Inkjet-Printed Monopole Antennas for Enhanced-Range WBAN and Wearable Biomonitoring Application

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ABSTRACT

In this paper, a monopole antenna backed by an inkjet-printed electromagnetic band gap ground (EBG) plane on paper substrate is proposed for wearable applications with drastically enhanced communication range. This novel design approach for WBAN and wearable biomonitoring applications alleviates the on-body antenna's performance degradation, which may cause a significant degradation of the wireless system's performance as well. The communication range improvement compared to conventional antenna is demonstrated by using a benchmarking commercial wireless temperature sensor module. In addition, the advantages and the integrability of the proposed wearable antenna topology into mobile wireless on-body health care systems is discussed in detail.

Categories and Subject Descriptors

B.8.2 [**Performance Analysis and Design Aids**]; J.6 [**Computer-aided Engineering**]: Computer-aided manufacturing (CAM)

General Terms

Design, Experimentation, Verification.

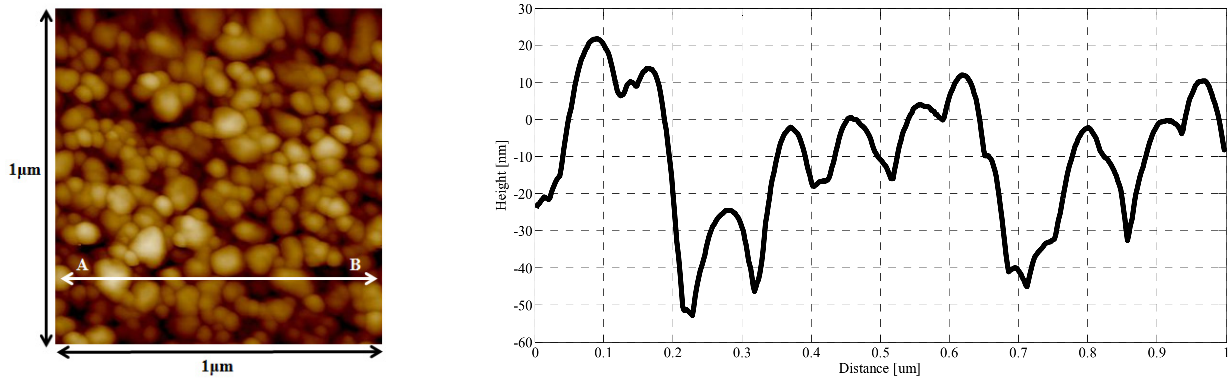
Keywords

Wearable antenna, Electromagnetic Band Gap (EBG) structure, inkjet printing, Personal Area Networks (PANs), Wireless Body Area Networks (WBANs), system level antenna integration.

1. INTRODUCTION

Nowadays, there is an ever increasing demands for ubiquitous computing system for wearable applications, such as wireless biomonitoring system. Especially, the development of novel low-cost enhanced-range wearable mobile healthcare systems for senior people, such as stand-alone wireless biomonitoring, alerting or tracking devices, is one of the hottest issues among the mobile healthcare area because of the dramatic increase of the population of aged people, that causes tremendous burden to traditional healthcare and biomonitoring approaches. Therefore, it is very important to design low cost, flexible, and on-body RF/wireless biosensor systems to maintain a reliable remote monitoring of biomedical information. To keep pace with it, there are plenty of proposals on systems applications and communication protocols for wearable or body area networks (BAN)[1][2]. However, most of existing works utilize or reuse the antennas designed for free space communications. This results in a decreased antenna gain, which is one of the most important parameters that determine wireless system link budget and range, while it leads to adverse biological effects, due to the proximity to the human body[3][4]. Therefore, deteriorated performance of the proposed systems and protocols is inevitable without the redesign of proper antennas for wearable/on-body applications. Patch-type antennas are popular for wearable applications ground plane below the patch can isolate the radiation of the wireless system from the human body [4][5]. Nevertheless, those proposed antennas are very thick or has low gain compared to normal patch antenna when the patch antenna is fabricated on thin fabric. This is because that the radiation efficiency and the thickness of the patch antenna are in the trade-off relationship. New approaches using electromagnetic bad gap (EBG) ground planes have been suggested to overcome the negative impact of the human body to the design of the antenna [7]. In this paper, we further analyze the performance of a novel EBG-backed antenna topology that features robustness against deformation and interference from the human body.

