

Personal Area Networks (PAN): Near-Field Intra-Body Communication

by

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B.S., Humanities and Engineering
Massachusetts Institute of Technology
February 1980

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN MEDIA ARTS AND SCIENCES
at the
Massachusetts Institute of Technology
September 1995

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Abstract

PAN is a wireless communication system that allows electronic devices on and near the human body to exchange digital information through near-field electrostatic coupling. Information is transmitted by modulating electric fields and electrostatically (capacitively) coupling picoamp currents into the body. The body conducts the tiny current (e.g., 50 pA) to body mounted receivers. The environment ("room ground") provides a return path for the transmitted signal. A low frequency carrier (e.g., 330 kHz) is used so no energy is propagated, minimizing remote eavesdropping and interference by neighboring PANs. Digital information is transferred using on-off keying with quadrature detection to reduce stray interference and increase receiver sensitivity. A low cost (<\$20) half-duplex modem is implemented using an analog bipolar chopper and integrator as a quadrature detector, and a microcontroller for signal acquisition. The technology used in the PAN can be integrated into a custom CMOS chip for lowest size and cost.

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

This work was supported in part by Hewlett-Packard Corporation and Festo Corporation.

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by

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Acknowledgments

I am indebted to my advisor, Neil Gershenfeld, for reacquainting me with the all-encompassing power of physics through his broad command of the discipline. His class Physics and Media succinctly reviews how important a knowledge of physics is to tackling any engineering problem. I would like to thank all the members of the Physics and Media Group; Josh Smith, Joe Paradiso, Rich Flecher, Barrett, Henry Chong, and David Allport for their camaraderie, team work, stimulating technical discussions, and friendship during a very busy and exciting eighteen months. I would like to particularly thank Joe Paradiso for all the advice, design discussions, and great music.

I would like to thank the Media Lab, that big box of very talented people, and those who build it and keep it running. Of particular merit is the work of Linda Peterson, Santina Tonelli and Suzanne McDermott. I came to the Media Lab because it has everything I am interested in under one roof, and my experience here have confirmed my belief. The Media Lab is truly a unique laboratory at a unique institution.

The visitors who come to the Media Lab for demonstrations have provided me with instant feedback on the usefulness and value of my research. Without their support and interest, the Media Lab would not exist. I would like to thank Dr. Hermann Klinger and the Festo Didactic Corporation for their enthusiastic support of our research and for the hospitality Dr. Klinger showed me on my visit to Germany. I would like to thank the Hewlett-Packard Corporation for their generous support of our laboratory, and my readers Professor Lettvin and Professor Smullin for their comments.

Finally I would like to thank my wife, Patricia Canon Zimmerman, for being the most wonderful, understanding, helpful, loving, and fun person I know. She sacrificed much to come here to see me through this process and now we can go back to California, both Masters, with our wonderful six month old son, Matthew Daniel Zimmerman.

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1. INTRODUCTION

1.1 *Previous Work on Electric Field Sensing*

The development of the PAN grew out of research at the Physics and Media Group of the MIT Media Lab on applying electric field sensing to position measurement. The group became interested in electric field sensing while trying to solve a measurement and instrumentation problem. Professor Neil Gershenfeld was trying to measure the position of Yo-Yo Ma's cello bow in a project with Professor Tod Machover. The concept was to extend Yo-Yo's playing technique by treating his bow as an elaborate mouse. The challenge was to measure bow position in two axes without encumbering Yo-Yo's playing technique. The resulting mechanism applied a low frequency RF signal (~ 50 kHz) to an antenna mounted on the body of the cello and measured the near-field signal strength at the ends of a resistive strip (~ 10 megaohm) mounted along the bow [Gershenfeld93]. In an attempt to make the sensing wireless, it was discovered that placing one's hand in the electric field attenuates the received signal dramatically. The sensing mechanism that emerged from this observation is described in [Zimmerman95].

1.2 *Current Trends in Wireless Networks*

Historically work on wireless networks has been focused on infrared (IR) light technology and radio transmission. The former suffers from line-of-sight limitations and the latter from regulations by the FCC. In 1985 the FCC released several frequency bands called the ISM bands, for Industrial, Scientific, and Medical applications. The ISM band allows up to 1 watt of peak output power for frequency hopping and direct sequence spread spectrum transmitters. The ISM frequency bands include 902-928 MHz, 2.2835-2.4, and 5.725-5.85 GHz [FCC93].

The standard criteria for wireless network performance is message bit rate. Kahn [Kahn92] presents analysis that shows it is possible to achieve data rates as high as 100 Mb/s using non-directional IR. Current IR systems perform up to 4 Mb/s. The system Kahn proposes uses infrared laser diodes located in the walls and ceilings of office

buildings, each consuming about 1 watt of power per 75 cubic feet of room¹. Although the transmitters require a large amount of energy, the receivers can operate at a fraction of the transmitter power. Typically a mobile user is transmitting keystroke and pointing device information, which can be accommodated with a 2400 baud modem. This asymmetry works well in favor of low-power mobile computer modems.

The first generation of radio wireless LANs were designed to interconnect stationary workstations and marketed as LAN extensions, consuming approximately 20 watts supplied by the mains. The current generation of wireless LANs use spread spectrum in the ISM band and achieve data rates as high as 20 Mb/s [Pahlavan95].

1.3 Motivation for Personal Area Networks

As electronic devices become smaller, lower power, and less expensive, we have begun to adorn ourselves with personal information and communication appliances. These devices include cellular phones, personal digital assistants (PDA), pocket video games, pen based computer pads, palm top computers, and pagers. Currently there is no standard method to interconnect these personal electronic devices. The personal area network is a means to interconnect these personal device, in a manner appropriate to the power, size, and cost of these devices.

1.3.1 WAN \Rightarrow MAN \Rightarrow LAN \Rightarrow PAN

Wide area networks (WAN) connect distant computers using microwaves, radio waves, coaxial cable, and fiber optic. Metropolitan area networks (MAN) connect computers in a city. Local area networks (LAN) connect computers in an office building. This thesis introduces the new concept of a personal area network (PAN); a wireless communication system that allows electronic devices on and near the human body to exchange digital information through near-field electrostatic coupling, developed by Neil Gershenfeld and the author [Gershenfeld95a]. The communication system is called a PAN to identify an evolutionary progression in the development of computer networks and mark a trend

¹ Khan's simulation was done using a 1 W source radiating an ideal Lambertian pattern to a room 5m x5m x 3m.

towards very personal computing and information appliances that are worn on and near the body. Devices that use PAN communication techniques for data transmission and reception are referred to as PAN devices.

1.3.2 Interconnectivity Reduces Redundancy

A person who carries a watch, pager, cellular phone, cassette/fm player/recorder, PDA, and notebook computer is carrying five displays, three keyboards, two speakers, two microphones, and three communication devices [Shivers93]. The duplicity of input/output (I/O) devices is a result of the inability of the devices to exchange data. All of these devices contain some logical processing unit, typically a microprocessor. With proper networking structure these devices can share computational resources, either performing distributed computation or relying on neighbors with more specialized and higher capacity processing power to perform functions too intensive for the resident processor. The ability to share resources is tempered by inter-communication channel capacity and system complexity.

1.3.3 Ubiquitous Computing vs. Distributed I/O

The ability of personal information devices to share data will increase their usefulness, synergistically providing features not possible with independent isolated devices. Often these new devices will be the interface between a user's intent and the machine/system that will satisfy the user's desire. A person in the future might find the time of her first meeting by calling out "When's my first meeting". The microphone in her shirt collar or watch would transmit her voice through a series of wireless transponders in her environment (e.g., shoe, desk, table, chair) to a remote voice recognition computer that searches her calendar and sends a response back through the network of transponders to a speaker on her collar or a visual display on her watch. The capability of autonomous yet interconnected devices may transform the notion of ubiquitous computing to distributed input and output (I/O). The computer does not have to be portable if the device are portable and continuously networked to stationary databases and computing machines. This concept of distributed networked computational resources has been referred to as a "computational cloud" [Pahlavan95].

1.3.4 Connecting to the "Outside" World

Allowing body-based devices to inter-communicate relieves each of the burden of supporting a communication channel to the outside wired world. If one PAN device is capable of communicating to all of the body-based PAN devices and to an external device attached to a wired network, then all the body-based PAN devices can communicate to the outside world. The body-based PAN device that communicates to the outside world can be a) any PAN device which happens to be at the moment optimally located to reach an externally networked PAN device, b) a PAN device well situated to communicate to the environment, for example a shoe-based PAN device, or c) a PAN device equipped with a traditional radio-based or infrared-based transceiver.

1.4 Comparison of Electrostatic to Infrared Transmission

Infrared communication relies on line-of-sight transmission which is not appropriate for devices that may be located in wallets, purses, or pockets. Infrared provides a higher bandwidth than can be achieved with electrostatic means since the optical carrier frequency is orders of magnitude higher than the PAN device carrier. Infrared transmitters, however, must produce a wide angle beam of high optical power to be received, on the orders of hundreds of milliwatts. Electrostatic coupled PAN devices can operate on a few milliwatts of power.

1.5 Comparison of Electrostatic to RF Transmission

An obvious competitor to electrostatic coupling as a physical communication channel for a PAN device is radio transmission; the propagation of electromagnetic waves. The main advantages of radio wave energy propagation, as compared to electrostatic coupling, is higher bandwidth and longer range. One might consider electrostatic coupling as the low frequency end of radio since the energy coupling mechanism to any receiver substantially within a wavelength of a radio transmitter is electrostatic or magnetostatic (the near-field or inductive field region) [Weston91, Mills93, Ramo94]. Considering the operating distance of PAN devices is under 2 meters, the carrier frequency of a radio transmitter would need to be in excess of 150 MHz to operate at far-field.

1.5.1 Antenna Size and Efficiency

The fundamental difference between PAN device near-field communication and radio-frequency far-field (broadcast) communication is clearly demonstrated in antenna design. To maximize electrostatic coupling, electrode area is maximized. To maximize broadcast transmitter signal strength, the electrical impedance of the transmitter is matched to that of free space.

The strength of the transmitted electromagnetic waves is a function of antenna current flow, which is inversely proportional to the reactance of the antenna. Maximum antenna current is achieved by operating the antenna at resonance; the frequency at which the reactance goes to zero. The shortest antenna length to achieve resonance is one half a wavelength long. Considering that common PAN devices are on the order of 25 to 80 mm long (see *SIZE*), a carrier in excess of 3.75 GHz would be required. Inductors can be used as a matching network to compensate for electrically short antennas², albeit decreasing the bandwidth of the antenna and increasing the power dissipation in the matching network [Orr87].

1.5.2 Interference

The nature of radiation is to propagate to infinity until stopped, with a field strength that falls off quadratically (in the far-field region). The electromagnetic spectrum is crowded with many sources, mostly human-made. Part 15 of the FCC specification allows unlicensed broadcasters of limited power and bandwidth, with the understanding that the broadcasters must accept interference from other licensed and non-licensed broadcasters. When a frequency band is opened up to consumer products, such as wireless telephones using the 900 MHz band, interference is probable.

It is not uncommon to have many people together in a small space, such as in public transportation, elevators, queuing lines, conferences, and auditoriums. Under these circumstances it would be unacceptable to have PAN devices fail due to interference from neighboring PAN systems. The challenge of operating many unregulated broadcasters is

faced by designers of wireless LANs. The emerging solution appears to be one of "spectrum etiquette" which promotes "listen before you transmit" and only transmit the power necessary to be heard by your listener [Pahlavan95].

The electric field in the near-field region falls off with distance cubed. This makes the non-radiating electric field inherently limited to short haul communication. Electrostatic transmitter and receiver electrodes are optimized by having large surface areas, yet they are extremely small compared to the wavelength of the carrier, making them very inefficient electromagnetic transmitters and receivers. There is therefore little interference between distant (e.g., >5 meters) transmitters and negligible transmission and interception of electromagnetic radiation. Multiple neighboring PAN systems, whose fields do significantly overlap, may run simultaneously by frequency, time, or code division.

Radiating transmitters are basically pollution to any receiver except the intended one. The number of wireless consumer products in use, such as pagers, cellular phones, and wireless phones, are dramatically increasing, yet the electromagnetic spectrum remains a finite resource. Therefore communication channels that have equal or better transmission media alternatives should choose them, rather than congesting the electromagnetic spectrum. If local personal device communication systems become as common as watches and credit cards, near-field communication can avoid a dramatic increase in local electromagnetic pollution.

1.5.3 FCC Field Strength Regulations

The FCC classifies electronic devices as intentional or unintentional radiators. A wireless microphone is an intentional transmitter while a pocket calculator is an unintentional radiator. PAN devices do not intentionally radiate power; their communication is based on near-field coupling. All electronic devices must comply with FCC emission regulations. Part 15 of the FCC specifications details the allowable electric field strength for electronic devices, summarized in the following table [FCC93]:

² Short compared to the ideal half wavelength.

<u>Freq. (MHz)</u>	<u>Field Strength (uV/m)</u>	<u>Distance (meter)</u>
0.009-0.490	2400/Freq. (kHz)	300
0.490-1.705	2400/Freq. (kHz)	30
1.705-30	30	30
30-88	100	3
88-216	150	3
216-960	200	3
>960	500	3

To check the compliance of a typical PAN transmitter with the FCC Part 15 specifications, the electric field strength is found by differentiating the field potential V_{field} with respect to distance r which is defined for a dipole at far-field by:

$$V_{field}=(P/4\pi\epsilon)(1/r^2)$$

The dipole moment P ($P=Qd$) is estimated by approximating the electrodes as a parallel plate capacitor, distance d apart, and calculating the resulting charge Q on the plates by the relationship $Q=CV_{osc}$, where V_{osc} is the voltage across the plates. A typical PAN transmitter measuring 80 mm x 50 mm x 8 mm (a thick credit card), transmitting at 330 kHz at 30 volts (typical for a resonant transmitter), has a field strength of 344 pV/m at 300 meters, 86 dB below the FCC allowable field strength. The approximations are sufficient to show that the PAN transmitter field strength is orders of magnitude lower than those allowed by the FCC.

The development of radiating networks has been delayed by the licensing requirements of the FCC. In the late 1970's Hewlett-Packard began experimenting with direct sequence spread spectrum transmission for wireless inter-terminal networking and petitioned the FCC to release some spectra for the commercial use of spread spectrum communication. After four years of study, the FCC released the ISM bands in 1985 [Pahlavan95]. The use of electrostatic coupled PAN devices can begin immediately without an FCC license. Approval for PAN transmitters under Part 15 should be easy due to the small electric field strengths generated.

1.5.4 Eavesdropping

A radio transmitter propagates energy, this is the nature of broadcasting. The signal

strength from an isotropic (omni-directional) radiator decreases with distance squared, a result of the radiator "illuminating" the surface of a sphere. Some of the data communicated among PAN devices will be of a sensitive nature, for example credit card and telephone numbers, client notes, diary entries, business communications, and computer passwords. Radio systems can be made secure with cryptographic strategies, requiring additional processing overhead, but the best security is a message that is never intercepted.

Electrostatic coupling, on the other hand, does not propagate electromagnetic energy. The electric field strength falls off with distance cubed, a result of the dipole charges canceling their fields. The greater signal attenuation with electrostatic coupling (the cube verses the square of distance), make electrostatic coupled signals more difficult to detect at a far distance. For example, the electrostatic-coupled signal strength at 300 meters, referenced to 1 meter, is 50 dB smaller than a comparable radiated signal.

If the distance between the transmitter and eavesdropper is large enough, the intercepted signal strength will be smaller than thermal noise, making reception of the message very difficult. In the previous section *FCC Field Strength Regulations*, it was shown that a typical PAN transmitter has a signal strength less than 400 pV/m at 300 meters. A very high impedance (e.g., 10^9 to 10^{12}) is required to measure such a small potential. As will be shown in *Cable Resonance Phenomena and Non-Ideal Op Amp Performance*, the thermal noise (also know as Johnson noise [Horowitz94]) for a 1 M resistor at room temperature is 41 uV, which is five orders of magnitude larger than the field potential across a meter at 300 meters. Stated another way, an ideal amplifier (no noise) with an input impedance of 10 kohm and 10 kHz bandwidth would need to operate below one degree Kelvin to receive a PAN signal at 300 meters.

In addition to the inherent security of dramatic signal attenuation with distance, the same security means used with LAN communication can be used in PAN systems.

1.5.5 Power

The energy consumed by electronic components increases with frequency due to the dissipative losses incurred discharging capacitances³, which amount to $1/2CFV^2$, where C is capacitance, F is charging/discharging frequency, and V is the capacitance charging voltage. A radio transmitting PAN device would need to run at frequencies in the MHz to GHz in order to efficiently transmit. Any increase in the frequency of the carrier beyond that required to contain the information is essentially wasted.

