IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 6, 2019, accepted June 19, 2019, date of publication July 12, 2019, date of current version August 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2928343

Assessment of Worn Textile Antennas' Exposure on the Physiological Parameters and Well-Being of Adults

KHUZAIRI MASRAKIN[1], HASLIZA A. RAHIM[1], (Member, IEEE),
PING JACK SOH[2], (Senior Member, IEEE), MOHDFAREQ ABDULMALEK[3], (Member, IEEE),
ISMAHAYATI ADAM[1], (Member, IEEE), MOHD NAZRI BIN MOHD WARIP[4],
QAMMER H. ABBASI[5], (Senior Member, IEEE),
AND XIAODONG YANG[6], (Senior Member, IEEE)

[1]Bioelectromagnetics Research Group (BioEM), School of Computer and Communication Engineering, Universiti Malaysia Perlis at Kampus Pauh Putra, Arau 02600, Malaysia
[2]Advanced Communication Engineering (ACE) Centre of Excellence, School of Computer and Communication Engineering, Universiti Malaysia Perlis at Kampus Pauh Putra, Arau 02600, Malaysia
[3]Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, Dubai 20183, United Arab Emirates
[4]Embedded, Networks and Advanced Computing Research Cluster (ENAC), School of Computer and Communication Engineering, Universiti Malaysia Perlis at Kampus Pauh Putra, Arau 02600 , Malaysia
[5]School of Engineering, University of Glasgow, Glasgow G128QQ, U.K.
[6]School of Electronic Engineering, Xidian University, Xi'an 710071, China

Corresponding author: Xiaodong Yang (xdyang@xidian.edu.cn)

This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant JB180205, and in part by the National Natural Science Foundation of China under Grant 61671349 and Grant 61301175.

ABSTRACT This paper presents the assessment of short-term wireless body area network (WBAN) exposure, which is operated at the industrial, scientific, and medical (ISM) band (2.45 GHz) in the vicinity of the human body. The experiment utilizes two popular textile antenna topologies, a planar monopole and a patch antenna as the radiating sources. The objective of this experiment is to investigate whether the exposure from WBAN may influence the physiological parameters (body temperature, blood pressure, and heart rate) and the well-being of the wearer. Counter-balanced, crossover, and the single-blind method was applied in the experimental setup. P-value is the probability value, under the assumption of no effect or no difference (the null hypothesis) of obtaining a result equal to or more extreme than what was actually observed. If $P < 0.05$, it indicates that P-value will be less than the level of significance. Thus, the null hypothesis (no effect or no difference) can be rejected, and it can be concluded that there exist effects to the respondents. The results showed that there is statistically no significant difference between the active exposure and the Sham (no exposure) which may affect the physiological parameters and well-being of the wearers, with $P > 0.05$, which failed to reject the null hypothesis (no effect).

INDEX TERMS Textile antennas, effects of radiofrequency exposure, physiological parameters, human well-being symptoms.

I. INTRODUCTION

The development of wireless body area networks (WBAN) has been accelerating due to the extensive utilization of wireless networks as well as the decreasing sizes of electronic devices [1]–[8]. The growing interest in a person's own well-being is a pivotal reason that intensified research activities in the field of WBAN [1], [3], [5]–[8]. WBAN architecture comprises of three types of communication tiers: Intra-BAN, Inter-BAN and Beyond-BAN [9], as shown in Figure 1.

Intra-BAN communication is defined as that between the master node and the wireless body sensor. In this tier, the wearable sensor is capable of sensing, sampling, processing and communicating to acquire specific data from subjects. This architecture allows the placement of sensors that can be attached on the body surface (on-body), close to the body (off-body) or inside the body (in-body) [1]. In-body communication is another type of Intra-BAN communication occurring inside the human body. This is known as invasive

The associate editor coordinating the review of this manuscript and approving it for publication was Yuan Zhang.

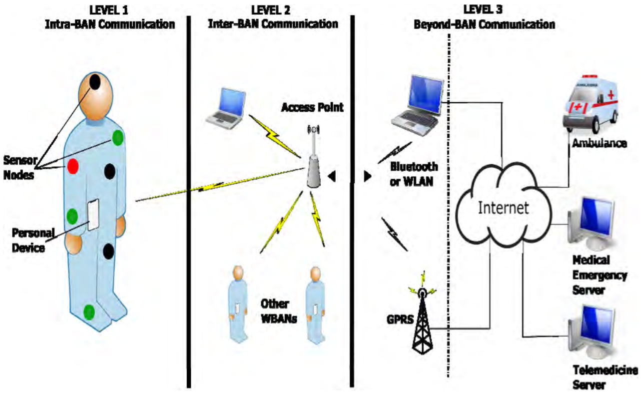


FIGURE 1. General architecture of WBAN [9].

WBAN, where the devices are implanted or placed inside the human body. In conjunction with this rapidly growing technology, IEEE published the standard IEEE802.15.6 in 2012 [10] for WBAN where ISM is defined as one physical layer technique to be used at the frequency ranges of 868 MHz and 2.4 GHz.

Meanwhile, Inter-BAN communication refers to the communications between the master node and one or more access points. This is the tier where other possible wireless technologies are involved, including the likes of wireless local area network (WLAN), Zigbee, Bluetooth, Third Generation (3G) and cellular network [4]. Finally, the Beyond-BAN or the third tier is defined as the communication of personal devices to the Internet. For example, it allows the authorization of medical personnel to access patient's health condition remotely by means of cellular network or Internet such as Wireless Fidelity (WiFi), Fourth Generation (4G) technology and so on. This can also be defined as one of the Internet of Things (IoT) applications [6].

In the near future, it is envisioned that the wearable devices system will be a main component in the upcoming Fifth Generation (5G) networks, featuring higher bit rates and lower outage probabilities in smaller microcells and picocells [11]. This future technology of such wearable systems will include IoT to enhance its availability, features and functions to the end user in healthcare and many other applications [6]. The work in [13] highlighted that health and wellness could be improved through wearable Internet of Things (WIoT), as such system is aimed at connecting body-worn devices to medical personnel through continuous assessment for the subjects (patients). The proper design of WIoT devices will enable comfortable and practical body-worn devices for the users. A Wireless body area sensors (WBAS) is an example of WIoT which is embedded with sensors, processors, storage capability, wireless transceivers and antennas. Also, BodyMedia armband is a peripheral wearable WBAS that aims to monitor fitness to encourage active lifestyle [13]. It is foreseen that one of the key enablers in WIoT will be the wearable antennas.