This paper is structured as follows: First, the inkjet printing technology for microwave circuit fabrication is introduced and a monopole antenna backed by an inkjet printed EBG ground plane on paper substrate is revisited. Next, simulations are conducted to demonstrate its performance on-body improvement compared to conventional antennas that are optimized for free space



(a) (b)

Figure 1. (a) The surface of the inkjet printed nano-silver ink (b) Cross section of the line AB[8]

communication. Finally, the feasibility of system-level integration of the proposed antenna into a proposed novel mobile health care system is discussed in detail.

2. ANTENNA AND HUMAN BODY

In this section, we first revisit the technical challenges for the fabrication of a wearable antenna. Inkjet printing technology using nano-silver particle is utilized to fabricate the antenna and a simple monopole antenna is backed by an inkjet printed electromagnetic band gap (EBG) structure to enhance the antenna's performance on the human body.

2.1 Challenges

The biggest challenge in the design of wearable antennas is the elimination/minimization of the interaction between the human body and the antenna. The human body can be considered as a material with high loss and dielectric constant in microwave frequencies since its dielectric constant (ε_r) is 52.5 and its conductivity is 1.78 S/m [7]. Because of these properties of the human body, most of radiated waves propagate through the body and dissipated in the form of heat resulting in a wider -10 dB return loss (S_{11}) bandwidth. This issue leads to decrease of the antenna gain since the radiation efficiency is drastically decreased due to the body absorption. The decreased radiation efficiency result in lower gains for the same directivity value of the antenna. The gain of an antenna is a figure of merit of how well the antenna converts delivered power into radiated waves toward a specified direction. When a wireless sensor module is mounted on the body it is unavoidable to expose its antenna to the body effect, necessitating the development of effective isolating structures.

In addition to the detrimental effect of the human body on the radiation performance, there are a couple of other requirements that should be taken into account in the design of a wearable antenna. This type of antennas should be bio-compatible and have flexibility to accommodate for the curvature of the human body and for typical body motions. In addition, the cost for the fabrication process of the antenna should be very low and allow for the easy fabrication of a large number of radiating elements.

2.2 Inkjet Printing On Paper Substrate

Inkjet printing technology utilizing nanotechnology-enabled conductive inks has many advantages for wearable applications. First of all, it is a very cheap, cost efficient, and environmentally friendly fabrication process. Unlike conventional fabrication method like etching which removes unwanted metal from the substrate surface, inkjet printing technology drops conductive nano-silver ink on the desired position and the printing process is completely controlled from the computer. Therefore, there is no byproduct such as acid for metal removal[9]. Inkjet printing process is typically followed by sintering process in order to increase the conductivity of the silver ink and dry up the solvent of the ink. Sintering is done by heating the printed pattern, so that the printed nano-silver particles are melted, tus forming a conductive metal layer.

The advantages of inkjet printing technology can be enhanced by introducing a paper as a circuit substrate. The paper is one of the cheapest material in the world and it is biocompatible since it is an organic material. Large scale production can be feasible when it is combined with inkjet printing technologies making it very attractive, especially for RFID and wireless sensor applications. Plus, paper-based inkjet printed electronics can feature hydrophobic or even waterproof properties when they are coated with water resist chemicals[10].

In this paper, the DMP2800 inkjet printer was used to fabricate the antenna [10]. For printing, the Dimatix 10pL cartridge (DMC-11610) was used, and a commercially available conductive ink CCI-300 [12] was jetted from the head of the printer. The sintering is performed in an industrial oven at a constant temperature of 130°C for 2 hours after printing. After sintering, the pattern has consistent a DC conductivity in the range 9×10^6 S/m ~ 1.1×10^7 S/m with roughness of 1μm [13]. The surface and