Electrostatic coupling can operate at very low frequencies (0.1 to 1 MHz), making them inherently more efficient than higher frequency radio transmission for short distance (<2 meters) low bandwidth (<100 kbits/sec) communication. For example, in the PAN system prototype which operates at 330 kHz at 30 volts with 10 pf electrode capacitance, 1.5 mW are consumed discharging the electrode capacitance. A majority of this energy can be conserved (recycled) by creating a resonant tank circuit between the electrode capacitance and an inductor (*see Boosting Transmission Power*).

1.6 Networking Standards

There are many choices and trade-offs in defining a networked communication system. The PAN system is an initial attempt to explore some of the design and engineering issues of intra-body communication using electrostatic fields. To be practical and useful a communication standard will need to be developed. The TCP/IP protocol allows over 20 million people to electronically communicate over dozens of different types of machines distributed across the globe. The MIDI (Musical Instrument Digital Interface) standard allows hundreds of musical devices from keyboard to drum machines and computers to communicate, integrating electronic music studios. Similarly a standard for personal information appliances needs to be developed to increase the usefulness and synergy, and reduce redundancies among these devices.

To understand how the PAN transmitter and receiver technology presented in the thesis

³ Novel techniques using resonant power supplies are being investigated to avoid capacitive charging losses, particularly for use in CMOS integrated circuits [Gershenfeld95b].

can be incorporated into existing computer systems, it is important to review network standards. The International Organization for Standardization (ISO) formed a subcommittee in 1977 to develop network standards to promote interoperability among computer communicating equipment. The subcommittee produced a report, ISO 7498, released in 1984, that specifies a seven layer model for communication functions [Stalling93]. The ISO network standard provides an explicit means to incorporate PAN devices into existing computer systems. The model defines the function of each layer to allow each layer to be developed independent of the others and assure they will operate together. The first layer is the physical layer; the electrical specification to transfer unstructured bits across a communication medium. The second layer established a data link, providing reliable data transmission through synchronization and framing techniques. The third layer provides networking to upper layers independent of the specific physical and data link techniques used. The seventh and last layer, the application layer, provides services to the user, such as file transfers.

The thesis is primarily concerned with the first layer, the physical layer, examining the electrical properties of the communication channel, and the second layer, establishing a reliable information link, in order to implement a working prototype of an electrostatically coupled PAN devices. The ISO network standard allows a system designer to incorporate PAN device into an application, by developing the third layer to connect the PAN devices to an application.

Work on the upper levels of intra-body network architecture is currently being conducted by Professor Michael Hawley and his personal information architecture group at the Media Lab at MIT [Shivers93]. The thesis is a product of applied research on electric field sensing conducted at the Physics and Media Group of the Media Lab at MIT described in [Zimmerman95].

1.7 Thesis Overview

The thesis starts with the physical layer, exploring the electrical nature of the PAN communication channel, developing a circuit model and empirically quantifying circuit

model component values through measurement. Physical design issues, including size, cost, power and device location, are then considered. Having established the physical constraints of the system, modulation and coding strategies are examined. Particular attention is given to spread spectrum, a broadband modulation technique, and narrowband transmission using a resonant transmitter, for both are well suited for PAN communication. Attention then turns to the more pragmatic issues of hardware and software development, particularly circuit design, programming, and development environments, in order to realize a PAN prototype.

Experiments are conducted exploring spread spectrum and on-off amplitude keying (OOK) modulating techniques. These experiments lead to the construction of a working prototype, allowing wearers of PAN devices to exchange business cards by shaking hands. The experience of developing a PAN device prototype raises many unanswered questions, some of which are posed in the chapter on future research. The section *Related Work* contains some research and development results relevant to electric field (EF) sensing, particularly the design of evaluation boards and transceivers, and the effect of cable capacitance and humidity on EF sensing.

2. ELECTRICAL MODEL OF PAN SYSTEM

2.1 Electrical Impedance Tomography (EIT)

PAN transmitters and receivers use the human body as a communication channel. In order to design and evaluate a PAN system it is necessary to characterize the communication channel. Extensive literature exists on the electrical properties of the human body. Electrical Impedance Tomography⁴ (EIT) attempts to image the internal organs and structure of the body by measuring tissue resistivity [Webster89]. A typical EIT system places a multitude of electrodes around the body (e.g., 24 electrodes), applies a constant current to one of the electrodes (transmitter), and records the potential at the remaining electrodes (receivers). The potential arises from tissue impedances between the

⁴ Also known as Applied Potential Tomography (APT).

transmitting and receiving electrodes. By sequencing the electrodes, sets of impedance measurements are collected. These sets are then processed to reconstruct the tissue impedances and formulate a low resolution image of body organs and tissues.

2.2 Resistivity of Mammalian Tissue

Barber and Brown [Barber84] conducted a survey of published resistivity values for mammalian tissues. They report the human arm as having a resistivity of 2.4 ohms-meter longitudinal, 6.75 ohms-meter transverse. Lung tissue range from 1.6 to 51 ohms-meter calculated under interstitial and intra-cellular conditions, receptively. Blood is reported to have a resistivity of 1.5 ohms-meter and the resistivity of fat is 12.75 ohms-meter. The highest resistivity is for wet bovine bone, reported at 166 ohms-meter. Although the reported resistivity value for any tissue might vary by several factors, it can be said with confidence that the bulk resistivity of the human body is on the order of ten ohms-meter or less, since the arm is less then 7 ohms-meter and blood, which pervades the body, has a resistivity of 1.5 ohm-meters.

2.3 Human Body Approximates a Perfect Conductor

To estimate the internal resistance R of the human body (beneath the skin), the relationship $R=r(L/A)$ is used, where R is resistance, r is the resistivity, L is the length of the conductor, and A is the area of the conductor. For an adult male 2 meters tall and an average diameter of 0.3 meters, with an average resistivity of 10 ohm-meters, a resistance of 251 ohms is calculated. The low internal body resistance is insulated from the PAN device electrodes by skin, air, and clothing, which collectively have a large impedance, on the order of megaohms to gigaohms. When compared to electrodes to body impedances (megaohms and gigaohms), the body can be considered a perfect conductor ($R=0$).

2.4 Basic Concept of PAN Communication

In general terms a PAN transmitter perturbs the electrical potential of the environment and the receiver detects these perturbations. Another way to state the communication mechanism is to say the transmitter is capacitively coupled to the receiver. In order for a non-radiating signal to flow from the transmitter to the receiver, a current return path

must be provided. The transmitter capacitively couples to the receiver through the human body. The return path is provided by the air (dielectric) and earth ground (dielectric and conductor), as shown in Figure 1. The earth ground refers to conductors and dielectrics in the environment which are in close proximity to PAN devices; close proximity is important since the electric field falls off with distance cubed (for an ideal dipole field).

The transmitter and receiver electrodes can be modeled as capacitor plates with everything in the environment in between them. Metals effectively bring the plates together, increasing the capacitance. Dielectrics allow greater charge Q to accumulate on the plates for a given voltage V , also increase the capacitance ($C=Q/V$). Conductors in the environment includes metallic furniture, wires, plumbing, reinforcement rods, metallic wall studs, office equipment, ventilation ducts, bodies of water, and the earth. Common dielectrics in the environment include air ($\epsilon=1$), wood ($\epsilon=3-4$), dry geological materials (4-8) [Kearey91], glass ($\epsilon=4-10$), plastic ($\epsilon=2-10$), rubber ($\epsilon=3-7$), and water ($\epsilon=78$). The environmental materials need to be electrically isolated from the body for any coupling between the body and the return path essentially shorts the current loop, as will become evident when we investigate an electrical model of the communication channel.

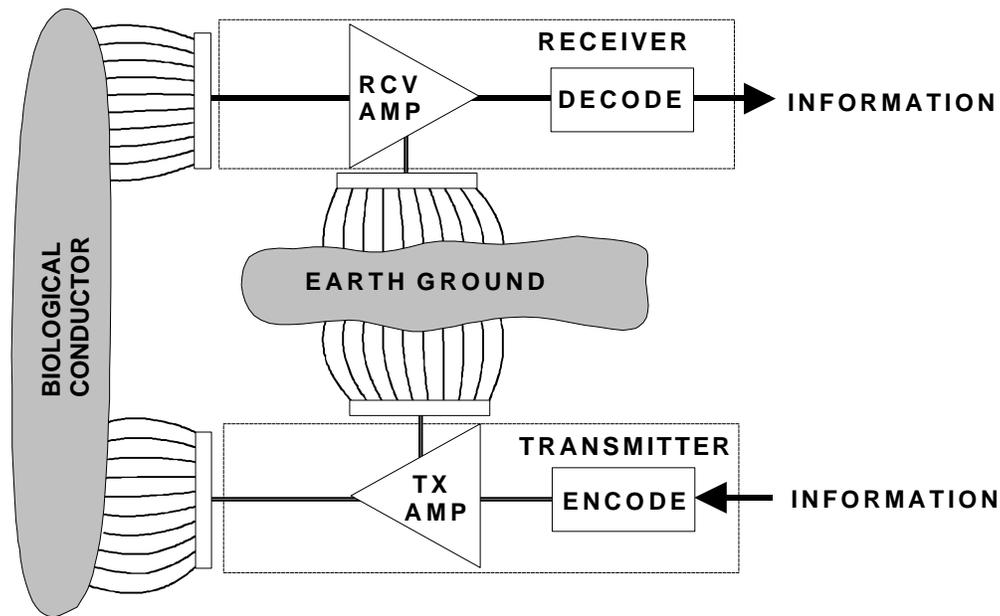


Figure 1. Block diagram of a PAN system. Information is encoded by modulating an electric field which capacitively couples to the body. The body conducts the tiny (picoamp) signal to a receiver which demodulated the signal. The earth ground provides a return path for the signal.

2.5 Lumped Model of Communication Channel: Symmetry Breaking

The basic principle of PAN device communication is to break the symmetry with which the transmitter electrodes "see" (have a lower impedance to) the receiver electrodes. Figure 2 shows a PAN transmitter and PAN receiver, and the capacitive coupling between the electrodes. The transmitter (oscillator) and receiver (differential amplifier) are two terminal battery powered devices. The devices each have a local electrical ground, but are electrically isolated from each other, and therefore do not share a common electrical ground.

There are four significant impedances among the four electrodes (transmitter and receiver pairs). The intra-electrode impedance between the transmitter electrodes presents a load to the transmitter and is ignored since the transmitter oscillator is treated as an ideal voltage source. The intra-electrode impedance between the receiver electrodes is dominated by the current amplifier which tries to maintain the receiver electrodes at the same potential, resulting in a low impedance between the receiver plates, and is also ignored. The four impedances of interest for understanding electrical communication between the transmitter and receiver are labeled A, B, C, and D.

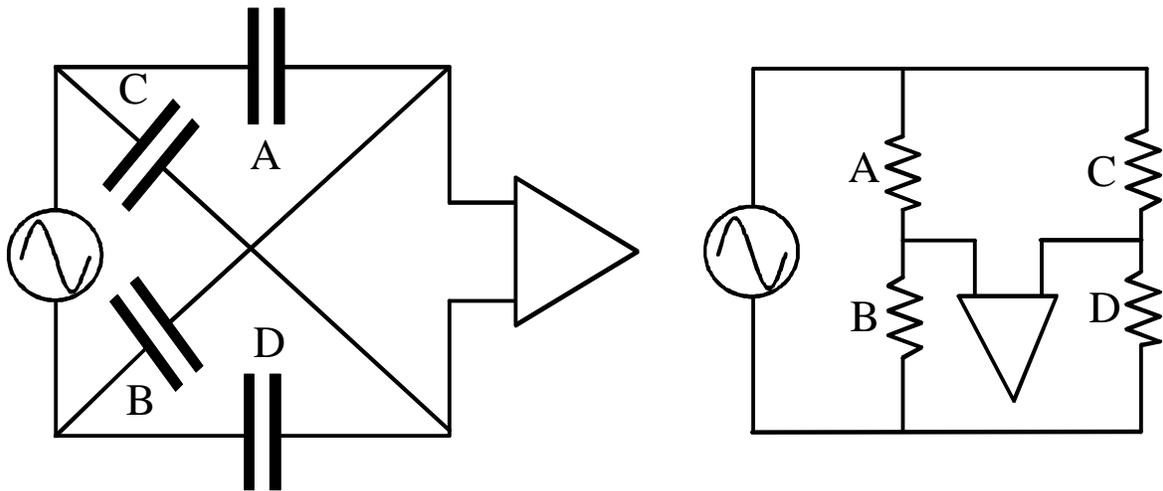


Figure 2. Electrical lumped model of PAN transmitter (oscillator) and receiver (differential amp). The complex impedances of capacitances are rearranged to reveal a Wheatstone bridge configuration. Any imbalance of the bridge causes a current through the receiver.

The four impedances are represented as purely reactive (capacitance), though they may contain a real (resistive) component. The circuit is rearranged to show how PAN device communication works by breaking the symmetry between the four electrodes. The circuit is a Wheatstone bridge where any imbalance of the relationship $A/B = C/D$ will cause a potential, and therefore a current, across the receiver. Since the ratios must be *exactly* equal to null the circuit, and body-based PAN devices are constantly in motion, there will always be an electrical communication path, as long as receiver is sensitive enough to detect the imbalance.

2.6 PAN Device Electrical Fields

A more detailed electrical model of PAN electrical communication is derived by identifying all the electric field paths in the system. Electric fields exist between all bodies with different potentials. Figure 3 illustrates an electric model of a PAN transmitter communicating with a PAN receiver. The PAN transmitter **T** creates an oscillating potential across two electrically isolated electrodes. The oscillation frequency is less than one MHz (wavelength greater than 300 meters) and the electrode size is on the order of

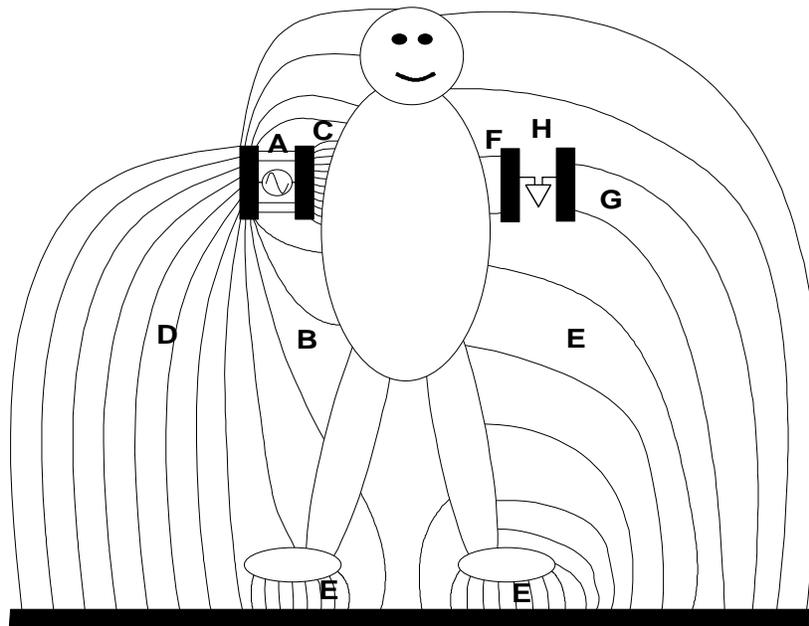


Figure 3. Electric fields produced by PAN transmitter T. A small portion of the electric field G reaches the receiver R.

centimeters so there is no appreciable energy radiated. All objects around the PAN devices are either electrically neutral (no static or alternating potential), or at least do not have the same exact potential (frequency, phase, and amplitude) as the PAN transmitter.

The concept of an environment electrode **e** and a body electrode **b** is introduced for convenience when referring to the electrode closer to the environment and closer to the body, respectively. There is no inherent difference between them; reversing the body and environment electrode of the transmitter or receiver results in a 180 degree phase shift in transmitted and received signal, respectively. The PAN device is designed so that one electrode is very close to the human body (the body electrode **b**) and the other electrode points away from the body (the environment electrode **e**). An electric field **C** forms between PAN transmitter body electrode **tb** and the human body. The body is modeled as a perfect conductor electrically isolated from the room potential and acts like a large plate of a capacitor, being charged and discharged by the transmitter. The charging of the body gives the body a potential different from its environment, resulting in an electric field **E** between the body and the environment. The body potential also forms an electric field **B** between the body and the transmitters environment electrode **te**.

The receiver environment electrode **re** on the “sees” the environment better (has a smaller impedance) than it sees the body, and correspondingly the body electrode **rb** sees the body better than it sees the environment. This asymmetry allows the receiver to detect the potential difference between the body and the environment. The potential of the body produces an electric field **F** to the receiver body electrode **rb**. The circuitry in the receiver **R** maintain the receiver environment electrode **re** at the same potential of the receiver body electrode **rb**, resulting in a small current measured by the receiver circuit. The oscillating potential of the body electrode **rb** is maintained on the environment electrode **re**, producing an electric field **G** to the environment. In practice the receiver cannot keep the electrodes at exactly the same potential so a small electric field **H** is created between the body and the environment electrode **re**.

