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A Review on Strategies to Enhance the On-Body Read Range of Passive UHF RFID Tag

DiviyaDevi Paramasivam[1,2], Raimi Dewan[1,2,3,4*], Kok Yeow You[2], Faishal Adilah Suryanata[1,2]

[1]Advanced Radio Frequency & Microwave Research Group, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[3]IJN-UTM Cardiovascular Engineering Centre, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.
[4]Department of Biomedical Engineering and Health Sciences, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

*Corresponding author: raimi.dar@utm.my

Abstract: Passive Ultra-High-Frequency Radio Frequency Identification (UHF RFID) tag has been implemented as a wearable device for numerous healthcare applications. However, the tag possesses limitations owing to the absorption of electromagnetic radiation by the human body, which significantly reduces the read range of the tag. Thus, the potential strategies to mitigate the effect of the human body need to be addressed. Recently, significant efforts have been made to overcome this shortcoming by incorporating metamaterials or introducing slots to the tag antenna structure. Therefore, this article provides insight into strategies that specifically employ slots, Artificial Magnetic Conductor (AMC), and Split Ring Resonator (SRR). Prior to this, the factors affecting the read range and previously reported studies are briefly discussed. Finally, the future directions for further improvement of these strategies are discussed.

Keywords: Metamaterials, RFID tag, read range, slot, wearable

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1. INTRODUCTION

Radio frequency identification (RFID) system is a wireless communication technology comprising of a tag, a reader, an antenna, and a computer to interpret the data, as shown in Figure 1. The RFID tag, also known as a transponder, is a device attached to an object that will be tracked. The tag consists of three main components such as a micro-chip for processing and storing data, a substrate, and an antenna for receiving and transmitting radio waves to communicate with an RFID reader [1]. Meanwhile, a RFID reader or interrogator is a device that will transmit signals in the form of radio waves to the tag through an antenna. The RFID tags are classified based on the requirement of the power source to function. For instance, the tags are divided into three groups, such as active, semi-passive, and passive tags [2, 3]. Among these, the passive tags are widely explored due to the absence of a built-in battery, which contributes to longer life and is lightweight [3, 4].

Besides that, the passive RFID tags are categorized into three bands, such as Low Frequency (LF) (125-135 kHz), High Frequency (HF) (13.56 MHz), and Ultra-High-Frequency Bands (UHF) (860-960 MHz and 2.4 GHz). When comparing the tags in terms of size, the UHF tag has a size that is very thin and almost two-dimensional (2D). In addition, the manufacturing process of UHF tags is much simpler than LF and HF tags. Moreover, the UHF tag operating at 860-960 MHz has a read range of up to 6 m [3]. This attracted the attention of the researchers to implement the passive UHF RFID tag in various applications, such as in access control systems for buildings, monitoring food quality by embedding in the packages, tracking the goods in logistics, and tracking the livestock in poultry farms [4]. Hence, this successful application of RFID in many sectors leads to its implementation in healthcare for real-time tracking of patients' location and data and the management of medical equipment [5].