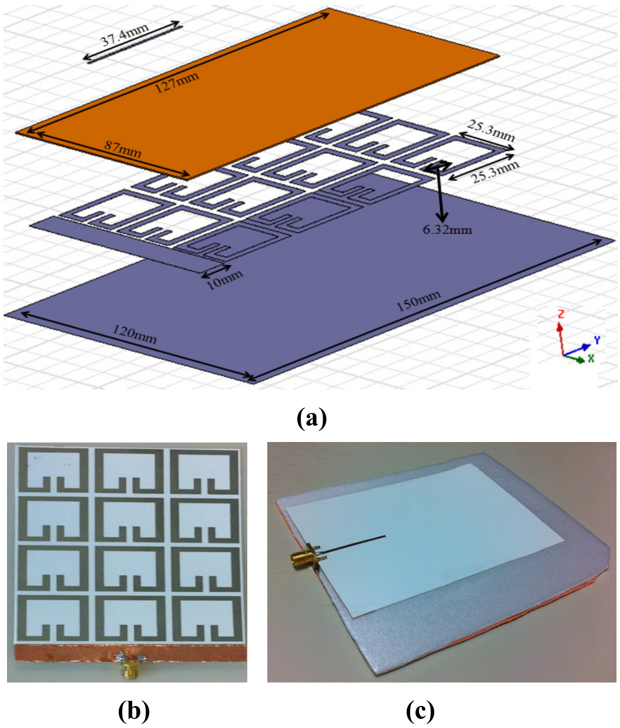


Figure 2. (a) antenna structure (b) Inkjet printed EBG structure (c) Fabricated antenna

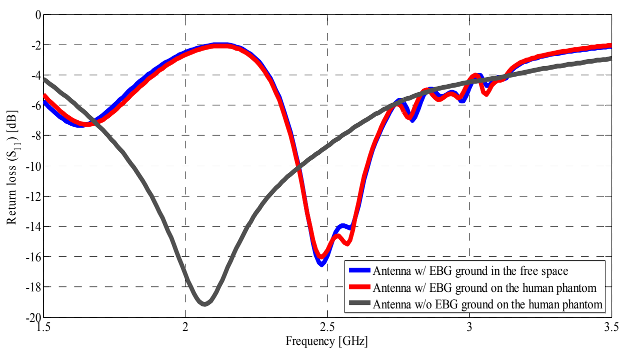


Figure 3. Return loss of the proposed antenna

cross section (AB) of the printed nano-silver ink after sintering from Veeco Atomic Force Microscopy (AFM) are shown in Figure 1.

2.3 Antenna Backed by EBG ground plane

The structure of the proposed antenna topology is shown in Figure 2. The thickness of paper substrate is 0.46mm with dimensions 127mm x 87mm, the length and width of the unit cell of EBG is 25.4mm, and 6.32mm long pins for extra capacitance is added to ring resonator. And the cell-to-cell distance between EBG cells is 2.53mm and the gap distance in the cell is 2.53mm. The monopole antenna which covers the ISM frequency band of 2.4 ~ 2.5 GHz was designed and is backed by an inkjet printed EBG layer and a metallic layer. The monopole antenna is 37.4mm long and 1.3mm thick. The EBG is a sort of a band stop or band pass filter for plane

