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Performance Comparison between Intra-Body and Radio Frequency Wireless Communication for Foot Plantar Pressure Measurement

*A.H.A. Razak, **A. Zayegh, ***R.K. Begg

*Faculty of Electrical Engineering, UniversitiTeknologi MARA, Selangor, Malaysia.
and College of Engineering and Science, Victoria University, Melbourne, Australia.
(abdulhadibin.abdulrazak@live.vu.edu.au)
**College of Engineering and Science, Victoria University, Melbourne, Australia.
***Institute of Sport, Exercise and Active Living (ISEAL) and
College of Sport and Exercise Science (SES), Victoria University, Australia

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Abstract

The sharp boost in healthcare demand has seen novel developments in health monitoring technologies, such as Intra-body communication (IBC). IBC technology envisions a network of continuously operating sensors that measure critical physical and physiological parameters, such as mobility, heart rate and glucose levels just to name a few. Wireless connectivity in IBC technology is the key to its success as it grants portability and flexibility to the user. While radio frequency (RF) wireless technology has been successfully deployed in most biomedical implementations, they consume a lot of power, are susceptible to electromagnetic interference and have security issues. IBC treats the human body as a transmission medium for transmitting and receiving electrical signals. Two IBC methods have been proposed in the literature: galvanic coupling and capacitive coupling. This paper compares and evaluates a binary frequency-shift keying (BFSK) modulation signal using RF, IBC galvanic and IBC capacitive coupling for foot plantar pressure sensors. IBC has characteristics that could naturally address the issues with RF for biomedical technology. The research targets IBC operating in the band from 1 MHz to 100 MHz, and RF operating at 2.4 GHz. Based on the empirical evidence; for this particular application, galvanic coupling shows more promising performance in power and signal-to-noise ratio measurements.

Key words

Intra-body communication, foot plantar pressure, pressure sensor.

1. Introduction

The current paradigm in healthcare is the notion of continuous remote patient monitoring using a network of wireless sensors. These healthcare sensor network systems (D. T. H. Lai *et al*., 2011), consisting of body area networks (BAN) and infrastructure area networks avoid the need for a manual self-administered health system and may enable users to take control most of their health disorders in the future. BAN is a wireless network of wearable computing devices. In particular, the network consists of several miniaturized body sensor units (BSUs) together with a single body central unit (BCU) (G. Z. Yang and M. Yacoub, 2006). BAN technology envisions miniaturized sensors worn or implanted on the body, continuously monitoring health parameters and acting to prevent the onset of critical health events.

Recently, IEEE defined an IBC technique in the IEEE 802.15.6 WBAN protocol (IEEE Standard 802.15.6, 2012). So far, IBC investigation is at an early stage. The research on the mechanism of electric signal through body and the channel model of a human body are still lacking concrete evidence (G. Yue Ming *et al*., 2009). Moreover, an agreement how to accomplish standard IBC measurement is yet to be realized (M. A. Callejón *et al*., 2012). In order to comprehend the IBC behaviour accurately, an exhaustive exploration of the communication channel (human body) properties is essential.

One important application of IBC is in foot plantar pressure. Where the feet are the essential parts of the human anatomy, and they are the main form of contact with the surroundings during locomotion. Accordingly, it is vital to identify a foot problem at an early phase for risk management, well-being and prevention. Foot plantar pressure analysis allows us to determine foot health. Analysis of such pressure distribution has many applications, such as: diagnosing diseases, injury prevention, sports analysis, footwear design, to the latest innovative application; monitoring posture allocation (E. S. Sazonov *et al*., 2011), human identification (F. Yong *et al*., 2011), rehabilitation support system (F. Neaga *et al*., 2011) and biometric (T. Yamakawa *et al*., 2010).

Zimmerman (T. G. Zimmerman, 1996), introduced IBC in 1995; since then, the study of IBC was primarily emphasized on the different implementation of methodologies, operating frequency, configuration of electrodes, and distinctive communication protocols (T. Handa *et al*., 1997, D. P. Lindsey *et al*., 1998, M. Wegmueller *et al*., 2005 and M. S. Wegmueller *et al*., 2007). Subsequently, two main types of IBC were established; galvanic coupling and capacitive coupling. In Galvanic coupling method, the signal is transmitted using an alternating current flowing through the human body with all the electrodes connected directly with the skin of the subject. On the other hand, in capacitive coupling, the signal is transmitted by an electric potential with the signal return path is closed through the environment from the transmitter to the receiver ground electrodes.

The modulation scheme selection has substantial effects on the transmitter design and the transmitter architecture. The architecture should remain as simple as possible for low energy consumption. For the IBC, FSK is widely used as the modulation scheme (M. Seyedi *et al*., 2013). Using an oscillator to modulate digital data it creates BFSK modulation. This method uses only a single oscillator as the modulator; therefore it reduces the number of external components. Furthermore, using oscillator as a direct modulation scheme, the output signal power depends solely on the output power of the oscillator. Consequently, direct BFSK modulation resulted in low hardware complexity, which is appropriate for low power IBC transceiver design (A. Fazzi *et al*., 2009).

