Combining Capacitive Coupling with Conductive Clothes: Towards Resource-Efficient Wearable Communication

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ABSTRACT

Traditional intra-body communication approaches mostly rely on either fixed cable joints embedded in clothing, or on wireless radio transmission that tends to reach beyond the body. Situated between these approaches is body-coupled communication, a promising yet less-explored method that transmits information across the user's skin. We propose a novel body-coupled communication approach that simplifies the physical layer of data transmission via capacitive coupling between wearable systems with conductive fabrics: This layer provides a stable reference potential for the feedback path in proximity to the attached wearables on the human body, to cancel the erratic dependency on the environmental ground, and to increase the communications' reliability. Evaluation of our prototype shows significant increases in signal quality, due to reduced attenuation and noise. Requirements on hardware and, subsequently, energy consumption, cost, and implementation effort are reduced as well.

Author Keywords

Body-Coupled Communication; Capacitive Coupling

ACM Classification Keywords

J.9.e Wearable computers and body area networks

INTRODUCTION

Current research efforts in body area networks use mostly radio communication, which tends to consume more energy and impedes battery-powered long-term operation due to high carrier frequencies, users' motion, and shadowing effects. In some cases, conductive wires woven into textile send information between body-worn units, though these suffer from less flexible cable joints. In [15], an alternative transmission approach has been investigated that uses the human body as a medium: *Body-coupled communication* considers body tissue as part of a transmission channel to interface between wearable devices. Such transmissions were shown to be promising for their energy-efficiency due to the reduced distribution volume, as well as less susceptible to eavesdropping.

Recent research in body-coupled communication continued to investigate *capacitive coupling*, where signals are transmitted and received using a pair of vertically configured electrodes: A signal electrode close to the skin that couples to the body, and a feedback electrode that provides a return path through the wearer's environment. By varying the potential of the signal electrode, the transmitter modulates the weak electric field of the body and induces a slight *displacement current*. Resulting variations of the electric field can then be detected at the receiver's side by measuring the tiny current flowing between the electrodes. This closing of the channel circuit through the environment's *common ground* has on several occasions been identified as an issue: While the transmission behavior of human tissue is adequate and predictable, the *feedback path* through the *environment* provides a stronger and highly varying attenuation, whose average is roughly in the order of $-60\,\mathrm{dB}$ [8]. As a result, communication tends to work reliably only when the modules' individual ground electrodes have an adequate return path.

Figure 1. Our body-coupled communication approach uses the human body as a transmission medium for the signal path, with a nearby conductive fabric for a robust feedback path, between wearable units.

We propose a body-coupled communication approach, which assumes the presence of *conductive clothing* nearby the wearable units, to reduce the channel attenuation and improve the signal-to-noise ratio. Its contributions are threefold:

- We introduce a minimal, *open-source* body-coupled communication module that benefits from lower energy requirements compared to wireless communication, while being robust to environment fluctuations by assuming that the user wears conductive textile nearby the units.
- Designed and evaluated for this module, a novel communication setup based on *pulse-width modulation* is presented, implemented on a low-power microcontroller, showing acceptable and robust data rates for up to $200\,\mathrm{kbps}$, applying *single-pulse symbols* at a center frequency of $250\,\mathrm{kHz}$.
- We evaluate the feasibility and the basic properties of such a setup with prototypes on the lower arm, which tends to suffer most from unreliable grounding and movement.

RELATED WORK

Several recent surveys [1, 3, 4] have summarized the current research challenges in the field of body area networks and intra-body communication. Wireless radio communication remains the most popular technique and is used in nearly every research, as well as commercial entertainment and healthcare products. This fact is mostly due to a considerable amount of fully developed, standardized, small, and low-priced modules. However, the energy efficiency of radio communication is still an issue, and having the human body in

