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From Rigid to Flexible and Stretchable: Considerations for Design of Wireless Electronics on Skin

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Abstract

In this paper, we consider the design challenges and solutions for achieving both good electrical performance and convenience of use for skin wearable electronics. User convenience includes both enhancing the benefit of using the device and minimizing the interference with normal life caused by the device. The electrical performance includes reliability of conductors and inter-connections to discrete components, as well as the RF performance of the antenna for wireless communication. We discuss flexibility and stretchability as solutions for user convenience, but also consider the negative effects they cause for the electrical reliability. Further, we identify size and height as important factors for both convenience and RF performance.

1 Introduction

Wearable electronics is a vivid research topic at least since early 1980's, when the first wireless heart rate monitors entered the market [1]. Stretchable chest belt including the electrodes for electrical ECG measurement incorporated with a rigid enclosure for electronics and wireless connectivity was the standard approach for heart rate monitors for years. In 2000's new approaches emerged with optical measurement (photoplethysmogram or PPG) in a wrist band, omitting the chest band.

On the medical side, wearable devices have had a slower start, but devices have entered the market, such as the on-line glucose meter *Libre,* a circular patch with a rigid frame (approx. 35 mm in diameter and 5 mm in thickness). The patch is worn directly on skin and has short range (4 cm) wireless connectivity to mobile phone [2].

Current research on wearable devices looks into flexibility and stretchability of electronics to further improve the user convenience in both fitness and medical application domains. A key paper generated a vision about e*pidermal electronics*, very thin, stretchable devices directly on skin, without any rigid parts [3]. The race to fulfil the vision is on-going in research field.

In this paper, we consider how flexibility and stretchability of skin wearable electronics affect the user convenience and electrical performance, including the antenna. As an example, we demonstrate skin wearable patch designs, such as Fig. 1, demonstrating possible solutions for user convenience.

Figure 1. FlexNode wireless sensor platform (left) with data communication over bluetooth to a SmartPhone receiver (right).

2 Flexibility and Stretchability

2.1 User Convenience

User convenience in wearable devices arises from comparing the benefits of the device to interference of normal living caused by the device: The more the user benefits from the device, the more the user also accepts interference from the device. For example, a diabetic patient is willing to take more interference, if the device significantly helps to keep the blood sugar level stable. The perception of the benefit can also be improved externally: e.g., device branding and exclusiveness can feed the positive perception. Even though these effects are not considered further in this paper, it can be stated that the benefit is heavily dependent in the application and personality of the user.

The interference caused by the device includes effects such as noticeability by self and others, restrictedness of movement, breathability, interruptions to normal life and reliability. These can be affected readily by design.

Restrictedness of movement: The wearable device should feel natural to wear: It should flex and stretch in similar manner as the skin. If the device is rigid, it should be as small as possible, so that skin can flex around it. Further, the device should be thin in profile.

Noticeability by self and others: It should look natural and socially acceptable to wear the device. It should either be small, thin and light to be unnoticeable, or look like a device people want to wear. E.g. the wrist bands measuring heart rate look like watches with beautiful design.

Breathability The device should not cause excess sweating, i.e. it should be of breathable material.

The interruptions to normal life: The user interface (in hardware and software) should be seamless to use. The device should be designed such that it requires minimal maintenance and requires replacement only seldom. All these acts interrupt the normal life, and are typically considered negatively by users - especially if the device sends unnecessary alerts.

Reliability: The device should be reliable and work as intended, providing high accuracy data for full lifetime.

2.2 Materials

Typical flexible substrate materials in wearable electronics include paper, polyethylene terephthalate (PET) and polyimide (PI). These are used as substrate for printed electronics, but PI is also available as for conventional printed circuit boards (PCB), under the commercial name Kapton. For stretchable substrates, a wide range of materials have been suggested, several plastic polymers, i.e. polyester (PE) and polyurethane (PU), as well as silicone-based materials, such as PDMS [3-4].

The plastic materials can be used down to thickness of about 10 um, enabling highly flexible substrates. The required material stretchability (or Young's modulus) depends on the application and substrate thickness. PDMS is the most stretchable, with Young's modulus in the order of 1 MPa, while PET and PU have typically Young's modulus of 3000 MPa and 100 MPa, respectively [5]. Young's modulus of the skin is 0.1 - 20 MPa depending on measurement techniques and position [6]. In [5], a nanocellulose-PU matrix is introduced for tuning the Young's modulus between 100-1000 MPa.

