CASPER: Capacitive Serendipitous Power Transfer for Through-Body Charging of Multiple Wearable Devices

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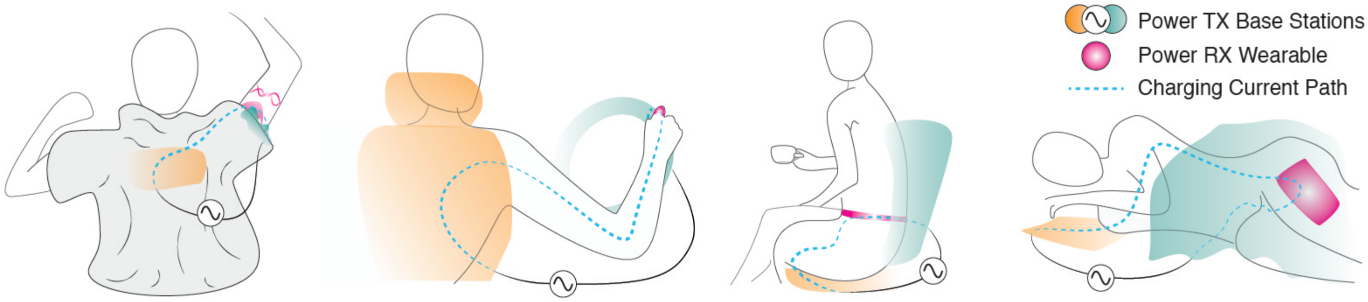

Figure 1. The CASPER charging solution enables wearable devices to charge serendipitously throughout the day by instrumenting clothing and furniture that a person frequently use to capacitively charge through the user's body.

ABSTRACT

We present CASPER, a charging solution to enable a future of wearable devices that are much more distributed on the body. Instead of having to charge every device we want to adorn our bodies with, may it be distributed health sensors or digital jewelry, we can instead augment everyday objects such as beds, seats, and frequently worn clothing to provide convenient charging base stations that will charge devices on our body serendipitously as we go about our day. Our system works by treating the human body as a conductor and capacitively charging devices worn on the body whenever a well coupled electrical path is created during natural use of everyday objects. In this paper, we performed an extensive parameter characterization for through-body power transfer and based on our empirical findings, we present a design trade-off visualization to aid designers looking to integrate our system. Furthermore, we demonstrate how we utilized this design process in the development of our own smart bandage device and a LED adorned temporary tattoo that charges at hundreds of micro-watts using our system.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Capacitive On-body Charging; Power Transfer; Wearables

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INTRODUCTION

Wearable devices are one of the next frontiers in ubiquitous computing systems. The current ecosystem of wearable devices concentrate on function packed, single point devices such as watches and glasses. More recently, a new class of wearable devices in the space of accessories, such as rings, necklaces, jackets, and even temporary tattoos, is emerging. This move towards distribution of smart devices across the body holds great promise for an augmented human experience. We open up opportunities like direct on-body health sensing across more than just a few set positions on the body and digitally augmented aesthetic accessories such as tattoos and jewelery. However, what comes with an entire ecosystem of these on-body electronics is the burden of having to keep them charged in order for them to function.

The challenge with charging wearable devices compared with charging most electronics such as appliances, computers, and even mobile phones is that wearable devices lose their functionality when they are being charged. Our vision is one where anything we wear can have smarts built-in to enrich their functionality without the cost of the user treating it as another electronic device that requires charging. We propose CASPER (standing for **Ca**pacitive **S**erendipitous **P**ow**er**), which is a charging solution for wearable devices that charges capacitively through the wearer's body when they come into contact with power transmitters embedded into furnitures and garments. In this way, the user only needs to keep a few common items plugged-in or charged to deliver power to everything else they want to wear. Our system's 13.56MHz transmitter can be integrated strategically into a user's favorite jacket, car, seat at the coffee shop, and in bed. As the user goes about their day and come into contact with these power transmitters, the wearable devices on their body serendipitously gets

*these authors contributed equally to this work charged. These power transmitting devices slowly tops-off all the device worn on the body to keep them functioning without the user having to think about charging each individual device. They just have to wear them. In this paper, we provide the electronic implementation of our through-body charging solution and a thorough characterization of the factors that affect charging speed. We provide a visualization of the design trade-offs to help designers qualitatively assess whether their end-application can be well supported by our system and potential adjustments that can be made to improve power transfer efficiency. Finally, we demonstrate how we used our own design process to bring two wearable concepts to life with our charging system. Our empirical findings show that our system's charging performance is enough to power a wound monitoring gauze pad for an entire day(at 305μW) and light up more than 10 LEDs bright enough to be observed in a dimly lit environment (at 248μW).