Such wearable antennas are typically placed very close to the human body, leading to radiation, possible penetration and partial absorption of electromagnetic field (EMF) inside the human body tissues. Due to the possibility of health issues, their effect on the human body has been mainly investigated using the regulated specific absorption rate (SAR) assessment [14]–[16]. It is known that the main biological effects from radiation is the rising of temperature at specific and sensitive organs resulting from the absorption of EM waves by the human tissues. Small temperature increments in sensitive organ determines the severity of the physiological effects [17]. For this reason, knowledge about the effects of WBAN exposure on the physiological parameters and well-being of adults is important and critically needed. Significant amount of research have been reported in open literature on the effects of radiofrequency (RF)-EMF radiation on the well-being subjective symptoms and human physiological parameters primarily resulting from focused on the wireless communication devices such as base station antennas operating in different frequency bands [18]–[21], mobile phones (MP) [22]–[26], WiFi [21] and Terrestrial Trunked Radio (TETRA) handsets [27]. The investigations in [18], [19] were predominantly motivated by a small group of people who believed they were sensitive to exposures to EMF (signals from mobile phones or base stations), further perceiving that they suffered from health-related symptoms. Other studies have reported the effects of MP exposure on well-being subjective symptoms, excluding self-proclaimed RF-sensitive subjects who experienced symptoms while using or being located close to RF sources. Oftedal *et al.* [23] investigated the effects of mobile phone signals operating at 902 MHz on 17 volunteers (five women and 12 men) who have been reported to develop symptoms analogous to those reported when mobile phones were used in the open-provocation test. The authors found no evidence that mobile phone exposure resulted in headache or other health symptoms. More importantly, this study discovered that the subjects were unable to distinguish between non-exposure (sham) and active exposure conditions, implying that a *nocebo* effect (negative expectation) may have affected these reported symptoms. Cinel *et al.* [24] further extended the investigations of the symptoms related to GSM mobile phone exposure using greater numbers of subjects in a double-blind, counter-balanced, randomized and crossover design. Although one group exhibited an induced dizziness during GSM exposure, no consistency was found in the other two study groups. Thus, it was concluded that there was no significant effects of mobile phone exposure on the well-being subjective symptoms. In addition to that, few other studies have reported that mobile phone [22], [23] and base station [19] exposures did not induce physiological effects on blood pressure and heart rate. In [25], Kwon *et al.* also found there is no significant physiological changes (heart rate, heart rate variability, and respiration rate) in both self-reported electromagnetic hypersensitivity (EHS) and non-EHS groups when exposed to third generation (3G) mobile phones operating using the wide code division multiple access (WCDMA). Moreover, Choi *et al.* [26] concluded that WCDMA does not affect the heart rate, respiration rate, heart rate variability and the subjective symptoms in adults. Malek *et al.* [20] also found that there is no indication of negative short-term effects by the base station signals on heart rate, blood pressure and body temperature. In a more recent study, Andrianome *et al.* [21] observed the effects of continuous RF-EMF exposure from signals emulating Global System for Mobile Communications (GSM) 900, GSM 1800, Digital European Cordless Telecommunications (DECT) and Wi-Fi 2.45 GHz signals. Similarly, it was also observed that these signals did not affect the autonomic nervous system, which includes blood pressure and heart rate variability of the EHS subjects.

However, to date, most available studies on the physiological parameters and well-beings of human are limited to the effects of mobile phone and base station exposures, without considering the effects of wearable antennas (and devices) attached directly to the human body. Based on an exhaustive literature review, there is no published investigations on the evaluation of exposure from wearable, textile-based antennas on the heart rate, blood pressure, body temperature and well-being of adults. The information gathered from such study will provide important insights into the significance of the effects of WBAN signal exposure on human. This is due to the location and operation of these antennas close to the human body, and can potentially influence the well-being and physiological parameters in terms of body temperature, blood pressure, and heart rate.

This paper presents an investigation on the exposure assessment of worn textile antennas on the physiological parameters and non-specific reported symptoms of adults. To the best of the authors' knowledge, such investigation is unique. Based on non-specific reported parameters of symptoms, blood pressure, body temperature and heart rate, the short-term exposure effects on the physiological parameters and well-being of adults are investigated. Furthermore, two types of realistic and fully textile antennas operating at 2.45 GHz are assessed: (1) a planar textile monopole (TM) antenna with a partial ground plane, and (2) a textile patch antenna (TP) with a full rear ground plane, respectively, and evaluate their exposures with blood pressure, body temperature and heart rate. Both antennas are suited for on-body implementation.

The rest of the paper is organized as follows. Section II presents the antenna topologies and experimental setup used in this study. Section III discusses the results for well-beings and physiological parameters as mentioned above. Finally, conclusions are drawn in Section IV.

II. METHODOLOGY

To determine the effects of WBAN RF radiation exposure on the well-being and physiological parameters, an experimental procedure was conducted to identify them in adults. These parameters, namely blood pressure, pulse pressure, body temperature, heart rate and unspecific reported symptoms are widely used in literature to confirm their associations with exposure, and the procedure is described in detail as follows.

A. SUBJECTS

Experiments were performed on 20 adults (10 males and 10 females; with an average age of 25 years and standard deviation (SD) = 2.4). The minimum age is 23 years and the maximum age is 31 years old. They were of normal body weights between 19 and 26 kg/m^2. The exclusion criteria include the use of artificial cochlea, hearing aids, pacemakers, smoking, psychiatric disease, regular consumption of psychotic drug in the previous six months, alcohol consumption of more than 10 drinks per week or caffeinated drinks of more than three cups per day, and polymorbidity with respect to chronic disease. In addition, those who sat in a long-haul flight for more than three hours of different time zones and shift workers within the month prior to the experiment were also excluded. Female subjects were matched to the menstrual cycle accordingly.

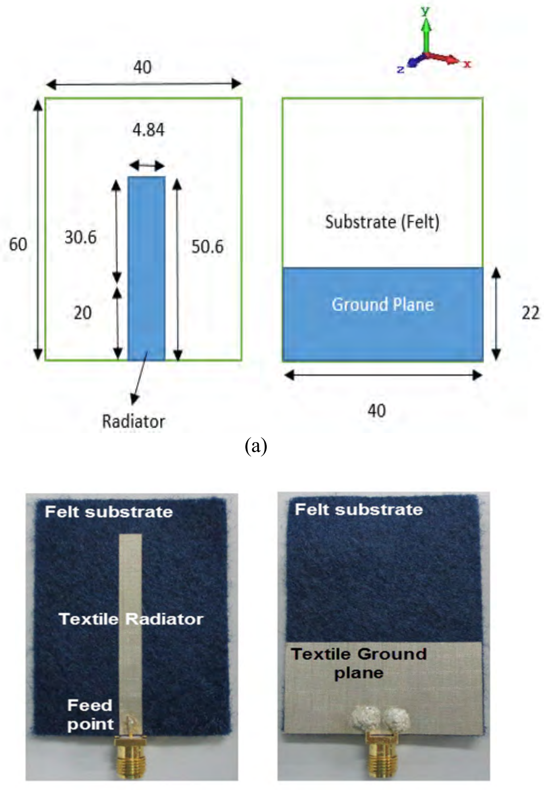
From the calculation, 20 participants per group were required to obtain the result of 0.90 power level and 0.40 small effect with detection significant of a model at $\alpha = 0.005$. Analysis of G$*$ power was used to ensure that the number of participants is sufficient to perform the experiment [28]. The sampling size is consistent with the studies performed in [23], [29].

Prior to the experiment, all the participants were informed about the aims of this study and written informed consent were obtained from participants who agreed to participate in this study. The methods conducted adhere to the approved guidelines, and were approved by the Ethics Committee, Universiti Malaysia Perlis (Perlis, Malaysia).

B. ANTENNA TOPOLOGY

A pair of quarter-wave planar TM was used in this experiment. It consists of three layers, a ground plane, a substrate and a patch. *ShieldIt Super*^{TM} conductive textile and felt were used to build the conducting material and the substrate material, respectively. The 1.7 mm thick felt substrate features a dielectric constant, ε_r of 1.4, and a loss tangent, $tan\delta$ of 0.025 at 2.58 GHz. The antenna is fed via 50Ω microstrip line with length, $L_m = 20$ mm, whereas the monopole length, that determines the resonant frequency is $L_m = 0.25\lambda = 30.6$ mm. The overall dimension of this antenna is 40 × 60 mm^2, as illustrated in Figure 2(a). Figure 2(b) shows the front and back view of the fabricated antenna prototype. The proposed antenna, which has a wider bandwidth and smaller size than the antenna in [30], can be applied for WLAN and Worldwide Interoperability for Microwave Access (WiMAX). The detailed description of the TM antenna and its performance is provided in [31], [32].

