Intrabody Buses for Data and Power

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Abstract

While wearable computers are empowering fashion accessories, they bring with them a tangle of wires which connect their parts. As these subsystems begin to decouple and operate on less power, it becomes possible to wirelessly distribute their required data and power using to the wearer's body. We have demonstrated systems that transmit and receive both data and power, and are working to combine the two.

Introduction

Over the last two decades the locale of computing has decentralized, moving from mainframe computing centers to networked desktop workstations to portable laptop "powerbooks" and "thinkpads". Wearable computing takes this progression one step further by decomposing the laptop computer's traditionally monolithic structure into loosely connected subsystems. Serial data links are used to connect heads-up displays and hands-up keyboards to waist-mounted compute engines.

Building on the work of [Zim96], we have built a new version of the personal area network (PAN) "body modem". Previous versions ran at 300 or 2400 bits per second (using AM and direct-sequence spread-spectrum encodings, respectively), while the current version provides half-duplex transfer rates from 1200 bps to as high as 9600 bps (using FSK). In addition, it is possible to build a PAN transmitter using a single 8-pin microcontroller and an LC resonant circuit.

Most interestingly, our use of electric fields fringing the body has evolved to include the wireless transmission of electrical power (PAP). Since each datum received through the body has a low *but nonzero* energy, the excess energy accumulated in receiving and demodulating these bits may itself be used to power circuitry.

Add to the notions of shoe-based computing [Zim96] the fact that several watts of power are available at the shoe in the ordinary adult gait [Sta96]. A power supply in the shoe can trade mechanical for electrical energy and store the latter, supplying wirelessly as needed to other devices worn about the body. The relationship between information and energy unfolds in this domain to reveal a pleasing symmetry.

PAN communication channels

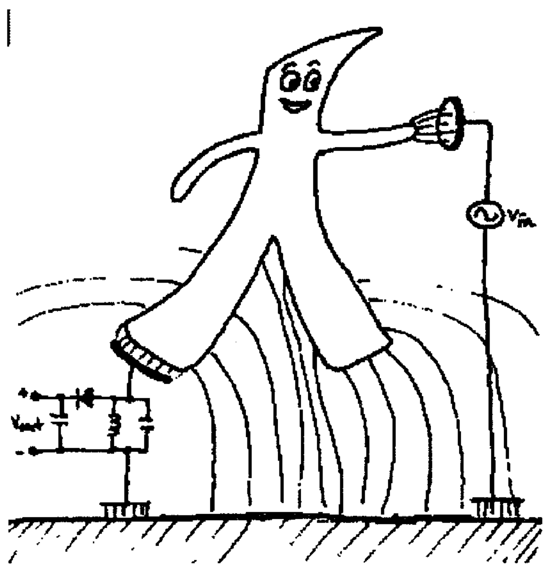

Figure 1: Intrabody electrostatic coupling: Note that the subject is floating above ground.

Figure 1 illustrates the basic principle of a PAN communication channel. The capacitive junctions **A**, **B**, **C**, and **D** correspond to regions of increased electric field strength, induced by the presence of conductive electrodes. A fifth junction labeled **E** represents all other electrostatic coupling between the body and the surrounding electrical environment, here taken to be AC-coupled to the ground potential.

The PAN transmitter is represented by an oscillator, and the receiver is represented variously in the figures as a simple tuned circuit and detector or as a differential amplifier.

This model is an approximation based on the more complete model of [Zim96]. In particular, we ignore the intraelectrode impedances of both the transmitter and the receiver, because the former is a load on an ideal voltage source, while the latter is taken to be an open circuit.

The remaining capacitive couplings of interest are

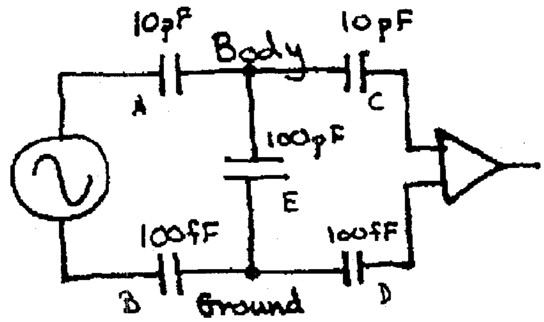

Figure 2: Capacitive bridge formed in Figure 1.

represented in Figure by their rough order of magnitude. Note that these values change with any motion which changes the electrode geometry.

