A Low-Cost Electromagnetic Tagging Technology for Wireless Identification, Sensing, and Tracking of Objects

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Abstract

A technical overview of near-field electromagnetic tagging is presented and described in the context of adding functionality, efficiency, and convenience to the spaces in which we live and work. A brief survey of all common forms of electromagnetic tagging is given, including shoplifting tags and RF-ID (Radio-Frequency Identification) tags. Focus is given to low-cost electromagnetic tags based solely on electromagnetic material structures. A unifying description of these materials tags is introduced which defines four main functions: identification, sensing, data read/write, and tracking of position/orientation. Encoding information into the material properties of an object is introduced as a means of making new connections between the digital world of electronic appliances and the physical world. Several commercial applications are given. A general theoretical framework to model near-field electromagnetic tagging systems is outlined, and a few new types of tags are presented along with experimental data.

Thesis Supervisor: Neil Gershenfeld, Associate Professor of Media Arts and Sciences

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Chapter I.

Introduction

As we enter the 21st century, it is not uncommon to refer to this time in history as the "Computer Age" or "Information Age." Certainly in the past decade, dramatic changes in communication and information technology are clearly evident through such things as widespread use of electronic mail, the Internet, and the World-Wide Web. Not only offices but also homes are now connected electronically, with digital information flowing among them; and to provide electrical connectivity to ambulant humans, a great deal of wireless and mobile electronic appliances have also permeated society.

Nevertheless, our electronic appliances are inadequate and inefficient for dealing with our growing demand for convenient communication and access to information. Most people cannot send or receive digital information (e-mail, FAX, images, sound files, video, etc.) outside of their office environment. And since the cost and complexity of most information devices is high, a relatively small proportion of the population has access to them. Therefore we need cheaper and more natural ways to network objects together and allow them to interact with the environment.

Part of the solution to dealing with the information around us is networking. If networking was sufficiently low-cost, then the common objects around us could have a means of communicating with each other. In addition to electronic devices in the workplace or in a factory, such an innovation could be applied to our home life. For example, I would be able to call up my refrigerator from work and ask it to defrost the chicken, or send an e-mail to my microwave oven with the cooking times from a recipe I just read on the Internet. Unfortunately our computers generally cannot communicate with our watches or portable phones, much less with our washing machines or microwave ovens. In addition, if a manufacturer wishes to add features to an appliance, it must have it's own computer with display and I/O devices, instead of sharing the resources of another appliance. This is inefficient in terms of information and in terms of cost. We are just starting to see new products which address this need, such as an e-mail terminal built into a telephone and a television internet browser, but we need network technology that is low-cost and flexible, so information capabilities can also be extended to other objects in the spaces we inhabit. At the MIT Media Lab, this level of networking is being developed by Professor Mike Hawley and the Personal Information Architecture Group.

However, perhaps even more fundamental than networking is the problem of sensing. Before we can have a network, we must have connectivity – not only with other objects but with people as well. Since our world isn't static or hardwired, connectivity means access; this requires a means of wirelessly sensing and identifying the objects and people that come in and out of our local worlds. Unfortunately, computers are quite blind to the physical world with which they must ultimately interact. Present computers lack the rich sensory interactions and related mental processes of humans. Devoid of all senses, our "high-tech" environments are severely handicapped and consequently lack two fundamental abilities: *awareness* of the world and the ability to *react* to it.

In short, the goals of information technology is to create not just information appliances, but information *environments*. Such environment would allow people to have access to information wherever they are. Such environments allow people the freedom to carry out their daily tasks without losing access to information. In fact, Professor Neil Gershenfeld states his future vision of information spaces in terms of the "Information Bill of Rights." Briefly stated, a person should have the right to send and receive information, whenever and wherever he or she pleases, be it on your sofa or on the beach. But in addition, a person should have access to privacy and anonymity if one so chooses. Like humans, objects should be able to communicate with humans as well as with other objects. But to have this freedom – to have the convenience of automatic door entry, automated package delivery, automated manufacturing, automated financial transactions, and automated retailing – we need better and lower-cost sensing technology.

Much of the work at the MIT Media Lab has been devoted to the goal of making computers more useful in order to improve the environments in which we live, play, work, and learning. Many of the technical solutions addressing the need for sensing have been motivated by a human perspective. Successful research has yielded camera-based systems which allow computers to see, identify, and react to objects around them. Other work, for example, has advanced the ability for computers to hear and understand human speech and environmental sounds; and haptic interfaces for sensing touch is starting to be explored.

