Identifying Physiological Features from the Radio Propagation Signal of Low-Power Wireless Sensors

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Abstract. The radio propagation signal between a pair of low-power wireless sensor nodes is analysed with the aim to identify and retrieve embedded physiological features. The latter is post-processed using popular time-frequency analyses, such as such as the Fast Fourier transform (FFT). The results show initial evidence that the electromagnetic wave propagation contains bio-mechanical markers, such as gait pattern and thoracic displacements.

Keywords: physiological features, wireless sensors, low power, radio propagation, on-body communications, bio-mechanical markers.

1 Introduction

Compact and low-power devices interacting seamlessly through wireless connections are now integral parts of our daily lifestyle. The ubiquitous wireless connectivity between different devices has enabled the real-time transmission of sensed information (i.e., wireless pervasive sensing). Wirelessly connected miniaturized sensors and actuators placed in, on, and around the body define a Wireless Body Area Network (WBAN) [1, 2], which combines the continuous, automated, and unobtrusive monitoring of physiological signs to support medical, lifestyle and entertainment applications. The continuous monitoring of patients recovering from surgery, without constraining their normal recovery activities, in hospitals and home environments are active research topics.

It is evident that different areas of the body have unique characteristics; hence, the travelling electromagnetic wave behaves differently (e.g., absorption and exposure level). Additionally, external perturbations, such as human mobility and operation in cluttered environments, define a complex environment for the propagation characteristics of wearable devices [3, 4].

The interest in biomedical research is especially directed at continuous monitoring and quantification of physiological body signals, as well as at the development of personalized healthcare devices. Tele-monitoring and tele-diagnostics systems in smart home environments provide large amounts of health-related information from

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strategically-placed body-worn sensors which sample, process, and transmit vital signs (e.g., heart-rate, blood pressure, skin temperature, pH, respiration, oxygen saturation).

Many studies have shown the potential of contactless sensors for the retrieval of physiological signals (e.g., breathing, heartbeat, gait pattern). Biomechanical features are embedded in the reflected waves which present shifts on frequency and phase when compared to the transmitted signal [5-8] (i.e., the Doppler Effect). The results presented in [8] indicate that heartbeat and respiration rates are clearly detectable at lower frequencies (i.e., 370 MHz) in the reflection coefficient of a single antenna. The physiological information was extracted using well-known non-linear filtering techniques. Other studies showed limb movement classification using the received signal values of multiple body-worn wireless modules. Different activities were recognized implementing supervised learning models such as support vector machine (SVM) and K-nearest neighbour (K-NN) methods [9]. The microwave sensors literature contains different contactless sensor prototypes. Different electromagnetic sources propagate within outdoor and indoor environments (e.g., Wi-Fi, GSM, GPS, Bluetooth, and ZigBee), to which human bodies are greatly exposed. Therefore, the radio propagation signal from each source could be used as a potential contactless sensing technology.

The current work investigates this possibility and the use of an alternative sensing method, by means of the received signal strength (RSS) of low-power wireless sensors operating in the 2.45 GHz ISM band. RSS is a commonly available parameter in commercially-available wireless transceivers, requiring no additional hardware. The received signal for a waist-to-chest channel is recorded in two different scenarios (i.e., motionless and jogging). The stored data is later extracted and characterized using well known time-frequency domain techniques, where the components of each signal is analysed and quantified at different scales.

The rest of the paper is organized as follows: Section 2 describes the in-house wireless sensors and the measurement procedure. In Section 3, the time domain signal acquired by the electrocardiograph is transformed to the frequency domain where main harmonic components are classified. Similar process is applied to the data recorded by wireless sensor nodes which is described in section 4. Additionally, the obtained results are compared with the spectral response of ECG signals. The conclusions are drawn in Section 5.

