Passive Wearable Electrostatic Tags: The Bodytag

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Abstract

We present novel methods to transmit both data and power wirelessly *through* the human body. The body may be modelled as a conductor surrounded by an insulator. Power and data signals may be coupled electrostatically to the body's interior and sent through it. We apply this technology to a new type of Radio Frequency Identification (RFID) tag that we call the *bodytag*.

The bodytag is a passive, wearable electrostatic tag. The wearable tag exploits the human body's natural ability to guide electric fields, and allows the wearer to present tags to tag readers through natural motions such as the grasp of a doorknob or the push of a button. The tag and reader imbue the user's physical gesture with digital meaning. The bodytag is also less expensive than conventional inductive RFID tags because it contains no magnetic flux coupling coil. We present the *loading mode* tag, which transmits data to the reader by modulating its own impedance, and the *transmit mode* tag, which transmits data by applying an electrostatic signal to the body.

1 Introduction

In this report, we describe how data and power can be wirelessly (and safely) transmitted *through* the human body. Within this general context, we present an application of this novel type of transmission to a new type of Radio Frequency Identification (RFID) tag that we call the *bodytag*. The bodytag is a *passive wearable electrostatic tag*. It is a wearable credit-card sized device that can compute as well as store, transmit, and receive information. It receives power and communicates electrostatically through the body. By *wearable*, we mean a tag that can be embedded into one's clothing, shoes, or other body-borne items.

The bodytag differs from inductively-coupled RFID tags in two important ways:

- The bodytag is significantly less expensive than inductive RFID tags because the magnetic flux coupling coil of an inductive tag is replaced by a discrete inductor. Furthermore, we may remove the discrete inductor from the tag without adversely affecting the performance of the tag.
- The body guides electrostatic fields from a tag reader to a wearable tag. This circuit is completed through a natural motion such as the grasp of a doorknob, so the tag and reader imbue the user's physical gesture with digital meaning.

We first present the model that explains the principle behind the bodytag and then describe the tag and reader.

2 The Model

The human body acts as a poor conductor connecting the tag and the reader [1]. However, displacement current, not DC current, passes through the user's body allowing the tag and reader to exchange data and power through the body. We call this type of communication *intrabody signaling*.

At low frequencies the human body appears to be a capacitive load; at higher frequencies the body radiates RF energy. Therefore, the frequencies used by the reader and tag are kept low to avoid interference and eavesdropping. We refer to this partitioning of space into personal areas of communication as *physical division multiple access* or PDMA [2]. The same region of the electromagnetic spectrum is shared by several disjoint networks, each of which relies upon the body (or connected bodies) to define its spatial extent.

The tag readers we describe operate at fixed frequencies below 1 MHz and use single electrodes (monopoles) as antennas. The wavelength of a 1 MHz uniform plane wave in free space is approximately 300 m. Therefore, all models and calculations presented in this thesis assume that the tag and reader are op-

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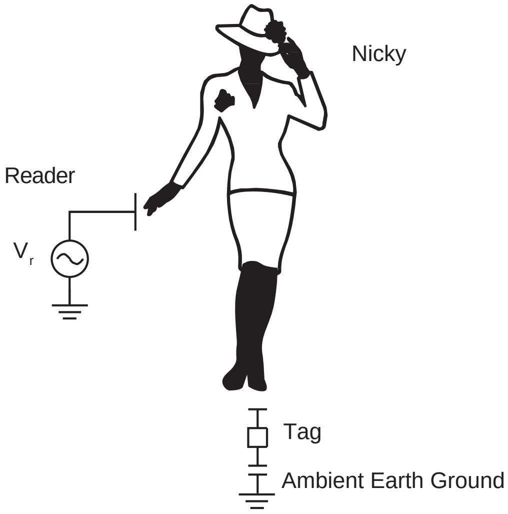

Figure 1: Model of tag and reader exchanging data and power through Nicky's body.

erating in the *electrostatic limit.* Specifically, we use lumped circuit elements in all of our models.

Figure 1 schematically depicts intra-body power and data transmission. We can send power and data through the body by capacitively coupling displacement current into the body and using the ambient ground reference provided by our environment as the current return path. This is a natural extension of earlier work in electric field sensing and data transmission which used the body and the ambient ground reference to create a circuit [1, 3, 4, 5, 6].

We model the human body as a solid ideal conductor (the briny interior) surrounded by an ideal insulator (the skin). We do not send DC current through the body because it is surrounded by an insulator – not to mention that it could be hazardous to present a constant voltage drop across the interior of the body. *However, we can easily send AC current through the body by capacitively coupling to its interior and using it as a single low-impedance node in a network of capacitors.* While charge carriers neither enter nor leave the body, there is a time-varying *displacement* of charge, which has the same effect as an actual current passing through the body. In Figure 1, the subject, Nicky, couples displacement current into her body by bringing her hand near the tag reader electrode.

