Performance evaluation of wearable antenna printed using syringe-based deposition system on fabric

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Abstract. Wearable antenna is recently known as part of clothing for communication purposes. Syringe-based deposition system had been proven capable of printing functional antenna structure but the printed antenna performances have not been discussed in details especially on resisting bending under various angles, curvature radiiuses and wet conditions. Hence, this paper discusses the performance of printed antenna under various bending angles, curvature radiiuses and wet conditions. The effect of several bending angles, curvature radiiuses and wet conditions on resonance frequency, return loss and radiation pattern were discussed and compared accordingly with simulation. The antennas were observed to resonate best at frequency of 1.571 GHz as expected and the return loss obtained was at -20 dB that is 30% more than simulation which offers better performance. The radiation pattern obtained was as predicted since larger magnitude for the main lobe was produced than the side lobe. The antenna exhibited exceptional elasticity as it resists bending up to 30° angle and 5 cm of vertical convex curvature radius. Polyester fabric performed as a good candidate for textile wearable applications and water had only minor effect on antenna performance makes the proposed antenna suitable for humid condition.

1. Introduction
Wearable electronic devices are becoming very popular in personal communications, computer systems and wireless monitoring of vital functions [1]. The main advantage is they are designed as elements of clothing capable of transmitting or receiving wireless signals [2]. Integrating antennas into clothing can improve the desirability of such systems, and novel methods of fabricating conducting structures on clothing will benefit of diverse applications [3]. This kind of incorporation will add the benefit of eliminating clumsy devices that can be entangled to some extent [4]. Syringe-based deposition system with conductive ink had proven capable of printing functional electronics structure previously via strain gauge sensor and antenna on fabric [5, 6, 7] as it provides flexibility [5] and

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compatible with different viscosity of materials since current printing techniques suffered from ink incompatibility especially on conformal substrates due to its rigidity and low flexibility [8]. The antenna structure is intentionally printed on life jacket to constitute as part of a rapid response device during emergency. Thus, the study is to investigate the printing of silver conductive ink track that makes up the antenna structure on fabric using syringe-based deposition system and at the same the performance of the printed antenna structure were evaluated since they have not been discussed in details before especially on resisting bending under various angles, curvature radiuses, and wet condition. The technique deposits inks using filamentary concept and the ink is required to be cured using mainly heating process via oven.

2. Methodology

2.1 Specification of Antenna Design
A type of micro-strip patch antenna was first identified and designed. The detail dimensions were determined and modelled using computer-aided design (CAD) software as shown in figure 1 respectively. The antenna is designed to operate at resonance frequency of 1.575 GHz as required by Multimedia Communication and Malaysian Commission (MCMC) for rescue signal. There were four essential parameters specified including the operating frequency ($f_o$), dielectric constant of substrate ($\varepsilon_r$), the height of the dielectric substrate (h) and the thickness of the conductor patch (t) as shown in table 1. The total length of the antenna designed is 158 mm long with a 0.80 mm width of track.

![Figure 1. Micro-strip patch antenna designed with its detail dimension (units in mm)](image)

| Specification          | Width (mm) | Length (mm) | Thickness (mm) |
|------------------------|------------|-------------|----------------|
| Dimension of ink track | 0.8        | 158         | 0.22           |
| Substrate (polyester fabric) | 30 | 30 | 0.15 |
| Ground plane           | 30         | 30          | 0.11           |

*Table 1. Specification of antenna designed.*

| Printing Parameter | Pressure (kPa) | Speed (mm/s) | Height Deposition (mm) | Nozzle Diameter (mm) | Viscosity (Pa.s) |
|--------------------|---------------|--------------|-----------------------|----------------------|------------------|
|                    | 160 - 240     | 5 - 9        | 1.20                  | 0.51                 | 2.40             |

*Table 2. Selection of printing and curing parameters*

| Curing Parameter | Temperature (°C) | Time (minute) |
|------------------|------------------|---------------|
|                  | 160              | 45            |

2.2 Printing and Curing Process
The antenna was initially simulated using Computer Simulation Technology (CST) Microwave Studio software to measure its resonance frequency, return loss ($S_{11}$ parameter) and radiation pattern intended, directional with bigger main lobe and smaller side lobe as required. An automatic syringe-based deposition system (Model: FISNAR 3-axis, F4200N.1) equipped with a teach pendant and industry’s leading dispensing software is used to deposit ink on polyester fabric as shown in figure 2. Conventionally, most of printing techniques only capable of printing on planar substrates and some of
them including screen printing and inkjet printing suffered from clogging [8] and limited type of materials to be printed with. A series of pilot tests were conducted to determine the range of suitable printing parameters [7]. The selected printing parameters were varied accordingly as depicted in Table 2 to obtain the desired dimension of antenna. The other two parameters including height deposition and nozzle diameter were set to be constant. A total of 25 samples were printed from the simplification method made using Taguchi method. Figure 3 shows the antenna that had been successfully printed using syringe-based deposition system and cured with oven to reduce the percentage of unwanted material in conductive ink since conductive ink is comes in liquid and required to be cured usually by heating process to reveal its metallic contents [6]. The curing process played an important role to provide a good conductivity of the ink tracks. Several pilot tests were performed to determine the optimum curing parameters that result in the lowest resistance. The optimum curing parameter selected is shown in Table 2.