2 Measurement Procedure

The measurements were taken in Queen Mary’s Human Performance Laboratory (i.e., indoor laboratory environment). The experimental research was carried out by a male subject of 168 cm height and 80 kg weight. The transmitter node (Tx node) was fixed on the right waist and the receiver node (Rx node) was fixed on the upper middle section of the thoracic wall (i.e., waist-to-chest channel). Fig. 1a shows Queen Mary's Human Performance Laboratory and Fig. 1b depicts the on-body locations for the on-body Rx and Tx nodes.

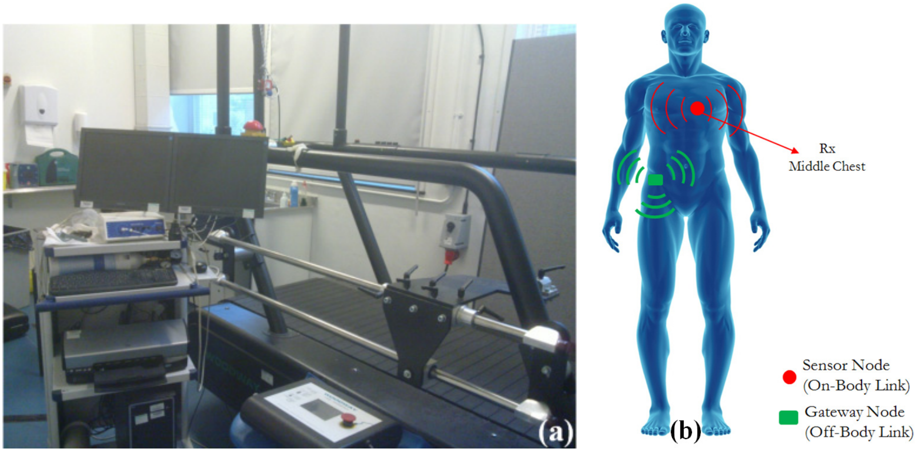


Fig. 1. Queen Mary's Human Performance Laboratory: (a) treadmill machine used for the experiments; (b) on-body location of custom-built wireless sensor nodes used for the radio propagation recording.

Each wireless sensor node is assembled using a Texas Instruments transceiver, the CC2420 [10], and an ultra-low power microcontroller, the PIC18F2620 [11]. The latter not only configures and controls the transceiver chip, but also records the radio propagation signal based on RSS characteristics in the internal flash memory. The acquired data was later extracted and analysed. The Tx and Rx nodes communicated using the IEEE 802.15.4 standard [12].

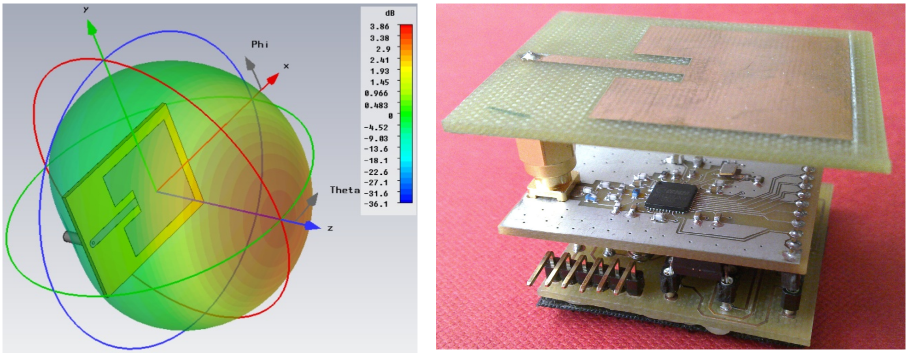
The radiating element of each wireless sensor node was a microstrip patch antenna printed on top of a FR-4 substrate material of 1.6 mm thickness. The simulated results of the microstrip patch antenna (i.e., 3D radiation pattern) and the custom-built wireless sensor node used for this study are shown in Fig. 2a and Fig. 2b, respectively. A summary of the performance of each antenna (i.e., Tx and Rx antennas) and additional information of the antenna design, radiation performance and the spectrum response of each low power wireless sensor can be found in [4, 13].

The acquisition of the data was taken in two different scenarios:

(a) Motionless test subject (i.e., standing on the treadmill machine),
(b) Jogging test subject at a constant speed of 5 km per hour (5km/h).