Contribution

1. Design and implementation of a through-body capacitive charging circuit that can support both short-term and long-term energy storage.
2. Characterization of through-body capacitive charging of skin-worn devices, which we distill into a design guideline for developers who want to use our system. Prior work has only demonstrated characterization of capacitive communication properties.
3. Demonstrate use of the design guide in multiple applications and provide realistic power transfer characteristics and corresponding utility for end application.

RELATED WORK

Ultra-wearable Devices

The target use case of CASPER is to enable trickle charging of wearable devices without the need to take them off. In particular, we are interested in enabling ultra-wearable form factors such as finger nail devices [2, 5], temporary tattoos [12, 6], clothing [8], and others in the space of beauty technology [11]. In much of our use case designs, we draw heavily from these prior work to help us come up with compelling form factors and applications to motivate our technology. Our contribution focuses on informing how CASPER's charging capability can enable certain scenarios through choices of sensors, displays, electrode shapes/positioning/material, and power management for functionality.

Capacitive Coupled Body Area Networks

Our work relates closely with capacitive coupled body area networks (BAN), which are adhoc networks established when devices connect to each other via a capacitive coupling link through the human body, a concept that was originally proposed by Zimmerman in 1995[13]. However, the work in BAN focuses on body channel communication and does not explore power transfer through the same channel. Nevertheless, the work in BAN is highly relevant to the underlying physical phenomenon our work relies on, which is capacitive coupling of AC signals over the human body. Our work specifically draws from BAN characterizations of human body's electrical permeability in the MHz range [10] and common ground dependence of capacitively coupled devices [3]. The work by Takahashi et al. informs our use of 13.56MHz as our transmitter frequency given the high permeability of the human body at this frequency. Grosse-Puppendahl's review of the importance of grounding in signal strength quality is extremely relevant for our power transferring use case.

Wireless Power Transfer

Conceptually, the capacitive coupling scenario of our system is most similar to the receive mode as described by Grosse-Puppendahl et al's Finding Common Ground [3], where the power receiver is coupled directly to the skin of the user and is loosely coupled with the transmitter through a common ground. In this configuration, our system also draws on similar concepts as power harvesting of 50/60 Hz AC electric field [1] where the receiver wraps around the AC power line and uses earth ground as a return path. In this configuration, any location along the powerline is emitting an electric field and thus by placing the receiver on any part of the powerline, with sufficient coupling to earth ground, a current will be drawn through the harvesting circuitry. In our system, the body acts like the powerline excited by the transmitter allowing the receiver to be placed anywhere on the body as long as there is a common ground in close proximity. Because of safety concerns of direct earth ground coupling to the human body, as any short in the system could potentially drive a dangerous amount of current through the person, our transmitter must be ground isolated, leaving it poorly coupled to environment ground. We address this issue by introducing a return path electrode embedded strategically in the transmitting furniture or clothing, resulting in a loosely coupled version of the bi-polar electrode setup in [4]. In this way, compared to Jegadeesan et al's method where both electrodes of the transmitter and receiver have to be aligned, we only need to loosely align one electrode while one electrode is coupled to the body.

CASPER HARDWARE DESIGN

Capacitive Charging

Near field AC coupling can occur either inductively using coils or capacitively using electrodes. Inductive charging tends to be more efficient than capacitive charging, but requires either a well-aligned coil in the case of Near-Field-Communication (NFC) or resonant coil designs, which typically cannot be deformed, which limits the design and wearability for wearable devices. For capacitive charging, a completed electrical path is created between a transmitter (TX) and receiver (RX) using two pairs of capacitively coupled electrodes that can be deformed and does not need to be of a specific shape. In our system (Figure 2), the transmitter (TX) and receiver (RX) both places an electrode on the body,we will call these body electrodes, which creates a capacitive link through the user's body as the dielectric. They each have another electrode facing away from the user, we will call these floating electrodes, which couples to each other through air as the dielectric. In this configuration, the electrical path is completed as follows: The TX body electrode » user's body » RX body electrode » RX power receiving circuit » RX floating electrode » air » TX floating electrode. Although the body electrodes are well