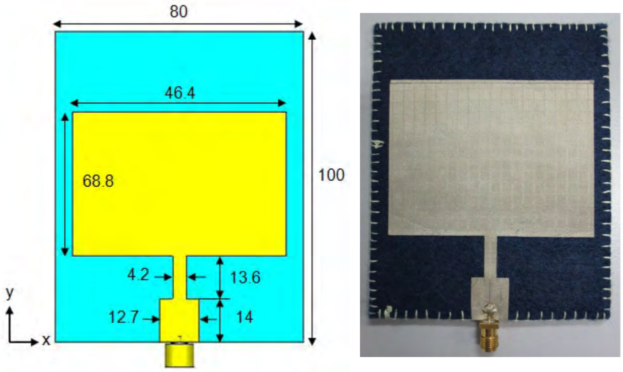
This investigation was expanded to consider the effects of exposure from another popular WBAN antenna topology, a textile patch (TP). Patch antenna was chosen due to its planar structure and simple integration into user's garment [33].



(a)

(b)

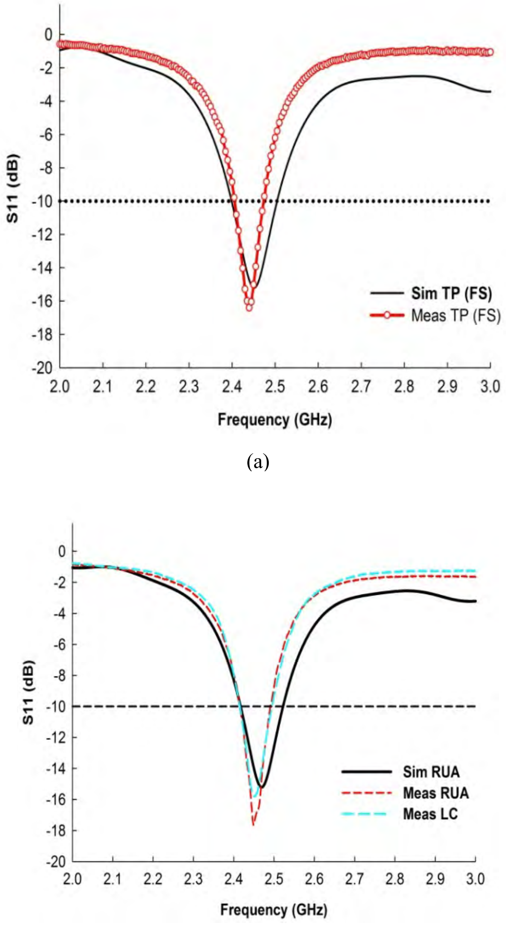
FIGURE 2. **Structure and dimension (a) of planar textile monopole antenna in millimeters and fabrication prototype (b) in front and back views [31].**



(a) (b)

FIGURE 3. **Prototype structure and dimension (a) of planar TP in millimeters and (b) prototype of front views.**

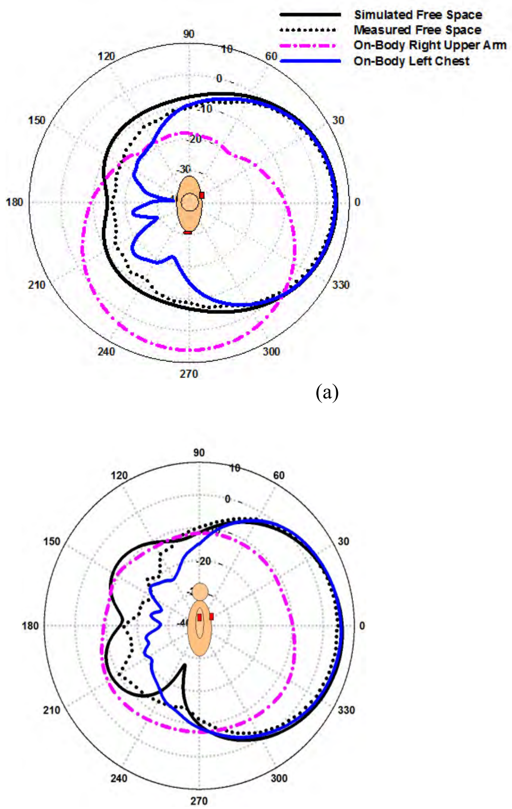
The 80 × 100 mm^2 TP antenna is designed to operate at 2.45 GHz, with a patch size of 68.8 × 53.4 mm^2. Its antenna schematic and a photograph of the fabricated prototype are shown in Figure 3. As with the TM, the conductive elements of the TP were fabricated using Shieldit Super, while felt was used as its substrate. A subminiature version A (SMA) connector feeds the transmission line at the bottom center of the TP, which is matched using a quarter-wavelength transformer between the 50 Ω (Z_o) input and antenna. There was satisfactory agreement between the simulated and measured reflection coefficient (S_{11}) in free space and on-body, as illustrated in Figure 4 (a) and (b). The radiation patterns illustrated in Figure 5 (a) and (b) indicate that the forward radiation of TP remained unchanged for free space and for on-body placements. The simulated and measured S_{11}, resonant frequency, and bandwidth were compared, indicating that the agreement is satisfactory. The comparison of gain, total radiated efficiency, and 3-dB beamwidth in free space and on body also are included in Table 1, indicating good agreements. The results also showed that S_{11} did not differ much when placed closer to the body, consistently maintaining a bandwidth of at least 70 MHz. The bandwidth exhibited by this antenna is higher compared to [34], and is satisfactory for operation in the ISM band. Due to its full rear ground plane, the TP enable shielding against the effects of the body, reducing power absorption and dielectric coupling, besides influencing its SAR level [14]. The choice of TP antenna is representative for slight influence of exposure. For such study, it is believed that the use of an antenna which will



(a)

(b)

FIGURE 4. **Simulated and measured S_{11} of TP antenna (a) in free space (FS) and (b) on-body.**



(a)

(b)

FIGURE 5. Simulated and measured S11 and radiation pattern of TP (a) *xz*-plane ($\varphi = 0°$) and (b) *yz*-plane ($\varphi = 90°$).

TABLE 1. Parameters of textile patch antenna in free space and on body.

Parameter		Textile Patch (TP)		
		Free Space	On-Body	
			Upper Right Arm	Left Chest
S_{11}	Simulated	-15.2 dB	-13.9 dB	-13.4 dB
	Measured	-15.0 dB	-12.4 dB	-12.3 dB
Resonance	Simulated	2.45 GHz	2.47 GHz	2.47 GHz
	Measured	2.44 GHz	2.45 GHz	2.46 GHz
Bandwidth	Simulated	101 MHz	103 MHz	103 MHz
	Measured	70 MHz	75 MHz	79 MHz
Realized gain	Simulated	6.33 dB	6.15dB	5.82 dB
Total radiated efficiency	Simulated	61%	53%	52%
3-dB Beamwidth	Simulated	68°	69°	75°

provide consistency in terms of performance with minimal influence from the body is of particular importance. In the extreme case of non-shielded antennas, the proximity of the body and its influence will typically results in fluctuations in reflection characteristics, unless that it is spaced sufficiently apart from the body. Most importantly, the results obtained at the particular frequency of interest will not be meaningful if, for example, the intended antenna used for the exposure study suffers from frequency shift and is operating in another frequency band instead when placed near to the body. Moreover, as a comparison, we have also performed the exposure experiments using TM, which can be influenced by the effects of the body, depending on the placement distance in [31]. Due to these justifications, we believe that the antenna must first display some level of immunity against the effects of coupling from the body before it can be deemed representative for such exposure assessments. Thus, these two textile antenna topologies are selected for examination to better understand their effects on the well-being and physiological parameters of adults. To provide an initial idea of the safety level of both antennas in terms of radiation, their SAR values are first calculated and simulated in an electromagnetic solver software (CST Computer Simulation Technology Microwave Studio, Munich, Germany). This is performed when the antennas are placed on a realistic Hugo body voxel model. SAR is defined as a measure of the power absorbed per unit of mass (human body tissue). It can be spatially averaged over the total mass of an exposed body or its parts, and it is calculated from the root-mean-square electric field strength, E defined in volts per meter (V/m). Meanwhile, the conductivity, σ is defined in Siemens per meter; and the mass density, ρ represents the biological tissue density in kilogram per cubic meter. SAR can be calculated as follows [35]:

