Continuous Wave Doppler Radar Occupant Count Estimation using Spectral Features

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Abstract—**Building occupancy estimation is important for efficient building management, energy consumption control, and occupant safety and well-being. Radar-based occupancy sensors have a potential to provide an effective tool for building occupancy monitoring, without privacy concerns inherent to camera use. In this paper we propose an occupant count approach based on spectral features of continuous wave Doppler radar signals in the presence of multiple occupants. The proposed approach is tested using envelope-transient simulation for the case of ten occupants, and it is demonstrated that spectral features change proportionally to the number of occupants.**

Keywords—Building occupancy, vital-sign sensing, envelope transient

I. INTRODUCTION

Building occupancy estimation is important for efficient management of real-estate utilization, heating, ventilation and air-conditioning (HVAC) control, building security, and occupant health and well-being [1]. Most commonly used occupant count sensors are based on measuring carbon-dioxide (CO2) concentration, assuming that CO2 increases linearly with the number of occupants [2]. However, changes in CO2 levels with occupancy have a significant time lag, and are highly dependent on the level of ventilation in the built environment. To address these limitations, other occupant count technologies have been proposed, including video-based methods [3], count of mobile device connections [4], and doorway crossings using infrared systems (IR) [4]. While video-based methods provide a fast response and high accuracy, they introduce privacy concerns [5]. On the other hand, the count of mobile device connections provides only a very rough estimate of building occupants, and IR infrared systems will not detect occupants that are stationary. Ultrasonic sensors are prone to false positives due to sound interference, air currents, and building vibrations for example due to HVAC system cycling.

Microwave radar-based occupancy sensing is an emerging technology that overcomes limitations of CO2 response time and video camera privacy concerns [6]-[8]. It was demonstrated effective for occupant count using time-frequency analysis with wavelet transform [9]; however, wavelet transform is complex to set-up and computationally intensive. This paper examines the spectral properties of received radar signals that could potentially provide a simpler method for estimating occupancy. It relies on the spectral content of the received signal, which includes modulation from all occupants in the room that are in the sensor field of view. It addresses the mixing of signals from multiple occupants at the receiver, and thus it is desirable to have all occupants covered within the same antenna beam, which is easier to achieve at lower frequencies. The spectral properties of received radar signals will be modeled using envelope-transient simulations [10]. The results indicate clear spectral changes in the presence of increasing number of occupants. The principle is illustrated through its application to a system operating at 2.4 GHz. This frequency is well-suited for in-door applications. It enables lower power consumption, a greater range, and better penetration through obstacles. It is also cost-effective and has the advantage of being an unlicensed frequency. Note that the method is not susceptible to interference from Wi-Fi and other sources within the same ISM band due to the coherent signal detection, i.e., only received signals that are coherent with the transmitted signal will produce a meaningful output in a very narrow bandwidth, and all other received signals will be filtered out. Reflections from stationary objects such as walls and furniture will result in a DC output which is also filtered out. We should also emphasize that the methodology can be extended to radar-based systems operating at higher frequencies.

II. ANALYSIS METHOD

This research considers a scenario where multiple subjects are in the field of view of a single-channel physiological Doppler radar system, as illustrated in Fig. 1. Radar block diagram (Fig. 1 (a)) includes a continuous wave (CW) signal source that provides a transmitted signal and a local oscillator (LO) for the receiver. The received signal is mixed with the LO using a quadratic non-linear element. In the case of a single stationary occupant within the radar field of view, the radar output will be approximately proportional to the occupant breathing signal. However, due to frequency mixer non-linearity, received signals from multiple occupants will