This paper compares the performance of the two methods IBC with the RF as communication approaches for specific foot plantar pressure system. The data from foot plantar pressure sensor is transmitted via body from above ankle to the waist where the intended data logger is placed, whilst for RF circuit setup the receiver is located 1 meter away from the transmitter. *In vivo* experiments were conducted to evaluate the performance of a BFSK modulation signal in RF, galvanic and capacitive coupled IBC methods. This paper has 5 sections. Part II surveyed the literature dealt with the comparison between RF, galvanic and capacitive techniques. Part III explained the methodologies of the *in vivo* experiment setup. Section IV presents experimental results and finally, section V layout the discussion and conclusion.

2. The Principle of RF and IBC Techniques

RF versus IBC

Monitoring human vital signals can be performed through miniature sensors. They are lightweight and intelligent devices, capable of sensing physical phenomena, perform basic processing and wireless transmission. Wireless data communications based on radio frequency (RF) have been successfully developed using popular protocols such as Bluetooth, Zigbee, and

ANT (S. Adibi, 2012, M. S. Wegmueller *et al*., 2010, B. Latre *et al*., 2011 and A. C. W. Wong *et al*., 2012). Different frequency band between 402 MHz to 10 GHz can be employed. Unfortunately these frequency bands are not suitable for HBC, due to high signal attenuation through the human body as well as severe shadowing effects. Instead, the operating frequency band of HBC is centred at 21 MHz with scalable data rates: 164 –1312.5 kilobit per second (kbps) (IEEE Standard 802.15.6, 2012). A major drawback of wireless RF propagation for miniaturized medical portable monitoring devices is the high-power consumption which limits the practical duration of operation. Current research claimed that Zigbee and ANT have a battery life of three years, but this is at a low operating data rate (S. Adibi, 2012 and M. S. Wegmueller *et al*., 2010).

One advantage of IBC is that since the signals pass through human bodies, electromagnetic noise and obstacles have little influence on transmission, and the signals do not leak through the skin. In IBC, the signal strength falls off very quickly with distance from the transmitter or person. (Radio signal power drops with the square of distance; IBC drops with the cube of distance). This property can be advantageous. The signal is therefore, more difficult to intercept, which is desirable for secure transmissions. The signal is also more isolated from IBC signals generated by transmitters carried by other people.

The downside of IBC it operates within low bandwidths. A second major problem is signal attenuation. Starting from a transmitter voltage of 20V, the received signal strength might be attenuated to the nanovolt or even picovolt range, making reception very difficult. The third major problem of IBC system is a large number of design variables exist. In addition to coupling location, other factors such as electrode size, transmit voltage; receive gain, most effective frequency, noise sources, and other interfering transmitters' parameters affect the overall system performance. The effect of all these parameters is not well understood. While short-term electrical damage (e.g. shock) is unlikely in a well-designed system, the long-term effects of electric fields are unknown. Many epidemiological studies have been performed to search for a link between electrical and magnetic fields and cancer, but the results have been inconclusive.

Galvanic and Capacitive Coupling

The two methods of Intra Body Communication namely, the Electrostatic/Capacitive Coupling method and the Waveguide/Galvanic Coupling method have been analyzed here. The merits and demerits of these approaches have been compared, and appropriate conclusions have been made (M. Seyedi *et al*., 2013). The important difference between the two solutions is that the communication behaviour in the capacitive coupling approach is strongly influenced by the environment around the body (T. C. W. Schenk *et al*., 2008). In the galvanic coupling approach, it is more influenced by the body physical parameters. Electrostatic coupling is not dependent on an external wire, but the transmission quality is dependent on the surrounding environment. Whereas when the human body is treated as a waveguide (H. Baldus *et al*., 2009), the high-frequency electromagnetic waves are generated at a terminal and propagated through the body, and are received by another terminal. In this method, external wires are not necessary and also the transmission quality is not affected by the surroundings. Thus, in waveguide intra-body communication methods, external cables are not required, with signals transmitted by high-frequency carrier waves.

The galvanic technique does not require connection with the ground. This technique is also known as galvanic coupling. The high-frequency electromagnetic waves are generated at an input terminal which is propagate through the body and are received by another terminal. Waveguide IBC generally achieves low data rate in the kbps ranges because the body effectively shorts the transmitter's electrodes (B. Joonsung *et al*., 2012 and M. S. Wegmueller, 2007). It makes use of the dielectric characteristics of human tissue; therefore, the flow of ions within the human body is the carrier of information. Here, the human body acts as a special kind of transmission line. While for galvanic coupling, electrodes need to be placed on the skin directly (P. Sio-Hang *et al*., 2011), where for capacitive coupling, there is no need for a direct human skin contact; however, close proximity of the coupler to the body is required. These electrodes can be structured horizontally or vertically where the spacing between them is filled by a dielectric material. The Galvanic technique requires neither return path nor common reference. Hence, this feature makes the technology attractive for networking biomedical devices on human body and draws much attention from recent studies.

