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Garment level power distribution for wearables using inductive power transfer

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Abstract— **Wearable and smart devices are gaining in popularity, with many users now using multiple devices. Each of these devices requires individual charging and power maintenance. This paper proposes power sharing between multiple wearables to alleviate some of the burden of charging multiple devices. To achieve wearable and smart device power sharing, we propose using the garments we wear as a power distribution backbone. To allow non-contact power transfer between garments, bi-directional inductive power transfer is used. We demonstrate a novel coil topology called Feed Coils constructed from flexible materials to aid garment integration and user comfort. Our system complies with international guidelines on time-varying magnetic field exposure to human tissue, allowing the system to be operated in close proximity to the body. Three preliminary experiments are conducted to characterize the bi-directional inductive power sharing system and to investigate the feasibility and human factors impacting wearable and smart device power sharing.**

Keywords—smart clothing; inductive power transfer; power sharing; wearable

I. INTRODUCTION

The recharging of our smart devices typically takes place at the device level. We charge each of our devices individually and the power stored in the device's battery is designed to maintain the function of this single device. We are now beginning to use and wear multiple smart devices, such as fitness trackers, smartwatches and smartphones. Each of these devices requires recharging and the individual attention of the user. In the case of fitness trackers when the device is removed from the body, for recharging, the device can no longer perform its intended function and the extra burden of recharging multiple devices can even lead to wearable device abandonment [1].

In this paper we propose power sharing between our multiple mobile devices and wearables. A mobile device whose battery carries significantly more capacity than a smaller device can be used to supply power to the smaller device, such as a smartphone to fitness tracker. The user can then recharge the larger capacity device, whilst prolonging the operational life of the smaller device in an effort to alleviate some of the charging burden placed on users from multiple on-body devices.

Traditionally on-body power distribution for wearables has been limited to having a power source on one garment [2] and power could not be distributed to other garments, without coupling the garments or user intervention to electrically join the garments. To overcome this limitation we propose using inductive power transfer between garments as a non-contact method of transferring power, whilst maintaining compliance with international guidelines on electromagnetic safety levels for human tissue. We propose leveraging the different garments we wear as a backbone for passing power between different parts of the body. The overlap between garments acts as a junction between the entry and exit coils of the inductive power transfer system.

To achieve between garment power transfer we propose a novel a coil architecture which facilitates power distribution. Additionally we use conductive fabric with the new coil architecture to allow for comfortable and flexible integration with existing clothing and form factors.

We use a bi-directional inductive power transfer circuit based on a LCL topology operating at 99 kHz to allow two way power exchange between smart devices. A serial communication protocol is modulated onto the 99 kHz carrier to allow information exchange between devices connected to the on-body power distribution network. Our laboratory bench tests show the garment power distribution system has a mean DC-DC efficiency of 39.210% over 3 hours transferring a mean power of 190mW to the smart device. In our exemplar scenario, a smart device is charged on the wrist from a removable power source placed in a user's jacket pocket, achieving a mean DC-DC efficiency of 25.555% and a mean power of 185mW delivered to the device over a 3 hour period.

Overall, this paper demonstrates the feasibility of sharing power between mobile and wearable devices. We demonstrate between-garment power sharing using inductive power transfer, a novel coil architecture and conduct preliminary experiments to assess the impact of human movement on the system.

II. FEED COIL ARCHITECTURE

Inductive power transfer was selected as an enabling technique for garment-level power sharing, due to the appealing nature of non-contact power transfer and the potential for high power transfer rates. Inductive power transfer to clothing has been proposed before [3], where energy was required by the garment itself. To realise power sharing on and between garments we considered using relay coils [4] or coupled resonators [5], as shown in Fig. 1. Relay coils propagate a time-varying magnetic field by using a tuned inductor and capacitor (LC) circuit at the incident frequency of the time-varying magnetic field. The induced current in the inductor by the incident time-varying magnetic field allows for a build-up of electric field in the capacitor of the LC circuit as the field starts to decay [6]. This interchange of energy stored in the electric field of the capacitor and in the magnetic field of the inductor allows the energy in the magnetic field to pass between relay coils, if strong coupling between the relay coils exists [4]. The coupling between relay coils is extremely sensitive to the distance between the coils and any movement between the coils can cause a significant drop in the amount of power delivered by this method. We envisaged using relay coils on the seams of garments to pass power around the garment and then at a predefined junction, such as the top of the trousers and bottom of a shirt, for between garment power transfer. Since the efficiency of power transferred by relay coils is extremely sensitive to the distance between the coils, any movement on the body could impact the power transfer; thus the technique was considered impractical for garment-level power transfer.