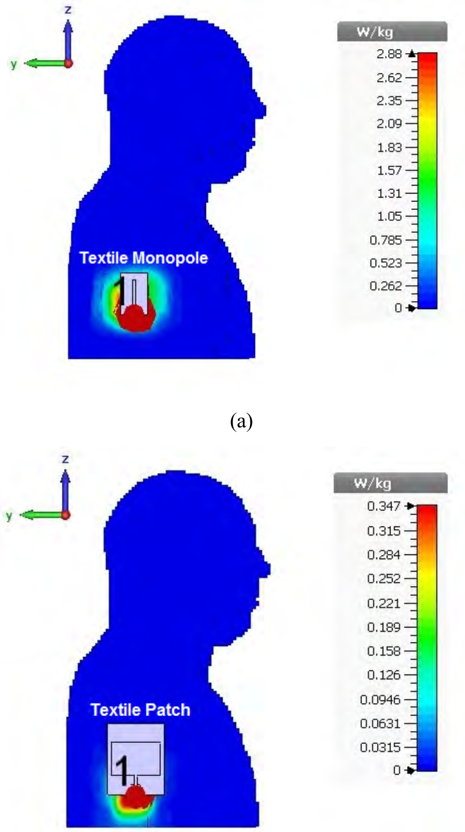
$$SAR = \frac{\sigma \cdot E}{\rho} = c \left.\frac{\partial T}{\partial t}\right|_{t \to 0^+} \tag{1}$$

SAR also describes the initial rate of temperature rise of a tissue, $\partial T/\partial t$ as a function of the specific heat capacity (c). During simulations, the voxel body model was truncated to reduce computation time. For TM and TP, the maximum 10g SARs are observed to be 2.88 W/kg and 0.35 W/kg, respectively, when placed on the right upper arm, as shown in Figure 6.

These SAR values are well below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limit of 4 W/kg (limbs) when SAR is averaged over 10g of tissue [36].

C. EXPERIMENTAL SETUP

The experiments were performed by mounting the transmitter (Tx) onto the upper right arm since it does not limit body movement and realistic for WBAN application [3]. Both the transmitter and the receiver antennas were both vertically-oriented (with the radiator placed on the top section) when mounted on the subject's body. The receiver (Rx) was mounted on the left chest of the subjects, as shown in Figure 7. This placement mimics the position of the electrocardiogram (ECG) sensor. Moreover, this location may represent the worst-case scenario when a non-line-of-sight (NLOS) propagation path is considered, compared to the widely-investigated transmitter placement on the chest [3]. It has the mean distance of 37.2 cm (for TM) and 37.8 cm (for TP), as shown in Figure 6. Both TM and TP were fed with continuous waves (CW) which are centered at 2.45 GHz (WBAN2450). The experimental session took a total of 60 minutes, where 5 minutes was allocated for pre-exposure, 50 minutes of exposure and 5 minutes of



(a)

(b)

FIGURE 6. SAR evaluation on Hugo body model at 10g on right upper arm (a) TM and (b) TP antennas facing outward.

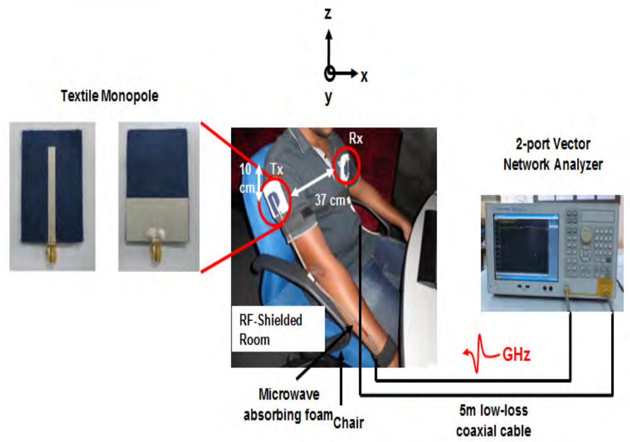


FIGURE 7. RF exposure experiment setup with on-body wearable TM antenna.

TABLE 2. Sample of well-being questionnaires completed by the subjects.

	No /Never	Slightly Annoying	Annoying	Very Annoying
1. Dizziness				
2. Fatigue				
3. Nervousness				
4.Chest tightness or muscle stiffness				
5. Headache				
6. Chest pain				
7.Difficulties with clear thinking				
8. Tension				
9.Wandering mind				
10.Easily distracted				

post-exposure. A 1-mW (0 dBm) input power which is higher than the minimum requirement of the IEEE802.15.6 WBAN standard was fed into the TM. Based on this standard, a transmitter should be able to transmit a minimum of -10 dBm equivalent isotropic radiation power (EIRP). Thus, devices should transmit lower power whenever possible in order to protect the safety of the human body [37]. In addition, according to [38], it is believed that 0 dBm is still to be a high transmitter power for WBAN, thus the choice of this level to be evaluated.

The coaxial cables were wrapped with microwave-absorbing foam (Eccosorb Flexible Broadband Urethane Absorber number FGM-U-20-SA) to minimize the spurious radiation from the coaxial cable and the coupling between them. Agilent Vector Network Analyzer (VNA) model ENA5071C was used in this experiment. Ports 1 and 2 of the VNA connect to the TX and Rx, respectively. This study was conducted in a comfortably air-conditioned, RF-shielded room sized at 4 × 3 × 2.5 m^3, furnished with a plastic armed chair, a table and a personal computer (PC). The room was protected from external electromagnetic (EM) interferences and other reflections by placements of flat metallic sheets on its walls. Measured shielding effectiveness of the room was performed prior to the exposure experiments, and was found to be more than 40 dB between 1.8 GHz and 3.2 GHz. Background RF radiation levels between the frequencies of 80 MHz and 4 GHz were also measured over the exposure area before and after the experiments to ensure that this level was under 1 mV/m. The room temperature and relative humidity were maintained and consistently monitored to be at 28.26°C±0.3°C and 40.2 %±2.5 % to ensure that these factors does not affect the results of the experiment.

Prior to the experiments, a questionnaire was provided to all subjects to identify possible symptoms experienced during and after the exposure sessions. The questionnaire consists of ten symptoms commonly reported by subjects exposed to RF radiation as in [19], [24], [26]–[27]. Each symptom is evaluated at a rating scale of 1 (not annoying) to 4 (very annoying) to identify the level of severity, as suggested by Kwon *et al.* [25] and Choi *et al.* [26]. Table 2 presents the questionnaires used in this experiment to assess the well-being subjective symptoms. In addition to that, changes in three physiological parameters (i.e., blood pressure, body temperature and heart rate) were also recorded.

Counter-balanced, randomized, crossover and single-blind technique was applied in the experimental session, consistent with the experimental procedure proposed in [20]. The human subjects underwent two types of exposure sessions, namely Sham (no exposure) and WBAN2450. The order for the subjects was random and both exposures were counter-balanced across subjects. Each exposure type was divided into three sessions: pre-exposure, during exposure, and post-exposure. A complete schedule of the order (1 to 20) for all participants was generated to ensure that the order is balanced. The single-blind condition means that the subjects will not know the type of exposure (Sham or WBAN2450) being applied to them, which is performed in a randomized crossover design. This ensures that the randomness occurs in each subject in which next exposure will not be affected by the preceding exposure.