2.3 Material and Substrate

A conductive ink used throughout the whole study is silver epoxy-based ink (Model: AG806) as shown in Figure 4 and direct usage of the ink is not possible due to high solid fraction thus an adjustment of viscosity via dilution with toluene solvent is necessary. It is important to ensure that during filling the ink into the barrel, it is properly packed to prevent any air pocket left in the nozzle. The fabric material used is made of polyester since it is suitable to mimic the actual fabric made for life jacket.

![Figure 2. Automated syringe-based deposition system](image1)
![Figure 3. Successful microstrip patch antenna printed on polyester fabric](image2)
![Figure 4. Silver conductive ink (Model: AG806)](image3)

2.4 Measurement.

Analysis of the antenna printed is consisted of measurement of width and thickness of the ink track using optical microscope. Its electrical properties were measured via inductance, capacitance and resistance (LCR) meter. A cross-sectional area of the ink track and its total length were determined accordingly to calculate the resistivity [6]. A measurement of resonance frequency and return loss ($S_{11}$) were determined using vector network analyser (VNA). The samples were tested next in semi-anechoic chamber to measure its far-field radiation pattern [7]. The antenna was aligned first to a horn antenna with adjustable polarization respectively. Since the antenna in a realistic on-body wearable antenna application will be subjected to bending and wetness thus, the effect of bending and wetness were investigated. All samples were tested on a customized curvature and bending jig as shown in Fig. 5 (a) and (b). The performances were tested on several curvature radiiues at two different positions; horizontal convex and vertical convex with different radius each; 2 cm, 3 cm, 4 cm and 5 cm. The bending performance were measured by applying bending angles from 0° to 180° and the test stopped when the ink track cracked. The samples were then measured in four different states of wetness involving fully wet, immediately wet, approximately dried and fully dried conditions. At first, the sample was kept under water for more than three hours and measurement was taken inside the water.
After that, the sample under test was taken out from the water and measured immediately. The sample was dried and measured again. Finally, the performance of the sample was tested when it is in fully dried condition. These four wet tests were illustrated in figure 7 (a), (b), (c) and (d).

![Figure 5: Bending performance test on customized jig (a) curvature and (b) angle jig](image)

![Figure 6: Relationship between cross-sectional area of the ink track with respect to resistance](image)

![Figure 7: Wet performance test conditions (a) fully wet (b) immediately wet (c) approximately dry (d) completely dry](image)

3. Results and Discussion

3.1 Electrical Properties.
Figure 7 shows the relationship between cross-sectional areas of the ink track with resistance obtained. The trend shows resistance is decreased as the cross-sectional areas of the ink track increased. The relationship obtained also validated the general formula of resistivity [6] where bigger cross-sectional area provides lower resistance since bigger area allows more electron to flow through. Resistance is defined as the interruption of the flow of the electrical charge in the track. For an electron to travel from terminal to terminal is not a direct route but rather in a zigzag path due to countless collisions with fixed atoms within the conducting material. Thus, cross-sectional area of the ink track affected the amount of resistance. Wider and thicker ink track provides larger cross-sectional area thus less resistance for the electric charge to flow. Moreover, the total length of the ink track also affected the amount of resistance. The longer the ink track causes the resistance to be higher because the electron travelled in longer path and more collisions occurred.

3.2 Resonance frequency, Return loss ($S_{11}$) and Radiation Pattern.
The result of simulated and measured performance of the antenna on resonance frequency and return loss of one of the good samples was shown in figure 8. The simulated antenna was radiated best at 1.575 GHz as required indicated by red line. The bandwidth expanded from the lower frequency of 1.54GHz to the upper frequency of 1.63GHz and the magnitude of the antenna was recorded at -14 dB. The measured antenna was observed radiated best at 1.571 GHz with a magnitude of -20 dB indicated
by blue line. The antenna averagely radiates best at 1.5833 GHz with the average magnitude of -23.2 dB. Although there is a slight difference bandwidth of the frequency by only 2.87% from the intended frequency, but it is still in the range of the intended frequency. The percentage difference between the simulated and measured resonance frequency is by merely 0.254% which is considered low thus the antenna designed is comparable to be used in wearable antenna application. In addition, the magnitude of $S_{11}$ parameter obtained from measurement indicated better performance as the magnitude is higher than the simulated by 30%. In the meantime, the simulated and measured radiation pattern of the antenna designed is depicted in figure 9 where the far-field directivity of the antenna by simulation was observed to be 3.77 dB at 1.575 GHz with the main lobe direction at 5.0 degree angle. Furthermore, the side level of the antenna is -2 dB. Besides, the measured result has a directional average directivity at 1.6203 GHz. The far-field directivity is recorded at 8.479 dB magnitude. The main lobe average angle is 6.66 degree. Both results proved fulfilled the requirement for the antenna designed previously.