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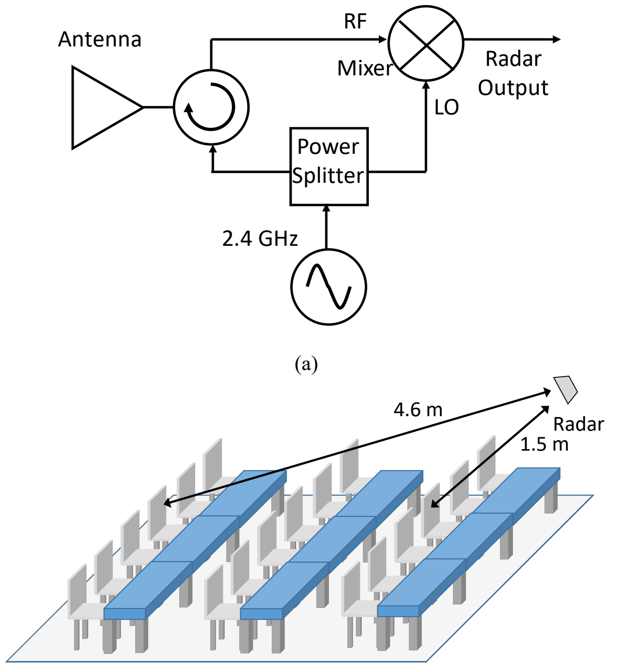

Fig. 1. Block diagram of a single channel continuous wave Doppler system (a) and illustration of a multiple occupant test scenario (b).

produce intermodulation products, which results in distinct spectral features that change with the number of occupants.

For the envelope-domain analysis, we will consider N different subjects. The antenna transmits the sinusoidal signal $V_t \cos(\omega_o t)$. Each subject (n = 1 to N) is at a distance d_n from the transmitter. The chest movement gives rise to a small increment of this distance $\Delta d_n(t)$. In this preliminary work, we will use a simple propagation model, based on the radar equation [11], which disregards multipath interference. The voltage amplitude of the reflected signals is given by:

$$V_n = \sqrt{\frac{P_t G_t}{(4\pi)^2 d_n^4} \sigma A_e 8 R_r} \qquad (1)$$

where P_t is the transmitted power, G_t is the antenna gain, A_e is the antenna effective aperture, R_r is the radiation resistance and σ is the radar section of the subjects, assumed equal. Due to the small magnitude of $\Delta d_n(t)$ in comparison with d_n, this increment has been neglected in the estimation of V_n. However, its effect is considered in the phase of the reflected signals, which is given by:

$$\phi_n(t) = -2\beta\left[d_n + \Delta d_n(t)\right] \qquad (2)$$

where $\beta = 2\pi / \lambda$. We will assume sinusoidal variations of $\Delta d_n(t)$, with an excursion ΔD_n, which, as in [9], will be randomized between 0.01 m and 0.03 m. Thus, we will have:

$$\begin{aligned}\phi_n(t) &= -2\beta\left[d_n + \Delta D_n \cos(\omega_n t)\right] \\ &= -2\beta\left[d_n + \Delta D_n \cos(2\pi f_n t)\right]\end{aligned} \qquad (3)$$

The frequencies f_n will also be randomized, between 0.2 Hz and 0.3 Hz [9].

We consider a quadratic model for the frequency mixer. Its inputs are the local oscillator signal $V_o \cos(\omega_o t)$ and:

$$\sum_{n=1}^{N} V_n \cos\left[\omega_o t + \phi_n(t)\right] \qquad (4)$$

The above summation can be written as:

$$\begin{aligned}\sum_{n=1}^{N} V_n \cos\left[\omega_o t + \phi_n(t)\right] &= \cos(\omega_o t)\sum_{n=1}^{N} V_n \cos\left[\phi_n(t)\right] \\ &-\sin(\omega_o t)\sum_{n=1}^{N} V_n \sin\left[\phi_n(t)\right]\end{aligned} \qquad (5)$$

Adding the local oscillator signal, we will define:

$$\begin{aligned}A &= V_o + \sum_{n=1}^{N} V_n \cos\left[\phi_n(t)\right] \\ B &= \sum_{n=1}^{N} V_n \sin\left[\phi_n(t)\right]\end{aligned} \qquad (6)$$