2.7 Electrical Model of the Communication Channel

2.7.1 Lumped-Circuit Electrical Model

Figure 4 shows an equivalent circuit of the electric fields illustrated in Figure 3. The body appears as a perfect conducting node (**body node**). **A** is the capacitive coupling between the transmitter environment electrode **te** and the environmental ground potential. **B** is the capacitive coupling between the transmitter environment electrode **te** and the body. **C** is the capacitive coupling between the transmitter body electrode **tb** and the body. **D** is the capacitive coupling between the transmitter environment electrode **te** and the environment. **E** is the capacitive coupling between the body and the environment. **F** is the capacitive coupling between the body and the receiver body electrode **rb**. **G** is the capacitive coupling between the receiver environment electrode **re** and the environment ground.

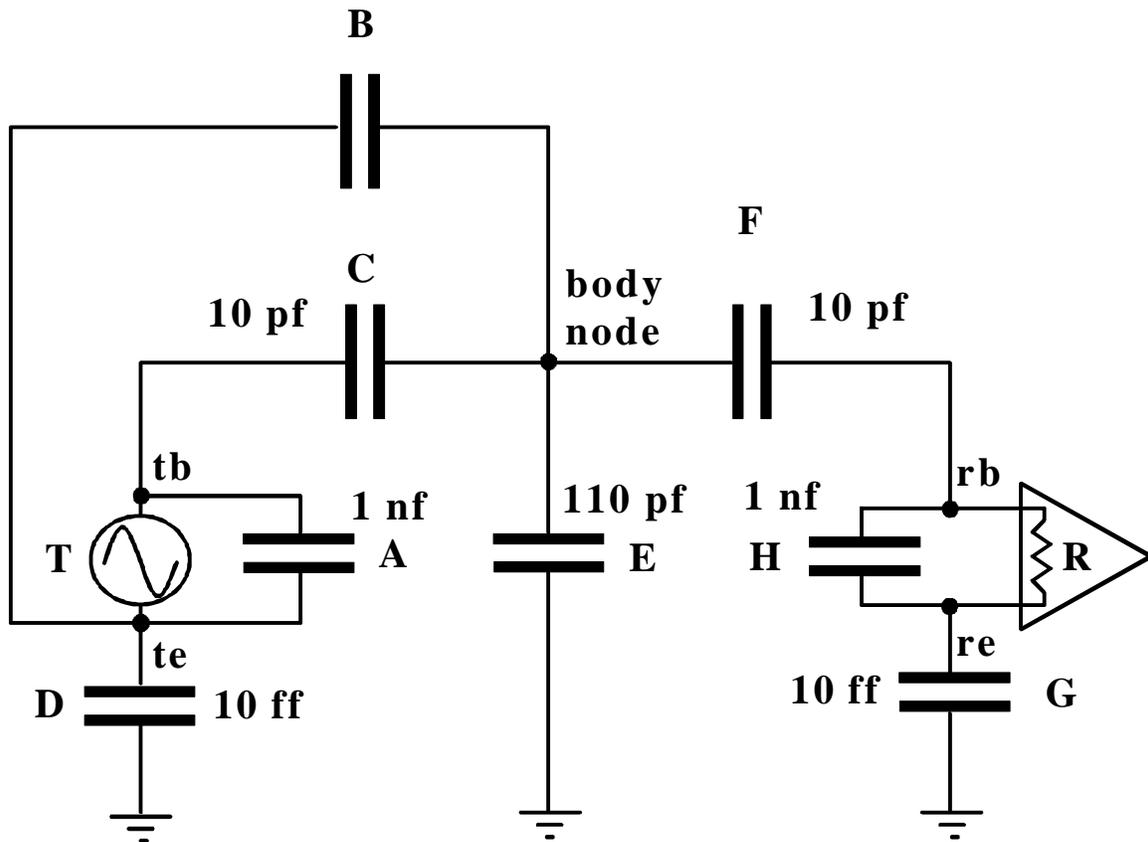


Figure 4. Electrical model of PAN system. Transmitter T capacitively couples to receiver R through

the body (modeled as a perfect conductor). The earth ground provides the return signal path.

The electrical model reveals that body capacitance to the environment **E** is detrimental to PAN device communication performance, shorting to ground the potential the transmitter is trying to impose on the body. In one experiment a current is capacitively coupled from a transmitter on the left wrist of a subject to a receiver on the right wrist of the subject who is wearing sneakers, under the conditions specified in *Electrode Capacitance Measurement*. The measured displacement current is attenuated -12 dB when the subject is barefoot, and -28 dB when a ground wire is connected to the subject's forehead.⁵ These measurements suggest that the performance of PAN devices will suffer when a wearer grabs a grounded water pipe, for example.

The electrical model suggests that feet are the best location for PAN devices; body and environment electrodes have the strongest coupling to the body and environment, respectively. This is particularly true for the environment electrode which is the "weakest link" (largest impedance) of PAN communication. Placing a large area environment electrode as close as possible to the physical ground (which is where shoes usually are) maximizes the magnitude of signal communication. Shoes are also an ideal location to capture some of the energy dissipated during walking, as discussed in *Sneaker Power*.

2.7.2 Body Capacitance Measurement

Some typical values of the electric model capacitances are included in Figure 4. The value for the body capacitance **E** to the environment is empirically determined by measuring the resonance frequency of a coil in parallel with the body⁶. The body-to-environment capacitance can be viewed as a capacitor formed by two plates separated by an insulator; the body is a large three dimensional plate and the environment is a gigantic plate, with air and other insulators as the dielectric. The body-to-environment capacitance depends on the geometry of the body (i.e.; size and shape), its spatial relationship to the environment, and the composition of the environment. Touching an electrically grounded conductor

⁵ The ground electrode is attached to the subject's forehead using a 1" square of copper tape with conductive adhesive. The subject is the author, male, 6' 2", 210 lbs.

⁶ The resonance frequency of a 33.5 uH coil is first measured to account for stray

increases body capacitance by effectively decreasing the distance between the plates. Skin is composed of dead cells and water filled cells enclosed in a fatty membrane, making the skin an insulator and dielectric. The insulating skin covers low resistance tissue and conductive blood. When a person touches a grounded piece of metal, the internal conductors (blood and tissue) are brought closer to the external conductor (grounded metal). For example a body capacitance of 107 pf is measured for an electrically isolated person. When the person squeezes an electrically grounded terminal, the measured body capacitance increases to 845 pf.

Body capacitance can be calculated analytically. A simple approach is to approximate the body as a sphere, the lowest order moment of a geometric model of the body. An isolated charged sphere produces a uniform electric field that extends radially. This simplification produces an equally simple result; the capacitance C of an isolated sphere of radius R is $C=4\pi\epsilon R$ where ϵ is the permittivity of free space. Approximating a person as a sphere of one meter radius results in a capacitance of 111 pf. Though the person might be smaller than a one meter radius sphere, this is compensated by the fact that the body is not isolated; the location of the zero potential is much closer than infinity, and is composed of all the conductors that make up the environmental ground potential. An exact solution would require using Laplace's equation to calculate the potential around the body and the application of Gauss's Law around a surface enclosing the body to calculate the charge on the body.

2.7.3 Electrode Capacitance Measurements

Electrode capacitance measurements were made using a lock-in amplifier⁷. Path impedances Z were determined and capacitances calculate by the relationship $C=1/2\pi FZ$, where F is the oscillator frequency. All impedances Z are treated as purely reactive (capacitive), reducing the problem to a network of reactive impedances and application of Kirchoff's and Ohm's law ($Z=V/I$). The measurement technique was to apply a 5 volts 100 kHz sinusoidal signal from the lock-in amplifier's oscillator to a transmitter electrode and

capacitance, then the resonance frequency remeasured with the subject touching the coil.

⁷ Stanford Model SR-850 DSP Lock-in Amplifier

measure the displacement current at a receiver electrode.

Circular transmitter and receiver electrodes 25 mm diameter are used to remove any sensitivity to rotation. A 4 cm x 4 cm x 1 mm sheet of plastic was placed in between the electrodes and skin to assure that the impedance is completely capacitive (no real resistive component). A battery powered current amplifier was used at the receiver electrode to eliminate any cable capacitive effects.

First the body-to-ground impedance Z_E ⁸ was measured as described in *Body Capacitance Measurement*. Body-to-electrode impedances, Z_C and Z_F , are assumed to be equal since they are the same size electrode (2.5 cm diameter). To measure Z_C and Z_F the transmitter electrode was attached to one wrist of the subject⁹ and the receiver electrode was attached to the subject's other wrist. The electrodes were attached 30 mm above the wrist joint with Velcro tape. The lock-in amplifier provided a low resistance ground, so impedances Z_D and Z_G are treated as zero ohms. The voltage at the body node was calculated using Kirchoff's voltage law (Z_E is known), and once known, allowed the calculation of the current through impedances Z_F , Z_H , and Z_R (the latter two are in parallel).

The outer-electrode to ground impedances, Z_D and Z_G , were determined by measuring the voltage drop across a 1 megaohm load resistor installed in between the transmitter oscillator and transmitter electrode. The resulting displacement current was calculated using Ohm's law. Once the displacement current and voltage were known, the transmitter electrode to ground impedance was calculated using Ohm's law.

3. PAN DESIGN ISSUES

3.1 Size

The design of the PAN devices is primarily driven by power consumption, size, and cost constraints. PAN devices take the shape of common objects found about a body, e.g.; a credit card, watch, belt, and shoe. A credit card has two large surface areas (face and

⁸ Z_E is the impedance across capacitor **E**. This notation will be used throughout.

⁹ The subject is the author.

back), one of which faces towards the body (body electrode), and the other faces away from the body (environment electrode), independent of location. A watch is a more challenging object since it has a smaller surface area and volume, with a variable orientation, though half of the watch band usually points away from the body. The watch band presents itself as a natural location for electrodes; the length could be sectioned and electronically multiplexed to optimally bisect the band into a body and environment electrode. A belt provides a larger surface area but can be electrically shorted by the close proximity of hands and arms. Some type of segmentation, or limitation of electrodes to areas away from those portions most likely to be shorted by hands and arms, may be necessary.

PAN device operation is optimized by having large area electrodes (collects more electric field) with small intra-electrode capacitance (shunts less displacement current that can be measured)¹⁰. The size, area and intra-electrode capacitance (calculated as ideal flat plate capacitors) of several electrode configurations are as follows:

<u>Item</u>	<u>Electrode Dimensions (mm)</u>	<u>Area (m²x10⁻⁴)</u>	<u>Capacitance (pf)</u>
Watch face	25 x 25 x 8	5	0.5
Heel patch	30 x 30 x 8	9	0.9
Watch bands	70 x 20 x 4	14	3.0
	70 x 20 x 8	14	1.5
Credit card	80 x 50 x 3	40	11.4
	80 x 50 x 8	40	4.3
Shoe insert	130 x 40 x 8	52	5.3
Belt	900 x 25 x 4	225	48.2

3.2 Power Consumption

3.2.1 Sneaker Power

A typical battery life design criteria for electric watches is three years [Helm95]. A typical

¹⁰ The intra-electrode capacitive shunting takes on less significance as the input impedance of the current amp decreases. The current amp used in the PAN prototype has an input impedance of 57 kilohms while the impedance of a 1 pf capacitance at 100 kHz is 1.6 megohms, representing a shunting loss of less than four percent.

watch battery has a energy capacity of 57 mWH¹¹, or 1.4 uA over three years. A hermetically sealed credit-card device does not permit batteries to be replaced. An embedded induction coil would allow a hermetically sealed battery or super capacitor to be recharged by close proximity to an external charging induction coil. Locating PAN devices in shoes benefits signal strength. Energy is dissipated in human gait; a 75 kg person dissipates approximately 400 mW with each step¹². A piezo ceramic pile charging a capacitor at an efficiently as low as 10 % provides enough power for a PAN device.

3.2.2 Energy Loss Due to Capacitor Charging

The PAN transmitter is an electrode driven by an oscillating voltage source referenced to another electrode. The simplest electrical implementation is to connect a digital square wave output directly to the transmitting electrode. The transmitter electrode appears as a capacitive load to the oscillator, discharged each cycle through a dissipative driving circuit, resulting in an energy consumption of $1/2CFV^2$; wasting a milliwatt of power in a typical PAN transmitter.

3.2.3 Resonant Transmitter

A majority of the energy required to charge the load capacitance may be recovered by storing the energy in the magnetic field of an inductor. An inductor placed in series with the load capacitor forms a LC tank circuit. Once the $1/2CV^2$ energy is put into the tank circuit, the only additional energy required is to replenish the energy dissipated by the real resistance of the tank components. This is only true when the tank circuit is driven at resonance; when the impedance of the capacitance X_C is equal to the impedance of the coil X_L . The resonance frequency f_r is set by the value of the inductance L and capacitance C :

$$f_r = 1 / 2\pi\sqrt{LC}$$

3.3 Cost

PAN device communication adds value to conventional personal electronic devices;

¹¹ D384 silver-oxide battery, 38 mAH at 1.5v, 7.7 mm diameter by 3.6 mm thick.

¹² Assuming 1 mm displacement, half of the body weight is applied to each foot, at a rate of one step per second; Power= $mgh/t=(37.5 \text{ kg})(9.8 \text{ m/sec}^2)(.001\text{m})/1\text{sec}=367.5 \text{ mW}$.

watches that display email and pager messages, PDAs that downloading phone numbers to cellular phones, calling cards that identifying the owner to a public phone, and people exchanging data by shaking hands. These value-added services can justify the additional cost of an embedded communication system. As will all commercial products, the lower the cost, the easier it is to incorporate the technology into a product. The prototype PAN transmitter and receiver presented in the thesis uses off-the-shelf low-cost components. Industrial incentives to produce low power, low cost operational amplifiers and microcontrollers helps reduce the cost of PAN devices.

One implementation of a low cost version of a PAN receiver may be constructed from an integrated AM receiver, such as the Plessey ZN414Z, which costs under \$2 in small quantities. The PIC16C71 used in the PAN transmitter and receiver prototypes costs under \$5 in large volumes. The inductor used in the PAN transmitter for creating the tank transmitter costs \$0.20 in small quantity. Since the carrier frequency used in PAN device communication is under 1 MHz, a single integrated circuit can be constructed using conventional CMOS technology to perform all of the analog and digital functions of a PAN transceiver. It might therefore be possible to create a single-chip PAN transceiver (combined transmitter and receiver) for under \$1 in high volume.

The Plessey ZN414Z specifications are worth noting for the device provides a good example of the realistic performance of an integrated PAN receiver. The ZN414Z is a 10 transistor tuned radio frequency circuit packaged in a 3-pin TO-92 plastic package. The circuit provides 72 dB of amplifier gain (three stages) with a -6dB bandwidth of 600 kHz centered at 650 kHz, a transistor detector, and a 20 dB automatic gain control (AGC). The circuit requires a supply current of 0.3 mA at 1.3 volts, consuming 0.4 mW of power.

3.4 Channel Capacity

A communication network is primarily judged by channel capacity, with a theoretical limit defined by the Hartley-Shannon law [Carlson86]

$$C = B \log(1 + S/N)$$

where C is channel capacity in bits/second, B is bandwidth, S is signal, and N is noise. To

achieve a high channel capacity for a fixed bandwidth, the signal-to-noise ratio must be maximized. The signal-to-noise ratio depends on transmitter signal strength and receiver sensitivity and noise performance.

The -3 dB frequency response of the prototype PAN receiver is approximately 400 kHz (100 kHz- 500 kHz). The minimum measured sensitivity of the spread spectrum receiver prototype is $S/N=0.0625$ (a noise-to-signal ratio of 16). These values produce a maximum channel capacity of 10.5 kbits per second. A more realistic signal-to-noise ratio of 10 provides a maximum channel capacity of 416.6 kbits per second. The PAN transceiver prototype implements a modest 2400 bit per second modem.

The capacitance values shown in Figure 4 represent two watches, one on each wrist, communicating with each other. The theoretical channel capacity can be calculated for the conditions of the PAN transmitter and receiver prototype; bandwidth=400 kHz, transmission frequency=330 kHz, transmission voltage=30 volts peak-to-peak. The minimum noise is limited by the thermal noise from the 1 megaohm feedback resistor (41 uV) and the noise of the TLO82 pre-amplifier (18 nV/ $\sqrt{\text{Hz}}$ [TI95], bandwidth=400 kHz, therefore 11.4 uV). The resulting noise is the square root of the sum of the square of the noise sources, which is 42.6 uV. Using Kirchoff's voltage and current laws on the circuit shown in Figure 4, the received current is 57 pA. The gain of the system is 10^8 (10^6 for the current amplifier and 10^2 for the programmable gain amplifier). The resulting signal is 5.7 mV, yielding a signal-to-noise ratio of 134 (5.7 mV/42.6 uV), and a theoretical channel capacity of 852 kbaud.