The jogging exercise was performed on a motorized treadmill machine equipped with a digital display and an electronic control console (see Fig. 1a). The tilt of the conveyor belt was set flat (no tilt), in order to simulate normal outdoor jogging.

In both scenarios, electrocardiogram (ECG) recordings were taken by a certified 12-Lead electrocardiograph, the Cardio Collect 12, with a sampling rate of 500 Hz. The ECG is a popular method to record the electrical impulses that the heart produces every time it beats. In this study, the ECG data provided additional information which helped with the data classification and interpretation.



(a) (b)

Fig. 2. Antenna used for on-body measurements: (a) simulated free-space radiation pattern for the microstrip patch antenna using CST Microwave Studio; (b) implemented wireless sensor node

VELCRO tape was fitted on each wireless sensor; thus, the location displacement due to the constant movement was significantly reduced. For each activity, the receiver node records an average of 6000 samples of the RSS at a rate of 14 ms per sample. For a jogging scenario, the receiver node started recording data only when the user had a constant speed. Both ECG recording and treadmill operation were controlled by a computer, thus avoiding synchronization errors.

3 Analysis of the Recorded Electrocardiogram Signals

The Cardio Collect ECG report gives average heart rates of 85 BPM and 108 BPM for a motionless and jogging activity, respectively. The ECG plots for each scenario are shown in Fig. 3a and Fig. 4a. The ECG recordings were extracted from the report for frequency analysis.

In order to recognize the main frequency components, a Fast Fourier Transform was applied to each recorded ECG signal. The time-sampled sequence, $x(n)$, is multiplied by a window function, $w(n)$, which limits the extent of the sequence and provides a more stationary spectral characteristic. The current study made use of a Hanning window. In our analysis, the length of the window $N = 4096$.

The resulting plots for a motionless and jogging activity are illustrated in Fig. 3b and Fig. 4b, respectively. The spectral plots identify main harmonics of 1.46 Hz for a motionless test subject (see Fig. 3b) and 1.77 Hz for a jogging test subject (see Fig. 4b).

A summary of the results is listed in Table 1. It is important to highlight that the transformation from time to frequency domain (the FFT process) has introduced a deviation of ≈3.4% from the average values given in the ECG report. The difference is mainly attributed to the truncation limits of the FFT summation, the FFT coefficient rounding errors and floating point arithmetic quantization errors. These results indicate the expected frequencies that should be observed based on thoracic wall movements for the two activities.

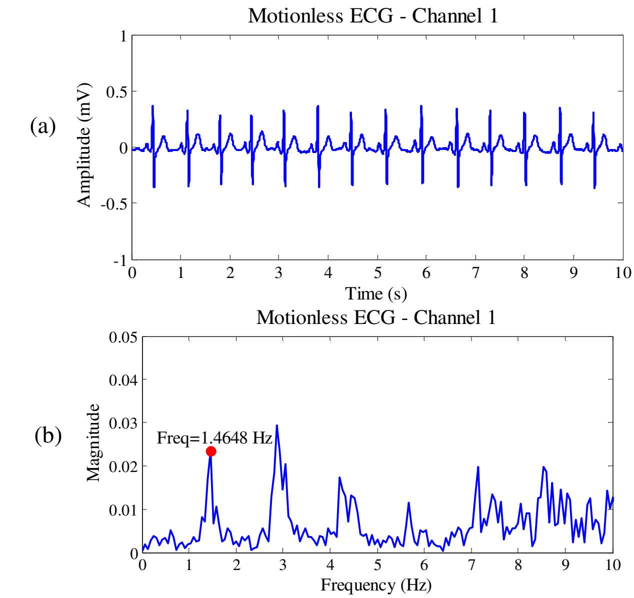


Fig. 3. Resulting plots while the test subject is standing on the treadmill machine (motionless scenario): (a) ECG signal acquired with the Cardio Collect 12. Average heartbeat is 85 BPM; (b) Spectral response of the recorded ECG signal.