Intra-body Communication (IBC) in which human body is used as a signal transmission medium. It can be concluded that intra-body transmission has many advantages as compared with the current short-distance wireless technology, including Bluetooth, Zigbee and others. IBC has shown promising characteristic in high transmission quality, high data rate, high security, easy network access and no communication bandwidth problem. Due to its unique characters, IBC technology is proposed as a novel and promising technology for personal area network (PAN), computer network access, implant biomedical monitoring, human energy transmission, etc.

3. Methodology

IBC BFSK Transmitter

The introduction of an IBC system, to enhance the applications of smart sensors is quite critical (B. P. Lathi, 2010 and S. Mishra, 2011).The design of such system requires a lot of sensitive devices and high quality materials. Fig. 1 depicts the block diagram of the employed IBC BFSK transmitter. The presented blocks consist of an analog multiplexer (MUX), analog to digital converter (ADC), parallel in serial out register (PISO) and 80 MHz voltage-controlled oscillator (VCO). Firstly, the pressure sensor is selected by the MUX. The MUX is needed so several pressure sensors can share one ADC and one communication line, instead of having one device per sensor. The sensor output signal is digitized by the 8-bit ADC. Thereafter, the data is serialized by a PISO. Data serialization is required to simplify the data modulation by using a single 80 MHz VCO. Finally, the digitized signal is sent to a BFSK wireless transmitter (based on direct modulation of the 80 MHz VCO). Fig. 3 (a) shows the digital part of the transmitter, whilst, Fig. 3 (b) is the actual backend of the transmitter, which is the 80 MHz VCO.

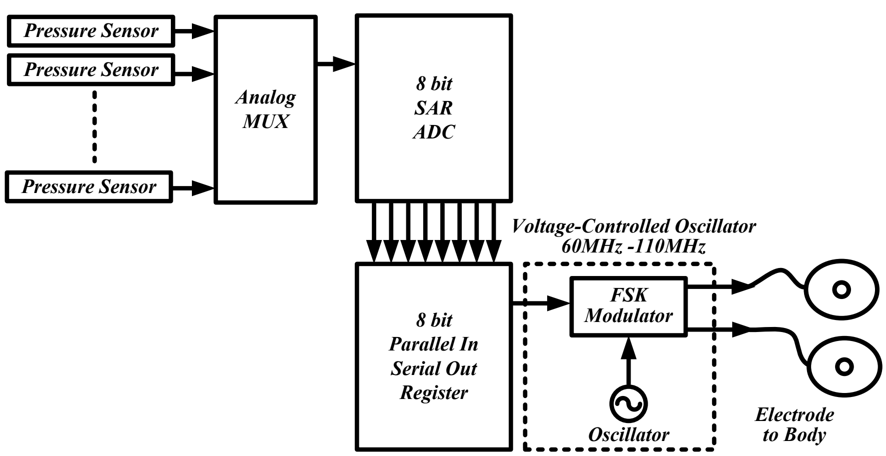


Fig.1. Binary frequency-shift keying intra-body transmitter block diagram

RF BFSK Transmitter

Fig. 2 depicts the block diagram of the RF BFSK transmitter. The presented blocks consist of an analog multiplexer (MUX), analog to digital converter (ADC), parallel in serial out register (PISO) and 2.4 GHz voltage-controlled oscillator (VCO). The digital blocks are exactly the same as the IBC transmitter. Next, the signal is digitized by the 8-bit ADC. Subsequently, the data is serialized by a PISO. Data serialization is required to simplify the data modulation by using a single 2.4 GHz VCO. Lastly, the digitized signal is sent to a BFSK wireless transmitter based on direct modulation of the 2.4 GHz VCO. The system used the same digital part so that we can compare it just based on the transmission procedure. Only the VCO is different for the modulation part so 2.4 GHz signal could use the RF antenna, and the 80 MHz signal could transfer through body. For the digital part we used the same circuit as the IBC transmitter which is shown in Fig. 3 (a) which is then connected to 2.4 GHz VCO and antenna, these circuit is depict in Fig. 3 (c).