3.5 Locating PAN Devices on the Human Body

PAN devices reside on the body for intra-body communication and external to the body for inter-body communication. Figure 5 shows several sites for PAN transceivers, which can take on the character of commonly worn objects such as watches, credit cards, eye glasses, identification badges, belts, waist packs and shoe inserts. Head mounted PAN transceivers include headphones, hearing aids, microphones, and head mounted displays. Chest located PAN devices can be used for detecting breathing and heart activity. Shirt

pocket PAN devices may serve as identification badges. The wrist watch is a natural location for a display, microphone, camera, and speaker. Waist mounted PAN devices can carry a PDA, cellular phone, or another devices that need large batteries. PAN devices incorporating sensors can provide medical monitoring such as EKG, blood pressure, and breathing rate. Pants pockets are a natural location for wallet based PAN devices to store information and identify the possessor. PAN devices located in the shoe can be self-powered and provide a data link to remote PAN devices located in the environment such as workstations and floor transponders that detect the location and identity of people in a room.

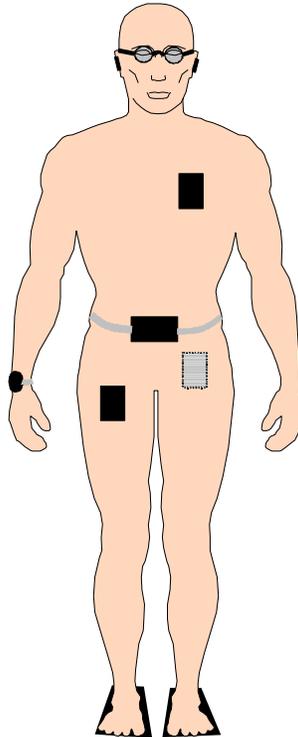


Figure 5. Locations and applications for PAN devices include head mounted display, headphones, identification badge, cellular phone (in waist pack), credit and phone cards (in wallet), watch with display, microphone, and speaker, and power sneakers (self powering computer shoe inserts).

4. MODULATION STRATEGIES

4.1 Modulation and Coding

Modulation refers to the manipulation of the signal being transmitted to benefit the

electrical characteristics of transmission and reception. For example AM radio refers to the amplitude modulation of a continuous carrier. Coding refers to the manipulation of the symbols containing the message being transmitted, typically for ease of processing, compactness, integrity, and confidentiality. For example a message may be organized as a sequence of message bytes assembled in a packet including error correction bits, where the bits in the message bytes are encrypted by a key known only by the sender and receiver to increase security.

4.2 Narrowband vs. Broadband Transmission

There are two basic types of carrier wave modulation; linear and non-linear¹³. Linear modulation translates the spectrum of the message up to the carrier frequency. The transmission bandwidth is narrow, never exceeding twice the bandwidth of the message, and the signal-to-noise performance can only improve by increasing the transmit power [Carlson86]. Non-linear modulation uses a non-linear process to modulate the carrier producing a broadband transmission much greater than the message bandwidth. The signal-to-noise performance of non-linear modulation increases with the bandwidth of the transmission, trading bandwidth for power.

4.3 Narrowband Transmission

Narrowband transmission is typically simpler to implement than non-linear modulation. The carrier can be digitally modulated by shifting the amplitude (on-off keying; OOK), frequency (frequency-shift key; FSK) or phase of the carrier (phase-shift key; PSK). The bandwidth of the all three techniques is approximately equal to the signaling (baud) rate [Carlson86]. The power spectrum of OOK and PSK have a second-order rolloff, while the FSK has a fourth-order rolloff, allowing more channels to occupy a frequency multiplexed spectrum.

Non-coherent FSK shifts between two frequencies to represent the state of a message bit to be sent. Typically FSK detection consists of two bandpass filters tuned to the carrier and the shift key frequency, respectively. Coherent FSK detection uses synchronous

detection and has better noise rejection performance but needs to synchronize to the frequency and phase of the transmitter.

Phase detection can be achieved without phase synchronization if the phase is differentially encoded before transmission in a technique called differentially coherent phase-shift keying (DPSK). The transmitter changes the phase of the carrier each time a logic one message bit is sent. The receiver uses the phase of the last bit as a reference to determine the current phase. If the phases differ by 180 degrees, a logic one message bit was sent. The carries must be an integral multiple of the message bit rate to assure phase changes occur on carrier zero crossings.

The energy efficiency of a modulation technique can be measured as the energy-to-noise ratio required to achieve a theoretical error probability; the lower the energy-to-noise ratio, the more efficient the modulation technique. The energy efficiency to achieve a theoretical error probability of one bit per ten thousand for several narrowband modulation techniques are [Carlson86]:

<u>Modulation</u>	<u>Signal Strength (dB)</u>
Phase Reversal Keying (PRK)	8.4
Differentially Coherent Phase Shift Keying (DPSK)	9.3
On-off Keying (OOK)	12.3
Frequency Shift Keying (FSK)	12.3

4.4 Transmitters, Receivers, and Transceivers

While some PAN devices may need only receive or transmit, making each PAN device a transceiver enables desirable features. A transceiver can tell neighboring transceivers of its existence, eliminating attempts to communicate with absent transceivers. Loss of data can be recovered by requesting re-transmission. Transceivers too distant for direct communication may communicate through neighbors acting as regenerative repeaters. Most of the component costs are in the receiver. Adding transmit capabilities to a receiver amounts to including a resistor, to prevent excessive driver loading due to inadvertent

¹³ Often referred to as exponential modulation in the communication field.

electrode shorting, and possibly an inductor and capacitor, to make a resonant transmitter.

4.5 *Half Duplex Transceivers*

Communication is the process of conveying information from one location to another. The communication can be one way (*simplex*), two way with each party taking turns (*half-duplex*), or both parties transmitting and receiving simultaneously (*full-duplex*). PAN transceivers use the same electrode pair to transmit and receive. The large electrostatic field necessary for transmission would saturate a sensitive receiver, making it difficult to simultaneously transmit and receive. Using separate electrodes does not help since they would be located near each other, decreasing the electrode area and sacrificing performance. PAN devices should therefore be designed as half-duplex transceivers.

4.6 *Broadband Digital Transmission*

The bandwidth of a narrowband communication channel is typically equal to the bandwidth of the information being sent. Broadband communication trades off power density for spectrum space, spreading the energy to be transmitted over a bandwidth many times wider than the information being sent. The resulting transmitted signal is less susceptible to noise and other interference since the contribution of any one frequency represents a small portion of the total signal. Spreading the energy over frequency rather than amplitude benefits the receiver's front end, decreases the likelihood of signal clipping. Two types of broadband digital transmission techniques considered for PAN devices are spread spectrum; where the carrier is a pseudo-noise (PN) generator, and frequency hopping; where the carrier skips among a multitude of frequencies. Both of these techniques allow several PAN devices to communicate simultaneously over the same channel.

4.6.1 Spread Spectrum

In a direct-sequence spread spectrum system the digital message to be transmitted is multiplied by a digital PN sequence, spreading the spectrum of the digital message. The broadband product is transmitted through the channel. The receiver retrieves the message by multiplying the incoming signal by the identical PN sequence. The transmitter and

receiver PN sequences must be in phase (synchronized) in order for the receiver to extract the message from the sequence. Synchronizing the transmitter and receiver PN sequences is the greatest challenge of a spread spectrum communication system.

4.6.2 Pseudo-Noise Sequence

The digital sequence is called pseudo-noise because it is a finite sequence that repeats ($x_n = x_{n+N}$ where N is the period of the sequence). A binary linear-feedback shift-register (LFSR) can be used to generate a PN sequence. An ideal PN sequence has the following properties; a) a flat power spectrum (every frequency is present with the same amplitude) up to the chip frequency (N /sequence repeat time), b) an autocorrelation of N at zero phase and $1/N$ for all other phases, and c) an equal number of 1's and 0's.

4.6.3 Synchronization & Manchester Coding

A common receiver synchronization strategy is to *acquire* synchronization when a transmitter or receiver is first turned on, then continuously *track* synchronization while the devices are communicating. Tracking adjusts the phase of the receiver to correct for differences in chip rate caused by imprecise matching of transmitter and receiver clocks (no two crystal oscillators have *exactly* the same frequency) and thermal drifts. A straightforward brute force method of acquiring synchronization is to successively shift the phase of the receiver sequence, in subsample increments, until synchronization is achieved. Tracking can be accomplished by comparing the synchronization of three slightly different phases and moving towards the phase with the best synchronization.

In order to acquire synchronization, some means must be provided to measure synchronization. One synchronization technique requires the transmitter to send a constant message known by the receiver, the equivalent of a test tone. Synchronization is achieved when the valid synchronization message is detected. Another technique takes advantage of the structure in the transitions of a return-to-zero coding strategy. Manchester coding, for example, introduces a sign change at the beginning of every bit. This pattern provides a feature the receiver can detect and use to synchronize to the transmitter. Manchester coding guarantees structure independent of the message by forcing bit changes, at the

expense of doubling the message size (each message bit requires two transmitted bits).

4.7 Resonant Transmitter

While designing electric field transmitters for our fish sensors (see *Related Work*), the author began using resonant tank circuits to boost transmission voltage to improve received signal strength. Applying a resonant tank circuit to PAN transmitters has additional benefits; the tank circuit produce a clean sine wave output from a square wave input, and allow the transmitter voltage to be digitally programmed. These desirable features justify the small additional cost of tank components. The resonant tank used in the PAN prototype is constructed from an inductor L and capacitor C, as shown in the lower section of Figure 6.

4.7.1 Boosting Transmission Signal Strength

Transmitter signal strength is directly proportional to transmitter voltage, and typically limited by power supply voltage. If the transmission is narrowband, a resonant tank circuit can be used to boost transmission voltage. The operation of the tank used in the PAN transmitter will now be reviewed by referring to Figure 6. The microcontroller (PIC16C71) generates a 5 volt square wave which is applied by the transmit line to the inductor L. The capacitor C is connected to the other side of the inductor L and the transmit electrode. When a square wave is applied at the resonant frequency of the tank circuit, the voltage on the transmit electrode quickly builds. The first few cycles of the square wave charges the tank. The energy in the tank circuit is alternately stored as a magnetic field in the inductor L and electric field in the capacitor C. Once the tank is fully charged the only energy required from the microcontroller transmit line is to replenish the energy dissipated by the real resistance of tank components; the inductor L, capacitor C, and transmit electrode capacitance.

The voltage on the transmit electrode is equal to the transmit line voltage (5 volts) times the Q (quality factor) of the tank circuit, so the Q directly boosts transmission gain. The inexpensive inductor and capacitor used in the PAN transmitter prototype has a Q of 5, creating a 30 volt oscillating potential from the 5 volt square wave.

As the carrier is modulated off the resonant frequency, the output voltage, and hence the transmit power, decreases. Transmission bandwidth is measured as half-power bandwidth; the frequency range in which the transmitter voltage is within 0.707 volts of the peak resonant voltage. Bandwidth decreases inversely with the resonator Q :

$$\text{Bandwidth} = f_{\text{resonance}} / Q.$$

A resonant transmitter is therefore ideal for narrowband transmission since the transmission bandwidth never exceeds twice the bandwidth of the message. The PAN transmitter prototype, with a $Q=5$ and $f_{\text{resonance}}=330$ kHz, has a bandwidth of 66 kHz, easily accommodating the 2.4 kbaud communication channel used in the prototype.

4.7.2 Digitally Controlled Transmitter Gain

A transmitter can conserve power by transmitting only the power necessary to achieve reliable communication, which is also a tenant of spectrum etiquette. PAN transceivers can negotiate transmission signal strength to find the minimum power necessary for reliable communication. Transmission signal strength is proportional to voltage, which may be controlled by a DAC, programmable gain amplifier, or programmable resistive element (e.g., FET). Transmitter voltage can be digitally controlled by varying the pulse width of a digital oscillator applied to a tank resonator. This simple amplitude control technique requires no additional hardware and is useful for multi-level M -ary signaling [Carlson86], where information is encoded in multi-value amplitude modulation.

4.7.3 Proximity Effect on Resonant Transmitter

The resonant Q of a tank is:

$$Q = 2\pi FL/R$$

where I is inductance, F frequency, and R is the resistance of tank components. To maximize the Q for a given transmission frequency F , inductance L is maximized and capacitance C is minimized, since the product LC must be constant. The minimum capacitance C is the inherent intra-electrode capacitance, determined by the size,

composition, and location of objects around the PAN transmitter electrodes, making the resonant frequency susceptible to all these variables. For example, if a person has a PAN device in his back pants pocket (e.g., a wallet), the load capacitance will increase when he sits down, decreasing the resonance frequency. The load capacitance of a watch mounted PAN device will change as the wearer's hand brushes past her body, as she crosses her arms, and places her hands in her lap.

The sensitivity of resonant frequency to orientation and environmental capacitance may be minimized by placing a large capacitor (relative to the intra-electrode capacitance) in parallel with the electrode capacitance. The larger the capacitor, the smaller the effect of intra-electrode capacitance variations, with a corresponding sacrifice in resonant Q .

4.7.4 Contactless Switch

The capacitive sensitivity of tank-based PAN transmitters to their electrostatic environment does suggest that the carrier, in addition to encoding messages, may convey proximity information as well. The resonant frequency of the carrier indicates the capacitance of the transmitter electrodes, directly effected by objects near the transmitter electrodes. The amplitude of the received signal is a function of the distance and orientation between the transmitter and receiver, and to a lesser extent the carrier frequency¹⁴. A receiver monitoring carrier amplitudes and frequencies of several PANs may be able to make coarse estimates of body orientation.

The ringing nature of resonant circuits provides a simple way for a PAN transmitter to monitor its own resonant frequency. By pulsing the transmitter and integrating the received displacement current, a PAN transmitter can monitor its resonant Q . The PAN transmitter could also sweep the transmission frequency to monitor its resonant frequency. When the wearers hand comes in close proximity to the PAN transmitter's environment electrode, the PAN transmitter can determine hand proximity. This may be useful for making a contactless switch, instructing the PAN device to start a transmission. A PAN

¹⁴ As the Q increases excursions of the carrier from the resonant frequency result in larger amplitude attenuations due to the narrow bandwidth of the resonator.

device could wake up every few seconds, pulse the transmitter and monitor hand proximity. If none was detected, it could go back into sleep mode, conserving power.

5. PAN PROTOTYPE DEVELOPMENT

5.1 Hardware Development

5.1.1 Development of a PAN Prototype

The goal of the PAN prototype is to demonstrate the digital exchange of data through a human body using electric fields by a small battery-powered low-cost electronic circuitry. The design is a combination of analog and digital circuitry, implementing an analog bipolar chopper controlled by a digital microcontroller. This approach allows the tiny (e.g., 50 pA) high frequency (330 kHz) displacement current to be integrated into a voltage that can be measured by a slow (50 kHz) low resolution (8 bit) analog-to-digital converter (ADC), provided by the microcontroller.

A bipolar chopper operates by selecting an amplified received signal or an inverted (multiplied by -1) version of the signal. By switching at the transmission rate and phase, the tiny received signal (microvolts) is synchronously rectified and integrated into a large signal (several volts). The hardware is used as a detector for several coding strategies, determined by microcontroller coding (see ***SOFTWARE DEVELOPMENT***). The PAN transceiver uses five “off-the-shelf” components, costing less than \$10 in large volumes (e.g., 10,000 pieces). The PGA (\$11 quantity 1) can be replaced with an automatic gain circuit (AGC) constructed from an inexpensive operational amplifier (e.g., TLO82, less than \$1 quantity 1). Ultimately the analog components and microcontroller can be combined into a single CMOS integrated circuit to produce a low-cost integrated PAN transceiver.

The bipolar chopper and microprocessor implements the basic function of a lock-in amplifier for less than \$10. The digital nature of the switching does make the detector sensitive to odd harmonics of the switching frequency. This can be compensated for by providing a low-pass filter, with a cutoff frequency below the first harmonic of the carrier.

As will be seen, the limited high frequency response of the amplifiers used in the PAN device prototype provide low-pass filtering.

5.1.2 System Components

The functional elements of the PAN transceiver is shown in Figure 6. The design uses analog circuitry to perform synchronous detection under the control of a digital microcontroller. This combination takes advantage of the ability of analog circuitry to integrate microvolt signals that are smaller and faster than the voltage and temporal resolution of the microcontroller's ADC, and capitalize on the crystal referenced digital microcontroller's temporal accuracy and programmable flexibility.