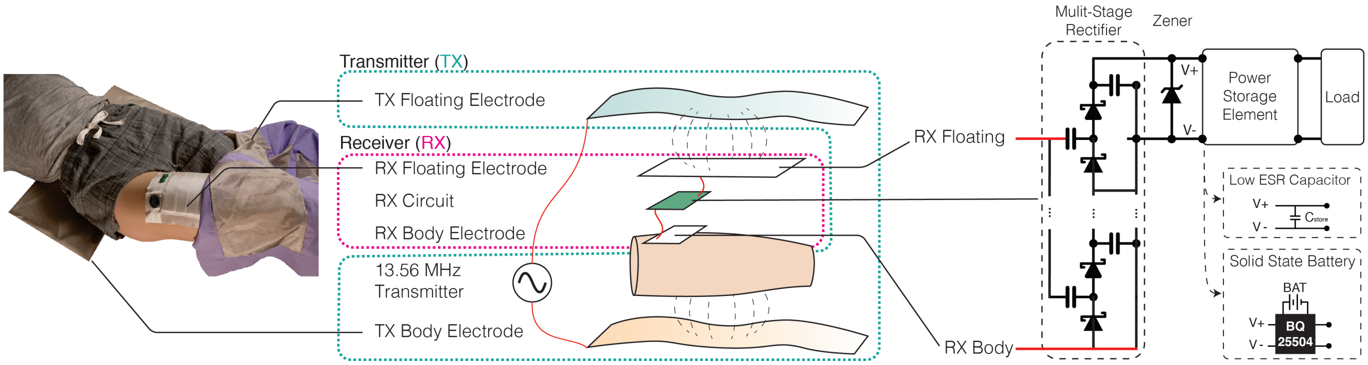

Figure 2. (Left) Prototype of a CASPER powered wound monitoring gauze pad worn on the user's leg. The bed sheet acts as the body electrode, while the blanket acts as the floating electrode. (Right) The RX floating and body electrode feeds the 13.56MHz coupled signal into a multi-stage diode rectifier network for AC to DC conversion. A Zener diode prevents the power storage from over-voltage. Depending on the application, the power storage can be a simple capacitor or a solid state battery with a BQ25504 charge controller. A load can then be run from the stored DC power.

coupled because the body is a poor dielectric, the floating electrodes may be poorly coupled because air is a good dielectric. If the floating electrodes are far apart, our system cannot induce a current through the receiver. In this paper, we characterize the various parameters that affect power transfer such as electrode designs and relative positioning of electrodes.

Power Transmitter

Our transmitter consists of an off-the-shelf 13.56MHz (5V @50mW) sine wave generator (FG-3020)[1], powered by an AC power bank. We found the average through body amperage to be 2mA, which is safe by ICNIRP standards [7]. The two ends of the transmitter are connected to sheets of conductive fabric (Safety Silk)[2] rated for <1Ω per inch^2. We found that it is important that the fabric has low resistivity. One sheet (TX body electrode) is positioned such that the user's body will come into contact, for example a bed sheet. The second sheet (TX floating electrode) is placed strategically in a location where the device worn on the body is likely in contact with, for example, the blanket. In this way, both the body and floating electrodes can have good coupling to promote current flow between the transmitter and receiver. The transmitter operates with AC, thus each electrode can act as either the body or the floating electrode. The key is that these two electrodes not be shorted, that one electrode is better coupled to the body, and that one electrode is close to the receiver.

Power Receiver

Body Electrode and Floating Electrode

To receive the transmitted power, the receiver also has a body electrode (RX body electrode) and a floating electrode (RX floating electrode). The RX body electrode is adhered directly to the skin using either conductive gel similar to that used for ECG electrodes or conductive gold leaf material, which couples well to the skin without gel. The receiver floating electrode faces away from the body. The size and construction of the electrode depends on the application, and in the following section on parameter characterization, we demonstrate extensive exploration of how varying the RX floating electrode can affect power throughput. The size of the RX body electrode has little effect on the power as it is directly coupled to the body using conductive gel.

Diode Rectifier Network

To convert the 13.56MHz signal to DC voltage to charge our power storage element, we used a standard rectifier diode network, similar to the RFID power harvesting design of the WISP by Sample et al [9]. We chose the BAT64-04W[3] diode with low leakage current of 2 μA at 30 V, 320 mV forward voltage drop and 4 pF capacitance at 1MHz. The design of the rectifier network can also be adjusted to perform voltage multiplication by increasing rectification stages. In the case of directly charging a capacitor, the output voltage from the rectifier network needs to reach the voltage to be used by the application, which is typically above 3.3V. We tested multiple stages of diode and found that in almost all conditions, a 8-stage rectifier network achieved a minimum voltage of 3.3V. Doing voltage step-ups, however, trades current for voltage. In the case where the power storage element is a battery, a charge management system will perform boost conversion internally, in which case, a 2-stage rectifier is used.