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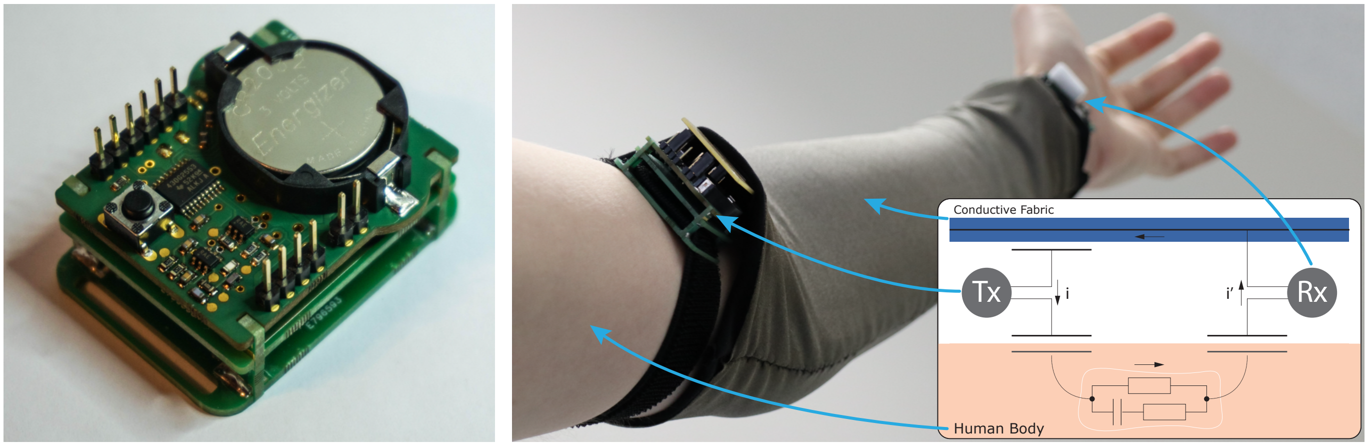

Figure 2. Our prototypes (close-up: left) communicate by capacitive coupling: The signal path goes via the wearer's body and the feedback path via nearby conductive textile layer (right). Induced displacement current i at the transmitter *Tx* and the much weaker counterpart i' at the receiver *Rx*.

immediate vicinity of the tranceivers tends to pose challenges due to shadowing and motion [1].

Google's project *Jacquard* is treading another route and utilizes *conductive threads* for wired communication of embedded electronics [12]. The wiring within the clothing is washable and comfortable to wear, but the individual and fixed signal and supply lines of the distributed components are inflexible in positioning. More flexibility can be achieved by two separated conductive layers within the clothing which the nodes are connected to via special pins [14].

Since all wearables are nearby the human skin, its use as a communication medium can reduce the energy requirements significantly. Initially triggered by [15], the *IEEE 802.15.6* working group for wireless body area networks *WBAN* considered *body-coupled communication* already in 2009 as the next communication standard for ultra-low power and secure *intra-body communication*. In contrast to radio transmission, the signals are induced into the user's bounded body and not radiated omnidirectionally into the large medium air. Although several different physical principles are known today, most research efforts have focused on the original idea of *capacitive coupling* [4, 6]. Due to the *high-pass characteristic* and partial resonance of the human body, the most suitable *frequency range* is reported to be $100\,\mathrm{kHz}$ to $50\,\mathrm{MHz}$. Thus, it demands only for baseband processing and no high-freuqnecy front end is needed which usually requires most power budget of radio communication [2, 9].

So far, high data rates of up to $2\,\mathrm{MBit/s}$ at $0.2\,\mathrm{mW}$ [13] or $80\,\mathrm{MBit/s}$ at $8.9\,\mathrm{mW}$ [5] have been achieved. In those approaches even the reference electrodes, necessary to close the transmission circuit, have been neglected. Thus, the established capacities, spanned between local ground potential and environment, get even more tiny. The already delicate return path, the *bottle neck* of the whole channel, is more affected and the desired signal tends to be much weaker. Consequently, a much higher effort of the signal's modulation, boosting, filtering, amplification, and demodulation is necessary to, nevertheless, enable this data rate.

Instead, systems such as the ones implemented in [7, 10] or the commercial *BodyCom* [11] by Microchip solve the issue of the delicate feedback path by providing a large ground plane in the vicinity. Due to the improved *direct coupling*, the prototypes can be kept simple and there is no need of complex circuits. The signals are directly generated by a microcontroller pin and the signal detection, amplification, and demodulation is either done by a simple transimpedance amplifier and the microcontroller in [7, 10] or an off-the-shelf *RFID* receiver chip in [11]. However, the large ground planes, needed for these solutions, make them challenging to adopt for more generic intra-body communication.

