Granular Mobility-Factor Analysis Framework for enriching Occupancy Sensing with Doppler Radar

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Article Info	ABSTRACT
	With the growing need for adoption of smarter resource control system in existing infrastructure, the proliferation of occupancy sensing is slowly increasing its pace. After reviewing an existing system, we find that utilization of Doppler radar is less progressive in enhancing the accuracy of occupancy sensing operation. Therefore, we introduce a novel analytical model that is meant for incorporating granularity in tracing the psychological periodic characteristic of an object by emphasizing on the mobility and uncertainty movement of an object in the monitoring area. Hence, the model is more emphasized on identifying the rate of change in any periodic physiological characteristic of an object with the aid of mathematical modelling. At the same time, the model extracts certain traits of frequency shift and directionality for better tracking of the unidentified object behavior where its applicabilibility can be generalized in majority of the fields related to object detection.

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1. INTRODUCTION

At present, in majority of the developing countries is known for its trendy, massive, and smart commercial complex powered by large number of resources in order to make it ready for production floor. One easiest means of automatically controlling, monitoring, and managing the existing resources in commercial building is by deploying occupancy sensor [1]. At present, there are various forms of occupancy sensor e.g. electromagnetic signal, image sensor, carbon-dioxide sensor, ultrasonic sensor, power meters, etc [2], [3]. The methods employed by such sensors are both terminal and non-terminal wise [4]. The base function of occupancy sensor is to involuntarily control the switching system of the resources in case of unoccupied spaces. At present, there are two dominant techniques for sensing the level of occupancy i.e. by using infrared sensor and ultrasonic sensor [5]. Basically, usage of infrared sensors resides in identifying any form of change in temperature of the monitored spaces whereas the utilization of ultrasonic sensor is found more on acoustics with high frequency in order to perform motion detection [6], [7]. There is also certain hybrid level of sensors that uses both of these techniques for enhancing the detection rate with better accuracy. However, such sensors are quite expensive in nature. There are certain set of research work which has highlighted that positioning of occupancy sensor is extremely important for its successful operation. At present, the classification of occupancy sensing process is essentially categorized in three forms (a) based on function, (b) based on method, and (c) based on infrastructure. [8]. However, it is normally noted that existing occupancy sensing mainly uses sensors where ultrasonic and microwave sensors are much preferred owing to its equivalent operation in the form of radar with Doppler shift [9]. Basically, Doppler effect is utilized in Doppler radar in order to generate the correct positioning of any object with its specific distance

using microwave signal. Usage of Doppler radar is more in aviation industry, meteorology, healthcare, ballistic, etc. Maximum usage of Doppler radar is less seen in occupancy sensing model owing to wavelength range, longer distances of operation, lack of enhanced frame rate, etc. Even it offers significant amount of problems in obtaining less than 1% of error in detection rate. Apart from this, performing system-on-chip operation along with compression followed by analysis is still an open challenge with non-compatibility of field upgradable. At the same time, there is also a contradiction of theory and practical usage. Occupancy sensor was originally meant of resource (energy) consumption but in reality user doesn't prioritize much on energy and emphasize more on their comfort. Majority of the upcoming application calls for instantaneous detection of physiological factors of subject where demands of accuracy is more dominant over any other issues e.g. resource consumption. We strongly believe that usage of Doppler radar can be truly used for enhancing the performance of occupancy sensor. The research area is quite novel as there is no much commercially success product on this idea of accuracy for occupancy sensing. Moreover, there is not much work being carried out towards exploring the direction of mobility of an object in occupancy sensing using Doppler radar. Therefore, we present an analytical model where Doppler radar as well as occupancy sensing is integrated with an objective of accomplishing better accuracy. The significant contribution of the proposed system is actually to incorporate more granularities in the mobility factor of the subject being traced by occupancy sensor using Doppler radar. Section 1.1 discusses about the existing literatures where different techniques of both occupancy sensing as well as utilization of Doppler radar are discussed for detection schemes used followed by discussion of research problems in Section 1.2 and the proposed research methodology as a significant solution in 1.3. Section 2 discusses about analytical model along with algorithm description followed by discussion of result analysis in Section 3. Finally, the conclusive remarks are provided in Section 4.