Power Storage Element

The storage element most suited for our system are storage capacitors or solid-state batteries. Capacitors are ideal for applications that need bursts of power whenever the user interfaces with a base station. To best optimize charging efficiency, we chose capacitors with low equivalent series resistance (ESR) and DC leakage (DCL). For our testing, we used the AVX TAJD477K006RNJ[4] capacitor having voltage rating of 6 V, 28 μA DCL, and 0.4 Ω ESR. Solid-state batteries are much higher density and can carry about 1000x the charge in the same footprint, which makes it ideal for more continued power delivery throughout the day. Furthermore, solid-state batteries are better alternatives to the common Lithium-ion polymer batteries for applications that involve direct body attachment as they do not rely on toxic chemical construction which could potentially burst under stress. Our system uses the BQ25504

[1]https://www.tequipment.net/GME/FG-3020/
[2]https://lessemf.com/fabric1.html

[3]https://www.mouser.com/datasheet/2/196/bat64series_2014-86090.pdf
[4]http://datasheets.avx.com/TAJ.pdf

Electrode Size		Electrode Insulation		Vertical Distance		Body Placement	
2"x 8"	514 ± 25	1"/4	611 ± 4	Short	899 ± 3	Thigh	718 ± 28
2"x 4"	307 ± 63	1"/32	474 ± 23	1/12"	307 ± 63	Chest	662 ± 16
1"x 4"	116 ± 2	1"/64	307 ± 63	1/6"	83 ± 10	Upper arm	558 ± 51
1"x 1"	- *	1"/256	234 ± 36	1/4"	43 ± 24	Forearm	307 ± 63
Size Matching		**Electrode Separation**		**Horizontal Alignment**		**BMI**	
1x	396 ± 24	4"	451 ± 91	Covered	307 ± 63	31%	267 ± 25
2x	464 ± 52	2"	307 ± 63	1/2	254 ± 6	27%	282 ± 19
3x	307 ± 63	Edge	373 ± 11	1/4	207 ± 30	21%	307 ± 63
10x	146 ± 37	Covered	346 ± 35	Edge	75 ± 36	17%	211 ± 12

Table 1. Average Power in μW recorded under different scenarios. Detail for each parameter and interpretation of the results can be found in the Parameter Characterization section. *The 1"x 1" case did not reach 3.3V when covered by a cloth layer. However, when electrically shorted, the wattage was 770μW.

charge management chip [5] to regulate the charging voltage of the Cymbet CB050 solid-state battery[6], with a rated capacity of 55μAh at 3.8V. The decision on whether to use a capacitor or solid-state battery depends on the application.

PARAMETER CHARACTERIZATION

To better understand through-body charging, we tested the charging speeds using a variety of electrode designs and varied the situations that affect the distance and alignment of the receiver and transmitter electrodes. All human subject involvement were approved under our institution's IRB. We change one parameter at a time to quantify the relative effects of each situation. The default set of parameters is as follows:

RX: 2"x 4" electrode made of copper worn on the forearm, insulated from the skin by 1"/256 Kapton, with body and floating electrode separation of 2".

TX: 13.56MHz at 5V. TX electrode made of Safety Silk conductive cloth. 10"x 10" TX body electrode placed on the seat. 4"x 6" TX floating electrode draped over the RX electrode with a long sleeve cotton shirt worn between them.

Subject: For all tests besides the body-mass-index (BMI) test, we used a subject of 21% BMI.

The charging rate was measured using a wireless, buffered, differential ADC connected to the 470μF capacitor being charged by the rectifier network. The wireless design is particularly important for proper characterization of the system because any connection to a external device will affect the coupling of the receiver and transmitter, thus invalidating our characterization. Our setup was built using the Tinyduino processor board, Tinyduino Bluetooth Classic RN42 board, TM7705 differential ADC board, single supply opamp buffer, and powered using a 150mAh battery. The average power transfered to the capacitor, C, in time t is calculated using Equation 1, where V_2 is 3.3 V and V_1 is 0 V.

$$P_{avg} = \frac{(V_2^2 - V_1^2) \times C}{2t} \quad (1)$$

[5]http://www.ti.com/product/BQ25504

[6]http://www.cymbet.com/pdfs/DS-72-01.pdf

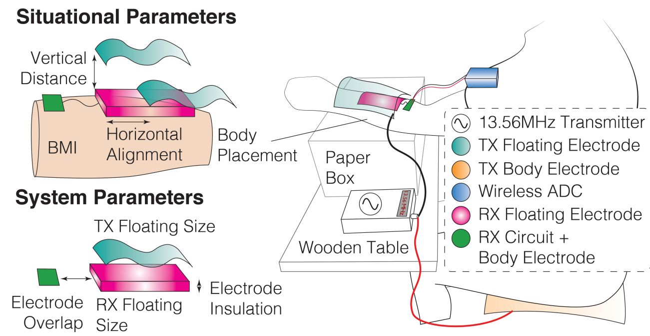

Figure 3. The parameter characterization was carried out with the receiver (copper electrode) and TX floating electrode (conductive cloth) placed on the forearm with the TX body electrode (conductive cloth) on the seat. A wireless buffered ADC was used to capture the charging rate.