SYSTEM DESIGN

This paper's design adds a *conductive clothing* layer to provide a stable ground potential in vicinity of the wearable transceiver units that are attached to the user's body. The usual capacitive coupling channel setup is thus simplified by replacing the environment with conductive fabric. As a result, the received signal amplitude and quality are increased, and the corresponding analog circuits can be simplified while also the coupler dimensions can be scaled down. Figure 2 shows the experimental setup at the arm, with two modules communicating via the tissues between wrist and upper arm, utilizing an insulated conductive textile sleeve as return path. Conductive texiles can be incorporated in regular clothing, and conductive *fabrics* come with additional properties such as elasticity, and are washable, as well as antibacterial due to the used metal coating of the threads. A stable potential of the common ground is provided by only one single module, for example the central base station or *gateway module* which relays the measurements to an external device such as a computer or smartphone. The conductive connection can be realized by a conductive hook-and-loop fastener, a snap fastener, or just a simple contact area. A small and even resistive connection is sufficient due to the tiny flowing *displacement currents* whose voltage drop is negligible. For all additional wearable units, there is no need of a conductive connection, as these couple capacitively to both the human tissues and the reference layer. Due to the principle of capacitive coupling, the presence of additional isolators between the electrodes and the corresponding medium is possible.

Hardware Design. Due to the significantly reduced channel attenuation, we could reduce the complexity of the analog front end of the receiver part, but also remove the LC tank circuit to boost the signal amplitude. This way, the transceiver mainly consists of a microcontroller as the central unit that

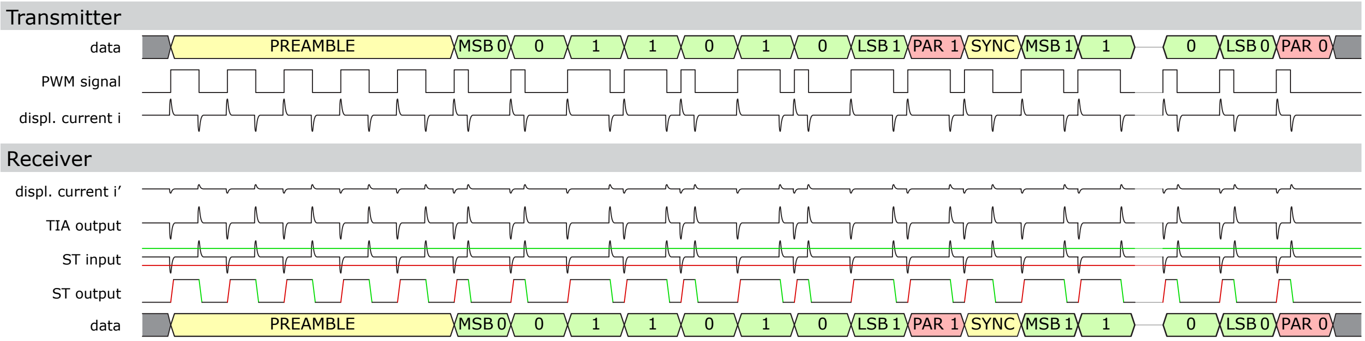

Figure 3. Communication with the stepwise transfer of information from the transmitter to the receiver. Top: Signal modulation at the transmitter and the resulting displacement current i in the body. Bottom: The weak displacement current i’ among the receiver electrodes, detection, amplification and filtering at the transimpedance amplifier (TIA), reconstruction at the Schmitt trigger (ST), with hysteresis of a threshold for rising and falling edges.

modulates and demodulates the signals in software. The prototypes, shown in Figure 2, are based on the low-power microcontroller *MSP430G2553* and the operational amplifier *OPA320S* for the analog receiver front end. The power is supplied by a 3 V coin cell. To link conductively or to couple capacitively to the fabric, a header including either a short pin or an electrode is attached on top of the basic module.

In *transmitter* mode, the microcontroller modulates the electric field by switching the signal electrode’s potential directly with a single output pin. As Figure 3 illustrates, the resulting signal form is a rectangular wave. The pin driver already enables abrupt edges that are crucial for the transmission principle and result in *significant peaks* of the displacement current. Due to the negligible load of the tiny electrode capacitance, no external driver stage is necessary.