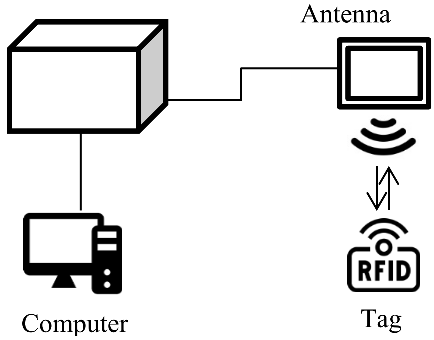

Figure 1. Working principle of a typical RFID system

Currently, the implementation of passive UHF RFID tags is on the rise, markedly in the field of healthcare. In particular, the tag has been implemented as a wireless body area network (WBAN) to monitor physiological data, such as blood pressure [6], and heart rate [7], and to monitor and detect the movement or pose of the wearer, [8], especially for the elderly, to detect a possible fall [9]. The incorporation of tags as WBAN in healthcare is driven by their low cost and ability to provide wireless data transmission and real-time monitoring. However, one of the major challenges of implementing the WBAN is the poor on-body read range. WBAN is reported that the UHF RFID tag's performance is affected in terms of read range by the presence of high-dielectric human tissues when it is implemented as a wearable sensor [10-12]. Accordingly, to address this deficiency, the researchers have investigated several different approaches, such as the inclusion of metamaterials and the introduction of slots. These metamaterials include Artificial Magnetic Conductor (AMC) and Split Ring Resonator (SRR). Several studies, including a thorough analysis by Marcus Gardil, summarise the on-body and off-body performance of the UHF RFID tag antenna [13]. However, the summary of the literature on on-body read range enhancements utilizing slot, AMC and SRR are not discussed. Therefore, this article aims to unravel the above-mentioned strategies to mitigate the human body effect. In this article, first, the factors affecting the read range and the reduction in on-body read range reported in previous studies are discussed. This is followed by the studies that implemented the slot, AMC, and SRR. Finally, the future directions for further improvement of these strategies are discussed.

2. READ RANGE OF UHF RFID TAG

The term read range refers to the greatest distance at which the RFID tag is able to receive the minimal threshold power that is required to switch on or activate the chip and backscatter the signal into the surrounding environment [14]. The Friis formula is used to calculate the read range of the tag (r) and it is expressed in Equation (1) [14]:

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{G\tau\, EIRP}{P_{th}}} \quad (1)$$

where λ is the wavelength of the RFID signal, G is the gain of the tag antenna, τ is the transmission coefficient, $EIRP$ is the regulated equivalent isotropic radiated power and P_{th} is the sensitivity of the chip.

The on-body read range of the tag is affected by several factors. The first factor is the antenna gain [15], which is defined as the capability of the antenna to transmit or receive signals by converting the input power to radio waves that are directed in a particular direction [15]. The reader antenna gain is a crucial parameter, as it provides the power that is required to regulate the read range. This can be observed from Equation (1) where the gain is directly proportional to the read range. Therefore, when a long-read range is required, a reader antenna with high gain must be used. Conversely, a lower antenna gain is used for applications that require a shorter read range [15].

Next factor is the tag size. Since the tag size is directly proportional to the read range, the bigger the size of the tag antenna, the longer the read range. In contrast, the smaller the size of the tag antenna, the shorter the read range [15]. Besides that, the tag orientation affects the read range when only a linearly polarized reader antenna is used [16]. This is because when the tag is tilted, the linearly polarized reader antenna will not be able to detect the tag. As a result, the power transfer between the tag and the reader antenna is reduced. This leads to a reduction in the read range and affects the tag performance. Therefore, the reader or the tag antenna needs to be rotated or positioned to align with the position of the tag along the direction of the polarization [3]. However, the tag orientation can be neglected if a reader antenna with circular polarization is used. This is due to the ability of the reader antenna to interact with the tag that is positioned in any orientation in the plane that is perpendicular to the tag-reader line [3].

On the other hand, tag placement is a crucial factor when using UHF RFID tags, as their performance is greatly affected by the presence of metal or water [17]. The presence of the metal causes the reflection of the RF energy, which results in the detuning of the tag [18]. As a consequence, the resonant frequency of the tag is shifted from the intended operating frequency band. Meanwhile, tagging the objects containing water or animal or human tissues causes the absorption of the RF energy [15]. Furthermore, the read range is substantially affected by a variety of environmental conditions. Fluorescent lighting, water, metal, other radio waves, and huge machinery are a few of the elements that will reduce the read range [15, 17]. The elements cause detuning, absorptions, and impedance mismatches, which result in a reduction of the read range [4]. The last factor is the reader's settings. The reader's power and sensitivity also affect the read range of the tags. When the power setting of the reader is high, the read range will be longer, and vice versa [15]. Similarly, when the reader's sensitivity is set to maximum, it is capable of detecting the weaker backscattered signal from the tags that are placed at a greater distance. Therefore, setting the reader with full power and higher sensitivity enables the maximization of the read range. When analyzing these factors for an on-body tag, the proximity of the human tissues severely affects the read range of the tag, and it is discussed in the following subsection.