Electrode Design

We identify the following parameters as having the most significant effect on charging speed: (a) size of RX floating electrode, (b) insulation between RX floating electrode and skin, (c) separation between the RX body and floating electrode, and (d) size matching of the TX and RX floating electrodes.

RX Floating Electrode Size

We tested four different electrode sizes: 1"x 1", 1"x 4", 2"x 4", and 2"x 8". We found that the larger the RX floating electrode, the better the coupling between the receiver and the transmitter. This in turn increased the power throughput because of the higher voltage potential across the capacitive charging circuit. In the 1"x 1" case, the voltage did not reach 3.3V, but when the RX electrode shorts with the TX electrode in this case, the power was comparable with the 2"x 4" shorted condition (Table 1: Electrode Size).

RX Floating Electrode Insulation to Skin

We used thin sheets of Kapton to test four different insulation thicknesses: 1/256", 1/64", 1/32", 1/4". Thicker insulations lead to less capacitive coupling of the RX floating electrode to the body, thus creating a higher voltage potential between the RX floating and body electrode. We observed that at an insulation of 1/4", the charging speed was almost triple that of the 1/256" insulation. (Table 1: Electrode Insulation).

RX Body and Floating Electrode Separation
We adjusted the separation distance between the RX body electrode and the floating electrode as follows: completely overlapped (covered), side by side (edge), two inches apart (2"), and four inches apart (4"). We found that the charging speeds for smaller separation distances were similar. The 4" separation creates the highest average throughput (Table 1: Electrode Separation).

Floating Electrode Size Matching
We tested four TX floating electrode sizes as compared to the RX floating electrode size: 1x, 2x, 3x, 10x. At smaller ratios, the charging speeds were comparable. This is caused by a balance between the surface area of the coupling electrodes and the surface area of the TX floating electrode and the body. With the larger TX floating electrode, more coupling to the body occurs, creating parallel electrical paths. This reduces the current that goes through the receiver. This is particularly noticeable with the largest TX floating electrode (10x) (Table 1: Size Matching).

Situational Effects

Depending on the situation, the coupling of the receiver and transmitter changes. We identify the following factors to have considerable effect: (a) vertical distance between TX floating and RX floating electrodes, (b) horizontal alignment of RX floating electrode by the TX floating electrode, (c) body placement of the receiver, (d) body-mass-index (BMI).

Vertical Distance between TX and RX Floating Electrodes
We varied the height between the TX floating electrode and the RX floating electrode using layers of cotton cloth: direct contact of the two ground electrodes resulting in an electrical short (short), 1/12", 1/6", and 1/4". The distance between the floating electrodes had the biggest effect on the capacitive power transfer. We found that the voltage potential drops exponentially and the system no longer charges to 3.3V past about 1/4" (Table 1: Vertical Distance).

Horizontal Alignment of RX Floating Electrodes by TX Floating Electrode
We aligned the TX floating electrode in four ways to change how much of the RX floating electrode was covered: fully covered, 1/2 covered, 1/4 covered, and not covered with edges aligned (edge). As the amount of alignment decreases, the power transfer is reduced. This is similar to varying the size of the TX floating electrode (Table 1: Horizontal Alignment).

Receiver Placement on the Body
We placed the receiver on various locations on the subject's body: forearm, upper arm, chest, and thigh. The power transfer increased as the receiver was placed closer to the center of the body. There are two effects at play. Because the TX body electrode in our experiment was placed on the seat, the closer the receiver was to the center of the body, the closer it was to the TX body electrode, which reduces the path loss. Furthermore, the cross section of the body part the RX is attached to impacts the impedance. The forearm's reduced power transfer is likely an effect of its smaller cross section. (Table 1: Body Placement).

Body-Mass-Index
We recruited 4 participants with varying BMI at 17%, 21%, 27%, and 31%, with BMI calculated as $weight(kg)/height(cm)^2$. We did not see a clear trend based on BMI, however, the charging speeds varied across individuals (Table1: BMI).

DESIGNING WITH CASPER

We distill our understanding of through-body charging into two opposing graphs that visualizes the factors that have the most significant negative and positive effects on charging speeds and power demands. These graphs show the axis that the designer can optimize and compromise on to best suit the end manifestation of the system. In the negative effects graph (Fig. 4: red) we include system wattage (Top: Wattage), continuity of power demand (Top Left: Power Continuity), body path length between body electrodes (Top Right: Path Length), vertical distance (Bottom Left: Distance) and horizontal misalignment (Bottom Right: Misalignment) of floating electrodes. In the positive effects (green) graph we include RX floating electrode size (Top: Rx Size), insulation to skin (Top Left: RX Insulation), separation from body electrode (Top Right: RX Separation), size similarity of TX and RX floating electrode (Bottom Left: TX Size Matching), and frequency of user contact with the transmitter (Bottom Right: TX Availability).