1.1. Background

This section discusses the existing research contribution towards enhancing the design of occupancy sensing. Eedara et al. [10] have presented a technique of sensing occupancy using metadata of standard WiFi interface and received signal strength. Study towards the dual-band based input-output based approach of sensing subject is carried out by Iyer et al. [11]. Liu et al. [12] have used pyroelectric infrared sensors to perform occupancy sensing using standard hidden Markov Model. The work carried out by Li et al. [13] has introduced deep sensing technique using the recursive mechanism of a mathematical model. Cooley et al. [15] have used a special form of capacitative sensor to perform detection irrespective of any illumination condition. George et al. [16] have presented an integrated prototype framework using inductive as well as a capacitative approach for designing occupancy sensor. Hossain and Champagne [17] have addressed the similar sensing problem with the aid of wideband spectrum considering a case study of cognitive radio. It has been seen that there are not much implementation using Doppler radar. On the other hand, the studies towards Doppler radar have addressed a different set of problem. Most recently, identification of the target is carried out by Cooper et al. [18] using an analytical model. Doppler Radar has also been reported to be used in the identification of wall breathing as seen in the work of Aversano et al. [19]. Implementation of Doppler radar towards phase-locked loop has been carried out by Mercuri et al. [20] to perform non-invasive monitoring of vital signs. Saho et al. [21] have used Doppler Radar for classification of the gaits of a different form of subjects in the form of simulation. Wang et al. [22] have presented a scheme for identifying the wind component using Doppler radar. Zhao et al. [23] have carried out an implementation of Doppler radar to perform detection of physiological characters mainly emphasizing on the low-power transceiver design. The problems associated with the correction of the radius in Doppler Radius is addressed in the work of Gao et al. [24] where radar of continuous wavelength of high precision is used. Gurbuz et al. [25] have used a similar form of waves to perform detection of simple mobile objects using radar signatures. Ritchie et al. [26] have performed feature extraction using multi-static waveforms of Doppler radar and was used for classifying flying objects. Identification of respiratory patterns using Doppler radar was carried out by Lee et al. [27]. The usage of Doppler radar of high frequency has also been reported in the work of Liao et al. [28]. The identification of various significant information from the satellites has been carried out by Vega et al. [29] where the Doppler radar is also equipped with double frequency as well as polarization. The work carried out by Ren et al. [30] has performed identification of heartbeats using demodulation of the complex signal for precise detection performance. Majority of the existing approaches using Doppler radar has been tested in hardware-based approach with a lesser computational model while the majority of the studies focuses on identification of the certain targets. The extracted research issues are briefly outlined in next section.

1.2. Research Problem

The significant research problems are as follows:

a. Existing techniques are much less on using Doppler radar for assisting in occupancy sensing modeling and implementation.

b. Less computational approach and more hardware-based approach towards Doppler radar usage render reduced scope in the presence of uncertainty and dynamic modeling.

c. Existing framework is capable of identifying the presence of certain objects; however, its granularity towards investigating the physiological characteristics is completely missing.

d. A robust mathematical model for integrating occupancy sensing and usage of Doppler radar is few to find in existing approaches.