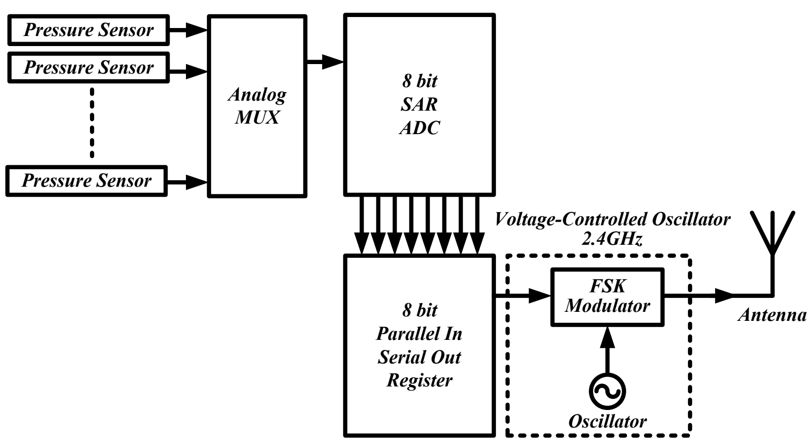


Fig.2. Binary frequency-shift keying 2.4 GHz wireless transmitter block diagram

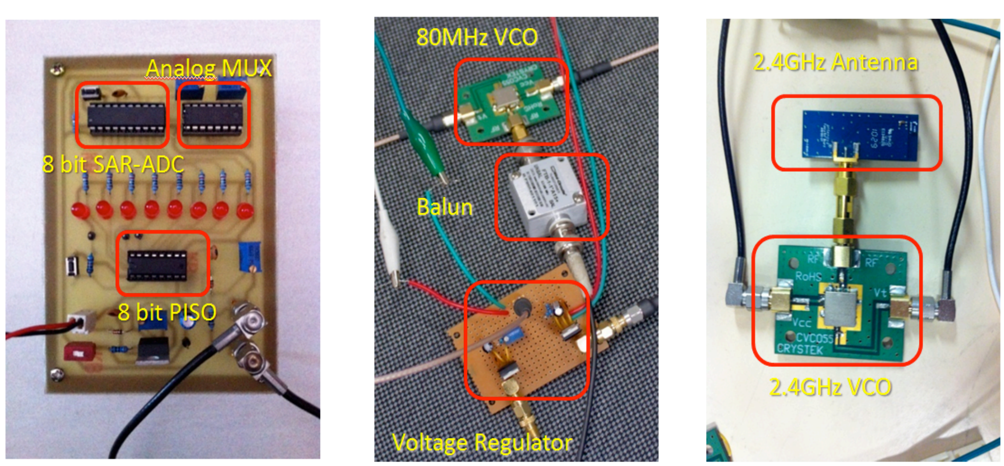


Fig.3. (a) Digital part of the circuit (b) 80 MHz voltage-controlled oscillator and balun (c) 2.4 GHz voltage-controlled oscillator and antenna

IBC Measurement Setup

Human body as a communication channel differentiates from any other communication medium. IBC communication uses the human body as the transmission medium; therefore, various tissue layers such as skin, fat, muscle, and bone have different electrical property's relative permittivity and effective conductivity just to name a few. These properties make the human body a unique communication medium for data transmission. These deviations of electrical properties resulted in the variation of the received signal power, signal distortion and noise level. These assortments have to be mull over in BFSK IBC receiver designs. In our system, we only measured signal transmitting between ankle and waist.

The measurement setup consisted of the designed BFSK transmitter modulating at 80 MHz, an NS-30 spectrum analyzer of NEX1, Noraxon self-adhesive silver/silver chloride (Ag/AgCl) electromyography (EMG) electrodes; EMG snap leads as connecting wires and a pair of baluns of Minicircuits Inc. (FTB-1-1+). Measurement of taking into account are output power, channel power, signal to noise ratio (SNR), and phase noise. These measurements were quantified by using the spectrum analyzer. In order to attain a more accurate IBC galvanic and capacitive coupled transmission path, baluns were used. Balun was used to remove the effect of the internal ground of both BFSK transmitter and spectrum analyzer; baluns also prevented the parasitic return path from being shorted; moreover, transform a single-ended signal into a differential signal.

The IBC experiments were handled with care to make sure accurate results were obtained. Three types of measurement setup were performed. First, we measure the communication parameters for the BFSK transmitter. This is the benchmark for our comparison. Second, through body using galvanic coupled, and lastly, applying the capacitive coupling. The galvanic coupling measurement setup is shown in Fig. 4. The two transmitting electrodes were attached to the skin above the ankle, and the two receiving electrodes placed at the waist. Fig. 5 depicts the setup for IBC capacitive coupled measurement. In the capacitive coupled case, the ground electrodes remained floating in the air. Fig. 6 shows the actual experimental set-up and an example of a data collection trial.

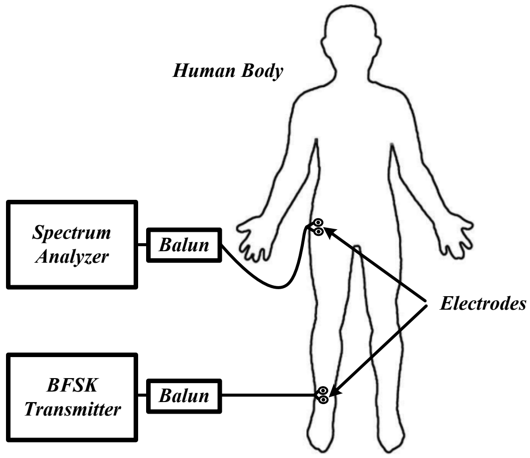


Fig. 4. Galvanic coupling setup.