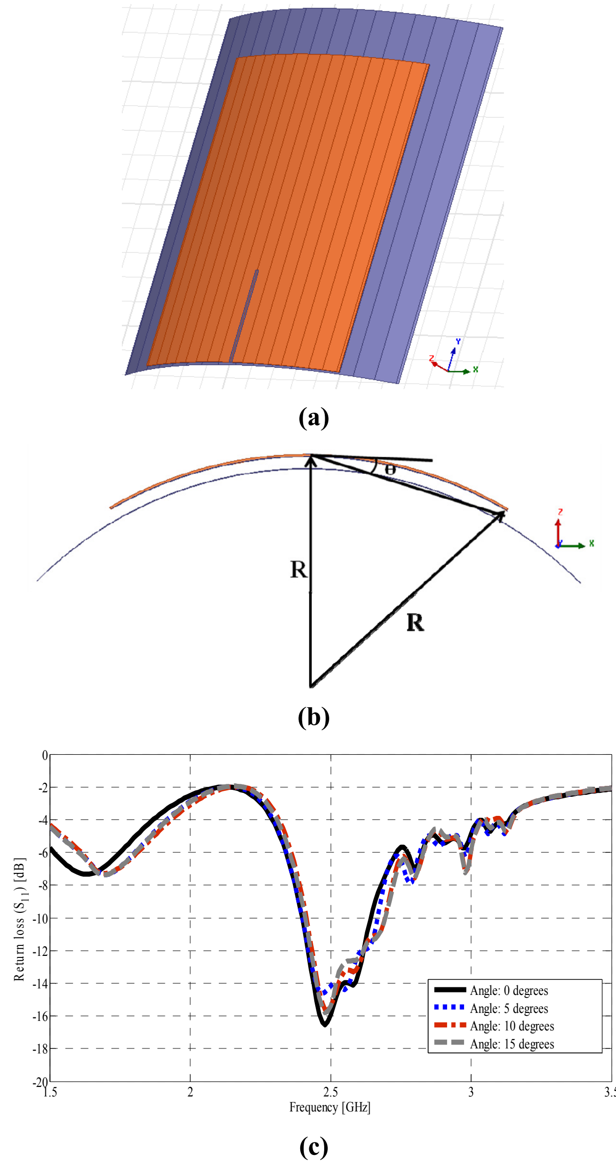
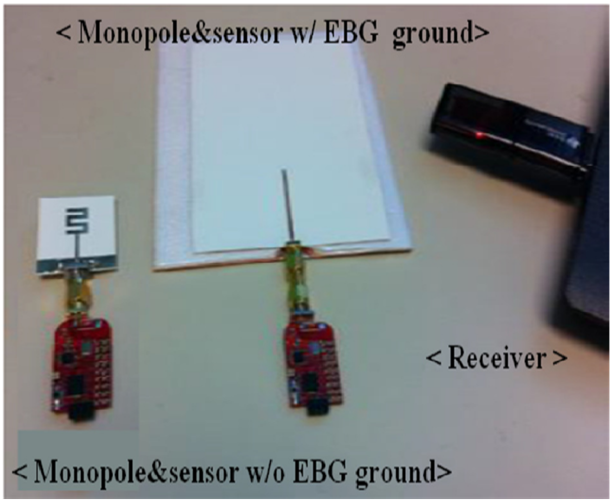
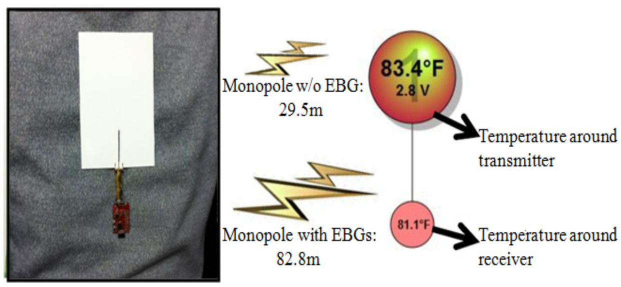


Figure 4. (a) Bent antenna geometry (b) Cross section of the bent antenna (R: radius of the cylindrical surface for antenna bending, θ: bending degree) (c) Return loss of the bent antenna

waves and plays a critical role in the isolation of the monopole antenna from the effects of the human body. Similar to the microwave filters, the EBG consists of periodic metallic structures that stop or pass the plane waves at desired frequency bands. The proposed EBG structure with ground plane was designed using the reflection phase characterization method [14], that assumes the illumination of a plane wave onto the infinite EBG surface backed by a ground plane and monitors the phase of reflection coefficient (S_{11}) on the surface of the EBG structure. The reflected waves from the surface of the EBG structure are going to be constructively added to radiated waves from the antenna when the reflection phase from the surface is in the range



(a)



(b)

Figure 5. (a) Communication range measurement setup (b) Communication range improvement

of -90° ~ +90°. In this way, the wireless communication system can be effectively "shielded" from the effect of the lossy human body.