Therefore, the problem statement of the proposed study can be stated as "*Designing an approach for offering better granularity in the mobility behavior of a moving object for enhanced occupancy sensing by harnessing the potential of Doppler Radar."*

1.3. Proposed Solution

The prime purpose of the proposed system is to perform an effective modeling of applying Doppler Radar for better occupational sensing. The contributions in the present work are a) inclusion of dynamic and uncertain mobility of subject b) incorporation of granularity of mobility by incorporating directionality factor. By the term granularity, it will mean that the proposed system not only perform detection of the presence of any subject within the specified range of Doppler Radar but also computes its rate of specific movement that is quite periodic. For simpler model construction, we consider to compute the rate of respiration for the subject as well as its direction towards and away from the reference point (where the radar resides). The flow of the proposed method is shown in Figure 1.
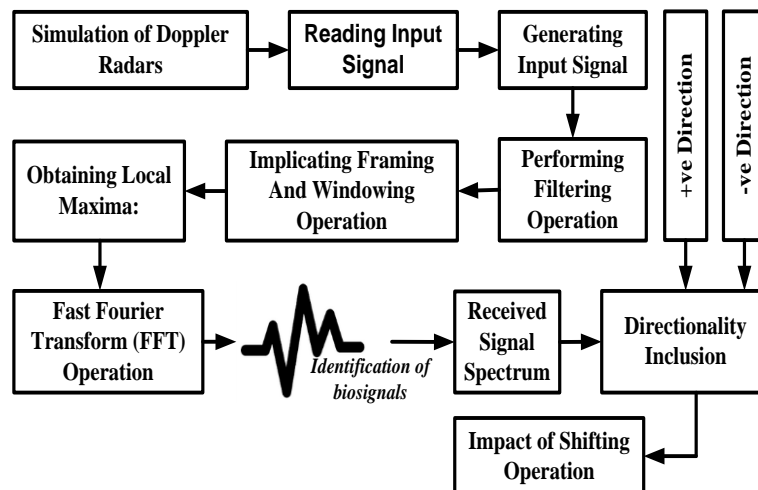

Figure 1. Proposed flow of Methodology

According to the proposed system (Figure 1), we first simulate the Doppler radar in order to perform more granular investigation of the biological signal by reading its input signal followed by generating the input signal performed by the filtering operation as well as implicating the framing & windowing operation followed by the accomplishment of the local maxima and FFT operation. The prime logic of proposed study is that there is a significant amount of shifting of frequency over the spectrum of input signal whenever a subject performs any motion. Depending on the velocity of the mobility of the subject, the direction, as well as score of frequency, can be computed. The proposed system, therefore, emphasize on the received signal spectrum. We also apply a simple modulation-based framework that considers uncertain mobility issues to trace the spectrum with shifted frequency. Hence, in a nutshell, the study will finally aim towards observing the shifted frequency of the spectrum to compute the rate of any action related to the biological signal. An analytical model is designed for this purpose where simpler mathematical modeling is applied for constructing the identification of the subject as well as computation of the rate of respiration under the very uncertain condition of mobility. The next section discusses the analytical model.

2.   ANALYTICAL MODEL

This section discusses the analytical model being implemented towards designing a novel occupation sensing system for uncertain and undynamic subject mobility using Doppler radar. The presented analytical model makes use of the Doppler shift to track the presence of any forms of biological signals of any object. The applicability of Doppler radar is quite high in this as according to theory, we can say that there is a periodical mobility associated with an object with the same frequency. However, the object might have a phase shift with time-varying nature, and therefore, it is much suitable for detection of any subject with the biological signal in a non-invasive manner. A simple example to understand this analytical implementation is the process of respiration that is characterized by periodic displacement of the chest. Moreover, such mobility factors will introduce a highly varying phase shift better proportion to the chest displacement considering signal wavelength. The proposed system applies modulation scheme of Binary Phase Shift Keying (BPSK) although other forms of modulation could also experiment. The algorithm develops a channel with MIMO form to construct channel object. The prime emphasize was offered in developing a cost-effective implementation of identification process of biological signals of any inhabitants of the specific area. Another uniqueness of proposed algorithm is that it doesn't offer any form of recursive operation. Thus it leads to faster response time as well as lower computational complexity in the form of storage complexity. All the computation is carried out at run-time, and there are no residual signals being left behind in memory. The complete modeling is carried out using six discrete operations, i.e., performing a simulation of Doppler radar, generating an input signal, performing filtering operation, implicating framing and windowing operation, obtaining local maxima, and finally performing Fast Fourier Transform (FFT) operation. Following are the brief outline of the proposed analytical model.