In this study, the P-value approach is used in the hypothesis testing to summarize the findings of the research [39]. It is defined as the probability value, under the assumption of no effect or no difference (the null hypothesis) of obtaining a result equal to or more extreme than what was actually observed [40]. Experimental hypothesis was designed to test the validity of the experiments, whether the radiation from the textile antenna could give significant difference or affect the tested parameters. P-value is known only after a result is observed. Hypothesis test outcome is one of two; to reject one hypothesis and accepting the other [41]. The level of significance, α, need to be set and it is the area in the critical region. The P-value is located in the area to the right or left of the test statistics. If the test statistic is located in the critical region, the P-value is less than the level of significance. Thus, null hypothesis (no effect or no difference) can be rejected, and it concluded that an effect exists. The hypotheses to be verified in this work are twofold, explained as follows.

- First, the null-hypothesis: There is no statistically significant difference with respect to tests on well-being conditions, and physiological parameters (body temperature, blood pressure, and heart rate) during Sham exposure, in comparison to the exposure to WBAN2450 signals.
- Second, the alternative hypothesis: There is a statistically significant difference of the well-being conditions, and physiological parameters (body temperature, blood pressure, and heart rate) during Sham exposure in comparison to the exposure to WBAN2450 signals.

To study the exposure effect of the wearable textile antennas on the subjective symptoms, Pearson chi-squared was performed for each symptom between Sham (Control group) and WBAN2450 exposure. A non-parametric Wilcoxon signed rank test [42] was used to analyze the possible effects of WBAN2450 exposure between two conditions, namely pre-exposure (before) and post-exposure (after). To further explore the effects of the WBAN2450 exposure on the physiological parameters, three sets of analyses were performed. The aim of the first analysis is to determine whether there is a significant difference between the two different signals (Sham and WBAN) for the average body temperature (BT), blood pressure systolic (BPS), blood pressure diastolic (BPD), pulse pressure (PP), mean arterial pressure (MAP), and heart rate (HR) under two exposure conditions, i.e., pre-exposure and post-exposure.

The second analysis was performed to examine whether the short-term WBAN2450 exposure affects BT, BPS, PP, MAP, and HR. This is performed by comparing the mean values of these physiological parameters obtained from pre- and post-exposure stages. The paired sample t-test was applied to analyze the probability effects between pre- and post-exposure of the WBAN2450 signals on the physiological parameters. The data is then analyzed using analysis of variance (ANOVA) repeated measures of the Greenhouse-Geisser F-test (Condition [Pre vs. Post] X Signal [Sham vs. WBAN2450]).

The third analysis was performed to compare whether the mean values of BT, BPS, PP, MAP, and HR are significantly different for the different antennas, within signals and for the interaction between the antennas and different signals. The possible interaction between the antennas and signals were analyzed using with the two-way ANOVA repeated measures (Antenna [TM vs. TP] X Signal [Sham vs. WBAN2450]). The null hypothesis was rejected at a significance level of 0.05 ($\alpha = 0.05$), represented by the P-value. Thus, a P-value < 0.05 is considered statistically significant [20], [26]. Each P-value is computed using Statistics Package for the Social Sciences (SPSS) software version 18.0, and will be presented in the following Results and Discussion section.

III. RESULTS AND DISCUSSION

The findings from the experiments based on the ten well-being parameters such as dizziness, nervousness, fatigue, headache, wandering mind, muscle stiffness, being easily distracted and muscle pain are summarized in Table 3. It shows that the majority of subjects indicated that the exposure was "not annoying" while a minority of the subjects chose "slightly annoying". None of the subjects chose "annoying" and "very annoying". The symptom of "slightly annoying" for WBAN exposure had more number of subjects, while Sham exposure had less number of subjects who reported "slightly annoying". During the WBAN exposure, an additional five more subjects reported "slightly annoying" wandering mind symptoms in comparison to the Sham exposure. However, no association was found between Sham and WBAN exposures (Pearson chi-squared, $P > 0.05$). In general, there was no significant association between the Sham and active exposures in any subjective symptoms, indicating that none of the symptoms that were experienced are associated with the WBAN exposure (Ps'$>$0.05). When the subjects have no knowledge whether they are being exposed to Sham (no signal) or WBAN signals, most of the subjects reported no symptoms in both exposure conditions. This demonstrated that both exposures (Sham and WBAN) give

TABLE 3. Results for well-being subjective symptoms.

Symptoms	Signal	Rating				*P*-Value
		1	2	3	4	
Dizziness	Sham	19	1	0	0	0.548
	WBAN2450	18	2	0	0	
Fatigue	Sham	20	0	0	0	[a]
	WBAN2450	20	0	0	0	
Nervousness	Sham	19	1	0	0	1.000
	WBAN2450	19	1	0	0	
Chest Tightness or Muscle Stiffness	Sham	19	1	0	0	0.311
	WBAN2450	19	1	0	0	
Headache	Sham	20	0	0	0	0.311
	WBAN 2450	19	1	0	0	
Chest Pain	Sham	20	0	0	0	[a]
	WBAN 2450	20	0	0	0	
Difficulties with Clear Thinking	Sham	19	1	0	0	1.000
	WBAN2450	19	1	0	0	
Tension	Sham	19	1	0	0	0.311
	WBAN2450	20	0	0	0	
Wandering Minds	Sham	18	2	0	0	0.212
	WBAN2450	15	5	0	0	
Easily Distracted	Sham	19	1	0	0	0.548
	WBAN2450	18	2	0	0	

Note: Ratings 1=Not Annoying, 2=Slightly Annoying, 3=Annoying, 4: Very Annoying. [a]No statistics were computed.

TABLE 4. Z-scores and *P*-values for the well-being symptoms experienced during Sham and WBAN exposures.

	Sham vs. WBAN2450	
	Pre-Exposure Z-Score (*P*-Value)	Post-Exposure Z-Score (*P*-value)
Dizziness	0.00[a](0.5)	0.00[a](0.5)
Fatigue	0.00[a](0.5)	0.00[a](0.5)
Nervousness	-1.41(0.08)	-0.58(0.28)
Chest Tight or Muscle Stiffness	0.00[a](0.5)	0.00[a](0.5)
Headache	0.00[a](0.5)	-1.41(0.08)
Chest Pain	0.00[a](0.5)	-1.41(0.08)
Difficulties with Clear Thinking	-1.00(0.16)	-0.58(0.28)
Tension	0.00[a](0.5)	0.00[a](0.5)
Wandering Minds	-1.00(0.16)	-1.41(0.08)
Easily Distracted	0.00[a](0.5)	-1.00(0.16)

Notes: Wilcoxon signed rank test is based on positive ranks. [a]The sum of negative ranks equals the sum of positive ranks. $*P<0.05$.

TABLE 5. The descriptive statistics for physiological parameters.

	Sham		WBAN2450		*P*-value
	Mean (S.E)	S.D	Mean (S.E)	S.D	
PreBT	36.41 (0.09)	0.38	36.48 (0.10)	0.46	0.16
PostBT	36.54 (0.07)	0.32	36.52 (0.08)	0.37	0.78
PreBPS	117.45 (2.38)	10.66	117.65 (3.06)	13.69	0.87
PostBPS	115.75 (2.62)	11.70	116.20 (3.79)	16.93	0.78
PrePP	45.00 (1.58)	7.06	45.20 (1.91)	8.56	0.89
PostPP	43.10 (2.35)	10.51	43.35 (2.94)	13.17	0.79
PreMAP	87.45 (1.90)	8.51	87.50 (2.30)	10.30	0.95
PostMAP	87.10 (1.60)	7.14	87.35 (2.65)	11.83	0.86
PreHR	76.45 (2.12)	9.48	76.70 (2.30)	10.29	0.50
PostHR	77.15 (1.85)	8.27	77.40 (1.99)	8.89	0.45

TABLE 6. Results of the statistical tests for the physiological parameters.