To demonstrate the antenna performance on the human body, the proposed antenna is simulated on the presence of a human body phantom. The human body phantom that has very similar material properties, such as dielectric constant (ε_r) and conductivity (σ), with the human body. Figure 3 shows the simulated return loss (S_{11}) of the designed and simple monopole antenna on the human body phantom. The dielectric constant and conductivity at frequency band of interest (2.4 ~ 2.5 GHz) is 52.5 and 1.78 S/m, respectively [7]. The simulation results shows that the EBG structure and ground plane effectively isolate the antenna's radiation system since the resonance frequency and gain of the antenna backed by EBG ground plane is changed slightly while that of the antenna without the EBG ground plane is shifted a lot. The gains of the antenna with EBG ground plane in the free space and on the human body phantom are 0.86 dBi and 0.6 dBi respectively, while that of the on-body antenna without the EBG ground plane is -9.8 dBi at 2.45 GHz. Last, but not least the effect of the human body's curvature on the proposed antenna is also studied and shown in Figure 4. The proposed antenna was bent along a cylindrical surface as shown in Figure 4. (a) and (b) with tested radii of the cylindrical surface of 84mm, 125mm, and 249mm to make bending angles (□) 5°, 10°, and 15°. The antenna's return loss (S_{11}) are almost unchanged even though the antenna is bent along the cylindrical surface as shown in Figure 4 (c), effectively verifying the fact that the proposed antenna doesn't experience performance degradation even when it is attached to body parts such as chest, upper arm and thigh.

3. WEARABLE SENSOR NODE

The proposed antenna topology was integrated with a Texas Instrument's wireless temperature sensor module in order to demonstrate its performance on the human body. The model name of the module is eZ430-RF2500 development tool [16], and its antenna part is modified to integrate the proposed antenna as shown in Figure 5(a). A female SMA connector is mounted on the circuit instead of the original chip antenna of the module, and the proposed antenna was connected. For the receiver antenna, the inkjet-printed meandered monopole antenna is used. The measurement took place on the top of a large parking deck to minimize multipath effects. For the communication range measurement, the transmitter was mounted on the chest of a human depicted in Figure 5(b). The transmitter was set at close distance from the receiver to ensure their communication. Next, the distance from the receiver was increased until the receiver lost signal from the transmitter. The large orange circle displaying the temperature around the transmitter in Figure 5(b) disappears if the receiver is unable to detect signal from the transmitter. In this way, the distance from the receiver to the transmitter was measured when the receiver failed to catch signal from the transmitter. The measured communication range of the on-body sensor with the inkjet printed meandered monopole antenna without EBG ground was 29.5m, while utilizing proposed EBG-backed antenna drastically increased the range by almost a factor of three to 82.8m on the human body. This type of topology can be easily integrated with previously proposed biomonitoring systems works to significantly improve the performance of body area networks (BANs) or mobile health monitoring systems.

4. ANTENNA AND SYSTEM INTEGRATION

Many researchers have suggested numerous novel mobile healthcare network systems and algorithm. S. Boudjit et al. suggested on data gathering management system for a wireless health monitoring [17], N.K. Vuong et al. suggested a real-time wandering detection algorithm for dementia patients [18], and A. Weder et al. suggested a mobile system for pulse transit time (PTT) monitoring [19]. All those proposed systems are utilizing wireless network system on the body to communicate with network controller and sensor modules while making use of the IEEE 802.15.4 (Wireless Personal Area Network, WPAN) and IEEE 802.11 (WiFi) standards typically operating in the 2.4 ~ 2.5