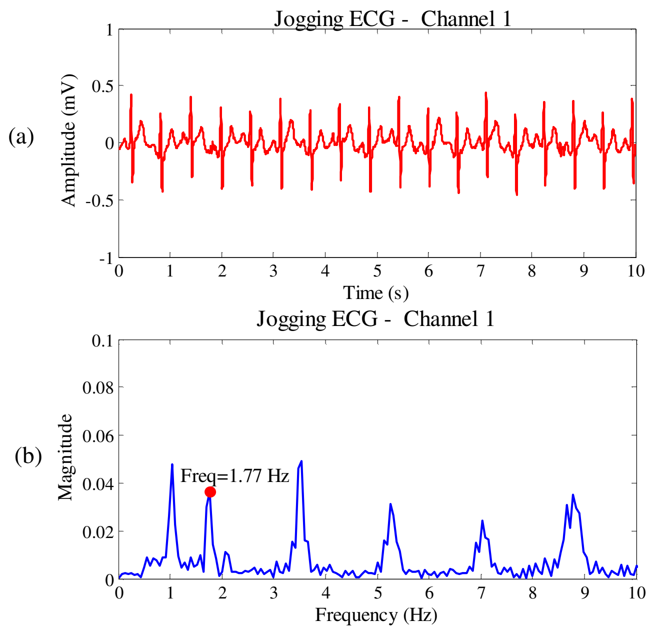


Fig. 4. Resulting plots while the test subject is jogging at a constant speed of 5 km/h (jogging scenario): (a) ECG signal acquired with the Cardio Collect 12. Average heartbeat is 108 BPM; (b) Spectral response of the recorded ECG signal.

Table 1. Comparison of estimated harmonics derived from ECG recordings acquired by the Cardio Collect 12, to the average heart rate provided by the Cardio Collect 12. Two different scenarios are considered: a motionless test subject and jogging at a constant speed of 5 km/h.

ECG Description	Average Heart Beat BPM	Spectral Harmonic Hz	Estimated Heart Beat BPM	Deviation %
Motionless	85	1.46	87.88	3.39
Jogging at 5 km/h	108	1.77	106.2	1.66

4 On-body Radio Propagation Analysis

It is evident that the practice of any sport activity will produce a high level of fluctuations on the received signal, which are the consequence of the continuous movement of the human body. In the case of jogging activity, our results show variations of ±15 dB from the average received signal; this is significantly greater than received signals of a motionless user, where the variations are ±3 dB. Fig. 5 depicts the received signal for both scenarios, jogging and motionless. The graph plots a 45 s window length of a waist-to-chest channel.

The data acquired by the on-body wireless sensors are rich in detail, but they are also highly non-stationary signals (i.e., frequencies, amplitudes and phases change with time). The transmitting node antenna radiates electromagnetic waves that propagate through both free space and human body. The main radiation beam of the

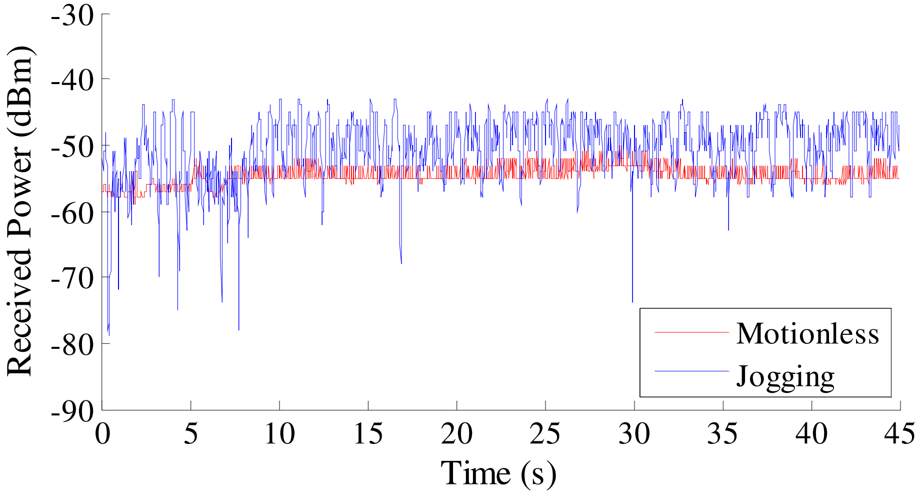


Fig. 5. Comparison of received signal, for a waist-to-chest channel, when the test subject is jogging and motionless in Queen Mary's Human Performance Laboratory