The goal of the graphs is to provide a visual guidance of the feasibility of using CASPER charging in the desired application. When designing a wearable device to be charged with CASPER, the first thing a designer will do is perform an initial assessment of the ideal manifestation of their end application. If the red area far outweighs the green, the charging throughput will likely be insufficient for reliable operation. The designer then decides which axis can be compromised and adjusted based on end application demands. As the designer iterates on their design, the visual guide continues to act as a reminder of which parameters can be tweaked and a reference for troubleshooting. In the following sections, we show how we used these parameter optimization to integrate CASPER into two different applications of health sensing and aesthetic skin augmentation devices to illustrate this process.

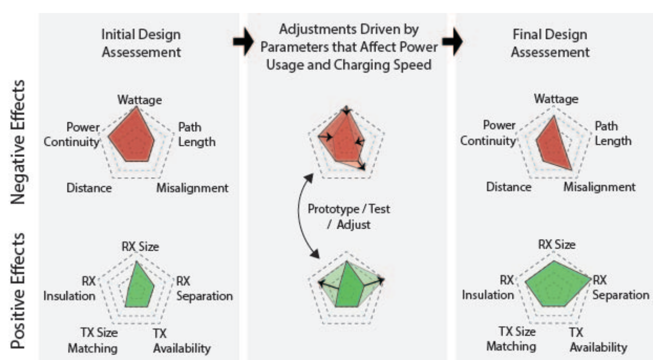

Figure 4. Designers first perform an initial assessment of their design's negative and positive impacts on charging. And then adjust their design to improve charging while maintaining application functionality by referencing the parameter axis. The final assessment helps visualize the system's charging capability.

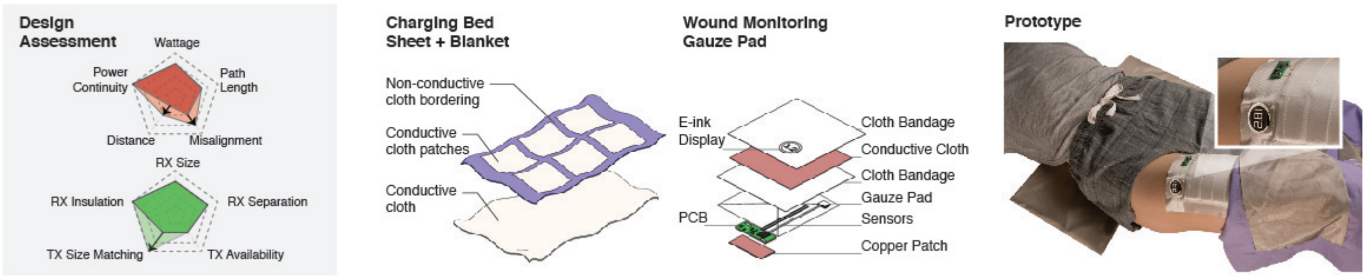

Figure 5. (Left) Dark areas show the initial design and the light areas show the adjusted design. (Center) CAD exploded view of the transmitter bed sheet+blanket design and receiver gauze pad with e-ink display and sensors. (Right) Prototype of the final system.

Distributed Physiological Sensors + Charging Bed

Current wearable health sensors revolve around single point trackers, but many physiological states cannot be achieved with these devices. We want to enable distributed physiological monitoring wearables that perform localized sensing. We explore a design of gauze pads that monitor the wound healing process and detect when to be changed. Bed sheets and blankets can then act as TX electrodes for charging each night.

Initial Assessment

Wattage: The monitor runs once an hour and displays the result. To perform the monitoring, the device utilizes a mutual capacitance sensor for wetness detection and optics based pH sensing for wound environment analysis. Our sensing system uses a 3.3V MSP430FR2633[7] (200μA active, 0.75μA sleep), with built-in mutual capacitance measurement (26μA), RGB photo emitter & detection pair (1.2mA), and a 34 pin e-ink display (20μA). Each measurement is set to take 33ms.

Power Continuity: Between each read, the sleep state of the MSP430FR2633 is rather low power. However, we expect the device to intermittently monitor throughout the day in active mode, leading to medium high power continuity.

Path Length: Placement will be anywhere on the body so the path length should be expected to vary from medium to far.

Distance: As the gauze pad often comes into direct contact with the blanket, the average distance will be low.

Misalignment: Again, with the blanket being bigger than the gauze pad, the horizontal misalignment will be low.

RX Size: The RX size is the size of the gauze pad, which will vary in size, but will likely be at least 3"x 3", which is average.

RX Insulation: The insulation is high because the conductive cloth will be above the gauze pad and cloth bandage.

RX Separation: The body electrode position is some what flexible, but the further it is, the larger the bandage as a whole will be. We used a 1" separation, which is average.