2.1 Effect of Human Body to UHF RFID Tag's Read Range

Tags in close proximity to the human body cause the absorption of electromagnetic (EM) radiation from the RFID reader. As a result, the radio wave received by the tag decreases, leading to a reduction in the radiation efficiency of the tag. Consequently, the tag antenna gain decreases to 80%, and this impacts the read range [19]. Moreover, it is worth noting that different body parts reduce the read range according to their tissue composition. This is due to the different electrical properties of the human body. Each body part has its own electrical properties, such as permittivity and conductivity, which vary according to the density of the underlying adipose tissues, muscles, and bones. Not only that the tissue composition also varied according to the weight of the human body. For instance, obese users tend to have more fat tissues compared to normal-weight users. As a result, the read range of tags on obese weight users is lower than the normal weight user [20]. Thus, reading range is crucial to consider the body part that the tag is going to be attached to and the tissue composition of the user's body. The effects can be seen from the reported studies that evaluated the on-body read range of the tag, as described in the following subsection.

2.2 State of the Art of On-body UHF RFID Tag

Currently, the researchers are exploring the possibility of implementing the tags as epidermal sensors with reasonable on-body read range. For instance, a wireless and battery-less epidermal sensor was developed by Camera et al. [21] to determine the body temperature [21]. The main purpose of this work is to assess the reliability of UHF RFID tag as the epidermal sensor and its capability to reproduce the measurements obtained using the standard axilla electronic thermometer. The tag has a smaller footprint with a dimension of 11 × 8 mm^2 compared to the overall size of the sensor together with the biocompatible silicone. Thin and small structure of the sensor enables the attachment of the sensor to human body parts like the axilla without affecting the comfort of the user. The performance of this sensor was assessed on volunteers in real-life situations. The result showed that this sensor's performance is comparable with the degree of agreement of ±1 °C with the conventional axilla thermometer. When analyzing in terms of the read range, the reader can only detect the sensor when it is placed in close proximity at a distance of 20 cm. Hence, this shorter read range is not feasible in real-life applications as the reader must be placed closer to the patients, impacting the movement and comfort.

On the other hand, a wearable UHF RFID tag with additional components such as batteries and inertial measurement unit (IMU) sensors was proposed by Colella et al. [22] for the biomechanical analysis of human body movement [22]. The tag consists of a meandered planar inverted-F antenna (PIFA) and an RFID chip (EM4325) with a dual-access memory that enables the connection of a wired serial peripheral interface (SPI) and wireless communication with the RFID readers. The battery was used to enhance the chip sensitivity and power the IMU sensor. This tag is realized on the FR-4 substrate. The data collected from the tag was then processed into software called OpenSense to obtain the biomechanical movement. The reader is able to detect the body movement of the volunteer when the volunteer is at a distance of 9 m. This higher read range is contributed by the use of batteries, which enhances the sensitivity of the chip to -24.38 dBm. However, the requirement for a battery contributes to the bulkiness of the overall structure, and the seamless incorporation of the tag cannot be achieved.

Next, Hughes et al. [23] developed a tag with a direct-driven resonant radiator (DDRR) antenna and an EM4325 chip integrated with an accelerometer to track the movement of the human body based on passive backscattering communications [23]. The reader was able to detect the sensor at a distance of 2.1 m when it was attached to the human body. This enables body movement tracking at a distance without the requirement of the reader being in close proximity.

On the other hand, a textile-based UHF RFID antenna with a simple configuration was embroidered on a surgical mask as preliminary experimentation and input to the implementation of the RFID system in health care [24]. The antenna with an operating frequency of 868 MHz was developed with a chip with a lower sensitivity of -10 dBm. Despite the lower chip sensitivity, the sensor can operate with a read range of 1.1 m and 0.8 m when the surgical mask is on the face and placed on the hand, respectively.