patch antenna is normal to the body; however, there are also electromagnetic waves travelling along the body's surface which are mainly triggered by the fringing fields and backscattering energy.

The spectral content for a motionless scenario (test subject standing on the treadmill machine) is shown in Fig. 6a. The latter takes into consideration the coherence gain factor (i.e., loss introduced due to the Hanning window). The search of the local maximum within expected frequencies (i.e., 1-2 Hz) shows 1.24 Hz as the local maximum. The small magnitude may indicate a sensitivity issue.

Fig. 6b plots the spectral components of the recorded RSS for a jogging scenario. Two main harmonics are clearly identified: the first at 0.9 Hz and the second at 1.79 Hz. It is known that human locomotion depends on two main factors, stride length and stride frequency, both of which contribute to a jogging activity [14].

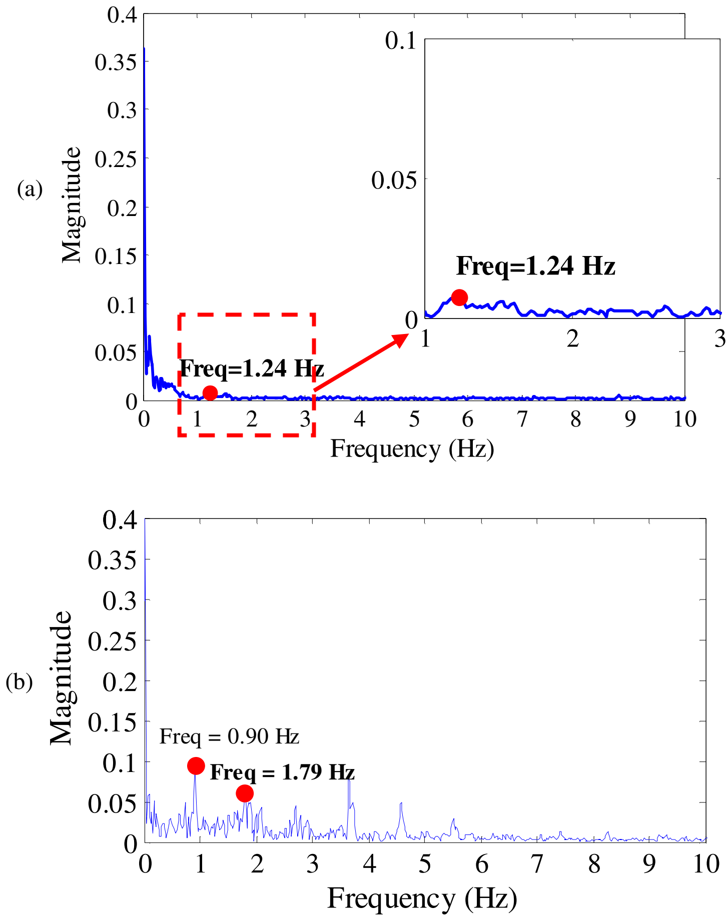


Fig. 6. Radio channel signal acquired by custom-built wireless sensor nodes: (a) spectral response while the subject is standing on the treadmill machine (i.e., motionless scenario), (b) spectral response of the received signal while jogging at a constant speed of 5 km/h.

The constant speed of 1.38 m/s (i.e., 5 km/h) and the average stride length of 1.5 m give rise to the first harmonic, 0.9 Hz. This is product of the periodic kinematic of the human body, which is mainly dominated by the head and the thoracic wall.