TX Size Matching: The blanket will be much larger than a gauze pad, leading to poor size matching.

TX Availability: Charging will be limited to at night. To provide power for the day, we incorporate the CB050 55μAh solid state battery with the BQ25504 charge management.

[7] http://www.ti.com/product/MSP430FR2633

Prototype, Test, and Adjust

The construction of the gauze pad involves a total of four layers: gauze pad to the skin, cloth bandage, conductive cloth for the RX floating electrode, and one more layer of cloth bandage at the top. We had initially used the conductive cloth as the outer most layer instead of having another cloth bandage, but found that the application of the gauze pad to be easier with the cloth bandage at the top most layer. This trades-off charging speed for ease of construction as it would be more ideal if the conductive cloth was at the top. We find that the insulation and size of the gauze pad, which we chose as a 4"x 4" pad with 6 cotton layers, provides a very good charging speed and needs no adjustment.

We constructed the charging bed sheet and blanket using the conductive cloth from lessemf. However, upon assessing our initial design, we recognized that the TX size mismatch is highly disadvantageous due to wasted coupling even though it makes horizontal coverage easy. A smaller floating TX electrode would be more sensible. But since we do not know where the gauze pad will be and the blanket will move around at night, horizontal alignment will be very poor if the patch is too small. We remedy this by using a number of smaller patches of conductive cloth bordered with non-conductive fabric. To gain the enhancement provided by the smaller patches, each patch is electrically isolated from the others during charging through time multiplexing.

Final Assessment

Our final assessment of the system rebalances the TX size mismatch and horizontal alignment to alleviate the issue of current loss through the body. We also trade-off minimum TX-RX distance by adding a cloth bandage for ease of construction. To fully assess whether the system is good enough, we performed a full charge sequence of an hour with our system in bed on one subject wearing the gauze pad on their upper thigh. The voltage of the battery was monitored every five minutes to check the charging rate. We found that the battery charged to 39μAh at an average rate of 305μW in 30 minutes. For our system to run a full day with a measurement every hour, it takes about 25μAh of our solid state battery. Based on this number, we find that despite increased distance, the system still charges at least 25μAh in the span of a night. Given that it takes about 30 minutes to charge the battery enough for a day's operation, the time multiplexing can be placed across at least 10 patches and still be enough to charge the battery in a 6-8 hour sleep time.

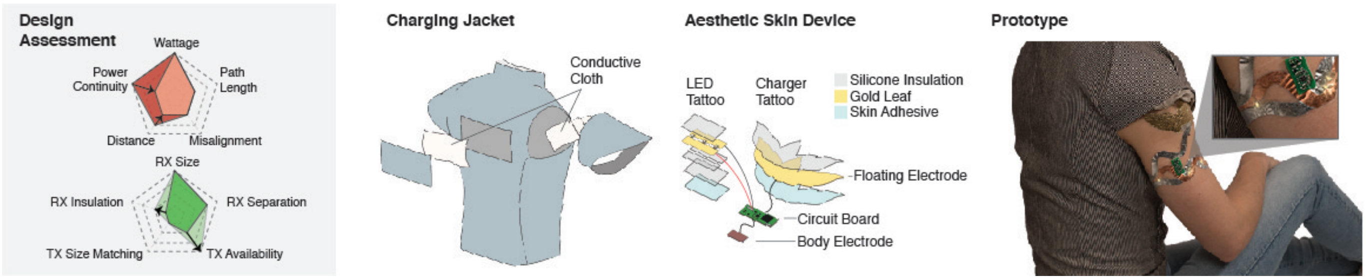

Figure 6. (Left) Dark areas show the initial design and the light areas show the adjusted design. (Center) CAD exploded view of the transmitter jacket design with the body electrode on the upper back + floating electrode on the sleeves and receiver tattoo for the floating electrode and the LED connected tattoo. (Right) Prototype of the CASPER enabled jacket+tattoo

Aesthetic Skin Devices + Charging Jacket

Temporary tattoos with electronics embedded can be made very wearable using tattoo paper and gold leaf layers[6]. Kao et al. demonstrated the use of NFC to perform deliberate charging of these devices. With CASPER, we can create temporary tattoo electronics that can be charged serendipitously without the visual constraint of a coil. We integrated through-body charging to a temporary tattoo accessory housing an array of LEDs worn as an arm ornament. Imagine the user is about to go out to an event and puts on the tattoo as an accent piece to their gown. Instead of worrying if the device is charged, the user puts on a stylish jacket to power the adornment on their body.

Conceptualization & Initial Assessment

Wattage: LEDs draw mA's at operating voltage, which is too high. However, when operated close to their turn-on voltage, for example 2.5V for a 3.3V white LED, they draw 10's of μA, which we achieved using a low loss μA 2.5V regulator. This limits the total number of LEDs that can be illuminated simultaneously.