The on-body read range of the above-mentioned literatures is summarized in Table 1. From Table 1, it can be observed that there is a reduction in the on-body read range, where it is reduced by 31% to 68% compared to the off-body read ranges, as reported in [22-24]. Similarly, shorter on-body read range of 0.2 m was reported in [21]. This is due to the presence of the human body, which consists of 60% water with a higher electrical permittivity and causes the absorption of electromagnetic radiation from the RFID reader [25]. As a result, the radio wave received by the tag decreases and leads to a reduction in the tag antenna gain that influences the read range, as expressed in Equation (1). Not only that, the on-body application of the tags causes poor impedance matching between the tag antennas and chips [26]. As a result, the read range is affected and decreased significantly [25]. Lastly, the different compositions of the tissue layers also affect the read range. This can be observed from the on-body read range reported in [24] where the placement of the sensor on the hand causes the read range to reduce by 68% compared to the read range when it is placed on the face (56%). Therefore, the effects of human body tissues need to be taken into account prior to designing the tag for on-body applications. The strategies that have been used to resolve this issue is discussed in the next section.

Table 1. Summary of on-body UHF RFID tags' read range reported in literatures

Refs.	Frequency (MHz)	Overall size (mm)	Off-body read range (m)	Body Part	On-body read range (m)
[21]	867	15.0 ×10.0	-	Axilla	0.2
[22]	866	133.0 × 68.0 × 3.2	13	Shoulder and pelvis	9.0
[23]	866	40.0 × 40.0*	3.6	Right arm	2.1
[24]	868	-	2.5	Face	1.1
				Hand	0.8

*Antenna with circular dimension

3. STATE OF THE ART OF THE STRATEGIES TO REDUCE THE EFFECT OF HUMAN BODY

Extensive research has been done to reduce the effect of the human body on the performance of the tag. Among them, the most commonly utilized methods are the introduction of slots and the incorporation of metamaterials. Metamaterials are groups of artificially engineered structures that do not exist naturally [27]. Hence, the incorporation of the metamaterial with a particular geometry or size contributes to desired and unique properties with the ability to manipulate the EM waves. This results in successful adaptation of metamaterials for wearables [28]. As of now, there are various classifications of metamaterials that are available, such as electromagnetic band-gap (EBG), SRR, AMC and High-Impedance Surface (HIS) [28]. Among these, AMC and SRR have been explored in studies by incorporating with the tag to decouple the tag antenna from the human body. Thus, this article explores the methods, such as slot, AMC and SRR that have been reportedly utilized in the studies.

3.1 Slot

Slots are made by cutting out certain parts of the radiating element according to the intended dimension or geometry, as depicted in Figure 2. The introduction of a slot increases the length of the path of the current, hence, inducing inductive and capacitive effects which modify the impedance of the antenna [29]. Thus, the slot is able to reduce the body effect by adjusting the impedance of the tag.

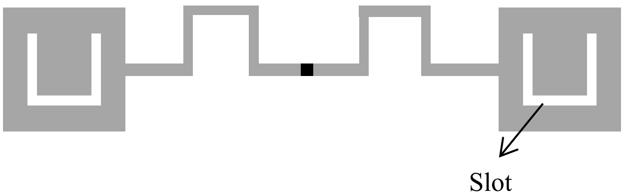

Figure 2. Double U-shaped slots in the radiating element of RFID tag

In a study conducted by Bouhassoune et al. [30] a five-slotted patch UHF RFID tag with a flexible bio-silicone substrate was proposed to reduce the human body effects on the tag antenna performance. Based on the numerical finding, the tag exhibited an on-body read range of up to 4 m. Similarly, Le et al. [31] proposed a miniaturized textile-based UHF RFID tag with the antenna having circular polarization. In this study, L-shaped slots with a cross are used to achieve miniaturization and mitigate the interaction between the human body and the antenna. The fabricated tag exhibited a maximum read range up to 5.8 m when it was tested on 4 different body configurations. Lastly, Ahmed et al. [32] proposed a slotted patch antenna for wearable a UHF RFID reader that was embedded in work gloves. The electro-textile antenna was made on foam with low permittivity and it is utilized to introduce a gap between the human body and the tag, which eventually improves the read range. It was reported that the antenna exhibited a read range of 3 m when the gloves were worn. However, it must be noted that introduction of the additional thick material will add thickness to the overall structure, which might be not preferred for seamless sensors. Besides that, Ahmed et al. [32] also proposed a SRR-based tag which will be discussed in subsection 3.3.