Zimmerman points out that the model can be rearranged to form a capacitive Wheatstone bridge, where each terminal of the receiver is fed by a voltage divider formed by the effective impedance paths from the source terminals. The potential across the receiver input vanishes only when these ratios are balanced. Since body-based PAN devices will always be in motion, there will almost always be an electrical communication path between them, as long as their receivers are sensitive enough to detect the imbalance.

PAN III

The basic structure of the PAN III transceiver is revealed in Figure 3. A resonant LC circuit with $Q \approx 8$ serves as a tuned receiver and increases sensitivity to the input frequency band. The voltage across this tuned circuit is buffered and then amplified by a series of gain stages. The amplified signal is fed into an FM detector comprising a VCO, a phase comparator, and a low-pass filter which generates the control voltage for the VCO. The control voltage varies linearly with the input frequency, and is finally compared with a reference voltage to generate digital data which correspond to the signal frequency.

To transmit data, an FSK (digital FM) signal is presented at the summing junction of the input buffer. This causes the inverting input of the buffer to follow with strong voltage compliance. The inverting junction thus drives the output electrodes, using the LC "tank" to boost the output voltage and recycle transmitter energy.

This circuit is implemented entirely in 5V CMOS, drawing 2 mA when transmitting and much less when receiving. Not shown is the PIC16C84 microcontroller [Mic96] which duplexes data between the PAN transceiver and an RS232 serial port.

Channel capacity

The theoretical upper limit on the capacity of a communication channel is given by the Shannon bound [Ham86]

$$C = \delta f \, log \, (1 + \frac{S}{N}) \tag{1}$$

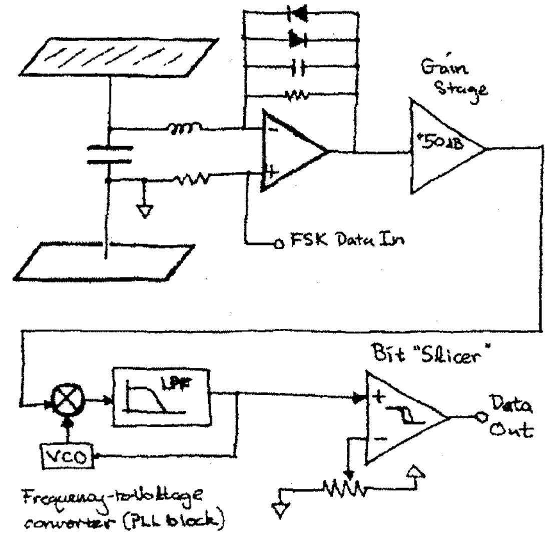

Figure 3: Block diagram of the PAN III transceiver.

which, for an estimated signal-to-noise ratio of about 10, gives a channel capacity $C \approx \delta f$.

In the current implementation of PAN (which represents data by frequency shift keying from 200 kHz to 250 kHz) the channel bandwidth is 50 kHz, giving an upper bound on the capacity of about 50 kbps.

AC power transmission

In ordinary wired circuits, power is distributed as a difference in electrical potential between two circuit nodes. Such power supply nodes are usually optimized to behave as ideal DC voltage sources, with good current compliance (low Thévenin impedance) and vanishingly small AC components.

By the same token, the distinction between power and data signals is often one of current compliance. If a circuit requires only a small amount of current to run, then it is possible by careful design to obtain that current from the data signals coming into the circuit.

Municipal networks distribute electrical power as an alternating current at a voltage much higher than what ultimately appears at your wall socket, to reduce the ohmic losses inherent in long-distance transmission and to facilitate the transformation from higher to lower voltages (or vice-versa) using inductive devices. The frequency of alternation is also regulated to provide a simple timing reference for motors, clocks, and video signals. Finally, to generate DC power from the AC power available at a wall socket, a power supply must rectify, filter, and regulate the AC signal by some means [HH90].

When AC power appears at a single-phase wall socket, it is as the difference in electrical potential (or voltage) between the "hot" and "neutral" leads. By convention, current is said to flow from higher to lower potentials, and the available power is simply the product of the potential difference and the amount of current flow. This somewhat pedantic explanation underscores the fact that power transmission relies upon the flow of current across a potential difference.

Displacement current

So far we have looked at AC power distribution over wires. Before considering wireless AC power distribution, we need a bit of the theory of electromagnetic energy propagation.