	Sham	WBAN2450		*P*-Value	
	Mean (S.E) (*P*-Value)	S.D	Mean (S.E) (*P*-Value)	S.D	Condition *Signal
Pre-BT - Post-BT	-0.13 (0.05) (<0.05)	0.21	-0.04 (0.10) (0.70)	0.45	0.31
Pre-BPS - Post-BPS	1.70 (2.26) (0.46)	10.08	1.45 (3.06) (0.64)	13.68	0.89
Pre-PP - Post-PP	1.90 (2.27) (0.41)	10.17	1.85 (3.03) (0.55)	13.57	0.98
Pre-MAP - Post-MAP	0.351 (1.28) (0.79)	5.72	0.15 (1.76) (0.93)	7.87	0.84
Pre-HR - Post-HR	-0.70(1.32) (0.60)	5.89	-0.70(1.43) (0.63)	6.40	1.00

negative effects to the well-being of the adults. Thus, this further confirmed that all symptoms evaluated, i.e., dizziness, fatigue, nervousness, chest tightness, headache, chest pain, difficulties with clear thinking, tension, wandering minds and easily distracted were not found to be related to the exposure to the WBAN2450 signals emitted from the textile antennas. This conclusion is consistent with the findings found in [18], [19], [23]–[27].

In a further analysis, the total symptom score, which measures symptom severity was analyzed by means of nonparametric statistics. Wilcoxon signed rank test was applied to investigate the effects of WBAN exposure on the well-being symptoms in two different conditions, i.e., before and after exposures. This is determined by the Z-scores and *P*-Values presented in Table 4. The Wilcoxon signed rank is used to determine the correlation between the conditions of exposure and well-being symptoms. This is due to the fact that a majority of individuals reported experiencing no symptoms in any conditions (WBAN and SHAM) [19], [27]. The results show that the minimum total symptom score for pre-exposure was ($z = -1.41, P > 0.05$) and for post-exposure was ($z = -1.41$, $P>0.05$). This indicates that the participants experienced the similar severity for both pre-exposure and post-exposure conditions. Neither the subjects who were exposed before nor after exposure showed significant differences in any of the ten subjective symptoms surveyed between Sham and WBAN exposures ($P > 0.05$). Thus, the well-being of the subjects was not affected by exposure to the WBAN signals emitted by the textile antenna. The results agreed well with the findings in [19], [24], [26]. Cinel *et al.* reported that the exposure to RF-EMFs cannot be attributed to all symptoms examined in their study, i.e., headache, fatigue, itching or tingling of skin, and sensations of warmth on skin [24]. Choi *et al.* also reported that eight examined subjective symptoms such as throbbing, itching, warmth, fatigue, headache, dizziness, nausea and palpitation) were not found to be related to exposure to RF-EMF of mobile phone for normal adults [26]. An idea of the effect of WBAN exposure on the resulting physiological parameters: BPS, PP, BT, MAP, and HR can be found by comparing the mean values between Sham and WBAN signals under two conditions during pre-exposure and post-exposure. This can be deduced from Table 5. The results demonstrated consistency of the physiological data during both Sham and WBAN exposures, with a maximum variation of 4 %. Table 6 presents the mean difference of two conditions (Sham and WBAN2450 exposure), in pre- and post-exposure, in terms of standard deviations, standard errors, and *P*-values. Table 7 shows the finding comparisons of proposed assessment to the previous studies.

TABLE 7. Findings comparison of proposed assessment to previous studies with respect to well-being and physiological parameters.

References	Exposure	Blind Design	Subject	Crossover	Measurement	Findings
[22]	Mobile phone; GSM 900 and 1800; 35 min	Double	32 adults	(GSM 900, GSM 1800, OFF)	Physiological parameters (BP and HR)	No effect on BP and HR
[23]	Mobile phone GSM 902.4; UMTS 2140; 30 min	Double	17 adults	(ON, OFF)	4 subjective well-being symptoms Physiological parameters (BP and HR)	No effect on subjective symptoms, BP and HR
[24]	Mobile phone GSM 888; Exp 1:45 min L/R; Exp 2:40 min L/R	Double	Exp1 & 3: 168; Exp 2:160 (GSM, CW) x (L,R)	(ON, OFF)	5 subjective well-being symptoms	No consistent effect on subjective symptoms
[18]	Base station UMTS 2140; 45 min, 2 m	Double	33 EHS; 84 control	(0, 1, 10 V/m)	5 subjective well-being symptoms	No effect on subjective symptoms
[19]	Base station GSM 900 + 1800; UMTS 2020; 50 min, 5 m	Double	44 EHS; 44 control	(GSM, UMTS, OFF)	6 subjective well-being symptoms Physiological parameters (BP and HR)	No effect on subjective symptoms, BP and HR
[27]	Base station TETRA 420 MHz; 50 min, 4.95 m	Double	51 EHS; 132 control	(ON, OFF)	6 subjective well-being symptoms Physiological parameters (BP and HR)	No effect on subjective symptoms, BP and HR
[25]	Mobile phone 3G WCDMA 1950; 64 min	Double	17 EHS; 20 non-EHS	(ON, OFF)	8 subjective well-being symptoms Physiological parameter (HR)	No effect on subjective symptoms and HR for EHS and non-EHS subjects
[26]	Mobile phone 3G WCDMA 1950; 64 min	Double	26 adults; 26 teenagers	(ON, OFF)	8 subjective well-being symptoms Physiological parameter (HR)	No effect on subjective symptoms and HR
[20]	Base station GSM 945, 1840; UMTS 2140; 2 m	Single	100 EHS; 100 non-EHS	(GSM 900, GSM1800, UMTS, OFF)	Physiological parameters (BT, BP and HR)	No effect on physiological parameters (BT, BP and HR)
[21]	Base station GSM 900, GSM 1800, DECT and WiFi 2.45 GHz; 5 min	Double	10 EHS; 25 non-EHS	(GSM 900, GSM 1800, DECT, WiFi, OFF)	Autonomic nervous system that include BP and HR	No effect on physiological BP and HRV
Proposed assessment	Wearable textile antenna 2.45 GHz; 50 min	Single	20 adults	(ON, OFF)	10 subjective well-being symptoms Physiological parameters (BT, BP and HR)	No effect on subjective symptoms and physiological parameters (BT, BP and HR)

The statistical analysis indicated that there was no significant difference between exposure to Sham and WBAN signals ($P > 0.05$) in any of the conditions (pre- or post-exposure) for all measured physiological parameters (see Table 6). This proves that the physiological parameters of the subjects were unaffected by the radiation from the TM worn by the subjects. The mean difference of BPS, PP, MAP, and BT between Sham and WBAN exposures is about 20.6 %, 2.6 %, 20.1 % and 69.2 %, respectively. The paired sample t-test pre-exposure and post-exposure indicated that there was no significant difference between Sham and WBAN ($P > 0.05$) for the physiological parameters (BPS, PP, MAP and HR) that were measured, except for BT in Sham exposure ($P < 0.05$). This is due to the higher mean BT during the post-exposure (mean ± S.E = 36.54 ± 0.07) in comparison to the mean BT during the pre-exposure (mean ± S.E = 36.41 ± 0.09) under Sham. Although indicating the highest percentage difference between Sham and exposure to WBAN signals, BT for the subjects remained under the normal body temperature range from 36.1°C to 37.2°C (see Table 5). In addition to that, the ANOVA repeated measures of the Greenhouse-Geisser F-test showed no significant interaction between the conditions and types of signals ($P > 0.05$). Thus, it can be concluded that there was no significant difference in the measured physiological parameters when the subjects were exposed to the WBAN radiation. These findings are

TABLE 8. Statistical test results for the physiological parameters using TM and TP prototypes.