Despite this existing research, however, it is prudent to explore other sensing technologies outside the human paradigm. As we have learned from the invention of the airplane, it is not always necessary to imitate Nature. Since computer applications are quite diverse and subject to a wide range of constraints, alternate means of sensing and interacting with the physical world is a worthwhile endeavor. The technology presented in this thesis is an example of such sensing technology.

A. Tags

A "tag" is something which can be attached to a person or object and thereby enables an information environments to remotely identify objects and people, track their position, or sense their state. The approach to wireless sensing presented in this thesis involves the use of electromagnetic fields, as opposed to optical means. In general, the information acquired via the tag is then used by some sort of electronic appliance to perform its function. In fact, a tag is a type of lower-level network which allows transfer of ID or sensor information. Since it is not economically practical to implant computers into common objects such as suitcases, golf clubs, books, or pens, these devices can communicate their information by proxy to more intelligent devices. As such, tags represent the lowest level on the information "food chain," illustrated in Figure 1. This thesis discusses the technology involved to create this bottom layer.

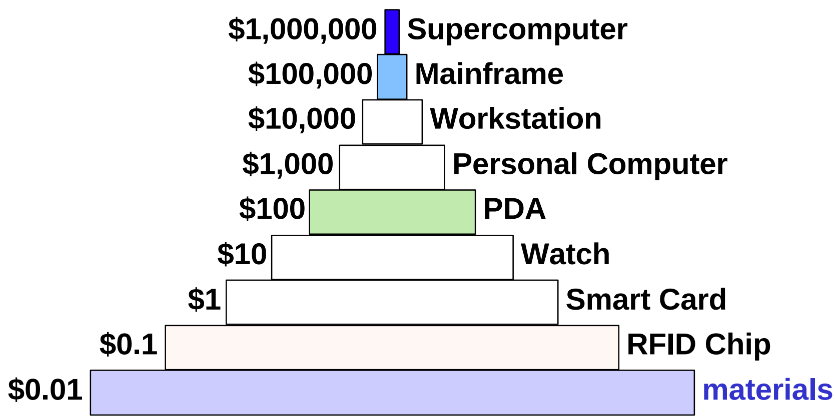

Figure 1. Illustration of "information food chain." As we move down the food chain, the potential number of devices increases dramatically, but lower cost per device is required.

B. Brief Overview of Current Tagging Technology

Tags in the form of radio transponders have existed for at least fifty years. The simplest example is a radio beacon that emits a unique signal which can be detected with a radio receiver at some distance (many meters or more). These are commonly used on all types of aircraft. Other radio tags function as transponders by responding only to a unique signal from a distant transmitter. These tagging systems have been used in a wide variety of applications ranging from wild animal tracking to military surveillance to stolen car retrieval. Such tags are comprised of a radio transmitter powered by some type of battery; naturally, greater battery power is required as the transmitting distance is increased. Other types of tags, such as a diode harmonic tag, simply modulates the transmitted signal which scatters off of it.

Until the 1960's, most of the interest in tagging was in far-field devices, which means that the sensing distance is long compared to the wavelength and to the size of the antennas involved. Although the optical barcode was invented in 1949, it was not until the mid-1960's that commercial interest began in the field of short-range wireless tagging for shipping, inventory, and retail applications. In 1967, the first commercial barcode scanning systems were installed in supermarkets; and in 1975 the first low-cost electromagnetic tagging systems began appearing in libraries and some retail stores. In the late 1970's a lock company started experimenting with electronic alternatives to the standard key. One group of the company explored a multiple-resonance swept-frequency approach (storing information in the frequency-domain) and the other group explored a chip-modulated fixed frequency approach (encoding information in the time-domain). The swept-frequency approach went on to be developed by Westinghouse for security access applications, and the other idea went on to become what we know today as RF-ID.

The technology known as RF-ID (Radio Frequency Identification) is presently the fastest growing form of near-field electromagnetic tagging. The earliest applications of this technology included tagging cattle and laboratory animals. This type of tag makes use of an electronic chip to communicate with a receiver at some short distance (~ centimeters). In an RF-ID system, the distance between the tag and the base station (known more appropriately as the *tag reader*) is sufficiently small that the signal between them is best characterized by the *coupling* between the tag antenna and the tag reader antenna. In fact, the term *antenna* is somewhat of a misnomer because no far-field transmission is employed as its connotation implies. Parts of the tag and parts of the tag reader are simply coupled together in a manner similar to transformer windings (*inductive coupling*) or as opposing plates in a capacitor (*capacitive coupling*).