3.2 Artificial Magnetic Conductor (AMC)

AMC is a metamaterial that imitates the characteristics of the perfect magnetic conductor (PMC), which has 0° reflection phases at its resonant frequency, as shown in Figure 3. Hence, the AMC acts as a shielding material between the human skin and the antenna, as the in-phase reflection characteristic effectively decreases the backward radiation of the antenna while decreasing the coupling between the antenna and the human body [28, 33]. This encourages the researchers to implement AMC with the RFID tag for on-body applications. For instance, in a study conducted by Casula et al. [34] a compact AMC with a footprint of 41.4×82.8 mm^2 was proposed to isolate the body from the tag to enhance the antenna gain and read range. It was reported that the on-body read range was enhanced by one order of magnitude (approximately 3 m) compared to the tag's read range without AMC. This was also achieved by the utilization of a biocompatible silicon-doped substrate with high permittivity, and a thin and flexible structure, which allows skin transpiration.

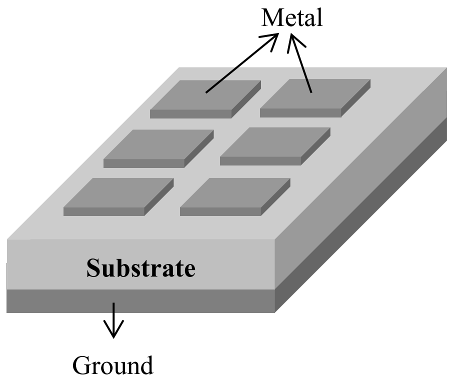

Figure 3. Structure of artificial magnetic conductor

Similarly, Hong et al. [34] proposed a 3 × 3 AMC structure to reduce the effect of body on the read range. The findings reported that the implementation of AMC improved the antenna gain by 3.34 dBi, whilst the on-body read range was 15.7 m when the reader's power was at maximum (4 W EIRP). In addition, Chiu et al. [35] fabricated a wearable UHF RFID tag with a 3 × 3 AMC structure using latex as the substrate that attached beneath the tag. The read range was tested in free space and on a human forearm model with the UHF RFID reader's power set to 4W EIRP output power. It was reported that the measured read range without AMC in free space and on the human model was 12.7 m and 6 m, respectively. Meanwhile, the measured free space and on-body read range with AMC were 17 m and 15.7 m, respectively. It is noteworthy that the incorporation of AMC with the tag enhances the on-body read range by 161.7% compared to the one without AMC. However, from the above-mentioned studies, it can be seen that the maximum read range of more than 15 m is obtained owing to setting the reader to the maximum power. Hence, the read range must be evaluated with minimum power to determine the least amount of power required to activate the chip and detect the backscattered signal from the tag.

3.3 Split Ring Resonator (SRR)

SRR is an artificially structured material that is typically made from copper and it comprises two rings with slits or gaps at the center, as depicted in Figure 4(a). The rings conduct current upon application of a magnetic field that is perpendicular to the ring plane. Hence, the flow of the current via rings serves as the inductor, meanwhile, the space (s) between the rings contributes to mutual capacitance [36]. Therefore, the equivalent circuit of the SRR can be represented using an LC circuit, as illustrated in Figure 4(b).

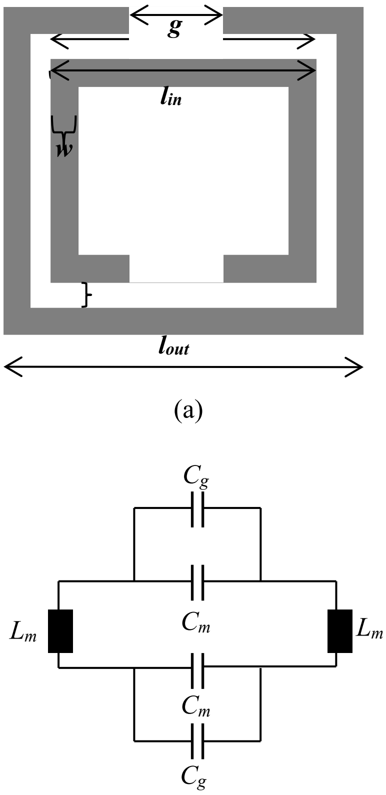

Figure 4. (a) Geometry of SRR (b) Equivalent circuit of SRR

Based on the equivalent circuit, the resonant frequency (f_0) can be calculated utilizing the Equation (2) [37]:

$$f_0 = \frac{1}{2\pi\sqrt{L_m(C_m + C_g)}} \approx \frac{1}{2\pi\sqrt{L_m C_m}} \quad (2)$$

where the inductance (L_m), and the capacitance (C_m) and (C_g) of each ring can be determined using the following Equations (3), (4) and (5):

$$L_m = \frac{\mu_0 s}{w}\left[l_{out} + l_{in}\right] \quad (3)$$

$$C_g = \frac{\varepsilon_0 \varepsilon_r t_c}{g} \quad (4)$$

$$C_m = \frac{A\varepsilon_0\varepsilon_r w(2l_{out} + 2l_{in} - g)}{2s} \quad (5)$$

where μ_0 is the permeability of the vacuum, w is the width of the rings and l_{out} and l_{in} are the length of the outer and inner rings, respectively. Meanwhile, ε_0 and ε_r are the permittivity of vacuum and substrate, respectively. Lastly, t_c is the thickness of the conductor and the A is an equilibrium constant.

Recently, the SRR has been explored in many applications, markedly, in wireless communication owing to its ability to enhance the performance of the antenna. In the case of the RFID tag, the implementation of the SRR is able to tune the impedance of the tag antenna, hence, the conjugate impedance can be achieved between the tag antenna and the chip. For instance, Ma et al. [38] proposed a two-layer circularly polarized UHF RFID tag with a footprint of π × 222 × 3 mm^3. The tag consists of two orthogonal meandered dipoles at the upper layer, whilst the SRR was utilized as the lower layer to achieve complex conjugate impedance matching between the tag antenna and the chip. These layers were built on top and bottom of the Ethylene-Propylene-Diene-Monome (EPDM) while the silicone was used as the substrate. The approximated read range that the tag exhibited is greater than 2 m. Besides that, Ahmed et al. [32] fabricated a SRR-based antenna for the glove-based UHF RFID reader. The tag exhibited a maximum read range of 1.8 m, which is lower than the slotted patch antenna discussed in subsection 3.1. However, the SRR contributes to a low profile as it has a simple and single-layer structure that is feasible to implement with the gloves. Lastly, a SRR-based wearable UHF RFID tag made up of copper tape and EPDM was proposed by Waris et al. [39]. The fabricated prototype was tested in free space and in body-worn configuration by attaching the tag to the back of the male volunteer. It was found the on-body read range was greater than 4 m. However, it must be noted that EPDM has also been together with the SRR-based antenna to reduce the body effect, thus, contributing to higher read range.

4. CONCLUSION AND FUTURE PERSPECTIVE

An immense number of researches have been witnessed in decades in employing UHF RFID tags for wearable applications despite the poor on-body read range. To overcome these shortcomings, various methods are being explored to mitigate the effect of the human body on the tag's read range performance. Hence, this review addresses the challenges and studies that are dedicated to enhance the on-body read range. This article begins with a brief description of the read range, the factors affecting the read range and an evaluation of the reduction in on-body read range based on the reported literature. Subsequently, the three most commonly utilized methods, such as slot, AMC and SRR are discussed based on the studies reported as these methods enhance the on-body read range.

Despite the efforts that have been made, some limitations need to be addressed for further improvement. In particular, the studies are only focused on evaluating the read range by setting the UHF RFID reader to a maximum input power of 3.28 W EIRP or 4 W EIRP. As a result, the minimum power required to activate the chip with tolerable on-body read range is not investigated. Therefore, the read range must be evaluated with different power level settings ranging from minimum to maximum power to determine the efficiency of the introduced method to reduce the human body effect. Lastly, EPDM or foam that has been utilized together with the antennas is not feasible for wearable or on-body applications as it contributes to the bulkiness of the overall tag structure. Hence, the low-profile tag with good on-body read range needs to be taken into consideration when fabricating a wearable UHF RFID tag implementing these strategies.

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