To remove the reliance on the distance between many relay coils we reconsidered the topology of the relay coil. By placing two relay coils in parallel we create the topology shown in Fig. 2 a), which we call the ‘feed’ coil.

A time-varying magnetic field incident at one relay coil, we denote as the entry coil, will store energy between the capacitors of both coils, which can be considered as one capacitance, C_t in Fig. 2 b), in accordance with (1). As the electric field decays in the capacitors a magnetic field of frequency equal to the incident magnetic field appears across both inductors, the entry and exit inductor, which can be considered as one lumped inductance in accordance with (2).

$$C_T = C_{ENT} + C_{EXIT} \quad (1)$$

$$L_T = L_{ENT} \,.\, L_{EXIT} \,.\, (L_{ENT} + L_{EXIT})^{-1} \quad (2)$$

Fig. 1. Initial relay coil prototype for garment based power transfer.

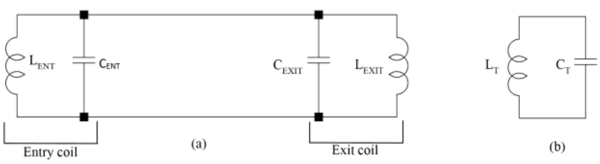

Fig. 2. a) Idealised electrical circuit diagram of the feed coil and b) the equivalent circuit.

To the best of our knowledge this is the first time relay coils have been joined together to create this topology and we call this arrangement a ‘Feed Coil’. Using the feed coil the energy from inductive power transfer systems’ transmit coil [3] and can effectively be moved over a distance, given by the connecting wires in Fig. 2 a) to a traditional receive coil [3] in a single feed coil system. The feed coil acts to reduce the multiple distance dependency of multiple relay coils, as the power transferred by the system is dependent only on entry and exit coil distances from the transmit coil and receive coil respectively, in a single feed coil system. Fig. 3 shows an early prototype feed coil constructed from rigid wire, measuring 320mm in length, and a flexible coil constructed from copper tape, measuring 634 mm.

The feed coils, shown in Fig. 3, were tuned to 99 kHz by constructing each half separately, including half of the connecting wires or connecting conductive fabric. A 22kΩ resistor was then placed in-line with a signal generator and an oscilloscope across the inductor. A frequency sweep around 99 kHz, *f*, was then performed and tuning capacitors added or taken away from the calculated capacitor value, *C*, from the measured inductance, *L*, given in (3), until a peak value was achieved at 99 kHz.

$$C = ((2.\pi.f)^2.\, L)^{-1} \quad (3)$$

Multiple feed coils can be cascaded together to bridge the boundaries between garments, though this significantly increases the complexity of the system and an appropriate distance between the coils must be established to achieve an acceptable coupling between entry and exit coils (in an analogous fashion to relay coils [4,5]). Multiple feed coils used to bridge the boundary between garments and create a non-contact power transfer method between garments are shown Fig. 4.

The circuit behaviour of a single feed coil can be analysed by considering the coupling between the transmit coil to feed coil, feed coil to receive coil and transmit coil to receive coil as demonstrated in [7]. When using multiple feed coils cascaded together the circuit behaviour can be evaluated using Equation 4 in [4].

In the remainder of the paper we examine the related literature to the feed coil and on-body garment power distribution, discuss international electromagnetic exposure limits for operation of an inductive power transfer system close to the body, present a circuit design and models supporting the design and conclude the paper with the results of our experimental tests involving the feed coil.