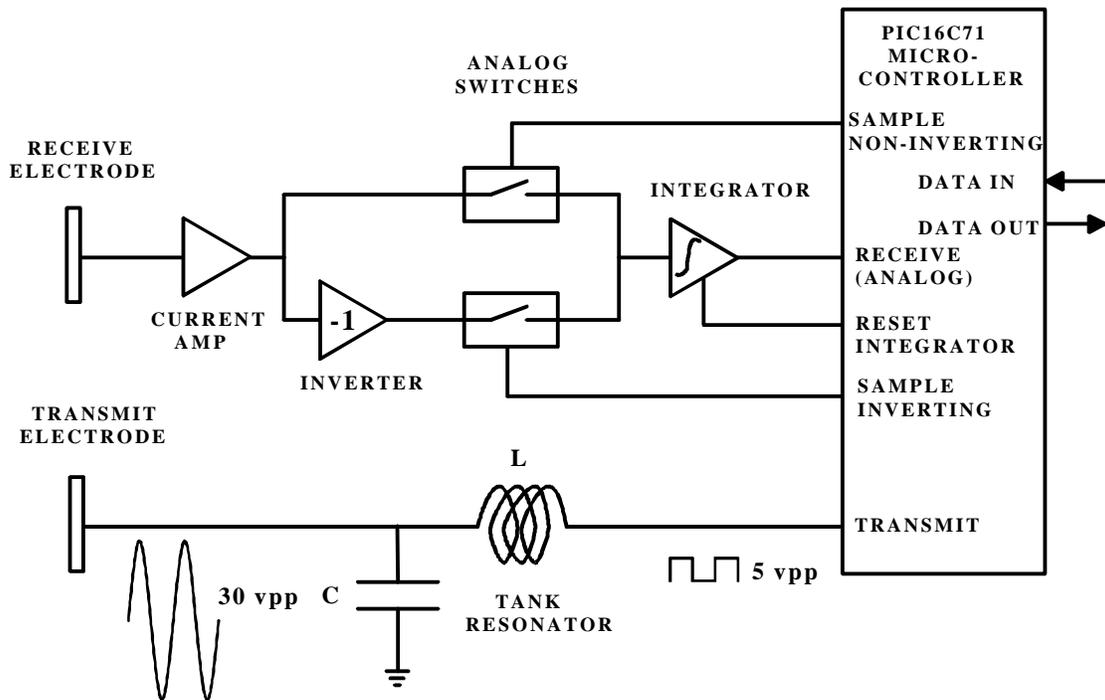


Figure 6. Block diagram of half-duplex PAN transceiver. Microprocessor controls analog switches to synchronously rectify and integrate amplified signal picked up by receive electrode.

The digital output of the microcontroller's transmit line drives the resonant tank circuit. The receiver consists of a current amp which converts the nanoamp received displacement current into a microvolt signal. Following the current amp (not shown) is a programmable voltage amplifier to provide digitally selectable gain (1, 10, and 100). The amplified voltage is either applied to an integrator directly, or through an inverter, which changes

the sign of the applied voltage. The selection is performed by the microcontroller, synchronous to the transmitted signal to produce a signal of constant polarity (either positive or negative), which integrates to a value large enough to be digitized by the microcontroller's ADC (0-5 volt, 8 bit, 19.5 mV per division). The microcontroller uses the digitized integrated signal to determine the logical state (0 or 1) of the received message bit.

The integrator is discharged after every message bit, a technique known as integrate-and-dump, which minimized inter-symbol interference (ISI), a phenomena where a message bit affects its temporal neighbor [Carlson86].

Once the message has been successfully received and demodulated, the microcontroller transmits the message to a host computer over an optical link (not shown). This is used to electrically isolate the transceiver, so the PAN transceiver can be evaluated independent of an electrical ground reference. The optical serial connection is extremely useful for debugging code since attaching electrical probes to the prototype transceiver affects the electrical performance of the receiver.

5.1.3 Circuit Review

Figure 7 shows a schematic of the PAN transceiver prototype. The electric field gradient across the receiver and transmitter electrode (RCV and TX ELECTRODE, respectively) creates a tiny (nanoamp) displacement current I through R_{14} . The feedback arrangement produces an output voltage V by the relationship $V=IR_{14}$; one nanoamp applied produces one millivolt. with $R_{14}=1$ M. The voltage is buffered by U1B and applied to a 16 kHz high pass filter constructed from C1 and R1. The high passed signal is amplified by the programmable gain amplifier (PGA), used by the microcontroller U6A as an AGC, with digitally selectable gains of 1, 10, or 100. The PGA output is high passed and applied, through a single-pole-double-throw CMOS switch U5, either directly to an integrator (U2B, R6, and C14), or indirectly through an inverter (U2A), under the control of the microcontroller U6A. The integrator implements the analog function $V=-\dot{Q}/RC$.

The amplifiers U1, U2, U3, and CMOS switch U5 all operate bipolar from a battery split supply (+9 and -9), so the integrator can produce a positive or negative result. The ADC on the microcontroller U6 is unipolar, from 0 to 5 volts. Resistor R7 and R8 scales and level shifts the 5 to +5 volts output of the integrator, to a 0 to 5 volts range applied to the ADC.

The microcontroller U6 is a PIC16C71, a high performance, low cost, CMOS fully static EPROM based 8-bit controller with on-chip ADC. The PIC16C71 has 1k of EPROM for program memory, 36 general purpose static RAM registers, a four channel 8-bit ADC (20 usec conversion time per channel), multiple interrupt sources, an 8 bit timer with 8 bits of pre-scaling, and 13 I/O pins capable of sinking 25 mA and sourcing 20 mA. The PIC16C71 requires a 5 volt supply, consuming 9 mA at 16 MHz, the frequency used in the PAN prototype. The microcontroller U6 requires four clock cycles per instruction (except conditional branches which require eight) resulting in 4 million instructions per second (MIPS). A 16 MHz crystal with TTL output driver U4 provides the system clock for the microcontroller U6.

Monitoring the operation and performance of PAN hardware and software is accomplished through an optical bi-directional serial communication to a host computer (an IBM ThinkPad 700C/PS2). A red LED D5 is driven directly by the microcontroller U6. A photoreceiver U7 consisting of a photodiode, amplifier, and Schmitt trigger incorporated on one die, produces a logic level (0 and 5 volts) in response to on-off keying modulated light. Software in the microcontroller U6 implements asynchronous half duplex communication at 19.2 kbaud.

The electro-optic components are Motorola devices with pre-assembled plastic screw-on connectors. The visible LED transmitter is the MFOE76 and the Schmitt trigger logic receiver is the MFOD75. A small interface board¹⁵ drives the LED, buffers and level shifts the logic voltage (0,+5v) of the photoreceiver into RS-232 signals (+12, -12).

¹⁵ Industrial Fiber Optic, P.O. Box 3576, Scottsdale, AZ 85271-3576.

Figure 7. Schematic of PAN transceiver. PIC microcontroller controls the analog bipolar chopper detector which integrates the amplified received signal. Received messages are sent to a host computer over optical light guides to eliminate any electrical ground.

5.1.4 Prototype Construction

5.1.4.1 *Electrode Issues and Construction*

The PAN transmitter and receiver prototypes, shown in Figure 8, are point-to-point soldered on a PIC prototype boards¹⁶ measuring 3 inches by 3 inches. The prototype board is a commercial printed circuit board, providing pre-laid out traces for a voltage regulator, crystal, and an I/O header. The boards are mounted with aluminum standoffs to aluminum cast cases measuring 94 mm x 120 mm x 37 mm. The aluminum cover of the transmitter is mounted 1.5 mm above the lip of the case by non-conducting nylon standoffs. The case serves as one transmitter electrode, and the cover as the other transmitter electrode. The receiver prototype board is completely enclosed by the conducting case, which serves as one electrode. The other receiver electrode is aluminum coated mylar film, the length and width of the case, mounted 1.2 cm below the case on a slab of insulating foam. By totally enclosing the receiver electronics in the case electrode, connected to circuit ground, any electric fields generated by control signals are enclosed in an equipotential electrode, shielded from the other receiver electrode.



Figure 8. PAN receiver (left) and PAN transmitter (right). The case and aluminized mylar mounted below the case are receiver electrodes. The transmitter lid and case are

¹⁶ MicroEngineering Labs, Box 7532, Colorado Springs, Colorado 80933

transmitter electrodes. A light guide cable connects the receiver to a host computer.

5.1.4.2 Prototype Power Consumption

Minimal power consumption is vital for PAN transceivers for small battery size and long life. The prototype, however, needs only to operate several hours using 9 volt alkaline transistor batteries, a convenient and low-cost power supply. Hence the power specification for the PAN prototype is less than ideal. The greatest power consumption is by the red LED used for optical communication, a circuit element that would not be on a PAN transceiver. The prototype power is supplied by two 9 volt transistor batteries, arranged as a bipolar supply (+ 9 and - 9 volts), which powers all the analog electronics. The +9 volt supply is regulated down to +5 and powers the microcontroller, crystal oscillator, and optical transmitter and receiver, accounting for the large +9 volt current drain. The power consumption for the prototype receiver is presented in the following table:

<u>Supply</u>	<u>Current (mA)</u>	<u>Components</u>	<u>Condition</u>
+9v	33	all except LED	receiving message bits
	31	all except LED	standby
	35	LED	on
-9v	13	all	receiving message bits
	10	all	standby

A practical integrated low-power version of a PAN receiver can consume less than 10 mW of power. This estimate is based on a PIC running at 4 MHz (1.8 mA @ 5 volts = 9 mW) and a Plessey ZN414Z front-end receiver (0.3 mA @ 1.3 volts = 0.4 mW). The additional power required for a bipolar chopper detector, to replace the simple AM detector in the Plessey receiver, can be compensated for by decreasing the clock speed of the PIC.

5.1.5 Hardware Development Environment

The receiver circuit was first tested on a Global Proto-board¹⁷, where components and wires are inserted without soldering. The proto-board system introduces impedances and electrical noise that would otherwise not be present on a properly designed printed circuit board. The hostile environment of the proto-board generally leads to robust designs since

¹⁷ Model PB-503 Global Specialties, New Haven, Connecticut

the final system assembly (point-to-point soldering or printed circuit) will typically be electrically cleaner (less parasitic coupling and noise) than the proto-board.

The point-to-point soldered board is first debugged using an attenuated signal generator as an input current. Then a simple program is written to send ADC values out through the optical serial port to check the operation of the battery powered, electrically isolated system.

5.2 Software Development

All PIC16C71 microcontroller coding is done in assembly language due to the critical timing requirements of synchronous detection and the small amount of RAM (36 bytes) and EPROM (1K) available on the microcontroller. A full speed in-circuit emulator¹⁸ is used when electrical connections are acceptable (e.g., examining bipolar chopper control line timing). For tests that require PAN transceivers to be electrically isolated (e.g., measuring the sensitivity of the receiver circuit), EPROM versions of the microcontroller are programmed¹⁹. A zero insertion force socket is used on the PAN prototype to allow easy insertion and extraction of the microcontroller. During the testing and development of the PAN system, the microcontroller was programmed approximately fifty times. Seven identical EPROM microcontrollers are sequentially programmed and tested, then erased en-mass for ten minutes under UV light, minimizing interruptions in the code development process.

6. EXPERIMENTS WITH CODING STRATEGIES

I investigated two modulation techniques for PAN devices; the simple linear method of on-off keying (OOK), and the non-linear method of direct sequence spread spectrum. Implementation issues for each modulation technique shall now be discussed.

6.1 Spread Spectrum Coding

The PAN implements direct sequence spread spectrum in the PIC microcontroller. A logic

¹⁸ ClearView, Parallax Inc, 3805 Atherton Road, #102, Rocklin, CA 95765.

¹⁹ PIC16Cxx Programmer from Parallax Inc.

one message bit is represented by transmitting entire PN sequence. A logic zero message bit is represented by transmitting the inverted version of the PN sequence. Received logic one and logic zero sequences integrate to large positive and negative correlation, respectively. If no signal is transmitted, the correlation will be near zero, since the correlation of noise to any zero-mean signal (except itself) is zero.

6.1.1 Generating the PN Sequence

PN sequences can be generated using a binary linear-feedback shift-register (LFSR) which can be compactly implemented in software by XORing selected taps of a register and shifting the XORed result into the register. The taps are selected for maximal length and are available in table form [Gershenfeld94]. As with most implementations of algorithms, there is a trade-off between speed and size. The most time efficient (fast running) method is in-line coding of the sequence; directly programming the state of the transmitter and detector control lines, for the transmitter and receiver, respectively. The first synchronization test impediments in-line coding of a 100 element PN sequence. Each element of a PN sequence is called a chip, a rectangular wave produced at the clocking rate of the PN sequence. A minimum of three instructions are required for each chip. An 8 MHz clock rate results in the desired chip rate of 1.5 usec (666 kHz).

The design goal of the thesis is to implement a 2400 baud modem PAN. Each message bit has a duration of 416.67 usec, requiring a 278 element PN sequence of 1.5 usec chips. Two sequences are necessary; a sequence for logic one message bit, and an inverted sequence for logic zero message bit. The PIC has a program space of 1,024 words (1 K), yet 1668 instructions are necessary to in-line code both sequences.

6.1.1.1 LFSR Generation

The most compact method of generating the PN sequence is to implement a LFSR. The 278 chips can be reduced to 256, generated from an 8 bit shift register, a convenient number for an 8 bit microcontroller. A minimum of 11 instructions are necessary to generate one chip, as presented in the following fragment of PIC code:

```

pos_out      mov    chip_count,chips    ;routine to send out chips
next_chip    mov    w,shift_reg        ;move shift register value into w register
             xor    w,#mask           ;xor w with the mask containing the taps
             setb   c                 ;makes branch same length
             jnz    z_is_one          ;jump if xor result is one
             clrb   c                 ;otherwise shift a zero into the shift register
             rr     shift_reg         ;rotate xor result into the shift register
             clrb   tx                ;transmit a zero
             djnz   chip_count,next_chip ;repeat this process for until finished
             ret                       ;return to whoever called this routine
z_is_one     rr     fr                 ;rotate xor result into the shift register
             setb   tx                ;shift a one (previously set) into shift register
             djne   chip_count,next_chip ;repeat this process for until finished
             ret                       ;return to whoever called this routine

```

6.1.1.2 ROM Stored PN Sequence

Currently the fastest PIC available is 16 MHz, with the fastest speed planned at 20 MHz. At 16 MHz an 11 instruction chip is 2.75 usec (363.63 kHz), about half the desired rate. As with any CMOS part, power consumption is proportional with clock speed. Typical supply currents are 35 uA @ 32 kHz, 1.8 mA @ 4 MHz, and 9 mA @ 16 MHz. It is therefore desirable to minimize clock speed.

A more compact method than in-line coding, yet faster than implementing a LFSR, is to organize all the runs of one's and all the runs of zero's as subroutines. The maximum number of sequentially identical states (all one's or all zero's) for a 256 element PN sequence is seven (by observation), requiring fourteen subroutines. The in-line code is a sequence of calls to these subroutines, with 5 instructions per chip (1.25 usec, 800 kHz @16 MHz). For example, the PIC code to generate the sequence 110001011101000 are calls to the subroutine that produces two 1's, three 0's, one 1, etc., as follows:

```

call two1
call three0
call one1
call one0
call three1
call one0
call one1
call three0

```

The PIC subroutines to produce the sequential runs are as follows:

```

one1      setb  TX
           ret
two1      setb  TX
           nop
           ret
three1    setb  TX
           nop
           nop
           ret
           ...
one0      clrb  TX
           ret
two0      clrb  TX
           nop
           ret
three0    clrb  TX
           nop
           nop
           ret
           ...

```

Each subroutine requires $N+1$ instructions, where N is the number of identical states. The total number of subroutine instructions is $N_{\text{maximum}}(N_{\text{maximum}}+3)$. For $N_{\text{maximum}} = 7$, 70 subroutine instructions are required. The number of calls to subroutines is equal to the number of identical sequence runs, typically about half the length of the PN sequence.

6.1.1.3 *Receiving the PN Sequence*

The receiver contains the same PN sequence as the transmitter and uses the PN sequence to de-spread the received signal. The receiver synchronously integrates the received analog signal, summing the received signal when the PN sequence element is 1, and summing the inverse (sign reversed) signal when the sequence element is 0. If the receiver's PN sequence is synchronized (in phase) with the transmitter, the received signal will integrate to a large positive value if the message bit is one, or negative value if the message bit is zero. If no message bit is sent, or the transmit and receive sequences are out of phase (not properly synchronized), the received signal will integrate near zero. A threshold is set to distinguish a valid correlation from noise.