For a mixer with the quadratic coefficient b, the output signal $v_m(t)$ will be:

$$\begin{aligned}v_m(t) &= b\frac{A^2 + B^2}{2} + b\frac{A^2 - B^2}{2}\cos(2\omega_o t) - bAB\sin(2\omega_o t) \\ &= V_{m,o}(t) + V_{m,2}(t)e^{j2\omega_o t} + V_{m,-2}(t)e^{-j2\omega_o t}\end{aligned}$$

(7)

where an envelope-domain representation has been introduced, having the slowly varying voltage envelopes:

$$\begin{aligned}V_{m,o}(t) &= b\frac{A^2 + B^2}{2} \\ V_{m,2}(t) &= b\frac{1}{2}\left(\frac{A^2 - B^2}{2} + jAB\right) \\ V_{m,-2}(t) &= b\frac{1}{2}\left(\frac{A^2 - B^2}{2} - jAB\right)\end{aligned} \qquad (8)$$

We are interested in the baseband component, which can be explicitly written as:

$$V_{m,o}(t) = \frac{1}{2}b\left[\begin{aligned}&\left(V_o + \sum_{n=1}^{N} V_n \cos\left(-2\beta\left[d_n + \Delta D_n \cos(\omega_n t)\right]\right)\right)^2 \\ &+\left(\sum_{n=1}^{N} V_n \sin\left(-2\beta\left[d_n + \Delta D_n \cos(\omega_n t)\right]\right)\right)^2\end{aligned}\right] \qquad (9)$$

The Fourier series of this component involves the Bessel functions of the first kind. We can expect the number of spectral lines to increase with the number of subjects.

III. Application Example

As in the work [9], we have considered $n = 1$ to $n = 10$ subjects. The distances to the transmitter range between 1.5 m and 4.6 m, as illustrated in Fig. 1(b). The oscillator frequency is $f_o = 2.4$ GHz, and its output power is P_{osc} = 7 dBm, the antenna gain is $G_t = 8$ dB and the mixer (Mixer:

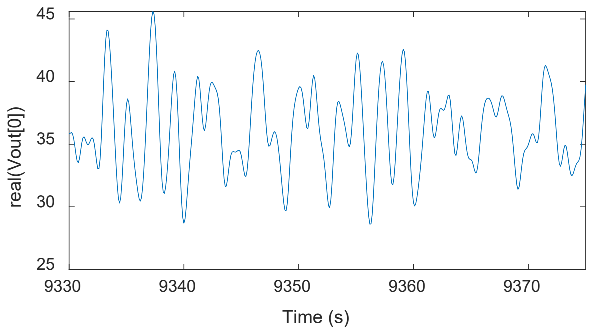

Fig. 2. Zoomed view of the baseband component of the output voltage.

Mini-circuits ZFM-4212+) has a loss $L = 5.8$ dB. The output signal passes through a lowpass filter and a high gain baseband amplifier. Using these specifications, we have performed an envelope-transient simulation, representing the system signals as:

$$x(t) = \sum_{m} X_m(t) e^{jm\omega_o t}$$

where the only fundamental frequency is the oscillator frequency ω_o. The coefficients $X_m(t)$ exhibit a time variation determined by the vital-sign frequencies f_n and their intermodulation components. We have carried out the analysis during a time interval of 5000 s, with a time step of $\Delta t = 0.1$ s. We have initially considered $n = 10$ subjects, which takes 9.28 s in an ordinary computer. The output signal is well sampled, as verified with the zoomed view of $V_{m,o}(t)$, shown in Fig. 2.