Now that current has entered Nicky's body, the only other thing we need to complete the circuit is a place for the current to go. *We use the ambient ground reference as a return path for the AC current.* In Figure 1, Nicky's foot is capacitively coupled to the tag and the tag is capacitively coupled to the ambient ground, giving the displacement current a return path to ground.

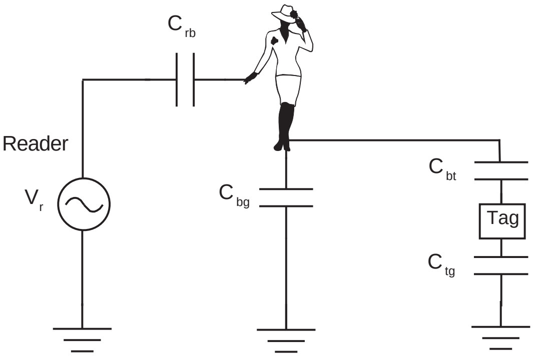

Figure 2: Equivalent circuit of tag and reader exchanging data and power through Nicky's body.

Figure 2 shows a circuit diagram of Nicky's interaction with the tag and reader, with several electrostatic links shown explicitly as capacitors. These capacitances are represented by

C_{rb} between the tag reader and the body,

C_{bg} between the body and ambient ground,

C_{bt} between the body and the tag, and

C_{tg} between the tag and ambient ground.

Each of these capacitances is on the order of 10 to 100 pF. Note that Nicky couples to one electrode on the tag, while the tag's other electrode couples to the ambient ground. If we put the body tag into the shoe, these electrodes could be the top and the bottom of an inserted pad.

In Figure 1, the reader sends power and data to the tag by modulating the AC voltage presented to Nicky's body. The tag is a passive device and has no power source of its own; it draws power from the time-varying voltage across its electrodes. The tag can send data to the reader by applying another AC voltage to Nicky's body or by modulating the load seen by the tag reader.

Why is the human body involved in the signalling between the tag and the reader? Without the body between the tag and reader, the capacitance between the tag and the reader is miniscule unless the tag and reader are within centimeters of each other. With the body between the tag and reader, there is a much higher capacitance (lower impedance) between the tag and the reader even at distances of a few meters.

One ideal electric location for the tag is in the user's shoe. In this geometry, the tag couples well to the user's body and to the ambient ground. Another good location might be on the head, perhaps in a hat, where power and data could be tapped to run a wireless, personal display device. Our ultimate goal is to be able to embed the bodytag anywhere on the user's body where there is a sufficient potential gradient from body to ground, such as in credit cards, wallets, and wristwatches.

Calculations indicate that if the tag is resonant, several milliwatts of power can be delivered to the tag if the reader is applying a 50 V sine wave to the reader electrode at the tag's resonant frequency. These calculations correlate well with observations made in the lab.

3 The Tag and Reader

There are two embodiments of the bodytag. Most commercial inductive RFID tags send data to the reader by modulating the impedance they present to the reader. We will call this method of data transmission *loading mode.* In contrast, very few commercial inductive RFID tags send data to the reader by applying a signal to the tag coil. We will call this method of data transmission *transmit mode.*

In both the transmit mode and loading mode readers the voltage applied to the reader electrode is $V_r = V_0 e^{j\omega_r t}$ where $\omega_r = 2\pi f_r$ and $V_0 \approx 50$ V. We now present both the loading mode and transmit mode tag and reader.

3.1 Loading Mode

In loading mode, the tag sends bits to the reader by modulating the Thevenin equivalent load that the reader sees through the body. The loading mode bodytag consists of a discrete 9.5 mH inductor (L_t), a V4050 inductive RFID chip from EM Microelectronic-Marin SA, and two electrodes (Figure 3). The 4050 contains an integrated 170 pF capacitor (C_t), so the tag is resonant at 125 kHz.

The 4050 is a 2-pin device that transmits data by Q-switching. R_t models the power dissipation of the tag, and R_p is the parallel resistance switched by the tag to modulate Q. The tag contains 1 kilobit of EEPROM that can be programmed *through the body.* Though the 4050 was designed for inductive RFID applications, it can be modified to function as a bodytag simply by adding an inductor to make the tag resonant, and by adding one electrode to couple the body to the tag (C_{bt}) and another to couple the tag to ground (C_{tg}).

The bodytag is less expensive than an inductively-coupled RFID tag: a coil has been replaced with two electrodes and a lumped element inductor. Coils are expensive to wind and to mount, while electrodes used in bodytags may be mounted or printed onto irregularly shaped surfaces. The electrode material may even have a high DC impedance.