a.   Performing Simulation of Doppler Radars

This algorithm is essentially meant for simulating the Doppler radar that is deployed for detecting the presence of any new subject by their biological signal. The algorithm takes the input of S (stream), M (order of modulation), N_t (transmitter antenna), N_r (receiver antenna), f_d (maximum Doppler shift for all path), t_s (input sample period), τ (path delay), p_{bd} (mean path gain), σ (antenna coefficient), N_{sam_f} (samples per frame), and N_{samp} (samples per frame) that after processing gives the output of h_s (Doppler spectrum). The steps included in the algorithm are:

Algorithm for Simulating Doppler Radars

Input: S, M, N_t, N_r, f_d, t_s, τ, p_{bd}, σ, N_{sam_f}, N_{samp}
Output: h_s
Start
1. init S, M
2. h=mc(N_t, N_r, t_s, f_d, τ, p_{bd})
3. h.TxCM➔α(σ)
4. **For** iF=1:N_{frame}
5.   Sig$_{in}$=mod(h$_{modem}$, arb(S, M), N_{sam_f}, N_t
6.   idx=(1:N_{sam_f})+(iF-1)*N_{samp_f};
7.   filter(h, Sig$_{in}$)
8.   **For** i=1: N_t
9.   [y$_1$, y$_2$, y$_3$, (idx, it)]=h.P$_{gain}$(it)
10.   **End**
11. **End**
12. Show PSD(h_s, 'N_{samp}/5')
End

The first step of the algorithm is to develop a set of local random number stream using Modified subtract with borrow generator with a seed for generating the local stream S (Line-1). The algorithm considers 2nd order of modulation M to create an object of BPSK modulation h$_{modem}$(Line-5). The input sample period ts is computed as follows:

$$t_s = \frac{\left(\dfrac{1}{R_{sym*\log_2(M)}} \right)}{N_{os}} \tag{1}$$

In the above expression, the input bit rate is obtained by the product of input symbol rate R_{sym} with the logarithmic function of modulation order M. The variable N_{os} is a factor of oversampling. The next part of the algorithm implementation is associated with the channel modeling by considering a number of the factors as shown in Line-2. The essential factors are path delay τ, mean path gains (in dB) p_{bd}, maximum Doppler shift allocated for all paths f_d, some transmitting / receiving antenna

N_t/N_r, correlation coefficient that is equivalent to the antenna correlation σ. The channel object h is created (Line-2), and we also derive a transmit correlation matrix shown in Line-3 using non-symmetric Toeplitz matrix over the argument of antenna correlation. The study computes all the number of the frames N_{frame} obtained by dividing a total number of channel samples N_{samp} by some samples per frame N_{samp_f}. A loop is created for all the number of frames (Line-4), where the prime task is to compute input signal Sig_{in}, index idx, and output. The input signal is formed by applying modulation function on modulation object hmodem, an arbitrary value of signal and modulation order, sample frequency, and a number of the transmitter (Line-5). The index is formed by adding all the individual sample frequency with the product of remaining frames with sample frequencies (Line-6). The output is formed by applying filtering operation on channel object h and input signal Sig_{in} (Line-7). Another nested loop (Line-8) is created for all the number of transmitters where the relative information of path gains P_{gain} concerning channel object h is computed respectively for y_1, y_2, and y_3 matrix (Line-9). Finally, a power spectral density psd is obtained (Line-12) to obtain the simulation of Doppler radar.

b. Generating Input Signal

The input signal is formed by considering synthetic biological signal data and representing it in the form of time (x-axis) and amplitude (y-axis).