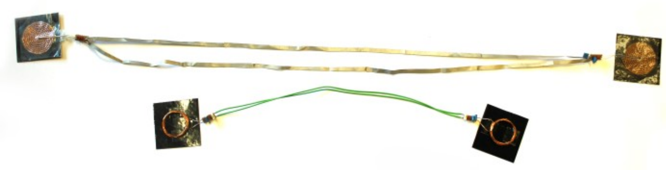

Fig. 3. Top: flexible form factor feed coil constructed from copper tape and Bottom: a prototype rigid 24 Standard Wire Gauge feed coil.

Fig. 4. Junction between two feed coils at the overlap of garments.

III. Prior art

Mobile smart devices and wearables are increasing in popularity [8]. However power is a contentious issue for some wearable users with frequent recharging placing an extra burden on the user and in some instances causing the user to abandon the device [1]. Energy harvesting techniques such as solar, thermoelectric and piezoelectric [9] aim to scavenge power from the local environment, though the energy produced in wearable form factors often falls short of smart device requirements with power-intensive displays or applications where continuous wireless communication connections are required. Energy transfer techniques such as inductive power transfer have been proposed to assist with powering electronics located on and around the body [3,10,11]. However each of these approaches suffers from the limitation of not being able distribute power around the body and the energy, in the form of a magnetic field, must be applied where required. Additionally, some systems proposing to body inductive power transfer do not consider guidelines on exposure to time-varying magnetic fields, an important aspect for protecting potential users.

Our work builds upon the work of Worgan et al. [10]. Worgan et al. propose using inductive power transfer from transmit coils within the ambient environment to receive coils at a specific location on the body. This technique allows for the passive recharging of on-body wearables. However there are several limitations including only providing power to one point on the body and that the user must be in close proximity to a transmit coil embedded in the environment for power transfer to occur. We extend this thinking with power sharing between smart devices, allowing magnetic energy to be picked up from a mobile device or wearable at one point on the body and redistributed to another device at another point on the body, using the garment as a backbone for power distribution, all whilst the user carries out their daily tasks and need not be aware of the interaction. Interest in smart garments and embedding electronics in clothing is growing in commercial interest, as highlighted by Google's Project Jacquard [12]. As in the paper by Worgan et al., our power distribution network complies with international guidelines on magnetic fields interacting with the body; the International Commission on Non-Ionizing Radiation Protection (ICNIRP) 1998 guidelines [13].

As an enabling technology for power sharing between body worn smart devices and wearables we select bi-directional inductive power transfer. Traditional inductive power transfer links typically operate in a one-way fashion, employing a dedicated transmit circuit and a receive circuit [3], each with a dedicated transmit and receive coil respectively. Bi-directional inductive power transfer circuits allow power to be received and sent by the same circuit and same coil [11,14]. Since we do not want to limit the directivity of power sharing between body worn devices, bi-directional inductive power transfer was selected as an enabling technology.

IV. Bi-directional Inductive power transfer circuit

The bi-directional inductive power transfer circuit used as the power transceiver enabling circuit for this project is shown in Fig. 5. The circuit is based upon a LCL inverter, as detailed in [14]. Two anti-phase square waves are fed into Input 1 and 2 respectively of the four inverter MOSFETs. The square wave was generated by an ATmega328P microprocessor from an Arduino Uno with a frequency of 99 kHz.

To allow the system to instigate and maintain a power sharing transaction between two devices, the circuit shown in Fig. 5, allows for the bi-directional serial communication at 9600 Baud. The serial data is modulated onto the 99 kHz power carrier and decoded using an envelope detector and a low pass filter. The serial communication flow diagram used for initiating and maintaining a power sharing interaction in the transmitter is shown in Fig. 6. The Arduino Uno used to generate the anti-phase square waves for Inputs 1 and 2, and is also used to send and receive serial communication across the system. When a device is placed in receiver mode, the software responds to a serial identify request and can terminate the transaction, for example if the battery is deemed to be fully charged. Additionally in receive mode, the gates of all the inverter MOSFETs are grounded. Fig. 6 shows the transmitter, which asks the receiver to identify itself every 1000 milliseconds during a power sharing interaction. This feature avoids the transmitter wasting power if the entry feed coil is misaligned with the transmit coil, such as when a garment twists or slips, and prevents magnetic field exposure to the tissue if the receive coil is misaligned with the exit part of the feed coil, see Fig. 10 for a cross-sectional view of the system. The next section will examine human tissue exposure to time-varying magnetic fields and how the garment level power sharing system complies with international guidelines on exposure.