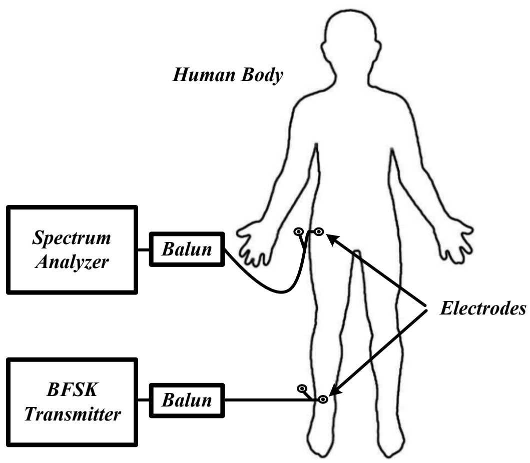


Fig. 5. Capacitive coupling setup.

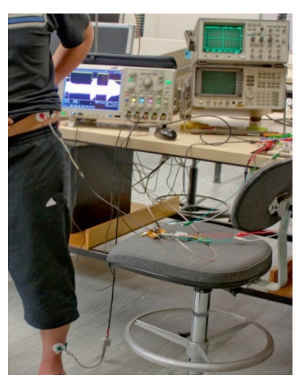


Figure 6. Intra-body communication measurement setup.

RF Measurement Setup

RF wireless communications have been widely used around the world for many applications. In this project the measurement was conducted to compare the output power, channel power, signal to noise ratio (SNR), and phase noise with the IBC setup by using the same circuit.

The measurement setup consisted of the designed BFSK transmitter modulating at 2.4 GHz and 2.4 GHz antenna. The same spectrum analyzer was used to measure all the properties. Two types of measurement setups were used for this experiment. First, we measured the communication parameters for the BFSK transmitter. This is the benchmark for our comparison. The other experiment was performed using antenna making the transmission wireless. The block diagram of measurement setup is revealed in Fig. 7. Fig. 8 depicts the actual setup for wireless RF measurement.

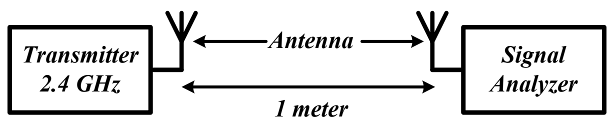


Fig. 7. Radio frequency block diagram.

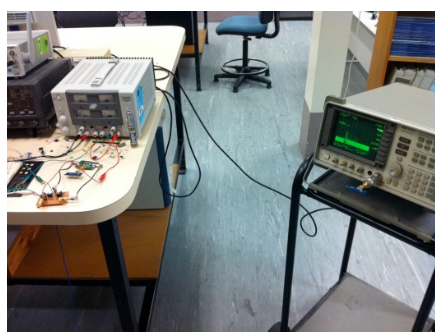


Fig. 8. Radio frequency measurement setup

Protocol

The BFSK transmitter was designed to induce AC current output of 3 mA and 6 dBm maximum output power. Notice that these levels were established well in the bounds of the study of World Health Organization (WHO) on the electromagnetic field exposure effects on health (World Health Organization, 1993) and the International Commission on Non-Ionizing Radiation Protection's (ICNIRP) regulations (A. Ahlbom *et al.*, 1998).

Although our frequency targeted band is between 1 MHz and 100 MHz, for testing and transmitter design we purposely selected transmission center frequency of 80 MHz with the bandwidth of 2 MHz. The center frequency selection was based on a previous study [21, 31] (M. Seyedi *et al*., 2013 and A. H. A. Razak *et al*., 2013), which concluded that in both methods, the minimum attenuation is within the frequency range of 70 MHz to 95 MHz. The signal attenuation for both types of couplings is shown in Fig. 9. In this experiment, the same baluns, electrodes and cables were used as per previous works [21, 31] (M. Seyedi *et al*., 2013 and A. H. A. Razak *et al*., 2013).

In IBC experiments, the receiver electrodes were attached to the subjects' left waist, and the transmitter's electrodes were positioned on the upper left ankle. The transmitter electrodes were 15 cm above the ground level. In the galvanic coupling experiment, as shown in Fig. 4, the ground electrodes were connected to the body. In capacitive technique, as presented in Fig. 5, the ground electrodes of the transmitter and receiver were left floating. During both experimental conditions, the distance between the centers of the transmitter and receiver electrodes was set to 1 meter. In addition, short sheathed cables were used to reduce potential radiation effects during measurements. Measurement for each position was repeated three times and the average reading was recorded.