The near-field coupling between the RF-ID tag and the reader serves two important functions. First, the coupling is commonly used as a means of supplying power to the tag. If all the necessary electronics inside the tag can be powered remotely from the reader, then the tag requires no local power source. Secondly, since the tag functions as an electrical load on the tag reader, the tag can communicate information to the reader simply by changing the value of its own impedance. The RF-ID tag accomplishes this task through the use of a small electronic chip, which is basically an active switch. As a result, the tag is not required to generate any transmitted signal, and the impedance switching pattern is used to encode the information in the tag. The basic elements of an RF-ID tag is shown schematically in Figure 2. This is not the only way RF-ID tags can function, but it is a common mechanism.

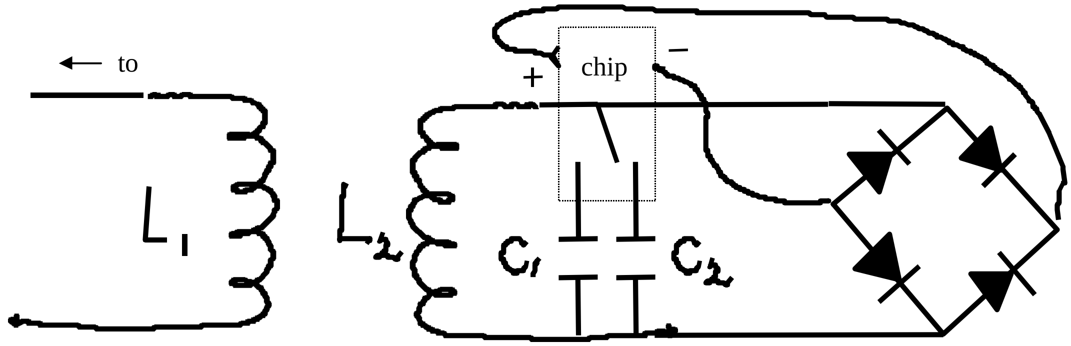

Figure 2. Functional diagram of a tag reader antenna inductively coupled to a battery-less RF-ID tag.

RF-ID tags can be made quite small due to their relative simplicity. For example, RF-ID tags can be embedded inside security badges, which can allow automatic access to secure doors that are equipped with tag readers. RF-ID tags are also embedded into clothing buttons and are used by commercial laundry companies to automatically sort clothing according to each clothing item's ID code.

Although the relative simplicity of the RF-ID circuitry provides a lower-cost alternative to radio tags, any amount of circuitry will always be much more expensive than the most common type of short-distance wireless tagging technology, namely the optical barcode. Since barcodes can be easily printed on a variety of surfaces, barcode tagging technology is extremely cost-effective. However, since reading barcodes requires line-of-sight and some degree of alignment between the barcode and the reader, there exists a certain amount of inefficiency in this approach. As a result, there exists a general desire for the invention of an "electromagnetic barcode" technology which would also be cheap, but would not require line-of-sight. The electromagnetic version of the optical barcode would allow the reader to be hidden behind a wall panel or under a table top. In addition, the electromagnetic transfer of information is generally not affected by operation in dirty environments; and since line-of-sight is not required, tagged objects could be "scanned in" at a faster rate without the need to pause to find the location of the barcode and orient it towards the reader.

C. Low-Cost Alternatives

RF-ID tags can be relatively cheap (~$.90) but optical barcodes are far cheaper (<$.01). Much of the cost of an RF-ID tag is not only due to the electronic chip but – more importantly – to the manufacturing complexity of the entire tag. As a result, the general approach to creating a low-cost electromagnetic tagging technology such as the "electromagnetic barcode" is based on eliminating the electronic chip, and reducing the manufacturing complexity. The challenge, of course, then becomes how best to encode electromagnetic information using materials alone. Since the development of the multiple-resonance frequency tags in the early 1980's, relatively little work has been done outside of RF-ID.

The tagging technology presented in this paper is based on the electromagnetic response of materials. While detecting specific materials electromagnetically is not uncommon – as demonstrated by metal detectors, shoplifting security systems, and medical Magnetic Resonance Imaging systems – it would be useful to create a unified, quantitative and general approach to this topic. By identifying the electromagnetic response of materials, we can view materials as physical representations of information. Furthermore, by knowing how this electromagnetic response depends on the local material environment, materials can also be viewed as remote sensors. The notion that any material structure or object around us can function as a sensor or repository of information can fundamentally change the way we manufacture and package all kinds of products, ranging from military airplanes to pizza boxes to sport shoes.

In terms of cost, material structures thus form a separate class of tagging technology that lies somewhere between RF-ID, magnetic stripe cards, and the optical barcode. Naturally, the cost of a particular tag would depend on the choice of materials and the design of the tag. A description of various materials tag concepts and their corresponding physical description are presented in the following chapters. Some promising potential markets for electromagnetic tagging and practical considerations are discussed in the final chapters, as well as a brief description of ongoing work in our lab.