3.3 Bending and Wet Performance.

The sample was tested on several bending angles and curvature radiuses and the results from table 3 shows that the sample was still resonated but not at its designated resonance frequency starting from 10° to 30° angles. But the sample was not resonated at any frequency after it was bended at 40° angle and more because of the ink track was cracked during experiment starting from 40°. It was observed that when the sample was bended, the resistance changed and the amount of changes is proportional to how big is the angle of bending and this cause the resonance frequency to shift. Similar case happened when the sample was bended by curvature radius when the only sample that resonated at frequency of 1.622 GHz was when it was less curvature bended at vertical convex position with radius of 5 cm. The measured return loss of $S_{11}$ parameter acquired was at 22.429 dB. In the meantime, table 4 shows the results for the wet performance test. The antenna did not resonate and function well at any frequency when the antenna was placed under water (fully wet) for 3 hours while in immediate wet condition, the antenna resonated but with slightly low frequency at 1.321 GHz and the measured return loss of $S_{11}$ parameter was obtained at -11.554 dB respectively. Besides, the antenna was well functioned when in approximately dry condition which the antenna started to resonate back at its designated resonance frequency. But there are some negligible effects of water and moisture on antenna performance. The antenna resonated at 1.455 GHz and the measured return loss of $S_{11}$ parameter is at -19.709 dB. Finally, the performance of the antenna was tested under fully dried condition and the performance recorded is remained unchanged similar to the approximate dried condition.
4. Conclusion
In conclusion, the antenna printed had proven could operate near to its designated resonance frequency. It could also be perceived that many aspects caused the measurement to have a slight difference by only a mere 0.254% from the simulation thus makes it compatible to be used for wearable antenna application. This slight difference may relate to fabrication tolerance and misalignment during measurement setup including imperfection in soldering of SMA connector which result in mismatching condition on port during testing. In addition, a fabrication tolerance also needs to be considered where the actual dimensional shape of the fabricated antenna is not the same shape with the designed of the ink track in simulation. However, the measurement offers a good performance since the return loss of $S_{11}$ parameter and the magnitude of the main lobe of radiation pattern is higher than the simulation. Besides, it had proven that the syringe-based deposition system is capable of printing functional electronics structure particularly antenna since the wearable antenna printed shown comparable results. The functional wearable antenna operated and radiated well at its designated frequency. Moreover, effects of bending and wetness on antenna performances indicated that the used of conductive ink provides some elasticity hence makes the antenna bendable but still well-functioned and polyester fabric performed as a good candidate for textile wearable applications. Minor effect of water on antenna performance makes the proposed antenna suitable for humid and robust condition consequently, evaluation of long-term behavior and durability may well be considered in future.

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| Condition    | Frequency (GHz) | $S_{11}$ parameter (dB) |
|--------------|-----------------|-------------------------|
| Fully wet    | Not available   | Not available           |
| Immediately wet | 1.321           | -11.554                 |
| Approximately dry | 1.455           | -19.709                 |
| Completely dry | 1.455           | -19.709                 |

4. Table 3. Result of bending with curvature radiuses and angles.

| Bending test | Angle, Position and Radius | Result | Frequency (GHz) | $S_{11}$ parameter (dB) |
|--------------|---------------------------|--------|-----------------|-------------------------|
| Angle        | 0                         | 1.586  | -23.654         |                         |
|              | 10                        | 1.628  | -22.439         |                         |
|              | 20                        | 1.662  | -17.406         |                         |
|              | 30                        | 1.662  | -17.406         |                         |
|              | 40 - 180                  | Not available | Not available |                         |
| Curvature    | Horizontal convex (radius = 2 – 5 cm) | Not available | Not available |                         |
|              | Vertical convex (radius = 2 – 4 cm) | Not available | Not available |                         |
|              | Vertical convex (radius = 5 cm) | 1.622  | -18.601         |                         |

4. Table 4. Result of water performance test.

| Condition          | Frequency (GHz) | $S_{11}$ parameter (dB) |
|--------------------|-----------------|-------------------------|
| Fully wet          | Not available   | Not available           |
| Immediately wet    | 1.321           | -11.554                 |
| Approximately dry  | 1.455           | -19.709                 |
| Completely dry     | 1.455           | -19.709                 |
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