c. Performing Filtering Operation

To perform filtering operation, the algorithm considers inclusion of a new variable δ that stands for preemphasis coefficient. The filtered outcome F is obtained as follows:

$$F = \phi([1-\delta], x_{bio}) \tag{2}$$

In the above equation, the function ϕ represents a filtering operation on x_{bio} (vector derived from the input signal) with the filter represented by [1- δ] and 1 in order to obtained filtered data F. The preemphasis coefficient δ is used for maximizing the measure of certain frequency of higher order for enhancing the cumulative signal quality. It is also responsible for controlling any form of possible effects of signal saturation, distortion, or attenuation, etc.

d. Implicating Framing and Windowing Operation

As the proposed system considers biological signals to be non-stationary therefore for stabilized computation, framing and windowing operation is highly essential. This algorithm takes the input of δ (preemphasis coefficient), T_w (frame duration for analysis), T_s (frame shift for analysis), f_s (Sampling frequency) which after processing yields an output of E (envelop). The steps involved in the algorithm are as follows:

Algorithm for Framing & Windowing

Input: δ, T_w, T_s, f_s
Output: E
Start
1. init δ, T_w, T_s, f_s
2. $F = \phi([1-\delta], x_{bio})$
3. $[N_w\ N_s] \rightarrow$ 1E-ψ, where ψ=3*Ts*fs
4. $Frames \rightarrow g_{v \rightarrow frame}(F, N_w, N_s)$
5. $E=[t_{max}\ t_{min}] \rightarrow \beta(F, c)$
End

The initial steps of this algorithm are same as that of performing filter operation in the prior stage (Line-1 to Line-2). The algorithm computes both durations as well as shifts of the given frame (Line-3) and then applies a function $g_{v \rightarrow frame}$ to perform framing and windowing operation (Line-4). This step is further followed by the computation of peak detection for facilitating windowing operation concerning maximum t_{max} and minimum t_{min} value of the envelope E (Line-5) considering the permissible envelop coefficient of c.

e. Obtaining Local Maxima

This process is responsible for computing the local maxima of the given biological signals of the Dopler Radar. The primary intention of this step is to obtain the interpolated version of an envelope obtained in the prior step. The complete operation of this implementation is similar to Line-1 to

Line-4 of an algorithm for framing and windowing with an additional step of applying a function of local maxima on obtained frames of Line-4 to correctly obtain upper and lower envelop.

f.   Fast Fourier Transform (FFT) Operation

This is the last stage of the proposed implementation where FFT operation is carried out on frame F. Accomplishment of this step confirmed the form of biological signals.

We use this model to generate the transmitted signal, that is normally unmodulated can be represented empirically as:

$$T_{signal}=cos(2\pi ft+(\pi/180)*30)) \qquad (3)$$

The next phase of the implementation is to construct a received signal. We formulate an algorithm that takes the input of c (velocity of light), f_1 (frequency), a (heart mobility factor), b (respiratory mobility factor), t_1(time), v (velocity of object), d_{ini} (initial distance) in order to yield an output of im (integrated mobility), R (received signal).

| Algorithm for obtaining the received biosignal concerning Mobility |
|---|
| **Input**: c, f_1, a, b, t_1, v, d_{ini} |
| **Output**: im, R |
| **Start** |
| 1. init d_{ini}, v, t_1, a, b, f_1, c |
| 2. im = d_{ini}+ v.t_1 + a + b |
| 3. R=cos((2πft)-((4πd_t)/(c/f_1)+ph) |
| **End** |

The complete formulation of the biosignals is carried out by ignoring the variation in amplitude. At the same time, we can signify the term vt_1 as a positive or negative sign for showing the forward and reverse the direction of mobility of the subject. The next part of the study is to formulate a spectrum for this which is generated by considering a periodic mobility due to heart beat (a) as well as respiration (b) in the form of [a b]=sin($2\pi f_a t$). According to our formulation, the routine mobility of the body is due to the heartbeat and respiration. This method is then continued by computing motion modulation where we consider samples per second to compute the wave in the form of:

$$x=\omega(fft(0.5.cos(2\pi F_c.t)+cos(2\pi F_{c1}.t))) \qquad (4)$$

The function ω represent FFT shift operation that leads to the generation of the spectrum concerning frequency and the absolute value of x/N, where N represents the number of the sample concerning time. This process offers an empirical response to mobility in forwarding direction concerning biological signal. The similar process is applied for computing mobility in a backward direction with (t-t_0) being replaced in the position of t in the above mentioned equation. We also compute the actuator result for both before and after shift concerning DFT value and normalized frequency value. According to our mobility model, the frequency spectrum will always be inclined towards +ve axis if the object is found to be moving towards Doppler radar by 2v/wavelength, while it takes the similar empirical value for reverse movement direction as it moves to the -ve axis.This formulation of directionality is carried out to resist any forms of uncertainty in the mobility model. The advantage of this model is that if the maximum peak is studied, it can give the true picture of its shifting behavior towards positive/negative axis which is directly a representation of a minor movement even like respiration that can be easily identified using the present model. At the same time, the system minimizes the dependencies on multiple radar system as complete information of mobility of an object can be tracked by the proposed system concerning its respective direction.

3.   RESULT ANALYSIS

The numerical values considered to carry out this analysis are: preemphasis coefficient δ of 0.01, modulation order M=2, input of symbol rate 10000, oversampling factor N_{os}=4, maximum Doppler shift f_d=0.5, 2 transmit antenna, and 1 receive antenna, average path gain of 0 dB, -15 dB, and -20 dB, correlation coefficient σ=0.7, number of samples per frame N_{samp_f}=1000, total channel samples=1.5×10^6. The corresponding outcomes are shown in Figure 2.
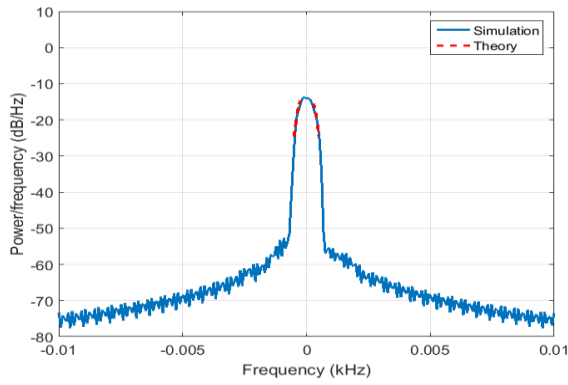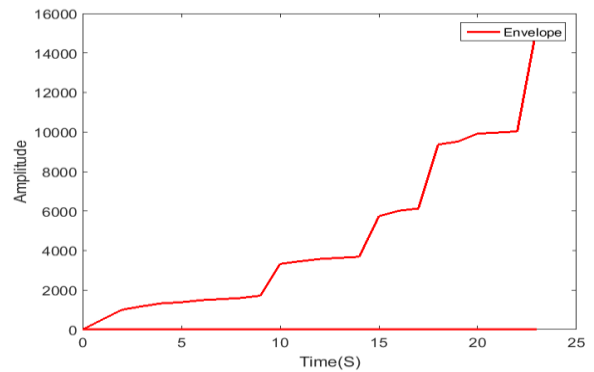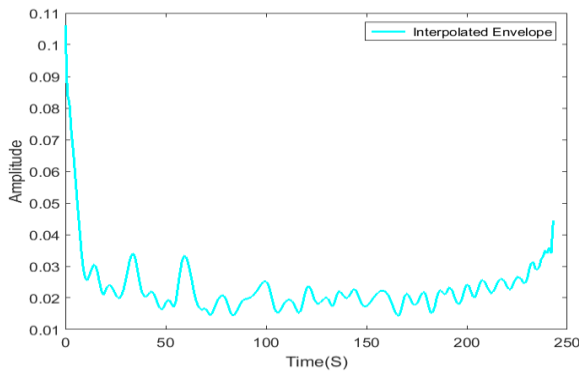
(a) Doppler Radar Simulation
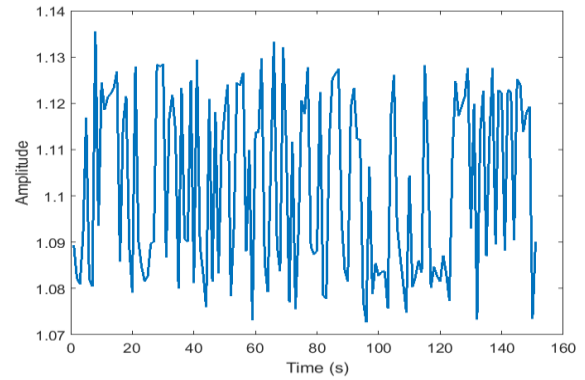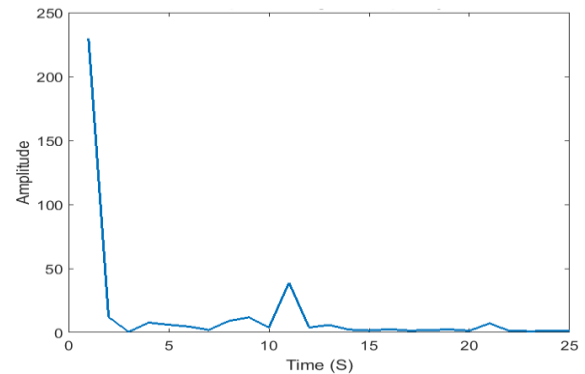