Breathability for water vapour varies significantly with the materials, and non-breathing materials can cause significant sweating under the device. PET is almost completely un-breathable, i.e. the water vapour permeability of PET is in the order of 0.1 $g\times mm/m^2/day$. The water vapour permeability is typically 10-, 1000- and 10000-fold for PI, PU and PDMS [5]. Breathability can be increased by perforation of the substrate.

Further, for the reliable and convenient use of skin wearable patches, the skin glues should be considered carefully. Many medical skin glues are readily available for different attachment strength and time.

2.3 Electrical performance

The more flexible or stretchable the substrate is, the higher the challenge in skin patch reliability, as the metallic connectors cannot tolerate repeated significant elongation. It has been shown that meandered copper conductors in horseshoe shape can tolerate about 2 000 cycles of 10 % elongation [4]. The substrate Young's modulus should be designed so that the elongation on the conductors remains reasonable. Also other, e.g. graphite based conductor materials with higher elongation have been suggested, but these materials typically have much higher resistivity, and these cannot be used in applications that require low resistance, such as power distribution, even though they can be feasible in high impedance applications, e.g. in voltage probes.

Silicon chips and discrete components are more rigid than the substrate. Thus, flexing and stretching of the patch leads to the area next to the discrete elements to be under higher stress to compensate for the lower stress on the rigid area, eventually leading to electrical connection opening, usually next to the component. This effect can be reduced by careful geometrical design, and minimizing the size of the discrete components as well as the size of the whole patch. Adding a thicker, rigid-part of substrate (semi-rigid PCB) under critical components, or a glop-top material over the components can help to overcome the issue.

3 Antennas on Skin

As a mounting platform of an antenna, human body is quite similar a challenge as a metal surface. This is due to the high content of salty water in the body, which results in high relative permittivity, typically between 10 and 60 at 2.45 GHz, as well as high conductivity, up to 1 S/m [7]. Depending on the exact position of the skin-attached device, there may also be different types of tissue beneath the device, which leads to varying electrical parameters and thus requires an antenna that is insensitive to the electrical properties of the mounting platform. This together with the requirement of low profile of a skin-attached device sets challenges for the antenna design.

A traditional and easy way of implementing an antenna on a printed circuit board is to form the radiator of the metal conductor on the board itself. However, when attached directly to skin, such a planar antenna is not ideal, since it couples its electric near field to the electrically lossy tissue. Forming a good radiator on a PCB would also require large area that is free of other components, which is typically not available in compact devices [8].

Small surface mount device (SMD) antennas are nowadays widely available in the market [9]. Thus, they are commonly used in small wireless devices. Their benefits include small size, easy integration and relatively good performance. They are one-terminal elements with the ground layer of the PCB operating as the second terminal of the antenna. Consequently, the size and shape of the ground metal of PCB has its impact on the antenna impedance and efficiency. Ceramic high-permittivity materials are commonly used in them, which increases the price. Such a component may be quite efficient in air, but when brought close to human tissue, has similar challenges as the antennas formed of the PCB conductor.

An ideal antenna arrangement to operate on skin prevents the electric near field of the antenna from penetrating the lossy tissue. In practice, implementing an efficient antenna under such conditions also favors the use of magnetic dipole as the main radiator. A solution that meets these requirements is known as planar inverted-F antenna or PIFA. However, a full-sized PIFA is a quarter wavelength structure that is too large for many compact devices. The concept of PIFA, however, can be varied to meet the specific requirements of a compact sized device [10]. In practice, the size of the antenna can be reduced at the cost of efficiency, impedance match and bandwidth. Forming a magnetic radiator as a part of the antenna requires some thickness of the structure. Even though low profile is typically a requirement for a skin-attached device, there are practically always e.g. a battery or some other components that define the minimum thickness of the device. Also some protective casing or a cap is typically used. Optimizing a device-specific antenna for a compact skin-attached device is all about taking advantage of this space.

4 Skin Wearable Patch Designs

At VTT we have been developing platform technologies for low power wireless sensors. In line with our sensor to the cloud strategy these platforms systems include sensor devices, readout electronics, wireless communication systems, gateway receivers and cloud server infra-structures. The electronics systems encompass flexible, stretchable and highly miniaturized patch type electronics.

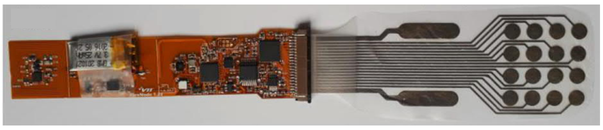

Figure 2. FlexNode wireless sensor platform (left) on polyimide flexible substrate has data communication over bluetooth to a SmartPhone receiver. Skin impedance measurement matrix (right) is fabricated on stretchable composite substrate [5, 11].