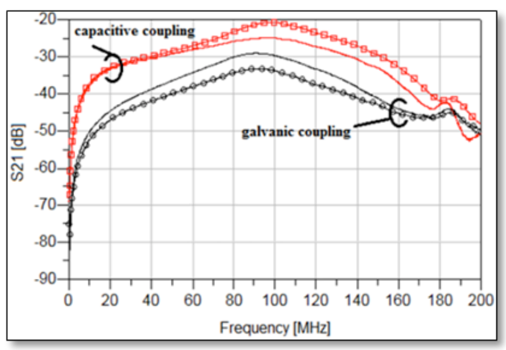


Fig. 9. Comparison of signal attenuation for both intra-body communication methods for frequency range 0.3 to 200 MHz (M. Seyedi *et al*., 2013)

In RF experiments, the receiver electrodes were attached to the subjects' left waist, and the transmitter's electrodes were positioned on the upper left ankle. The RF experiment is shown in Fig. 8. During the experiment, the distance between the centers of the transmitter and receiver electrodes was set to 1 meter. Further, short sheathed cables were used to reduce potential radiation effects during measurements. Measurement for each position was repeated three times, and the average was recorded.

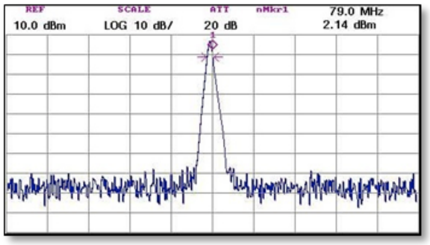
5. Experimental Result

Power Measurement

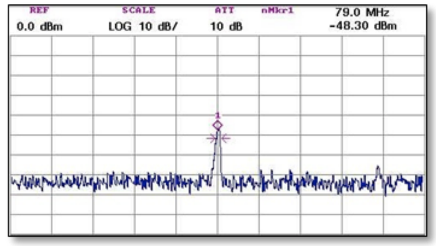
Power measurement is a must in any communication systems; this is to ensure whether the power level is high enough to be captured in the receiver side, and it is also important for designing a suitable amplification at the front end of the receiver without any loss of vital data information. Fig. 10 illustrates the spectrums' analyzer output power of the IBC transmitter, receiver power through IBC galvanic and capacitive method. Fig. 10 shows that the output power is at 2.14 dBm (= 1.64 mW) for IBC transmitter, -48.3 dBm (= 14.8 nW) after the body via IBC galvanic coupling and -66.5 dBm (= 0.22 nW) for the IBC capacitive approach. Correspondingly, Fig. 11 shows that the output power is at -2.50 dBm (= 0.56 mW) for RF transmitter and -57.88 dBm (= 1.63 nW) at RF receiver. These signify that capacitive coupling had the highest insertion loss of 68.64 dB. RF receiver had the second-worst loss with 55.38 dB, and the lowest insertion loss is the galvanic's method, which is at 50.44 dB. Likewise, the channel power in Fig. 12 proves that capacitive method has higher loss compared to wireless RF and galvanic coupling. The channel power for galvanic coupling was -44.36 dBm, for wireless RF it was -56.50 dBm whilst, for capacitive condition it was -61 dBm.

Signal to Noise Ratio Measurement

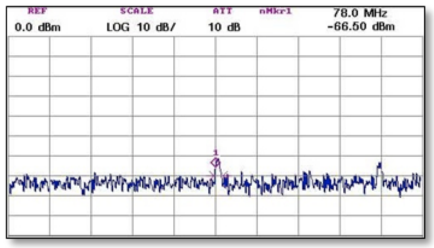
Another standard measurement that represents the quality of a communication system is, signal to noise ratio (SNR). SNR compares the level of a desired signal to the level of background noise. This information is an integral part in transmitter and receiver design. The designed IBC transmitter has 68.58 dB SNR as revealed in Fig. 14.a, whilst the designed RF transmitter has 58.36 dB SNR as disclosed in Fig. 15a. When the signal is transmitted through the human body, the SNR is reduced to 31.17 dB and 13.59 dB for galvanic and capacitive coupling respectively as displayed in Fig. 14b and 14c; however, at RF receiver, the SNR is reduced to 10.67 dB. Thus, RF and capacitive approach will require a more sensitive receiver compared to galvanic approach for our specific application.