In *receiver* mode, the transmit pin is switched to input, so that the resulting high-Z input impedance does not impede the signal. The displacement current that flows between the electrodes, induced by the varying electric field of the body, is then transformed into a voltage signal using a transimpedance amplifier. To enable the measurement of both the positive and negative peaks, the operating point is set to half the supply voltage by a buffered voltage divider. The frequency response is adjusted with an additional capacitor in the input line to suppress low frequencies in order of mains supply. The circuit behaves as an active, first-order inverting band-pass filter. The more robust voltage signal is then forwarded to a Schmitt trigger circuit that reconstructs the original rectangular pulse wave per detection of the positive and negative peaks.

Modulation and Demodulation. While in our approach most of the noise is shielded by the conductive textile, that acts as a *Faraday cage*, traditional modulation schemes have to use large symbols and extensive techniques to be robust against such noise induced by the surroundings. Our modulation scheme, in contrast, is based on [10] at which a *pulse-width modulation PWM* scheme has been introduced to represent the binary values by the two duty cycles 25 % and 75 %. Due to the channel’s *high-pass* characteristic, the signal’s DC part gets lost, but the information is still present in the zero-crossings. Then, the recovered pulse wave is low-pass filtered to extract the information by sampling the analog mean. Due to the analog filter’s slow response, several pulses of the same duty cycle have to represent each symbol and binary value.

In our adaption, we improve this inefficiency by applying a *digital demodulation* technique that direcly extracts the information from the duty cycles: The microcontroller’s internal timer captures the elapsed time to calculate the pulse width and stores the measures in a ring buffer. Afterwards, those are converted into the corresponding binary values within the main routine. We introduce a third duty cycle of 50 % to enable calibration and byte synchronization. As Figure 3 illustrates, the preamble consists of numerous pulses to define a reference value. Each bit is represented by a singular pulse of a 25 % or 75 % duty cycle and every byte, followed by a parity bit, is again separated by a 50 % pulse. This one, as well as the preamble of several 50 % pulses, is used to synchronize the bit stream and to recalibrate the bit interpretation.

EVALUATION

Several experiments have been executed to enable the evaluation of our approach and to determine its *advantages*. While the transmitter is not crucial, the receiver consists of two critical parts that limit the maximum performance: The analog input stage with its certain transmission behavior and the microcontroller that is hosting the demodulation routine.

Analog Input Stage. The input circuit shows sufficient performance to process center frequencies up to 1 MHz while suppressing noise and DC disturbances. The small slew rate of the low-power operational amplifier (10 V/µs) chamfers the abrupt slopes and narrows the rectangular pulses considerably, depicted in Figure 4, which no longer shape a trapezoid but a wedge with lowered amplitude. Thus, the output of the Schmitt trigger is not ideal, but the threshold of the microcontroller input is low enough to cope with that. The widths of the recovered pulses is specifiable and the actual 50 % reference value is recalibrated continuously. In case of weak coupling, in Figure 5, the current peaks are too flat, too close to the thresholds, and pulse recovery is unsuccessful.

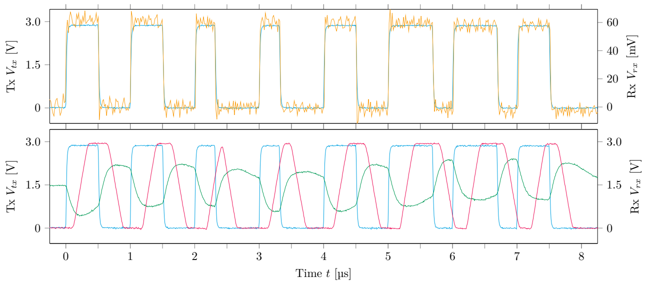

Figure 4. Survey of direct coupling signal electrodes without air gap. Battery-powered transmitter and receiver, notebook-battery-powered oscilloscope for data logging, separated potentials. Original 1 MHz, 3 V transmitter signal (blue), received 60 mV signal (yellow), transimpedance amplifier output (green), Schmitt trigger output (red).

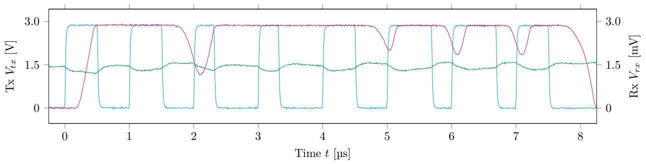

Figure 5. Weak coupling, air gap of about 3 cm, insufficient signal amplitude after transimpedance amplifier (green). Thresholds reached too late to raise or sink output punctually with available slew rate of operational amplifier. Only insufficient notches or completely ignored pulses.