	Sham				WBAN2450				*P*-Value
	TM		TP		TM		TP		
	Mean (S.E)	S.D	Mean (S.E)	S.D	Mean (S.E)	S.D	Mean (S.E)	S.D	(Antenna), (Signal) (Antenna*Signal)
BT	36.36 (0.09)	0.39	36.35 (0.08)	0.38	36.32 (0.11)	0.47	36.46 (0.11)	0.49	(0.22), (0.23) (0.11)
BPS	116.45 (2.42)	10.84	117.20 (2.06)	9.19	116.10 (3.26)	14.6	117.10 (2.80)	12.53	(0.58), (0.81) (0.85)
BPD	74.40 (1.73)	7.76	73.95 (1.87)	8.34	72.95 (2.61)	11.65	73.80 (2.39)	10.69	(0.87), (0.54) (0.26)
PP	42.05 (1.86)	8.32	43.25 (1.41)	6.29	43.15 (2.49)	11.16	43.30 (1.42)	6.36	(0.70), (0.65) (0.50)
MAP	88.40 (1.78)	7.97	88.40 (1.82)	8.16	87.35 (2.57)	11.48	88.20 (2.46)	10.99	(0.69), (0.54) (0.38)
HR	75.80 (1.77)	7.93	76.70 (1.85)	8.28	75.65 (1.98)	8.84	76.35 (2.44)	10.93	(0.31), (0.63) (0.76)

similar with results reported in [19], [25], [26], as shown in Table 7.

Table 8 shows the values of statistical test results for the different antenna topologies: TM and TP. The absence of a rear ground plane in an antenna is expected to influence the SAR levels. In [14], it was found that antennas without a rear ground plane were producing almost three times the SAR of textile antennas that feature a full ground plane. This may induce changes on the physiological parameters of adults; thus, an additional validation effort was made to quantify this aspect. The results indicated that a maximum of 1.2 % BPD difference when exposed to WBAN signals emitted by the two different textile antennas. Although TM produced consistently slight lower body temperature, minor differences can be observed in terms of blood pressure and heart rate when the subjects are exposed to signals between TM and TP. The use of the partial ground plane in the TM provided limited shielding against the RF radiation. However, a larger distance between the TM antenna and the body, d_{TM}, is needed to avoid severe performance degradation of the antenna [31]. This was set at 10 mm in the experiments, which may contribute to minor variations of physiological parameters. This is to emulate a realistic practical worn spacing on a 5-mm thick jacket and 5-mm air-gap to allow for spacing between jacket and the body [14], [31]. In comparison, the distance between the TP and the body, d_{TP} is set closer, at 4 mm. Moreover, in Sham exposure, all measured physiological parameters differences are minimum or remain consistent, validating that there is no changes on the measured BT, BPS, PP, MAP and HR in the absence of WBAN radiation. The statistical analysis in Table 8 shows that there is no significant difference between the monopole and patch antennas ($P > 0.05$), no significant difference between the two signals ($P > 0.05$), and no significant interaction between the antennas and the types of signals ($P > 0.05$). Thus, it is confirmed that the measured physiological parameters were unaffected by short-term WBAN exposure radiated by different antenna topologies.

IV. CONCLUSION

In this paper, the short-term exposure of worn textile antennas is assessed at 2.45 GHz on the physiological parameters and well-beings of adults. The results highlight that there are no association between ten subjective symptoms of well-being and the short-term WBAN exposure on adults under pre-exposure and post exposure. Measured physiological values also suggested that there are no negative health impacts on the adults when exposed to the WBAN signals, even when using different antenna topologies. Thus, it may be concluded that the RF radiation emitted by the textile antennas worn on body has not affected the physiological parameters and well-being of adults.

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KHUZAIRI MASRAKIN was born in Johor, Malaysia. He received the bachelor's degree in computer network engineering from Universiti Malaysia Perlis (UniMAP), in 2016, where he is currently pursuing the master's degree in communication engineering with the School of Computer and Communication Engineering (SCCE).

He was an Assistant Engineer with Propel Network Sdn Bhd, Shah Alam, Malaysia, during his internship program, in 2015, being involved in signal drive tests for various Internet service provider, such as Maxis and Celcom. As a master student, he is also involved in providing teaching assistance and assessments for courses, such as real time systems. His research interest includes antenna and propagation involving radio-frequency (RF) signal and electromagnetic field (EMF). He is also a Silver Award Winner for his project entitled Smart Climate Monitoring for Airport Operation by Enabling Internet of Thing (IoT) in UniMAP Invention Exposition 2017.

HASLIZA A. RAHIM received the bachelor's degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA, in 2003, the master's degree in electronics design system from Universiti Sains Malaysia, Malaysia, in 2006, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, Perlis, Malaysia, in 2015. In 2006, she joined the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP), as a Lecturer, where she is currently a Senior Lecturer. She is the Programme Chairperson for the postgraduate studies at SCCE, UniMAP, where she is also a Researcher with the Bioelectromagnetics Research Group. She was leading the Malaysian Communications and Multimedia Commission Research Grant (worth U.S. $150k). She has been mentoring several undergraduate students and about 12 graduate students. She has authored or coauthored about 100 leading international technical journal and peer-reviewed conference papers, including three articles in Nature Publishing Group journals (such as *Scientific Reports*), three patents, and two book chapters. Her research interests include wearable and conformal antennas, metamaterials, antenna interaction with human body, on-body communications, green microwave absorbers, wireless body area networks (WBANs), bioelectromagnetics, physical layer protocols for WBAN, and 5G massive multiple-input-multiple-output systems. Several research funds were granted nationally and internationally, such as the Fundamental Research Grant Scheme, the National Science Fund, and the Short Term Grant of UOWD (worth U.S. $375k). She has been a member of the technical program committee of several IEEE conferences and a Technical Reviewer for several IEEE and other conferences. She is also a member of the IET and IEEE MTT-S and a Graduate Member of the Board of Engineers Malaysia. As an Advisor, her supervised projects have also won prizes, such as the Third Place at the IEEE Malaysia Section Final Year Project Competition (Telecommunication Track), in 2017. She was recognized as the Excellence Woman Inventor by UniMAP, in 2011. She received the Silver Medal at the International Invention, Innovation & Technology Exhibition (ITEX 2018).

PING JACK SOH was born in Sabah, Malaysia. He received the B.Eng. and M.Eng. degrees in electrical engineering from Universiti Teknologi Malaysia (UTM), in 2002 and 2006, respectively, and the Ph.D. degree from KU Leuven, Belgium, in 2013.

From 2002 to 2004, he was a Test Engineer with Venture Corporation. In 2005, he joined Motorola Solutions Malaysia as an Research and Development Engineer, where he was involved in the characterization and testing of new two-way radios' antennas and radio-frequency (RF) front ends. In 2006, he joined the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP), as a Lecturer, where he was the Deputy Director of the Centre for Industrial Collaboration (CIC), from 2007 to 2009. He went on leave from UniMAP, in 2009, to pursue his Ph.D. degree and research attachment at KU Leuven. He was a Research Assistant, from 2009 to 2013, and a Postdoctoral Research Fellow, from 2013 to 2014. Upon his return to UniMAP, he resumed his role as a Senior Lecturer and concurrently served as the Deputy Dean of the university's Research Management and Innovation Center (RMIC), from 2014 to 2017. He is currently an Associate Professor with SCCE, UniMAP, and a Research Affiliate with KU Leuven. His research interests include wearable antennas, arrays, metasurfaces, on-body communication, electromagnetic safety and absorption, and wireless and radar techniques for healthcare applications.

