity to the orientation of the body in practical subject measurements [6].

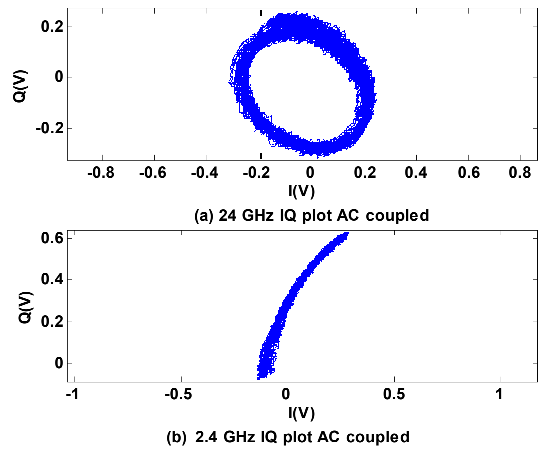


Figure 2. IQ channel signals plot on complex plane. (a) the arc of 24GHz radar is consisting 460.8° of a circle. (b) the arc for 2.45GHz radar is consisting 47.06° of a circle.

To verify the efficiency of integration, an analog signal of 1 Hz, and 200 mV was generated from a signal generator to feed to the conversion stage. It was first converted from analog to digital using an NI-DAQ, processed in Matlab and then sent out from the same DAQ as analog signal. The original and converted signals were aligned together, shown in Fig.5. The solid line is the original signal from signal generator and green line is the analog output of the DAQ recorded by another channel of the DAQ. It shows an estimation of system latency. The delay between input and output is 130 ms.

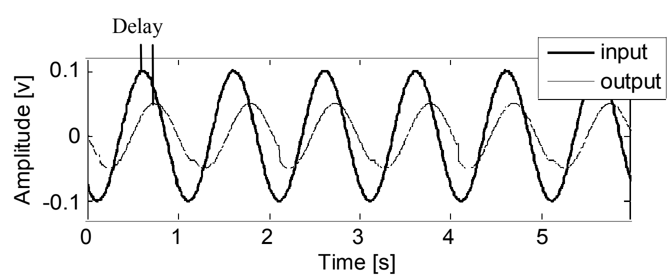


Figure 3. Comparison of the orginal and converted analog signal.

V. Conclusion

The measurement results indicate the successful operation of a compact dual frequency radar with simultaneous digital to analog conversion. The latency measurement was performed for cancellation of dc signal and is expected to be more for complex operations. As the measurements for sleep study are of 8 hour duration, any latency less than a 500 ms could be considered acceptable. This allows individual events to be viewed simultaneously on a single trace, at a useful time scale for assessing respiration, heart, and body activity. The next step is to assess the performance of the PRMS when integrated with the Sandman system, for planned overnight PSG tests to be performed on a selection actual sleep patients..

In this research, a system integration of physiological radar monitoring system and clinical sleep monitoring system was proposed. Two microwave Doppler radars working at 2.45GHz and 24GHz were utilized to perform non-contact physiological monitoring, aiming at a complimentary measure for sleep study. The system design was robust, offering flexible measurement with a good sensitivity and resolution. The measurements were demonstrated with very small latency, making the technique acceptable for use in near real-time sleep studies.

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