6.1.2 Acquisition of PN Sequence

The transmitter and receiver have an identical crystal time base (up to the tolerance of the parts, typically 100 ppm), so the transmitter and receiver produce a PN sequence at the same frequency. The task of the acquisition algorithm is to match the phase of the receiver's PN sequence to the transmitter's PN sequence, by sequentially correlating the receiver's PN sequence with every phase, and selecting the phase with the highest correlation.

The first synchronization experiment is to display the correlation as a function of phase using PAN transceiver hardware. The transmitter code is simple; a battery powered PIC continuously transmits the PN sequence. The receiver is more difficult; a battery powered PIC performs a correlation (integration using the PN sequence to control the bipolar chopper) and sends the correlation result (amplitude of integration) to the host PC for display via the serial (19200 baud) optic link. While it is possible to write receiver code which simultaneously correlates and sends the results to the PC, the current drawn by the optical link's LED (34 mA), and the resulting 19.2 kHz square waves, cause unacceptable interference with the extremely sensitive high gain receiver, which share the same power supply and are located within 2 centimeters. The tasks of correlation, ADC conversion, and serial transmission of the results are therefore done sequentially. Since these tasks take different amounts of time, a technique of message framing is used to allow the receiver to perform all tasks sequentially and stay in synchrony with the transmitter.

6.1.3 Message Byte Framing

A transmit frame consists of the transmission of the PN sequence followed by a period of inactivity. This frame is repeated precisely at 1.2 kHz, initiated by a crystal controlled timer interrupt in the transmitter's PIC. A receiver frame consists the following sequence; a) integrate the received signal (presumably a PN sequence), b) digitize the integration result, c) discharge the integration capacitor, d) serially transmit the integration result to the host PC, e) wait for next frame interrupt. This frame is repeated precisely at 1.2 kHz, initiated by a crystal controlled timer interrupt in the receiver's PIC.

6.1.4 Phase Slippage

Originally the phase of the receiver was shifted by making the period of the receiver frame slightly shorter than the transmit frame, causing a slip in phase, producing successive correlations. The slip proved to be too large due to the nature of the PIC timer which is 8 bits with an 8 bit pre-scalar. To produce a 1.2 kHz interrupt, 2400 instructions need to be counted (the timer is incremented with each instruction or an integer divisor thereof). A pre-scale of 1:16 is used to bring the count to less than 8 bits. Each “tick” is therefore 16 instructions, producing a full phase scan (1/1.2 kHz) 16 times a second, which is too coarse and fast to be observed. The original 1.2 kHz period produces an inherent phase slip every 2.46 seconds due to the slight mismatch in crystal speeds (a mismatch of 339 ppm). This has serious consequences, however, for the receiver will slip one chip (1.5 usec) in 4.43 msec, about the length of a message byte at 2400 baud (4.167 msec). Tracking, therefore, needs to be performed several times per message byte.

6.1.5 Random Number Generators

A library routine from the Microsoft C library is used as a source of random numbers. The library routine produces a sixteen bit integer number. The LSB is used to create a random binary sequence. Figure 9 shows the correlation results of the random number table sequence. The correlation is the sum of the ANDed sequences i.e.; the number of times a chip of the phase shifted sequence had the same logical value as the chip in the unshifted sequence. The sequence is wrapped around (modulo 256). The correlation result centers around 128 since the probability of two random bits being the same is 50%.

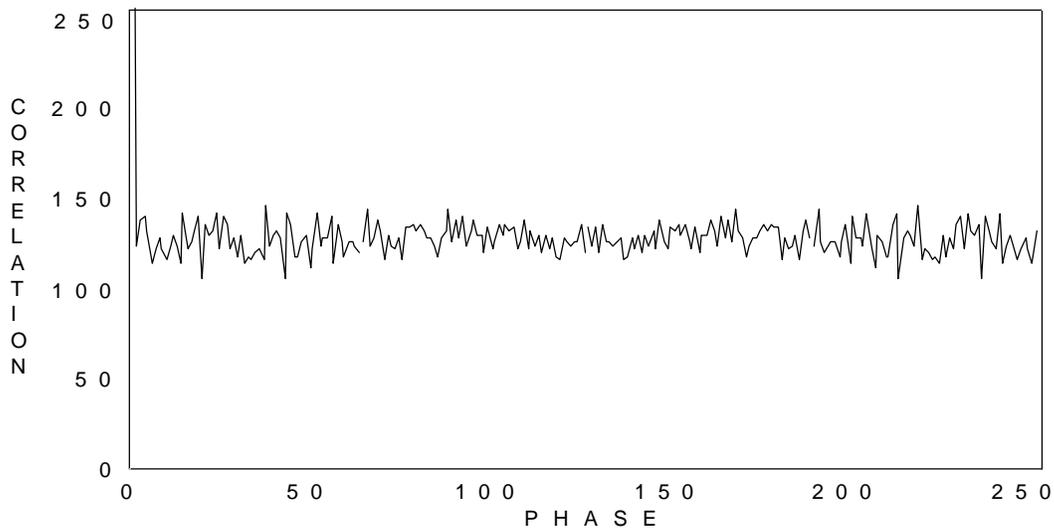


Figure 9. Correlation of a 256 element pseudo-noise (PN) sequence generated from the Microsoft C library routine. Phase is the number of samples shifted. Correlation is the sum of the number of samples that are the same. The correlation at 0 phase is 256 (perfect correlation). Random correlation is 128 (50% chance a pair will have the same value).

6.1.6 Problems With Spread Spectrum

6.1.6.1 Tracking Phase

The original design of the PAN prototype includes spread spectrum modulation strategy. Receiver synchronization is crucial for a temporal error of one chip will result in lost signal. This necessitates vigil tracking of the phase of the transmitter PN sequence. Tracking can be accomplished by comparing the amplitudes of three correlations, each with a slightly different phase, and seeking the phase with the largest correlation. Some type of filtering must be applied to dampen the tendency to track amplitudes that are large due to other mechanism (e.g., noise).

6.1.6.2 Mysterious Negative Correlation

For reasons not understood, the correlation peak at zero phase changes polarity as the phase moves off zero. Perhaps the effect is due to frequency dependent phase shifts in the receiver amplifier and high pass filter. This effect makes tracking the phase difficult when the sampled phase is on the far side of the negative peak, where advancing towards zero phase would decrease the correlation (make it more negative). Further, the effect will have a serious impact on message bit decoding if the sign of the correlation is used to determine

message bit values.

6.1.6.3 Oscillations in the Current Amplifier

Spread spectrum revealed a design problem in the current amplifier. The broad spectrum of the received signal excited oscillations in the current amplifier absent when using narrowband signals. Apparently the receiver had enough phase shift to cause positive feedback and therefore oscillations. A 10 pf capacitance added to the feedback loop of the current amplifier is sufficient to decrease the high frequency gain responsible for the oscillations.

6.1.6.4 Inefficient Energy Use of Channel

The frequency response of the PAN receiver is shown in Figure 10. Two single pole high pass filters separate the amplification stages, producing the high pass response. The gain-bandwidth of the amplifiers accounts for the low pass response. Spread spectrum greatly increases the bandwidth of the transmitted message. The energy is spread from the PN sequence repetition rate (3 kHz) to half the chip rate (330 kHz)²⁰, with additional odd harmonics generated by the rectangular chip waveform. Only a fraction of this wideband energy is received by the PAN due to the bandpass nature of the receiver circuitry. The rest of the transmitted energy is essentially wasted. The chip harmonics may radiate energy as the wavelength approaches the scale of the electrodes, and may not meet FCC emission regulations.

²⁰ The highest frequency is the sequence 1010, generating a square rate of half the chip rate.

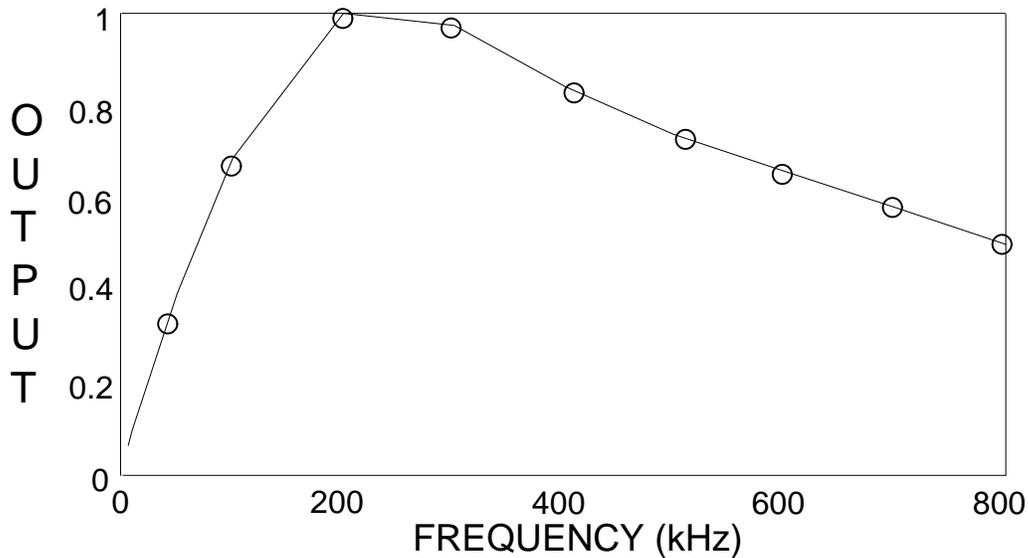


Figure 10. Normalized frequency response of PAN receiver. A test signal is applied directly to the receiving electrodes. Bandpass quality is a combination of the two pole high pass filter and the gain-bandwidth product of the amplifiers.

A shorter spreading sequence may be used to match the transmission bandwidth to the receiver frequency response. If the full spread sequence is used for a message bit, spread spectrum does have the advantage that once the sequence is acquired and tracked, bit framing is also capture. However, if the sequence needs to be shorter than the message bit to limit the bandwidth of the transmission, coding and tracking would be easier if the sequence is an integer divisor of the message bit length.

6.2 Continuous Wave On-Off Keying

On-off keying (a quantized version of amplitude modulation) is the simplest method of encoding data in a carrier. A one is represented as the carrier on, a zero as the carrier off. Due to the synchronization problems of spread spectrum and the advantages of a resonant transmitter, on-off keying is used in the PAN prototype.

6.2.1 Experiments With Resonant Transmitter

Since on-off keying produces a bandwidth equal to the bandwidth of the data, which is less than 2.4 kHz, a resonating transmitter can be used. The resonator produces a very

clean sine wave from a square wave oscillator, delivering all the energy at the carrier frequency. The amplitude of the sine wave can be digitally modulated by varying the pulse width of the digital oscillator. The carrier is either on or off when using on-off keying.

The tank used in the experiments is constructed from a 1.5 mH surface mount, ferrite core wound inductor, and a 27 pf monolithic capacitor, which resonates at 355 kHz. When the top plate electrode is placed on, the frequency shifts down to 336 kHz due to the additional capacitance of the electrode. The Q of this circuit is measured as 7, with a corresponding -6 dB bandwidth of +/- 10 kHz.

Multiple PANs may transmit simultaneously on different frequency channels. The narrow spectrum also eliminates higher frequency harmonics that may radiate RF energy and interfere with RF communication.

6.2.2 Experiments Comparing Spread Spectrum to On-Off Keying

Two types of modulation techniques are compared; direct sequence spread spectrum and on-off keying. Both modulation techniques use the same PAN prototype hardware, and are determined by PIC programming. The PAN transceivers are placed on a wooden platform, spaced 20 cm apart, measured from the closest edges of the transceivers. The magnitude of the integrated received signal, in ADC units (255 maximum) for all combination of transmitter and receiver modulation techniques, are as follows:

<u>TX</u>	<u>RCV</u>	<u>RECEIVED SIGNAL</u>	<u>COMPARISON (%)</u>
spread	spread	149	100
OOK	OOK	90	60 (with tank resonator)
OOK	OOK	62	41 (no resonator)
OOK	spread	27	18
spread	OOK	2	1

Spread spectrum produces the largest received signal. A tank resonator increases the performance of on-off keying about 50%, but is only 60% as effective as spread spectrum modulation.

6.2.3 Selection of On-Off Keying Over Spread Spectrum

There is typically little stray electric field in the environment, due to the significant attenuation of electric field strength with distance and the absence of large (hundreds of volts) oscillating electric fields in the frequency range (100-1000 kHz) and proximity of PAN transceivers. The largest source of electrical interference is 60 Hz utility power, which is strongly attenuated by the two pole 16 kHz high-pass filter in the PAN receiver.

In light of the complexity of tracking the phase of a spread spectrum PN sequence and the relatively "clean" received signal (large signal-to-noise ratio), the much simpler OOK modulation is chosen. A message bit of logic one and zero is represented as carrier on and off, respectively. A quadrature detector in the receiver detects the OOK carrier independent of phase. The demodulated signal is compared to a fixed threshold.

A fixed threshold is susceptible to false triggering by large input signals accompanied with a large noise floor. Touching the receiver increases plate area, increasing the magnitude of both signal and noise, for example. A more sophisticated detection circuit utilizes automatic gain control (AGC) or adaptive thresholding. Automatic gain control can be implemented digitally, as in the PAN prototype²¹, or with analog electronics, commonly used in radio circuits. A preferred method of adaptive thresholding sets the detection threshold as a fraction of the average signal strength, determined by an envelope follower - a peak detector with a dissipative element.

7. DEMONSTRATION PROTOTYPE

7.1 The Business Card Handshake

The demonstration prototype of the PAN system, shown in Figure 11, consists of an autonomous battery powered transmitter, a battery powered receiver, and a host computer running a terminal program. The transmitter contains a PIC microcontroller continuously transmitting a series of ASCII characters stored in program memory. The lower plate of the transmitter is in close proximity to the earth ground (environment electrode). The

²¹ Although the PAN receiver contains a digital AGC (the PGA and microcontroller), the

upper plate of the transmitter is in close proximity to the woman's body (body electrode), coupling a modulating electric field to her body.

The lower plate of the receiver is in close proximity to the earth ground (environment electrode). The man has his foot on the upper plate of the receiver, as he would if the receiver were in his shoe²², coupling the upper plate to the man's body (body electrode). When the woman and man are in close proximity, particularly when they shake hands, an electric circuit is completed, allowing the nanoamp transmission signal to pass from the transmitter through her body, to his body, to the receiver, and back through the earth ground. When completed, the circuit passes the ASCII characters to the receiver, which are demodulated and sent to the host computer over a serial optic link. The ASCII characters are displayed by a terminal program running on a laptop computer.

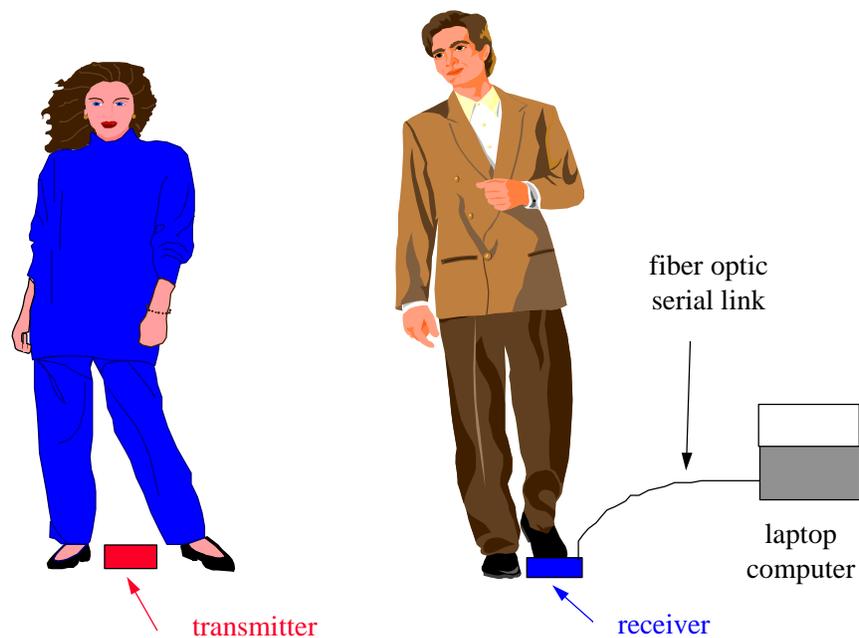


Figure 11. PAN demonstration system. When they shake hands, she downloads her electric business card to him. The transmitter near her feet couples a modulated electric field into her body. The transmitter contains a microcontroller that continuously transmits ASCII characters stored in program memory. When she shakes hands with the man, nanoamp current flows into his body and down to the receiver by his foot. The receiver decodes the ASCII characters and sends them through the optical cable to a laptop computer which displays the characters.

PGA gain is fixed at 100, indicating a need for greater pre-PGA signal gain.

²² Dr. Sholls manufactures a product line of shoe inserts.