(b) Input Signal
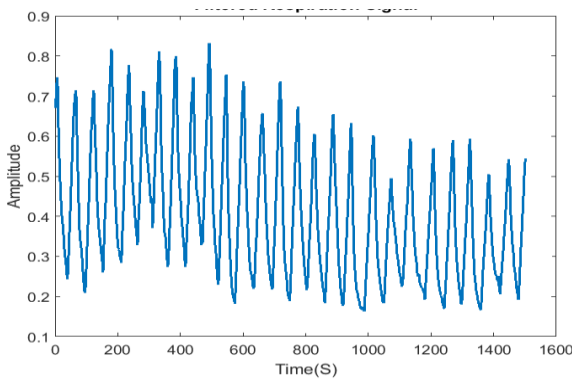
(c) Filtering Operation

(d) Framing & Windowing Operation

(e) Applying Local Maxima

(f) FFT Operation

Figure 2. Graphical Outcome of Proposed System

The graphical outcome shown in Figure 2 shows an effective identification of the biological signal that can effectively trace any form of dynamic or random mobility subjects. The complete computation time is found to be 0.024487 seconds in core-$i3$ windows machine. The complete analysis is carried out using synthetic respiratory data. The streamlined pattern of the curve in Figure 2(d) to Figure 2(f) shows that proposed system can provide significant assists in extracting the rate of respiration with a higher probability of lower resource dependencies. The next part of the experiment for mobility considers frequency as 10^6 Hz, the speed of light as $3*10^8$ mps, samples per second as 100, F_c=5 Hz, and F_{c1}=0.1 Hz, time t_0=1 sec. Figure 3 highlights that proposed system is completely capable of analyzing forward motion (Figure 3(a)) and backward motion (Figure 3(b)). Similarly, a better visibility of the spectrum as an impact of shift operation can be seen in Figure 3(c) and Figure 3(d). Owing to the non-recursive formulation of the complete technique of occupancy sensing in the proposed system, there is a significant scope of better compatibility in low-