Digital Demodulation. The maximum clock of 16 MHz defines the *resolution* of the pulse width capturing. Thus, the captured values are small compared to the register size, the ratio of deviation to pulse width is gaining, as well as jitter and noise get an increasing impact. Consequently, the demodulation performance is limited, illustrated in Figure 6. Above a center frequency of 250 kHz the *Nyquist-Shannon* sampling theorem is violated and the measures tend to be incorrect.

Transmission Range. Due to the absence of advanced circuits, the prototype enables only naive *near-field coupling*. Thus, placing two modules close to each other at a distance of about 0.5 cm, a wireless link can be established through air. With common ground even a wider range of 10 cm is possible. Attaching the modules' signal electrodes additionally to the *human body* enables to easily detect the 1.85 V signals beyond the entire body, but without shared ground, the range is limited to 3 cm. Applying the conductive fabric instead, the signal's amplitude is only 190 mV, but the range is extended and enables distance-independent communication over at least 30 cm, solely limited by the sleeve's length.

Energy Consumption. The energy consumption has been measured for a reference signal of 250 kHz with 50 % duty cycle, either been generated or demodulated. In transmitter mode (8 MHz clock) this resulted in an average consumption of 2.5 mA (7.6 mW) and in receiver mode (16 MHz clock and enabled analog front end) in 6.3 mA (18.9 mW).

CONCLUSIONS

We presented a novel approach for *body-coupled communication* between wearables, where data can be sent reliably across the user's body using *capacitive coupling*. Our approach utilizes an additional layer of *conductive clothing* to extend the range of *near-field coupling* by providing a stable reference potential and reliable, nearby feedback path that results in a lower channel attenuation and a negligible noise level. The implementation effort of the tranceiver modules is lowered significantly, since neither LC resonator circuits to boost the transmitter's amplitude, nor complex filters to extract data from a noisy signal are needed.

A prototype for such data transmissions has been presented and evaluated for communication between wrist and upper arm. The utilized *PWM* scheme is based on three duty cycles to not only represent the binary values, but also to continuously *recalibrate* the symbols, and to *synchronize* the bit stream of up to 200 kbps at 250 kHz. Evaluation shows that our approach is feasible and especially suited for applications in which motion- or biophysical sensor nodes are placed on the body surface. The reception (18.9 mW) consumes more energy than transmission (7.6 mW), caused by the higher clock frequency of the microcontroller and the dissipative analog front end. Due to obligatory conductive fabric layer, our design suits especially applications that utilize any kind of functional clothing, vest, or all-in-one suit.

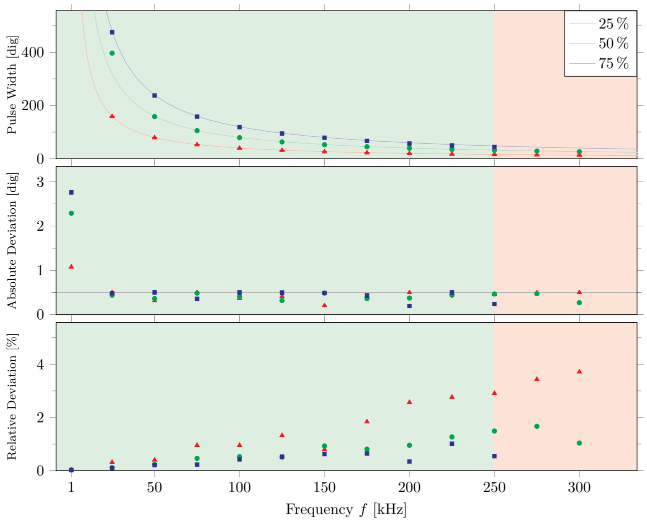

Figure 6. Captured pulse widths and deviation of duty cycles 25 %, 50 %, 75 % (red, green, blue), and center frequency 1 kHz to 300 kHz. Green area: Successful and reliable pulse width measurement. Red area: Eratic. Top: Timer values (ideal curve blurred). Middle: Absolute standard deviation, converging to 0.5 of quantization noise. Bottom: Relative standard deviation in % (desired pulse vs. actual measure).

To facilitate reproduction of our approach, we have open-sourced our design and provide both the hardware and software files at: `http://ubicomp.eti.uni-siegen.de`

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