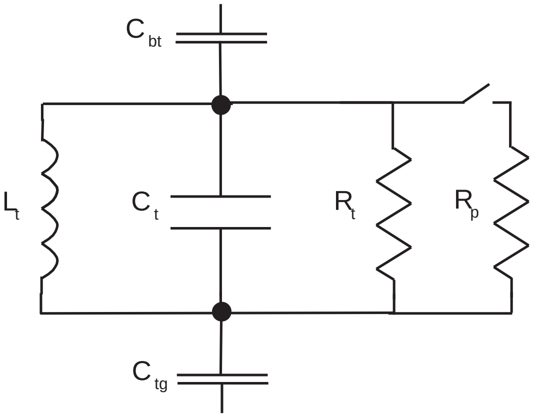

Figure 3: Loading mode tag with Q-switching data transmission.

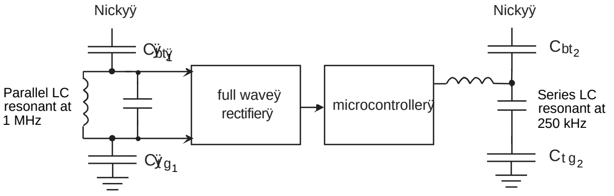

Figure 4: Block diagram of the transmit mode bodytag.

We may also remove the inductor without greatly decreasing the tag's read range or increasing the errors in the tag's data transmission. We have demonstrated that the loading mode system presented here functions without L_t.

The loading mode reader has a resonant front-end receiver to increase sensitivity to the small AM signal from the bodytag. The loading mode reader quadrature demodulates the AM signal from the tag to recover the baseband signal containing the tag data. The reader 100% amplitude modulates the voltage on the reader electrode to send data to the tag. The reader was designed with $f_r = 125$kHz.

3.2 Transmit Mode

Transmit mode differs from loading mode in that the tag actually transmits a signal back to the reader through the user's body (Figure 4).

The bodytag rectifies the current moving through the tag electrodes and uses the rectified current to power a PIC16LF84 microcontroller running at 8 MHz. The PIC then transmits frequency shift keyed (FSK) ASCII data through a series LC tank to the reader. The PIC presents a 2.5 V amplitude square wave to the series LC tank, which boosts the transmission voltage by a factor of the tank's $Q \approx 10$. The FSK frequencies are 200 kHz and 250 kHz.

Note that the tag's power comes in on one pair of electrodes and the tag's data is transmitted on another pair of electrodes. We are working to combine these electrodes into a single pair.

The transmit mode reader contains two electrodes. One electrode puts out a 50 V amplitude sine wave at 1 MHz. This electrode electrostatically powers the transmit mode tag through the tag's parallel LC tank.

The other electrode is attached to a receiver which demodulates the FSK data sent by the tag [5]. The receiver demodulates the data with a PLL and transmits the ASCII data from the tag to a PC. The user touches both electrodes simultaneously to initiate a tag interrogation.

Initial observations of the transmit mode tag indicate that the transmit mode bodytag may be more robust than the loading mode bodytag.

4 The Magic Doorknob

One of the most common applications of inductive RFID systems is for electronic access to buildings. To demonstrate the utility of the bodytag, we created what we call the *magic doorknob*. In this demonstration, the reader electrode is a brass doorknob (covered by an insulator) and the bodytag is embedded in the user's shoe. The user simply touches the doorknob, at which point the bodytag and reader exchange power and data, and the door unlocks itself if the user is authorized to enter.

5 Conclusions and Future Work

We have presented a novel method to transmit data and power through the body. We applied this technology to an RFID bodytag that can transmit data through the user's body to an RFID reader. Furthermore, since the bodytag has an EEPROM, it can be seamlessly updated with new information at any time.

The current challenge with the bodytag is to improve its performance so that the tag does not have to be embedded in the user's shoe but can be placed in the user's back pocket in the same form factor as a credit card.

Current findings and guidelines lead us to believe that no health threats are posed by the tag reading and powering schemes we have described. Our system operates well below the FCC guidelines and current Notices of Proposed Rulemaking [7] regarding safe levels of RF exposure, which assumes that at frequencies above 30 kHz the most important hazardous biological effect of RF energy is the local or bulk heating of body tissue.

The bodytag has two important advantages over a traditional inductive RFID tag. First, the bodytag is cheaper than an inductive RFID tag. We have replaced the coil of an inductive RFID tag with a discrete inductor and a pair of electrodes. We may also be able to remove the inductor without adversely affecting the performance of the bodytag. Second, the bodytag is wearable. The user does not need to bring the tag to the reader. The user presents the tag to the reader simply by bringing his hand or another body part near the reader. The presentation of the tag to the reader is embedded in a very natural gesture. The bodytag is a step towards natural and transparent human-computer interaction.

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