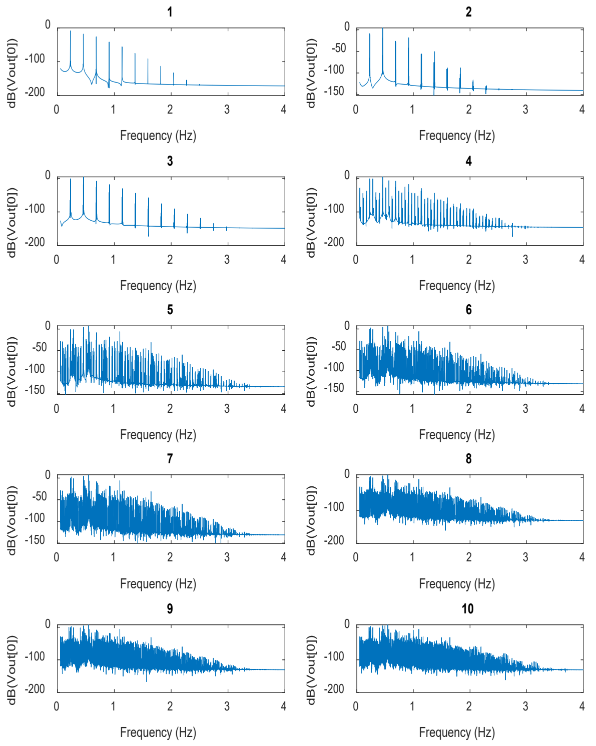

Fig. 3. Evolution of the spectrum with the number of subjects, going from $n = 1$ to $N = 10$.

After amplification and suppression of the DC signal, the spectrum evolves as shown in Fig. 3, where n has increased from 1 to 10. With a larger number of subjects, the spectrum becomes denser, due to the intermodulation effects resulting from (9). The results are in good agreement with the experimental measurements of [9]. In Fig. 4 we have represented the number of spectrum peaks above −100 dBV versus the number n of occupants. Note that, as already stated, the subjects are at randomized distances from the transmitter. We have also integrated the voltage amplitude spectrum obtained for each number of occupants n. Its variation with n is shown in Fig. 5. Thus, envelope-transient simulations enable the estimation of building occupancy in a simple and efficient manner.

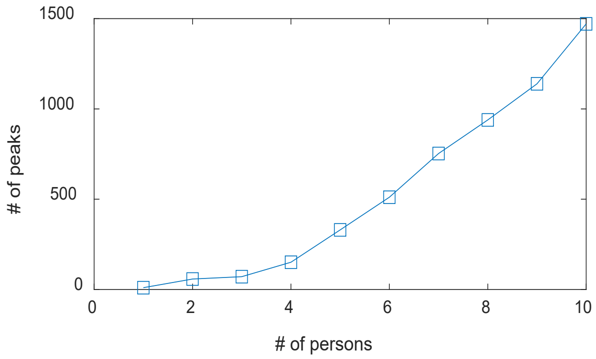

Fig. 4. Evolution of the number of spectrum peaks with the number of subjects n.

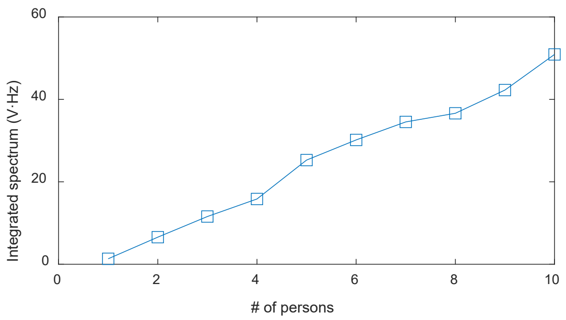

Fig. 5. Integral of the spectrum versus the number of subjects n.

Note that the method based on envelope transient has a general applicability and can account for varying breathing rates and background movements. Here we have assumed constant vital-sign frequencies f_n to enable comparison with [9] and to emphasize the intermodulation effects.

IV. Conclusion

Continuous wave Doppler radar is an emerging technology for building occupancy monitoring that preserves privacy. Due to non-linear properties of radar receiver, signals from multiple occupants produce intermodulation products resulting in distinct spectral features that can be used to estimate a number of occupants. This work presented a theoretical background and simulation results for ten occupants using envelope-transient method, demonstrating the potential of using spectral features for occupancy estimation.

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