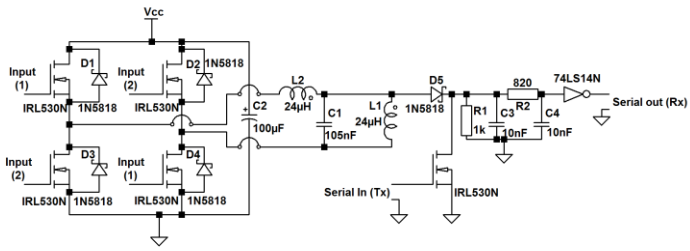

Fig. 5. Bi-directional inductive power transfer circuit diagram.

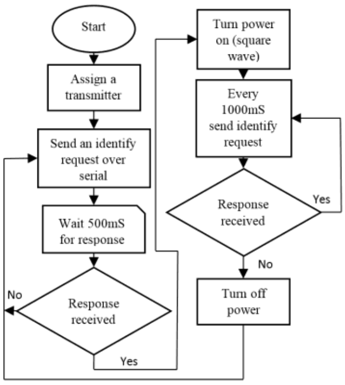

Fig. 6. Power sharing transmitter flow diagram.

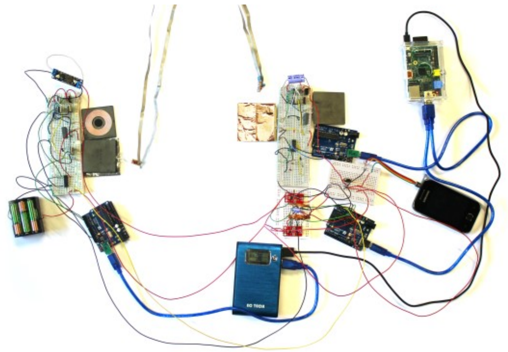

Fig. 7. Experimental setup of the power sharing system, with the transmitter on the left, feed coil connecting the two circuits and receive circuit on the right. Also on the right is the current sensing and data logging equipment.

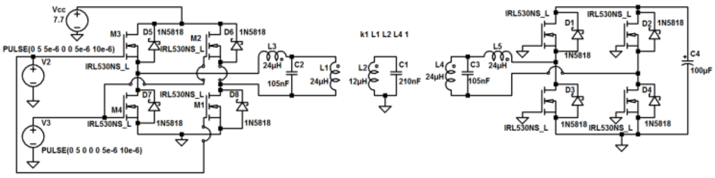

Fig. 8. Circuit diagram of entire power sharing system, with the transmitter on the left, feed coil in the middle and the receive circuit on the right.

V. Compliance with Non-Ionizing Radiation Protection Guidelines

Garment level power distribution using inductive power transfer has the potential to expose the tissue of the user to time-varying magnetic fields. Following from Maxwell's equations, a time-varying magnetic field in close proximity to a medium with a non-zero conductivity will induce an electric current in the medium [10], where these induced currents are often referred to as eddy currents. International guidelines exist to protect users exposed to time-varying electric, magnetic and electromagnetic fields. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) issue guidelines on exposure with the 1998 levels [13] acting as policy across the European Union [15]. For the power sharing system we comply with the ICNIRP 1998 basic restrictions for general public exposure, Table 4 in [13], the most stringent basic restrictions. An operating frequency of 99 kHz was selected for on-body power sharing for analogous reasons to Worgan et al. [10]; maximising the time-varying magnetic field to produce higher induced receive voltages in the receive coil, whilst remaining below 100 kHz. Above 100 kHz the ICNIRP 1998 basic restrictions require a current density measurement and specific absorption rate (SAR) measurement, with SAR typically obtained from specialist electromagnetic modelling software such as finite difference time domain methods. Below 100 kHz the ICNIRP 1998 basic restrictions require only a current density measurement, which can be practically inferred using a search coil and oscilloscope, as detailed in [10]. To facilitate reproducibility of our garment level power sharing approach, we opt to restrict our operating frequency to sub 100 kHz, where compliance can be practically inferred using common test and measurement equipment.