powered and low-cost hardware design in future. We have also performed computation concerning other modulation scheme as well as by changing other simulation variables. However, in the majority of the cases there is a uniformity in the detection performance, and thereby it exhibits the better reliability in its outcome with an accuracy of 97.85%. Hence, the proposed system offers a cost-effective approach to model occupation sensing concerning direction.
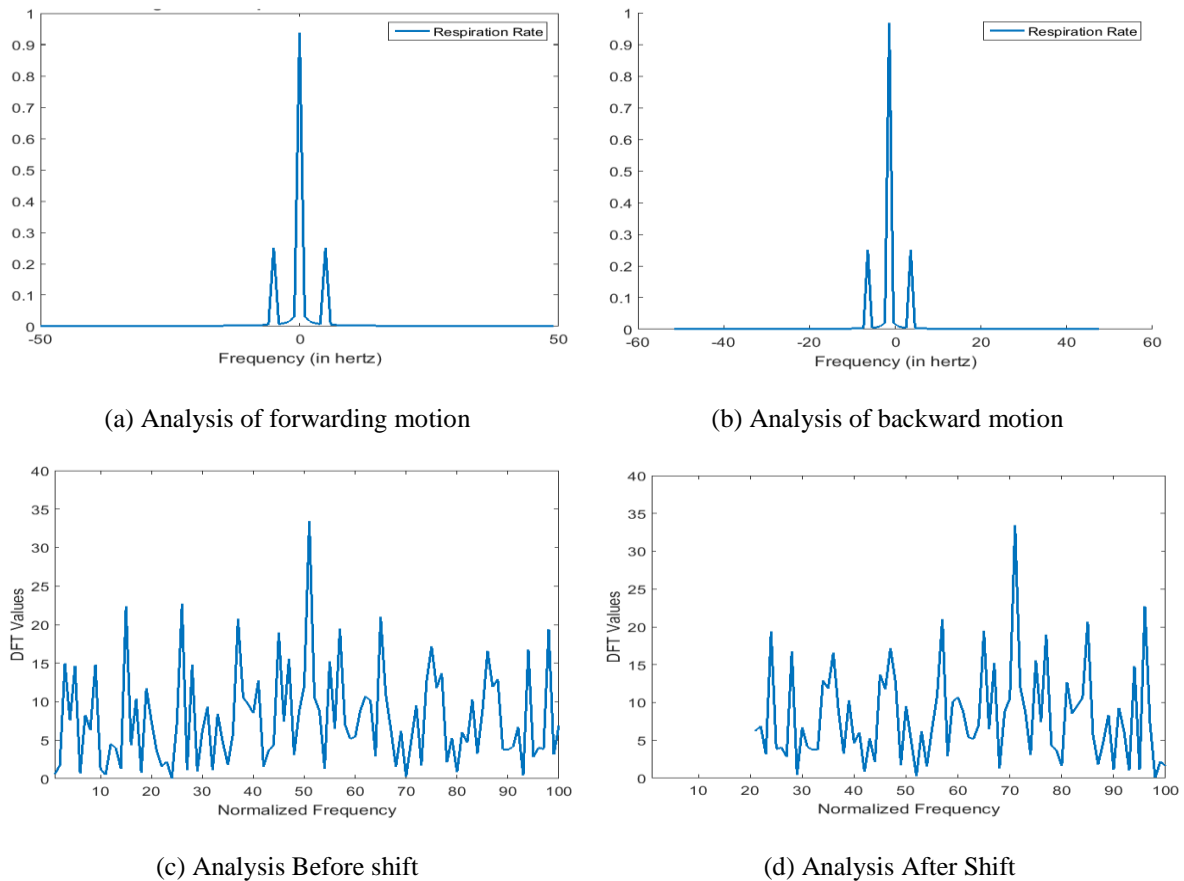

(a) Analysis of forwarding motion

(b) Analysis of backward motion

(c) Analysis Before shift

(d) Analysis After Shift

Figure 3 Analysis of Mobility Patterns

4. CONCLUSION

Usage of occupancy sensing, as well as Doppler radar, is not novel from an individual viewpoint, but the integrated usage of both is very less reported in existing literature. Although there is an existing system to perform detection of a moving object, they miss granularity in modeling the mobility behavior. Therefore, the proposed system introduces an analytical model that is used for computing the periodic physiological factor of a mobile subject under the monitoring range of the radar. An explicit modulation technique is applied to study directionality of object movement using the positive and negative axis of frequency. The study outcome shows that proposed system offers better resolution of the waveforms for enriched investigation of the dynamic mobility pattern of any object.

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