(a)

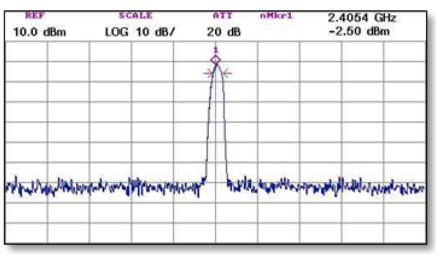


(b)

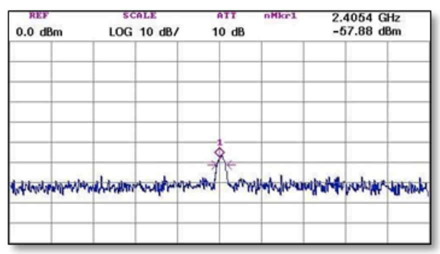


(c)

Fig. 10. Intra-body communication output power measurement: (a) transmitter, (b) galvanic coupling receiver and (c) capacitive coupling receiver

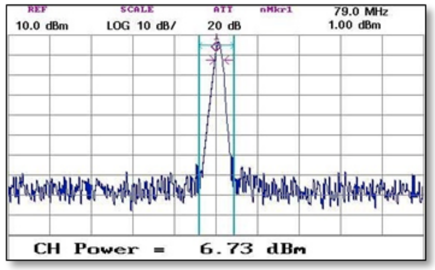


(a)

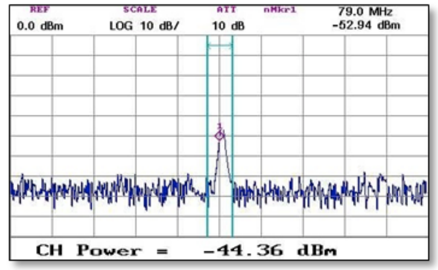


(b)

Fig. 11. Radio frequency output power measurement: (a) transmitter, and (b) receiver



(a)



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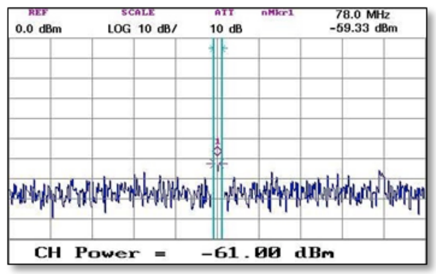
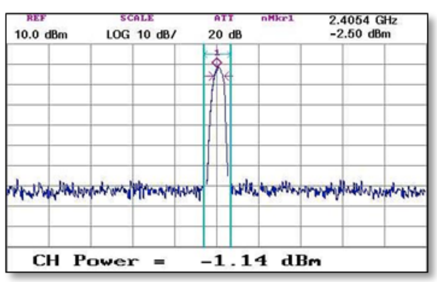
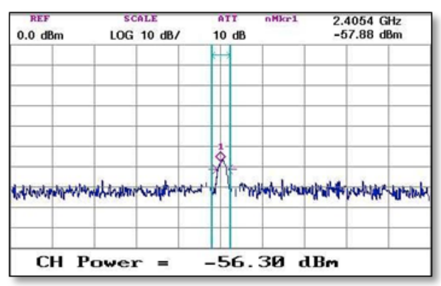


(c)

Fig. 12. Intra-body communication channel power measurement: (a) transmitter, (b) galvanic receiver coupling and (c) capacitive receiver coupling



(a)

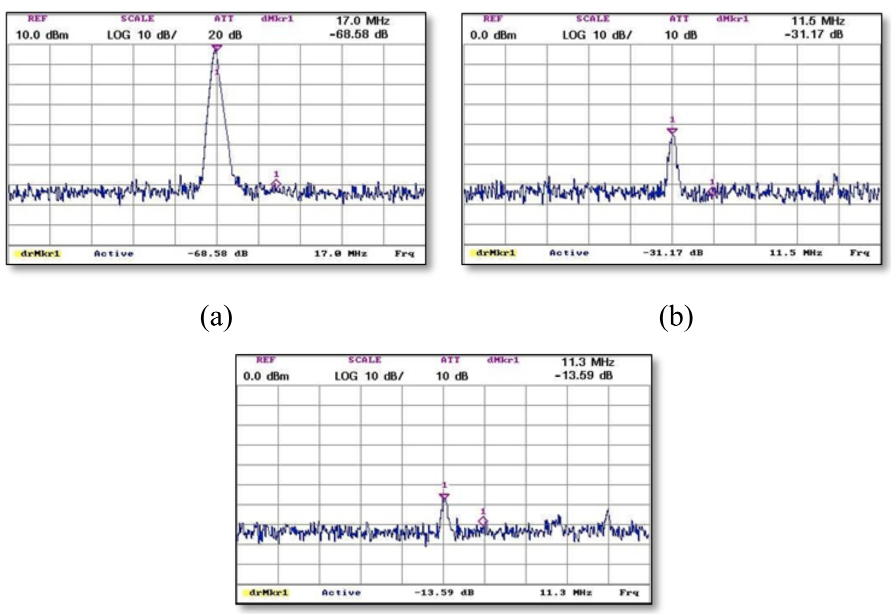


(b)

Fig. 13. Radio frequency channel power measurement: (a) transmitter, and (b) receiver