Power Continuity: The power delivery is continuously in the 10 - 100's of μA depending on the number of LEDs.

Path Length: By placing the TX body electrode on the upper back of the jacket, path length is relatively short for placement for an arm band or in another design such as a necklace.

Distance: Jackets tend not to be tight so the distance may vary and is likely medium to high.

Misalignment: TX floating electrodes can line the cuff and collar, which is where accessories tend to be worn. Because jackets don't move drastically, misalignment will be low.

RX Size: RX size depends on aesthetic design, but can be made adjusted to be both visually appealing and relatively large. We used a patch of about 2"x 4".

RX Insulation: Insulation is thin for maximum wearability, but the gold leaf cannot touch the body. Our initial design applies the gold leaf to a single layer insulation.

RX Separation: Separation depends on aesthetics, but can be moved to improve charging.

TX Size Matching: We lined the cuff with the conductive cloth, which is about the same size as the RX electrode.

TX Availability: We want the jacket to not be needed for continuous operation of the device, so charging will only occur between the wearer putting on the jacket at home, and potentially leaving it in the car or coat check.

Prototype, Test, and Adjust

Our initial TX floating electrode lined the inner side of the cuff very closely, which made it very inconspicuous. However, because the jacket loosely wraps around the shoulder, the vertical distance was too high. We alleviated this by ruffling the conductive cuff to close the space, which significantly improved charging speed, while still maintaining the loose fitting nature of the jacket arms.

Our first iteration of the RX ground electrode tattoo exposed the gold leaf to provide direct coupling with the TX electrode cuff. But the gold leaf was too fragile and rubbed off easily, which resulted in the need to insulate it with a layer of thin silicone. We compensated for this loss in direct coupling by adding another layer of silicone insulation between the skin adhesive and gold leaf.

Our ideal system would not require the jacket to be worn all the time. However, we found that even at full charge, the 55μAh battery could only operate the LEDs at 2.5V for less than an hour. We did find that by reducing the brightness using current limiting resistors or turning them off intermittently, this duration can easily be extended. However, continuous power delivery for an entire evening may not be possible without the user keeping the jacket on as part of the outfit at least intermittently throughout the evening.

Final Assessment

Our iterative design process improved the charging speed by closing the vertical distance through the ruffled conductive cloth design, but reduced charging speed by adding a layer of silicone to protect the gold leaf. We tested our through-body charging LED tattoos on one user to determine the performance of the system. The device was worn on the upper arm with the floating electrode directly under the TX floating electrode on the sleeve opening. We found the battery charged to 33μAh at an average charging power of 248μW in 30 minutes. So with a half hour commute to an event, a user can have about 33μAh stored at 3.88V. This confirms that if the user wants a whole evening of LED adornment, the LED brightness will need to be dimmed or regulated to turn on only intermittently, or the jacket has to be part of the outfit.

DISCUSSION & CONCLUSION

System Limitations

To conform to human subject testing requirements under our IRB, our system on average delivers approximately 2mA through the body. According to the ICNIRP recommendation [7], human exposure to 13.56MHz current should be kept under 20mA to avoid painful shocks. For comparison, a typical body-composition measurement scale that uses bioimpedance measurement uses about 0.5mA at 50kHz. To keep the system safe for frequent use while delivering usable power for applications, our system operates in hundreds of microwatts. This aligns with our vision of frequent charging of many devices that each have their specific function and thus reduce individual power demands.

Study Limitations

Although we do not formally analyze the transfer efficiency, we estimate it to be about 1-9 %. This is based experiments showing an average power input of about 10 mW compared to the charging rate of 100-900 μW.

Our results are specific to the electrode design we chose and cannot be generalized to every design and any condition. As such, the design guide is meant for a qualitative analysis of the intended design and requires engagement from the developers to iterate on their own design to effectively utilize through-body charging. We believe that through our parameter-driven guide, most designs should achieve similar charging ratings in the hundreds of microwatts.

Envisioning a Wear It and Forget It Wearable Ecosystem

In this paper, we presented a characterization of through-body charging of on-body devices using both transmitters embedded in furniture and clothing. We envision that the ideal realization of our system is an ecosystem where there are a few common charging base stations embedded in common places such as the bed, in the car, in public spaces like cafes and libraries, and in specialized garments like the jacket previously mentioned. With enough of these base stations surrounding our life, we could one day put on multiple wearables, each having their own function, and charge as we go about the day. These devices get topped off serendipitously and simply function as an object that we put on, much like we would with an ear ring, bandage, hat, etc, but also perform digital functionalities, without the user having to worry about making sure it is charged. When you wear it, it will charge.

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