Dr. Soh is also a member of the IET, ACES, and URSI and a Graduate Member of the Board of Engineers Malaysia (BEM). He was a recipient of the IEEE Antennas and Propagation Society (AP-S) Doctoral Research Award, in 2012, the IEEE Microwave Theory and Techniques Society (MTT-S) Graduate Fellowship for Medical Applications, in 2013, and the International Union of Radio Science (URSI) Young Scientist Award, in 2015. He was the Second Place Winner of the IEEE Presidents' Change the World Competition, in 2013. Two of his (co)authored journals were also awarded the CST University Publication Award, in 2012 and 2011. He is also an Associate Editor of the *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields* (Wiley). He is also a Chartered Engineer registered with the U.K. Engineering Council and a Professional Technologist registered with the Malaysia Board of Technologist (MBOT).

MOHDFAREQ ABDULMALEK received the B.Eng. degree (Hons.) in electronic and communication engineering from the University of Birmingham, U.K., and the M.Sc. (Eng.) degree (Hons.) in microelectronic systems and telecommunications and the Ph.D. degree in electrical engineering (applied electromagnetic) from the University of Liverpool, U.K.

He held industrial positions for five years at Alcatel Malaysia and Siemens Malaysia. He was with the Asia Pacific Regional Centre of Competence, Alcatel, specializing in mobile radio network design. He was with the Information and Communication Mobile Division, Siemens, where he developed the mobile strategy for the Malaysia market. He was with Universiti Malaysia Perlis. He is currently an Associate Professor with the Faculty of Engineering and Information Sciences, University of Wollongong in Dubai (UOWD), where he teaches a broad range of engineering courses, including network engineering, circuits and systems, engineering electromagnetics, engineering design for sustainability, wireless communication systems, essentials of engineering mathematics, and power engineering. He maintains a broad range of research interests that covers a wide range of applied engineering, including applied electromagnetic, telecommunication engineering, antenna, microwave absorbers from agricultural wastes (rice husks, sugar cane bagasse, and banana leaves), microwave drying, effects of radio frequency (RF) on health, RF energy harvesting, and wireless communication. He believes in hybrid, multi-disciplinary teamwork and collaboration with researchers from other disciplines. He has obtained various national research and commercialization grants at the national level in Malaysia. He has generated total Research and Development funds of AED 4.8 million over the past seven years, coordinated 28 research projects, published over 350 peer-reviewed scientific articles, received over 1000 citations, chaired seven international conferences, and successfully graduated 20 Ph.D. students. He has authored or coauthored seven books/book chapters. His research outcomes have appeared in journals, such as *Scientific Reports* (Nature Publishing Group) and the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.

Dr. Abdulmalek is also a Professional Member of the Institute of Engineering and Technology (IET). He received 52 medals and one Special Award (World Invention Intellectual Property Association) at a number of high-profile international exhibitions.

ISMAHAYATI ADAM (M'16) received the M.Eng. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia and the Ph.D. degree from Universiti Malaysia Perlis, Malaysia, in 2008 and 2018, respectively, where she has been a Lecturer with the School of Computer and Communication Engineering, since 2008. Her research interests include antenna design and radio frequency (RF) energy harvesting.

MOHD NAZRI BIN MOHD WARIP was born in Selangor, Malaysia. He received the B.Eng. degree (Hons.) in electronic and electrical engineering from the University of Portsmouth, U.K., in 1996, the M.Eng. degree in electrical-electronics and telecommunications from the University of Technology, Malaysia, in 2007, and the Ph.D. degree from the University of Strathclyde, Glasgow, U.K., in 2013.

He has over 12 years of industrial experience in networking and telecommunications and has successfully delivered projects in many sectors, including giant telecommunication companies, universities, banks, airports, and enterprises. From 1996 to 2000, he was a Network Systems Engineer with Sapura IT, where he was involved in network and ICT infrastructure implementation. In 2001, he joined Datacraft (Dimension Data), Malaysia, as a Network Engineer. He is currently a Senior Lecturer with the School of Computer and Communication Engineering, Universiti Malaysia Perlis. His research interests include GMPLS, SDN, green networking, wireless sensor networks, control plane, optical switching, network security, VANET, IP over WDM, GMPLS, 100-Gb Ethernet transport, passive optical networks, broadband networks, grid networks, network architecture and cross-layer interaction design, optical network modeling, green networks, energy harvesting, and emerging trends in future core/metro/access networks technologies. He is a Chartered Engineer in U.K., a Chartered IT Professional of the BCS, a chartered institute for IT, and a Professional Engineer of the Board of Engineers Malaysia.

QAMMER H. ABBASI received the B.Sc. and M.Sc. degrees (Hons.) in electronics and telecommunication engineering from the University of Engineering and Technology (UET), Lahore, Pakistan, and the Ph.D. degree in electronic and electrical engineering from the Queen Mary University of London (QMUL), U.K., in 2012. In 2012, he was a Postdoctoral Research Assistant with the Antenna and Electromagnetics Group, QMUL. From 2012 to 2013, he was an International Young Scientist with the National Science Foundation, China, and an Assistant Professor with UET. From 2013 to 2017, he was with the Center for Remote Healthcare Technology and the Wireless Research Group, Department of Electrical and Computer Engineering, Texas A&M University (TAMUQ), as an Assistant Research Scientist, and was then promoted to Associate Research Scientist and Visiting Lecturer, where he was leading multiple Qatar National Research Foundation grants (worth U.S. $3 million). He is currently a Lecturer (Assistant Professor) with the School of Engineering, University of Glasgow. He is also a Visiting Research Fellow with QMUL and a Visiting Associate Research Scientist with TAMUQ. He has been mentoring several undergraduate and graduate students and postdoctoral researchers. He has a research portfolio of around U.S. $3 million and has contributed to a patent, five books, and over 100 leading international technical journal and peer-reviewed conference papers. His research interests include nano-communication, radio-frequency (RF) design, and radio propagation, biomedical applications of millimeter and terahertz communication, wearable and flexible sensors, compact antenna design, antenna interaction with human body, implants, body-centric wireless communication issues, wireless body sensor networks, non-invasive health care solutions, physical layer security for wearable/implant communication, and multiple-input–multiple output systems. He is a member of the IET and a Committee Member of the IET Antenna and Propagation and the Healthcare Network. He has been a member of the technical program committee of several IEEE flagship conferences and a Technical Reviewer for several IEEE and top-notch journals. He has contributed to organizing several IEEE conferences, workshops, and special sessions in addition to the European School of Antenna Course. He received several recognitions for his research. He was the Chair of the IEEE Young Professional Affinity Group. He acted as a Guest Editor for numerous special issues in top-notch journals. He is also an Associate Editor of IEEE ACCESS.

XIAODONG YANG is currently with the School of Electronic Engineering, Xidian University, Xi'an, Shaanxi, China. He has published over 80 papers in peer-reviewed journals. His main research interest includes body area networks. He received the Young Scientist Award from the International Union of Radio Science in 2014. He serves on the Editorial Board of several IEEE and IET journals, including the IEEE JOURNAL OF ELECTROMAGNETICS, RF AND MICROWAVE IN MEDICINE AND BIOLOGY. He has a global collaborative research network in the related fields.

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