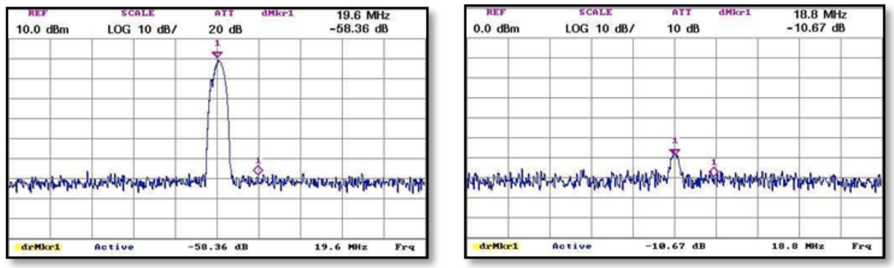
Phase Noise Measurement

Phase noise is the frequency-domain representation of rapid, short-term, random fluctuations in the phase of a waveform, caused by time domain instabilities. Any short-term frequency instability results in diminished performance. Lower phase noise can result in better performance. The NS-30 spectrum analyzer has the capabilities to measure phase noise at offset frequency range of 10 Hz to 100 kHz. For this experiment, we measured the phase noise at 1 kHz, 10 kHz and 100 kHz frequency offset. First, we measured the IBC transmitter phase noise. The result shows -41.75 dBc/Hz at 1 kHz offset, -52.64 dBc/Hz at 10 kHz offsets and -102.1 dBc/Hz at 100 kHz offsets. Secondly, we measured the RF transmitter. The result shows -31.39 dBc/Hz at 1 kHz offset, -41.97 dBc/Hz at 10 kHz offsets and -81.19 dBc/Hz at 100 kHz offsets. For galvanic coupling, the result shows -34.67 dBc/Hz at 1 kHz offset, -39.81 dBc/Hz at 10 kHz offsets and -69.08 dBc/Hz at 100 kHz offsets. Next, for capacitive coupling, the result shows -32.78 dBc/Hz at 1 kHz offset, -35.19 dBc/Hz at 10 kHz offsets and -57.69 dBc/Hz at 100 kHz offsets. Lastly, for RF wireless transmitter, the result shows -30.81 dBc/Hz at 1 kHz offset, -35.03 dBc/Hz at 10 kHz offsets and -36.97 dBc/Hz at 100 kHz offsets. The introduction of IBC increases the phase noise but the RF wireless transmitter has the worst performance in terms of phase noise. From the result presented it can be concluded that the phase noise of both IBC method has minor difference in performance, nevertheless, both IBC method achieved much better phase noise compared to RF system.



(c)

Fig. 14. Intra-body communication signal to noise ratio measurement: (a) transmitter, (b) galvanic receiver coupling and (c) capacitive receiver coupling



(a) (b)

Fig. 15. Radio frequency signal to noise ratio measurement: (a) transmitter, and (b) receiver

6. Discussion and Conclusion

Intra-body communication offers an attractive alternative towards the application of foot plantar pressure sensing systems. IBC is a new short-range non-RF wireless communication technique specified by the IEEE 802.15.6 using the human body as a transmission medium. Using IBC as the communication scheme for foot plantar measurement, the communication transceiver requires lower power to transmit through the body, since body has better conductivity compared to air, which is the medium for traditional radio frequency (RF) transceivers. As it stands, the IBC technique potentially offers a more power efficient and naturally secure short-range communication method for body sensor networks, compared to wireless RF. Though ratified in a standard, there are still remaining challenges such as the effect of user motion on transmission quality, increasing data rates for low frequency carriers and effect of long-term use on health, which requires further advances before this technology matures. Moreover, IBC operates in low bandwidth; hence the transmission data rate is kept at a lower speed this is suitable for our application, as the application targeted on the human gait, which only necessitate low rate of communication data transfer.

An empirical comparison on galvanic, capacitive coupled intra-body communications (IBC) and wireless radio frequency (RF) using binary frequency-shift keying (BFSK) modulation transmitter for foot plantar pressure sensor was presented. Regarding our specific application, galvanic coupling proved to have superior data transmitting performance. For received power measurement, galvanic method detected more than 10 dBm (= 10 mW) higher. The galvanic approach also showed more than 10% better immunity to harmonic distortion over the rest. Moreover, galvanic coupled IBC have nearly 20 dB better SNR over capacitive coupled and RF wireless. Nonetheless, only phase noise results showed relatively similar performance between galvanic and capacitive.

On the other hand, wireless RF communication performed the second-best in every measurement except phase noise, where RF has the lowest performance. Another point we could conclude is that comparing these three types of communication methods IBC capacitive coupling showed the least reading in every measurement we took except for phase noise, where IBC capacitive method has better result compared to RF.

These results have allowed us to assist in the design of the BFSK IBC receiver for foot plantar systems. Further studies are needed in order to clarify other effects that have been out of the scope of this paper, like the dependence of the measurement results on the particular user body, and the effect of human movement towards IBC performance since our application is predominantly concerned with human gait studies.

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