The second component is characterized by the quasi-synchronous movement of the arms and legs. The cyclic movement of the extremities, which is repeated during the entire jogging process, creates angular variations on the radiation of the patch antenna (i.e., normal to the body) and changes in the multipath propagation (i.e., multipath fading channel), and thus producing a harmonic at 1.79 Hz, almost twice that of the main frequency component. Although this harmonic is mainly dominated by small scale fading introduced by the upper extremities motion, it is also expected to embed the relative movement of the thoracic wall (due to the limbs movement), which not only contains comparative contributions of the limb motion, but also human breathing process and heart palpitation. The relative magnitudes of these aspects are much smaller than the fading observed due to motion. It may be that the coincidence of heart rate and motion harmonics can be avoided with different stride rates, allowing the thoracic wall movements to be detected; this is an objective of our future work.

The spectral content of the electrocardiogram maintains a high level of detail, unlike the spectral plot of the signal recorded by the wireless sensor nodes. This is likely the result of the sensing methods acquiring different aspects of the heart. The ECG mainly records electrical variation of the heart over a period of time across the electrodes, whereas the wireless nodes are affected by the mechanical movement of the heart over a period of time, thus recording the thoracic movement produced by each palpitation on the propagation of the electromagnetic wave.

Additionally, the spectral plot of a jogging scenario (see Fig. 6b) presents main harmonic components that can be classified as gait pattern descriptors of the test subject (i.e., human motion and limb movement). A summary of the obtained results is presented in Table 2. The results are compared with those obtained by the electrocardiograph.

The computed deviation of a resting scenario, shown in Table 1 and Table 2, is higher than of a jogging scenario. In both cases, the deviation is highly affected by three factors: (1) the heart rate variability (HRV) over a period of time (i.e., R-wave to R-wave interval fluctuations); (2) the angular variation of the radiating beam due to motion; and (3) the truncation limits of the FFT. For example, if the RR interval variance is 2000 ms^2, the acquired heartbeat data will fluctuate between 79.93 BPM and 90.74 BPM and the deviation would change accordingly (between 6.91% and 18%, respectively). Moreover, the radiating beam of the current antenna is normal to the body which makes it more sensitive to multipath fading. Future work will enclose wireless sensor nodes housing antennas that radiate tangentially to the human body thus the main propagation path is alongside the thoracic wall; therefore, changes produced by the respiration process and heartbeat are maximized. Although the initial results are only compared with ECG recordings, further studies will use a cardiopulmonary kit which can measure and monitor ECG and respiratory signals while synchronized to the treadmill machine. It will also consider different stride lengths in order to distinguish the harmonics from the human kinematics and those produced by the heartbeat and breathing process.

Table 2. Comparison of estimated harmonics derived from RSS recordings acquired by the custom-built wireless sensor nodes. Two different scenarios are considered: a motionless test subject and jogging test subject at a constant speed of 5 km/h.

Wireless sensor nodes	Average Heart Beat BPM	Spectral Harmonic Hz	Estimated Heart Beat BPM	Deviation %
Motionless	85	1.24	74.4	12.47
Jogging at 5 km/h	108	1.79	107.4	0.55

5 Conclusions and Future Work

The paper presented the radio-channel characterization of a particular on-body radio link (waist-to-chest channel). It was shown that the continuous movement of the human body, trunk and the limbs, for non-stationary scenarios (e.g., jogging exercise) produces cyclic changes in the multipath propagation, thus producing signal fluctuations of ±15 dB (maximum level from the average received signal).

Comparison of the on-body radio channel (which not only include radio propagation characteristics, but also embed biomechanical information, such as the gait pattern and thoracic wall movement) for a motionless and jogging activity showed noticeable differences in channel parameters. Moreover, the analysis of the signal spectra identified distinct frequency components for each recorded scenario. The analysis and quantification of the spectral components in the context of the activities and physiological signals provide a potential model for activity recognition and bio-mechanical feature extraction. The work proposed in this paper may open up a new possibility of non-invasive physiological monitoring based on EM sensing from on-body wireless sensor nodes.

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