In examining Maxwell's equations, we note that $\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$ is Ampere's law as modified by Maxwell, where $\vec{J}$ represents an actual current (density) and $\partial_t \vec{D}$ represents a so-called *displacement current*.

This displacement current is very real: when alternating current flows through the terminals of a capacitor, there is an equal displacement current "flowing" between its plates. The same is true of extended capacitors formed by the electrostatic coupling between surfaces in the PAN geometry.

Intrabody power

A capacitor's impedance at a given frequency is inversely proportional to both its capacitance and the frequency of interest. For example, at 1.0 MHz, a 10 pF series capacitance presents an impedance of approximately 16 kΩ. If a 30 V_{rms} source drives a matched load through this capacitance, it can deliver 56 mW of power to the load. Note that this power will be dissipated in the load, not the conductors which form the backbone of the circuit.

As a proof of the principle, we have built a small remotely powered system that can fit in a shoe. It powers up when the user makes contact with an electrode such as a doorknob, at which point it uses part of its harvested energy to send serial data in Morse code and other formats by flashing an LED.

The subject in Figure 1 is actually standing on an intrabody power receiver much like the ones used in the demonstration units. The differences are in various engineering issues:

- **Full-wave *vs.* half-wave rectification**: one can go further and use voltage doublers and triplers [HH90] and so forth.
- **Active rectification**: This requires a hybrid approach, and resembles the design of switching power supplies, which must "bootstrap" their control circuitry from an uncoditioned AC line.
- **Other choices of tuned circuit**: Besides LC resonators, we have had success with other tuned elements, including ceramic and quartz resonators. These have inherent Q-factors of 10^3 and 10^4 respectively, but require active tuning of the power supply to acheive good coupling.

We are beginning to experiment with supply-side loading-mode measurements as well as PAN transmission of received power estimates, in order to close the control loop and build smart supplies which deliver constant power to devices as their coupling changes.

Efficiency

Under reasonable conditions, an available power of 200 mW at 1.0 MHz applied at one hand leads to the recovery of about 20 mW of rectified, filtered DC power at one foot. This figure of 10% roughly reflects the proportion of the body's electrostatic coupling available at one foot in the presence of an electrode.

At the time of this writing we are working to power a PAN transmitter from intrabody power. This is not so much a matter of having available power as it is one of duplexing the channel between power and data transmissions.

How this differs from radio

Both PAN and PAP are near-field phenomena. In the near field, electrostatic field strength decays as the cube of distance from the source, while power radiated to the far field falls off as the square of distance from the source. Furthermore, the geometry of PAN and PAP does not a good antenna make, so power stays in the near field and out of FCC Part 15 regulations.

Our model also makes explicit the necessity for symmetry breaking in order to achieve a differential coupling to the body and to the environment (the ground return path, as it were).

Conclusions

The promise of such techniques is readily illustrated in many contexts:

- **In personal applications**: Credit and debit cards may be replaced by a shoe- or pocket-based e-wallet.
- **In business settings**: Cryptography in the shoe will make electronic signatures commonplace. Brokers will be able to trade stocks more quickly, reliably, and authentifiably, by sealing deals with a handshake.
- **In a hospital**: Every interaction between staff members and patients can be logged in a passively-powered bracelet, removing the uncertainty and expense of paper-based audit trails.

In our model of these phenomena, the body is a node of comparatively low impedance (internally, of order 100Ω) to which circuits capacitively couple. This low internal impedance admits very little ohmic dissipation. We consider this safe, especially when compared to personal microwave communication devices which operate at tens of mW at 2.4 GHz, a band in which energy is readily absorbed by water molecules and turned into heat. Nonetheless, we are performing a survey of regulations and safety issues which may apply to the use of PAP.

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References

[Ham86] Richard W. Hamming. *Coding and Information Theory.* Prentice-Hall, 1986.

[HH90] Paul Horowitz and Winfield Hill. *The Art of Electronics.* Cambridge, 1990.

[Mic96] *Microchip PIC16/17 Microcontroller Data Book*, 1996. http://www.microchip.com.

[Sta96] Thad Starner. Human-powered wearable computing. *IBM Systems Journal*, 35(3):??, 1996.

[Zim96] Thomas G. Zimmerman. Personal area networks: Near-field intrabody communication. *IBM Systems Journal*, 35(3):609–617, 1996.