One such platform, named FlexNode, is illustrated in Fig. 1 and in Fig. 2 with skin impedance measurement. The FlexNode implements a wide range of sensing devices on a single platform. The platform, measuring 20 x 90 mm^2, is implemented on a polyimide flexible substrate. This enables a wide range of applications including integration with textile wearables, over molded inside fixtures or attached by adhesive directly on skin. FlexNode includes 3-axis acceleration, temperature, pressure and humidity sensors. It allows data streaming over Bluetooth low energy to a mobile device, or data logging in an on board 64 Mbit flash memory for later communication. It is powered by a 25 mAh rechargeable battery which gives a usage time of 24 hrs when streaming acceleration data at 100 sps or a usage time > weeks with lower duty cycle. Additionally, the platform includes an inductively coupled wireless charging functions with enables over molding or embedding of the platform in side structures. The FlexNode platform has been adapted for a number of wearable applications, one example of which is an online wound care monitoring device which can be integrated into a wound dressing (see Fig. 2) [11].

FlexNode is quite large, and even on a flexible substrate, the device restricts some movement, and is cannot be easily concealed. Furthermore, the large area of polyimide does not breath, and causes some sweating. On the positive side, the wireless charging enables charging without removing the device e.g. in bandages, and the device has proven to be electrically reliable. However, FlexNode uses a planar dipole antenna that is integrated on the flexible PCB. Attachment on skin compromises the performance of this antenna, as described in Chapter 3.

The restriction to movement and breathing has been improved in the impedance measurement electrode array, which is fabricated on nanocellulose substrate with tunable stretchability [5].

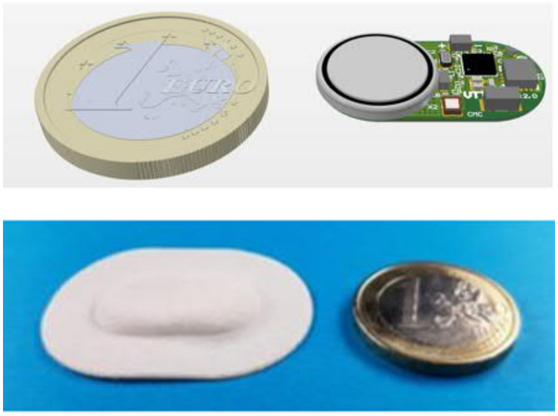

Figure 3. FlexDot, patch type wearable activity monitor (3 axis acceleration sensor). Electronics module 3D model (top), and patch packaged device (bottom) both with a euro coin for scale.

One of the descendants of FlexNode, FlexDot, is shown in Fig. 3. The device aims to be the world's smallest on-skin attachable activity tracker with only a 3-axis acceleration sensor. The electronics module measures 12 x 23 mm^2 and is implemented on a 0.5 mm FR4 substrate. Owing to the tiny size of the device, it was considered that a rigid substrate can be used without any major restriction of movement. The device includes a primary 20-mAh coin cell battery, which allows 24 hrs of continuous streaming or over a week of usage time at lower sampling rates. As the device is fully encapsulated, and ultra low power 'shake to wake' function was implemented consuming, about 1 uA and enabling a shelf life of more than one year.

The small size, height and weight of the FlexDot makes it almost unnoticeable to the user. Rigid board can be used over a small area. Small area also reduces sweating, as skin can breath under the edges of the board. Rigidness also improves electrical reliability.

FlexDot is equipped with a small SMD antenna, the matching circuit of which has been optimized on skin. This provides adequate operation range, but preliminary tests with new antenna prototypes show that the antenna performance can be improved by a PIFA-based antenna structure integrated into the package shown in Fig. 3.

5. Conclusion

We have considered user convenience in the design of skin wearable electronics. User convenience in wearing the device can be increased in many cases by choosing a breathable, flexible and stretchable substrate with few and small rigid parts. We have considered possible substrates and the challenges flexibility and stretchability introduce for achieving a reliable electrical design and RF antenna performance.

We demonstrated skin wearable patches with rigid, flexible and stretchable designs, and discussed their pros and cons for achieving user convenience. The application defines the required complexity of the electronics and thus the minimum size of the patch. Most convenient design is typically the smallest, thinnest and lightest design. However, a good antenna requires some space and thickness in the design, limiting the miniaturization. Preliminary tests indicate performance improvement with PIFA-type antennas.

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