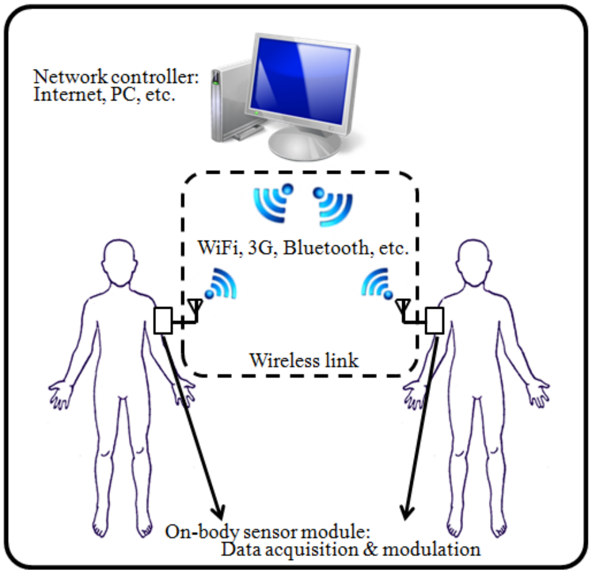


Figure 6. Wireless on-body mobile system network

GHz frequency band. Therefore, the proposed antenna topology can be easily integrated with the wireless sensor modules of the previously proposed body area network systems and detection algorithms. Basically, the schematic of a common wireless on-body mobile sensor system network can be simply depicted as in Figure 6. The on-body sensor module acquires and modulates the data before sending to network controller such as PC or internet. The modulated data signal is radiated from the antenna at a certain frequency band determined by the chosen wireless communication standard and collected/processed by network controller. Especially, the on-body transmitting antennas are playing a pivotal role on the quality of the wireless link of the system consisting of the network controller and the on-body sensor modules, as the available power at the receive antenna is proportional to the gain of the transmitting antenna in the free space according to the Friis equation[20]. It is possible to estimate the system's required link budget through the Friis equation and the effect of the human body on the wireless system can be easily figured out. In the Friis equation listed below, P_r is the delivered power to the receiving antenna, G_t and G_r are the gain of the transmitting and receiving antenna, respectively, λ is the wavelength at the frequency of interest in the free space, R is the distance between the transmitting and receiving antenna and P_t is the delivered power to the transmit antenna. In this paper, the transmitting antenna is assumed to radiate all delivered power, so that the P_t can be considered as radiated power.

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 P_t$$

In this kind of on-body wireless link, P_r and G_r are fixed due to the receiver's sensitivity, while the communication distance, R, also can be fixed or constrained due to required minimum communication range. Therefore, the transmitting antenna's gain (G_t) and the delivered power to the transmitting antenna (P_t) are critical to establish a stable wireless communication link. However, in the normal case of free-space optimized antennas, the human body absorbs most of radiated power since the waves tends to propagate through the high dielectric material like the human body ($\varepsilon_r \approx 52.5$), thus leading to the deterioration of the antenna characteristics, such as gain and return loss (S_{11}) as shown in the section 2.3.

The proposed EBG-backed antenna geometry guarantees that most of the power is delivered to transmitting antenna when the transmitting antenna is placed on the body in order to detect transmitted signal from the wireless module at a large range. It has to be noted that the gain and return loss of the proposed antenna do not change even though it is placed on the human body, and it is possible to establish a wireless system network with small amount of power for wireless communications. In addition to that, Specific Absorption Rate (SAR) caused by radiated waves can be minimized since the EBG ground plane blocks the wave propagation through the human body. SAR is a measure of energy deposited by an RF field in a given mass of tissue, and it is directly related to body heating effect caused by RF signal. Therefore, not only required power to establish an enhanced-range wireless communication system but also SAR can be reduced by introducing the proposed designed wearable antenna.

A couple of implementation issues of the proposed antenna can be aroused. The area of the proposed antenna is quite bigger than the conventional antenna because of the EBG structure and it requires connector to connect the sensor board to the antenna on paper substrate as shown in Figure 5. Therefore, minimization and integration schemes are necessary to overcome these issues. The suggested EBG structures can be minimized by meandering the unit cell[21], and the whole system consists of the antenna and the sensor can be built utilizing inkjet printing technology on homogeneous substrate such as paper or FR4[22]. In this way, the aroused issues on the proposed antenna will be able to be solved with minimal performance degradation.

5. CONCLUSION

Previously, many researchers have proposed and demonstrated a variety of novel systems and algorithms for wireless body area network (WBAN) applications. However, the presence of the human body causes adverse issues to on-body wireless communication network systems such as reduced range and biological effects due to the significant radiated power absorption from the body. To overcome these issues, we proposed a novel antenna topology consisting of a wearable inkjet printed monopole antenna backed by an EBG ground plane, that effectively isolates the human body from the wireless network system, and could potentially enable to realization of power-efficient and enhanced-range conformal on-body wireless system networks. The capability of the drastic improvement of performance of previously reported wireless systems through the use of the proposed wearable antenna topology is thoroughly studied and verified through simulations and experiments.

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