The transmitter continuously transmits pre-programmed sequence of message bytes containing the eight names of the current members of the Physics and Media Group. A button on the transmitter selects a second message contains the name, address, and email address of the group. These messages represent the group's business card.

The receiver continually demodulates the received signal. Any demodulated signal below a fixed threshold is interpreted as a logic 0 message bit. The receiver clears the top bit of every message byte received to prevent erroneous message bytes from being interpreted as control characters. No error correction is performed, in order to demonstrate the degradation of the received signal with distance. An operational PAN would use error correction techniques, well known to practitioners of digital communication.

7.1.1 Transmitter Dimensions

The transmitter uses the tank resonator previously described to produce a potential of nominally 30 volts across the transmitter electrodes; the aluminum case and the electrically isolated aluminum cover. The case measuring 94 mm x 120 mm x 37 mm. The case cover measures 94 mm x 120 mm, and is suspended above the case by insulating nylon stand-offs, creating a 1.5 mm gap between the case and cover.

7.1.2 Receiver Dimensions

The receiver uses the circuit described in *Circuit Review*. The electronics are totally enclosed in an aluminum case, having the same dimensions as the transmitter. The sealed conducting case electrically shields the electronics, serves as an electrode, and is connected to circuit ground (zero volt) reference. The second electrode is mounted below the case, separated 1.2 cm by a slab of foam (see *Prototype Construction*).

7.2 Receiver Signal Processing

7.2.1 Approximations To Quadrature Detection

Synchronous quadrature detection is the operation

$$V_{out} = \sqrt{(V_{in} \times \sin \theta)^2 + (V_{in} \times \cos \theta)^2}$$

which produces a signal V_{out} equal to the magnitude of received signal V_{in} , independent of the phase ϕ of the received signal V_{in} . Two bipolar choppers, square, and square-root functions are required to fully implement quadrature detection. The prototype has only one bipolar chopper (as required for spread spectrum), and the microcontroller has a reduced instruction set (which makes it fast and inexpensive) that does not include multiplication, division, or square roots. Three compromises are made to eliminate the squares, square roots, and to utilize one bipolar chopper.

The single bipolar chopper is time multiplexed to simulate two bipolar choppers. Since a message bit maintains phase over the duration of the message bit, the single bipolar chopper is first used to integrate half of the message bit using zero phase (the sine component). The integrated result is digitized by the microcontroller's ADC, then discharged. The second half of the message bit is integrated at 90 degrees phase²³ (the cosine component), and the integrated result is digitized. The absolute value of the two components are added together and used as the demodulated signal, ignoring the square and square root functions. The operations performed by these approximations are:

$$V_{out} = V_{in} \times \sin \phi + V_{in} \times \cos \phi$$

These approximations add dips to demodulated signal, at 0, 90, 180, and 270 degrees phase, which must be greater than the bit detection threshold. However, these dips are the true magnitude of the V_{out} vector. All other phase values are greater than the vector, which is acceptable since the demodulated signal V_{out} need only exceed a detection threshold.

7.2.2 Message Timing

The receiver integrates 63 cycles for each phase. A cycle is one period of the carrier, which is 3 usec (333 kHz frequency carrier). This sets the upper limit on the message bit rate at 5.3 kbaud. However there is only one bipolar chopper so the integration must be repeated at ninety degree phase. Further, there is a 32 usec delay in between each phase integration, representing the time required to perform an ADC (20 usec), discharge the

²³ The timing of the bipolar chopper control lines are delayed 0.75 usec, one quarter of the

integrator capacitor (6 usec), and code overhead (6 usec). The total time to perform synchronous quadrature decoding on a message bit is 410 usec, resulting in a baud rate of 2439, fast enough to perform 2400 baud communication. However the baud rate is further sacrificed to simplify debugging, bit synchronization, and experiments in receiver sensitivity. A complete timing diagram of message bits and bytes is presented in Figure 12.

Message Synchronization

The transmitted bit (TX BIT) is sampled three times by the receiver (RCV BIT SAMPLES). The receiver detects a start bit when one of the samples exceeds the detection threshold. When this occurs, the detector uses the second of the three samples as the valid sample. This synchronization technique guarantees the valid sample is completely within the frame of the transmitted bit (TX BIT).

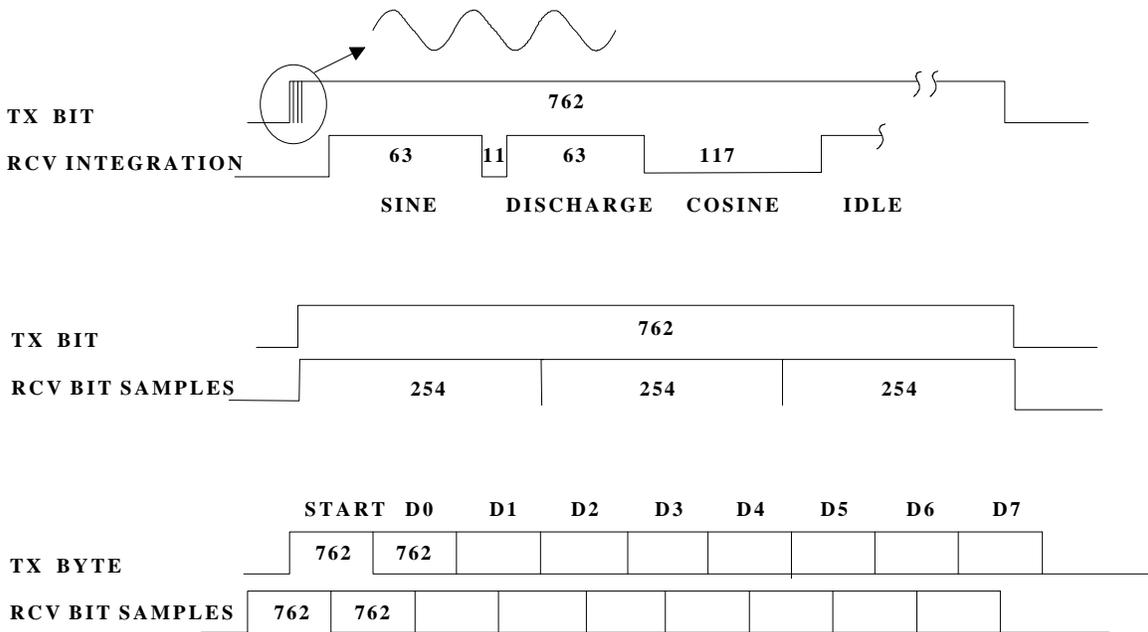


Figure 12. Timing diagram of transmit frame containing message byte and bits. Units are cycles, where a cycle=3 usec. The format is similar to the RS-232C protocol for asynchronous communication.

carrier period, to produce the 90 degree phase signal.

8. RELATED WORK

Several topics and areas of research and engineering related to electric field sensing and signaling are included and elaborated upon in this section.

8.1 *Fish Evaluation Board*

A prototype evaluation board is constructed to allow researchers to explore electric field sensing. The system is called a fish since a) fish navigate in three-dimensions while mice (the optomechanical pointing device and mammalian creature) only navigate two dimension, and b) weakly electric fish navigate and communicate with electric fields [Bullock82]. The fish evaluation board, based on a Motorola 68HC11 microprocessor, supports one transmitter, four receiving channels, and communicates using RS-232, RS-485, and MIDI protocols. Synchronous detection is performed using analog electronics and the resulting demodulated signal is digitized by an 8 bit analog-to-digital converter (ADC) contained in the 68HC11. The demodulated signal has a dynamic range and resolution that exceeds the resolution of the ADC so potentiometers are used to allow adjustment of the gain and bias of each channel. These adjustments prove to be rather tedious; every change in electrode geometry requires multiple iterative adjustments. Approximately fifty fish units have been produced and distributed to researchers; the design has been superseded by the smart fish (see *Smart Fish Evaluation Board*).

8.2 *Transceiver Design*

Multiple electric field receivers allow low-resolution imaging of objects in the electric field [Smith95]. It is beneficial to electrically move the transmitters through multiplexing to provide multiple views of the object. An N by N array of transmitter multiplexed sensors provides $N(N-1)/2$ unique sensor readings. Switching electrodes between receiver and transmitter circuits is a challenging design problem since the received signals are so small (nanoamps) and any capacitance to ground attenuates received signal and effects the performance of the current amplifier (see *Cable Resonance Phenomena and Non-Ideal Op Amp Performance*).

A simple solution is to use the current amplifier as a transmitter by driving the non-inverting input with the transmit signal, as shown in Figure 13. An op amp with negative feedback will adjust its output to minimize the voltage difference between the inputs. When the transmitter voltage is applied to the non-inverting input, the output will follow the transmitter voltage. The high impedance of the feedback resistor **R1** and the receiver electrode capacitance **C** introduce an RC lag in the response. The back-to-back diodes (**D1** and **D2**) minimize this lag by turning on when the voltage difference between the op amp output and electrode exceeds the diodes forward conducting voltage (nominally 0.6 volts). The diodes limit the output to 0.6 volts, which is adequate for front-end amplification of nanoamp currents. Resistor **R2** (typically 1 k) provides a ground return for the non-inverting input of the op amp when SW is open (receive mode).

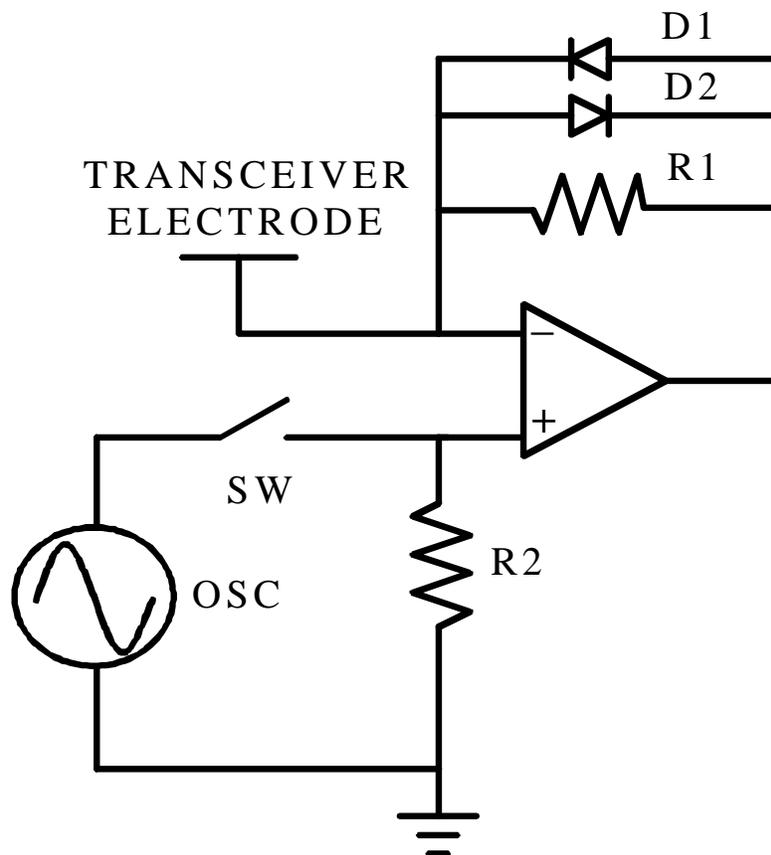


Figure 13. Schematic of transceiver. With SW open, circuit behaves as a receiver. With SW closed, circuit is a transmitter. Diodes D1 and D2 prevent transceiver electrode from lagging oscillator.

The capacitance of the feedback diodes decreases the gain of the op amp, while decreases the resonance effect of the circuit, as shown in the frequency response curves in Figure 14. The flattened frequency response is desired for spread spectrum. The attenuation due to the diodes (approximately 6 dB) can be compensated by additional amplification, or preferably by increasing the transmit frequency, resulting in a faster update rate.

8.3 *Smart Fish Evaluation Board*

8.3.1 Introduction

A second generation electric field evaluation board is designed to a) capture the full dynamic range of the electric field sensor, b) eliminate the need to manually adjust circuit parameters, and c) explore other modulation techniques (including spread spectrum). The new evaluation board is called the smart fish since the system can adjust system parameters automatically and implement many modulation techniques by software programming.

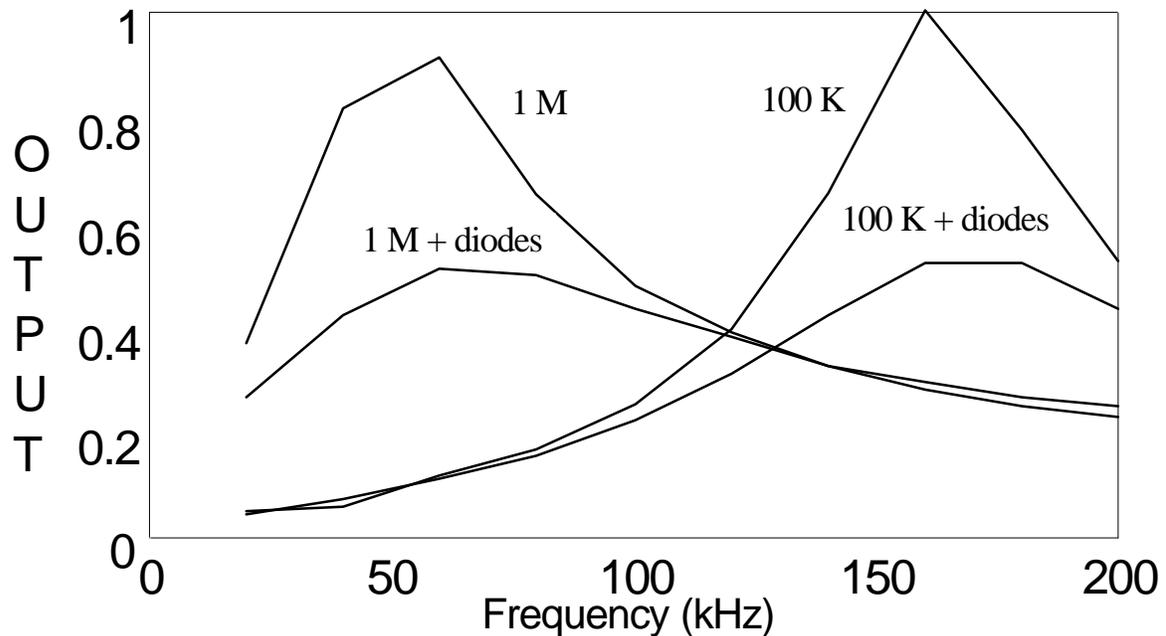


Figure 14. Receiver frequency response of transceiver. R2=1 K, R1=100 K or 1 M, and diodes D1 and D2 installed or absent (see comments near curves).

The received displacement current is converted into a voltage by a current amplifier, as done in the original fish. The voltage is biased by a programmable voltage from a digital-to-analog converter (DAC), and amplified by a differential programmable gain amplifier (DPGA). The programmable voltage effectively nulls (to the resolution of the DAC) the applied voltage. Any difference is multiplied by the DPGA and digitized by a twelve bit ADC. The process is controlled by a digital signal processor (Analog Devices AD2101) running at 20 million instructions per second. The transmitter oscillator is digitally implemented; the digital signal processor (DSP) controls a 12 bit DAC. The DSP can also enable a circuit that measures the current loading of the transmitter electrodes. Other modulation and detection strategies are possible since the transmitter modulation and detection demodulation is performed in software.

The smart fish evaluation board is designed to be a general purpose data acquisition system, in addition to the specific application of electric field sensing. Complete schematics, parts and vendor list, and programming manual for the DSP and 68HC11 are provided to assist those who might build, use and extend the operation and functionality of the smart fish.

8.3.2 Hardware Review

Figure 15 presents a functional block diagram of the smart fish. The 68HC11 microprocessor communicates with a host computer through a serial interface (either RS-232 or MIDI). The AD2101 DSP performs all the low level data acquisition. Figures 16-19 are the detailed schematics of the smart fish board. These schematics represent the current state of the prototype design; please contact the Physics and Media Group for the latest update.

Figure 15. Smart fish block diagram.

Figure 16. Smart fish RECEIVER schematic.

Figure 17. Smart fish TRANSMITTER schematic.

Figure 18. Smart fish DSP schematic.

Figure 19. Smart fish CPU, INTERFACE, POWER schematic.

8.3.3 Parts List

The following is a parts list of smart fish components:

<u>Quantity</u>	<u>Part Type</u>	<u>Designators</u>
32	.1	C1 C2 C3 C4 C5 C6 C8 C9 C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C21 C22 C25 C32 C33 C34 C35 C36 C37 C38 C39 C40 C41
26	0	R8 R11 R12 R16 R17 R18 R19 R42 R43 R44 R45 R46 R47 R48 R49 R50 R51 R54 R55 R56 R57 R58 R59 R60 R61 R62
7	1K	R6 R7 R9 R10 R13 R14 R15
2	1K RP	RP1 RP2
10	1M	R30 R31 R32 R33 R34 R35 R36 R37 R38 R39
16	1N914	D3 D4 D5 D6 D7 D8 D9 D10 D11 D12 D13 D14 D15 D16 D17 D18
2	1N4001	D1 D2
1	4.7K	R20
1	6N138	U6
1	8MHZ	XTAL1
1	8SW/DIP16	SW3
8	10K	R1 R2 R3 R4 R5 R52 R53 RP3
1	10M	R21
4	20K	R26 R27 R28 R29
1	20MHz	XTAL2
1	22uF	C28
2	27pf	C23 C24
1	74HC368	U7
1	74HC393	U19
1	74HC574	U20
1	74HC589	U4
2	100K	R40 R41
3	100uF	C7 C26 C27
2	220	R24 R25
2	330	R22 R23
1	27512	U18
1	75155	U1
2	AD684	U26 U27
1	AD2101	U17
2	BUTTON	SW1 SW2
1	D25	J4
1	DB9/F	J1
1	DG406	U14
2	DIN-5	J2 J3

1	HEADER 5	JP1
1	HEADER 8	J7
1	IDC10	J5
1	MAX120	U16
1	MAX333	U5
1	MAX532	U9
1	MC68HC11E2	U2
1	MC34064	U3
2	not installed	C29 C30
1	PGA204	U15
1	POWER	J6
9	RCA	J8 J9 J10 J11 J12 J13 J14 J15 J16
2	TL082	U10 U11
8	TLO82	U8 U12 U13 U21 U22 U23 U24 U25
1	GREEN	LED1
1	RED	LED2
1	YELLOW	LED3

8.3.4 Vendor List

The smart fish costs approximately \$550 in materials, including printed circuit board, power supply, and case. The following is a vendor list, complete with vendor part numbers and price estimates:

Vendor: Digi-Key
Phone: 1-800-344-4539
FAX: 218-681-3380
Address: 701 Brooks Ave. South PO Box 671
Thief River Falls, MN 56701-0677

<u>Part</u>	<u>Description</u>	<u>Price</u>
A1700-ND	FIBER OPTIC CABLE OD=.089 5M	11.20
FB111-ND	REPLACEMENT EMITTER/DETECTOR	6.00
MAX120CNG-ND	ADC 500KSPS 12BIT	32.59
MAX333CPP-ND	QUAD SPDT CMOS SWITCH 20PIN DIP	6.39
MAX532BCPE-ND	DUAL SERIAL V OUT 12BIT DAC	18.00
MAX427CPA-NA	LOW NOISE OP AMP 8PIN DIP	3.57
74ACQ574PC-ND	OCTAL FLIP-FLOP W/TRISTATE	2.79
6N138QT-ND	OPTOISOLATOR	1.363
P300-ND RED	T13/4 DIFFUSED	.168
P303-ND GREEN	T13/4 DIFFUSED	.23
P306-ND AMBER	T13/4 DIFFUSED	.249
CTX116-ND	16MHZ TTL CRYSTAL	3.25
P6632-ND	47UF 25V ELECT. CAP RADIAL	.263

P6633-ND	100UF 25V ELECT. CAP RADIAL	.30
P2105-ND	1UF TANT CAP	.198
100XBK-ND	100 RESISTOR 1% 1/4 WATT	.04135
220XBK-ND	220 RESISTOR 1% 1/4 WATT	.04135
330XBK-ND	330 RESISTOR 1% 1/4 WATT	.04135
1.00KXBK-ND	1K RESISTOR 1% 1/4 WATT	.04135
4.7KXBK-ND	4.7K RESISTOR 1% 1/4 WATT	.04135
10.0KXBK-ND	10K RESISTOR 1% 1/4 WATT	.04135
20.0KXBK-ND	20K RESISTOR 1% 1/4 WATT	.04135
1.00MXBK-ND	1M RESISTOR 1% 1/4 WATT	.04135
0.0QBK-ND	ZEROOHM JUMPER WIRE 1/4 WATT	.02465
761-3-R1K-ND	DIP RESISTOR PACK 16PIN (8 RESES)	.655
27C512-12/J-ND	512K EPROM 120NS	10.90
A2120-ND	28PIN PLCC SOCKET	1.64
A2123-ND	52PIN PLCC SOCKET	2.03
A2124-ND	68PIN PLCC SOCKET	2.25
ED3314-ND	14PIN MACHINE DIP	.506
ED3316-ND	16PIN MACHINE DIP	.578
ED3320-ND	20PIN MACHINE DIP	.723
ED3324-ND	24PIN MACHINE DIP NARROW	.867
ED3328-ND	28PIN MACHINE DIP NARROW	1.012
ED3628-ND	28PIN MACHINE DIP	1.012

Vendor: Allied Electronics
Phone: 1-800-433-5700
FAX: 617-255-0468
Address: Rm 130 1408 Route One
Norwood, MA 02062

<u>Part</u>	<u>Description</u>	<u>Price</u>
735-2746	TL084CN Quad Op-Amp	1.25
735-2742	TL082CP Dual Op-Amp	.87
735-9994	SN75155P RS-232 TX/RCV Driver	1.25
839-2426	RCA pc mount right angle	.74
748-2039	capacitor .1uf .1" spacing	.48
879-0125	Triple power supply	48.00
806-5155	Hammond blue box 1.58"h	25.00
870-6058	Switch momentary on	.40

Vendor: Analog Devices
PO BOX 9106 Norwood, Mass
Phone: 617-461-3131

<u>Part</u>	<u>Description</u>	<u>Price</u>
ADSP-2101-KP-80	DSP PLCC package 20MHz version	\$40.00

8.3.5 Smart Fish Programming Manual

The following is a preliminary programming manual included to present a glimpse of the operation of the smart fish. Please contact the Physics and Media Group for the latest version of this information.

8.3.5.1 SMART FISH FUNCTIONAL OPERATION OVERVIEW

The HC11 communicates to the host through MIDI or RS232 using the asynchronous port. The HC11 communicates with the DSP and DIP8 switches through the synchronous port. The HC11 directly selects the transmitter (TX1 and/or TX2) and can enable the circuitry to measure transmitter load. The DSP selects the following acquisition parameter; receiver channels, channel gain, transmit frequency and amplitude, sample phase, and number of samples accumulated per channel. The HC11 sends a *request record* to the DSP specifying these acquisition parameters, basically requesting the DSP to get a bunch of samples. The DSP goes off and does the acquisition and sends back a *data record* to the HC11 containing the requested measurements.

8.3.5.2 COMMAND STRUCTURE (HC11 to DSP)

Command Byte followed by any number of optional Data Bytes, as in;

	<i>COMMAND_OP_CODE</i>		<i>DATA</i>		
Command	OpCode	Data #1	Data #2		Comment
Read receiver	0000BBBB				Read receiver bank
Frequency period D	0001RRRR	D15-P8	D7-D0		Set receiver R to transmit
Phase1 phase D	0010RRRR	D15-D8	D7-D0		Sample receiver R at
Phase2 phase D	0011RRRR	D15-D8	D7-D0		Sample receiver R at
Samples channel	0100RRRR	D7-D0	-----		Number of samples per
Transmit Load	01010000	D7-D0	-----		Read transmitter D times
User channel	01100UUU	-----	-----		Read user channel U
Receiver	RRRR	0000=1, 0001=2, ... , 1111=16			

Since there are two transmitters and eight receivers, there are effectively 16 receiver channels, each with their own transmission frequency and phases. The DSP samples the receiver twice, at two different times (phases). Typically they are set at 90 and 180 degrees to measure the phase shift of the channel. When the transmitter load is measured, the transmitter power is attenuated so good receiver measurements can't be made while measuring transmitter load.

8.3.5.3 DSP & HC11 COMMUNICATION

Synchronous communication requires one device to be the master and generate a synchronization clock. For the smart fish the device transmitting is the master. The HC11 starts by being the master sends a request record to the DSP. The HC11 then turns into a slave and the DSP (as master) sends back a data record when the DSP is finished reading all the requested channels. There are no codes that specify end-of-record so the HC11 and DSP must know how many bytes to expect in a record. This is determined by an agreed upon command structure of the form command/data.

To send a request record to the DSP, the HC11 first prepares a record to send to the DSP in a buffer. The HC11 then configures the SPI as a master and enables SPI interrupts (see SPCR-SPI Control Register). This starts an interrupt driven routine called by the flag **SPIF**- SPI Transfer Complete Flag that sends out a byte from the buffer until the buffer is empty. The routine sets **TSYNC1**, puts the data byte in the SPDR-Serial Peripheral Data Register, then clears **TSYNC1**. After the last byte of the request record is transmitted, the HC11 is configured as a slave. When the DSP sends its first byte of the data record to the HC11, the SPIF will cause an interrupt which should vector into a receive routine that puts each received byte into a receive buffer. The HC11 should know how long the record is since the HC11 requested the data record. When all the bytes are received, the HC11 takes the full data record and sends it out the asynchronous port to the host, either in MIDI or RS232 format.

8.3.5.4 DSP READING RECEIVER CHANNELS

The DSP has only one analog-to-digital (ADC) converter so a multiplexer (MUX) is used to select one of sixteen inputs; eight receiver channels, a transmitter load channel, and seven user port channels. A differential amp with programmable gain (DPGA) follows the MUX allowing the DSP to select channel gain from 1-1000 in decade increments. The DPGA multiplies the difference between the input channel and an output from one of the two channels of the digital-to-analog (DAC). This allows the DSP to offset the anticipated value of the channel (e.g., the last reading from the channel), and amplify the difference, greatly increasing the dynamic range of the system. The DSP selects the receiver channel and channel gain by writing to any external data memory location. All external data memory locations are latched by an eight bit latch (data lines D8-D15).

To read a receiver channel pulse the SAMPLE control line high for at least one microsecond. This holds the analog value of each receiver channel *before* the MUX. Select the MUX channel for the receiver channel you want to read, then set the gain of the DPGA. Wait 8 microseconds for the DPGA to settle, drop ADC CS/ (bit 15 of DSP Memory Write) . Then read external memory 2 microseconds after dropping ADC CS/.

To read transmitter load or any of the user ADC channels, the sample-and-hold (S/H) is not connected to these channels and therefore the SAMPLE control line does not need to be pulsed. The DPGA still needs to settle though after the MUX channel selection address (MUXD-A) and/or GAIN is changed.

8.3.5.5 DSP WRITING TO THE DACs

The DAC has two channels, each with 12 bits resolution. Channel 0 controls the transmit voltage. Channel 1 controls the DPGA offset voltage. Both channels are updated together as one 24 bit serial word, composed as three sequential 8 bit serial transmissions, sent on SPORT0. DAC0 (DAC channel 0) is the transmit voltage. DAC1 is the offset voltage applied to the subtracting input of the DPGA.

8.4 Cable Resonance Phenomena and Non-Ideal Op Amp Performance

The receiver circuit of the fish prototype exhibits an amplitude sensitivity indicative of a resonant system. The resonant frequency is observed to be determined by the length and type of receiver cable used, and is independent of transmitter cable.

In order to understand the resonance phenomena, the deviation of an operation amplifier from its ideal behavior is examined. The operation amplifier relies on negative feedback for stable operation. The feedback signal at the inverting input should be -90 degrees²⁴. The inverting input adds another -90 degrees of phase shift, producing the desired -180 phase signal. An ideal op amp maintains constant phase over its entire bandwidth. In practice op amps have a number of internal phase shifts and phase compensation circuitry to produce a single pole phase shift starting at about 10 Hz. The TLO82 used in the fish has a single pole at 10 Hz and maintains a flat phase shift of -90 degrees from 100 Hz to 1 MHz. Oscillation will result if the phase of the signal at the inverting input is shifted an additional -90 degrees at a frequency where the gain exceeds unity. Damped oscillations (i.e., ones that does not blow up) would explain the observed resonance phenomena.

The feedback resistor R and the cable capacitance C form an RC network at the inverting input to the op amp, which shifts the phase of the feedback signal. A 53 pf cable capacitance combined with a 1 M feedback resistance shifts the phase of a 30 kHz signal an additional -90 ; a necessary condition for oscillation. The cable capacitance has an additional detrimental impact on the performance of the receiver amplifier. Cable capacitance shunts a portion of the received current at the noninverting input to ground, stealing current that would otherwise be converted to voltage. At 30 kHz a 53 pf capacitance has 100 K impedance, shunting 91% of the received current (assuming a 1 M feedback resistor).

The cable impedance also decreases the effective gain of the op amp by an order of magnitude by decreasing the feedback attenuation factor; the ratio of the input resistance

²⁴ Minus sign indicates inverting input lags the output signal.

to the sum of the input resistance and feedback resistance²⁵. The open loop gain of a TLO82 at 30 kHz is 100. The feedback attenuation factor reduces this gain to 9. The small gain means the non-inverting input (hence the receive electrode) deviates from a virtual ground, having a signal equal to 9% of the op amp output.

The feedback resistor can be decreased to raise the resonance frequency, moving the pole to a higher frequency, and increase the feedback attenuation factor, at the sacrifice of some current to voltage gain. However the loss of gain can be made up in a second stage of amplification. Noise calculations indicate that thermal noise ($4KTRF_{bw}$ [Horowitz94]) from the 1 M feedback resistor accounts for 98% of the noise in the current-to-voltage circuit. Reducing the feedback resistor to 100 K decreases the circuit noise 9.3 dB, from 41 uV to 14 uV.

8.5 Humidity and Permittivity

The displacement current from transmitter to receiver electrode is primarily a function of geometry. As the distance between the transmitter and receiver electrode decrease, the displacement current increases. The displacement current also depends on the permittivity of air which has a slight dependence on temperature and humidity. Since these parameters change on a time scale orders of magnitude slower than the modulation rate (minutes and hours compared to microseconds) they do not affect the integrity of PAN communication. However, changes in displacement current measurements may effect the long term reliability of electric field sensing. The magnitude of the effect of humidity on air permittivity is calculated using the following equation [Fraden93]:

$$\epsilon = 1 + (211/T)(P + (48SH/T)) * 10^{-6}$$

where T= temperature in Kelvin

P= pressure of the moist air in mm Hg

S= pressure of saturated air in mm Hg (temperature dependent)

H= relative humidity (in percent, i.e.; 0-100)

²⁵ Attenuation factor = $100 \text{ K} / (100 \text{ K} + 1 \text{ M}) = 0.09$

Assuming $T=20^{\circ}\text{C}$, $P=30$ mm Hg, $S=17.535$ mm Hg, permittivity is calculated for two humidities:

H=50%	$\epsilon=1.000125$
H=60%	$\epsilon=1.000146$

The permittivity changes 0.0021% when humidity changes 10%, a small change indeed.

9. FUTURE RESEARCH

The research of the thesis has uncovered a novel means to perform local communication using electric fields. The trade-offs among cost, speed, size, power, and operating range must be further studied and quantified in order to engineer practical PAN devices. Many of the design and engineering techniques of radio and digital communication can be applied to PAN devices, for a PAN device is basically a radio with a near-field antenna. A radio captures far-field electromagnetic radiation using a resonant antenna; a PAN receiver intercepts near-field electric fields using electrostatically coupled plates. PAN devices therefore benefit from advances in tiny micro-powered radio circuits.

A communication network is primarily judged by channel capacity. Telephone modems have pushed modulation and digital signal processing techniques to their limits. The application of modem telephony techniques to PAN devices may deliver channel capacities of 100 kbits per second. Data compression also increase the effective capacity of PAN communication.

The concept of power sneakers is intriguing. A piezo ceramic pile may be used to charge a capacitor, powering PAN electronics. Piezo elements produce a large charge across a small capacitance, resulting in a large voltage. Super capacitors on the order of Farads, typically used to back up RAMs, may be used to increase the capacitance and hence, decrease the piezo voltage. Surface mount components mounted on a flexible printed circuit boards can produce a comfortable networked computer shoe insert.

The thesis explored the first two layers of a network. The upper networked layers must be addressed to make a practical PAN. Applications need to be deeply considered. Privacy and other cultural issues are raised when personal data can effortlessly be exchanged. As with other communication and data systems, there is a trade-off between access and

security, reminiscent of the Chinese character that simultaneously represents hazard and opportunity. The thesis is a technical work and does not begin to address these broader issues, which will continually be explored and resolved as electronic devices such as PANs permeate the social fabric of our information society.

The next step, from my perspective, is to push the sensitivity and bit rate of the PAN receiver in order to realize a watch-sized PAN transceiver. Ultimately PAN devices will be judged a success when they appear as common objects and perform magic; from picture telephone Dick Tracy watches to self-powered smart sneakers that seamlessly interconnect us to a world-wide network.

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