The ICNIRP 1998 basic restrictions call for the induced current density to be below 0.198 A/m^2 RMS at 99 kHz to ensure compliance. To check the power sharing circuit compliance with the ICNIRP 1998 basic restrictions the on-body power sharing circuit was physically constructed, see Fig. 7 and simulated in LTSpice, see Fig. 8. A supply voltage, Vcc in Fig. 5, of 7.7V was used to drive the designated transmit circuit. This supply voltage corresponded to a simulated transmit coil current of 395.26mA peak and a measured transmit coil current of 144.17mA peak, both with a coupling factor of 1 to the feed coil. The finite element method software package FEMM was used to ensure the simulated circuits compliance. The transmit coil was modelled as an 18 turn, 30mm diameter, 24 SWG coil to mimic the prototype coil seen in Fig. 3, with 0.279 A RMS (0.3953 A peak) in the transmit coil. The FEMM simulations indicated a maximum induced current density of 0.2025 A/m^2 RMS was present in human muscle tissue (with a conductivity of 0.362 S/m at 99 kHz [16]), exceeding the ICNIRP 1998 guideline limit of 0.198 A/m^2 RMS at 99 kHz.

Since with only the transmit coil present the maximum current density exceeded ICNIRP 1998 guidelines, shielding was added to the back of the coil. The shielding consisted of two ferrite sheets of 60mm × 60mm × 0.2mm with a relative permeability of 200 and copper tape of 60mm × 60mm × 0.1mm with conductivity 59.6×10^6 S/m, where the copper was placed closest to the body. Ferrite acts to provide a low reluctance path for the magnetic field and copper converts the magnetic energy which could reach the tissue into eddy currents, thus drastically reducing the energy reaching the tissue. The FEMM simulation was run again for the shielding arrangement, with the same electrical parameters, and the maximum induced current density was found to be 0.07522 A/m^2 RMS. The results of the simulation are shown in Fig. 9 and demonstrate a maximum induced current density of less than half the permitted value for ICNIRP 1998 compliance. For the equivalent physical setup, with the shielding in place, the maximum inferred current density at the back of the coil was measured as 3.0688×10^{-3} RMS A/m^2 using a search coil of 10 turns and 8mm diameter which gave a peak induced voltage of 284mV and converted to the inferred current density using the equations in [10]. The discrepancy between the FEMM simulation results and bench setup could be attributed to electrical losses in the MOSFET switching and the LCL tuning circuit. Additionally, the simulation assumes a perfect coupling between the feed coil and transmit and receive coils, which in practice will not be achievable even when the coils are coaxial due to losses in the air core transformer, such as resistance of the coil and flux leakage.

The 24µH coils used in the bi-directional power sharing circuit, L1 in Fig. 5 and shown in Fig. 7, use the windings from the TDK WT525225-20K2-A1-G 43mm diameter Qi coil. Since Qi operates between 110-205 kHz the coils are electrically suited to operating at 99 kHz and the availability of commercial components facilitates reproducibility of the power sharing system. The windings of the coils were placed in the centre of the 60mm × 60mm shielding. The overhang of shielding helps to prevent magnetic field interaction with tissue if a misalignment between the exit feed coil were to occur, due to garment movement, as depicted in Fig. 10.

An example use case for power sharing between mobile and wearable devices is shown in Fig. 11. The user is using a mobile phone in their jacket pocket to transfer power to their fitness tracker, worn on the wrist. As previously mentioned, movement between the mobile devices or in the garment can lead to misalignments between the transmit or receive device and the feed coil. The misalignments will impact the power transferred. In order to assess the impact of misalignments on the bi-directional inductive power transfer circuit, horizontal misalignments between the feed coil and transmit / receive coil were simulated and measured. The transmit coil and feed coil were horizontally misaligned from zero misalignment, or coaxial, to 10mm of misalignment in 2mm increments. The coupling factor for each misalignment increment between the feed entry coil and the transmit coil were obtained from physical inductance measurements [17], where five measurements of inductance at each increment were taken and then averaged. The resulting coupling factors were used to find the open circuit voltage in the designated receiver as both an LTSpice simulation, as shown in Fig. 8, and repeated on the bench, see Fig. 7. The results of the experiment are shown in

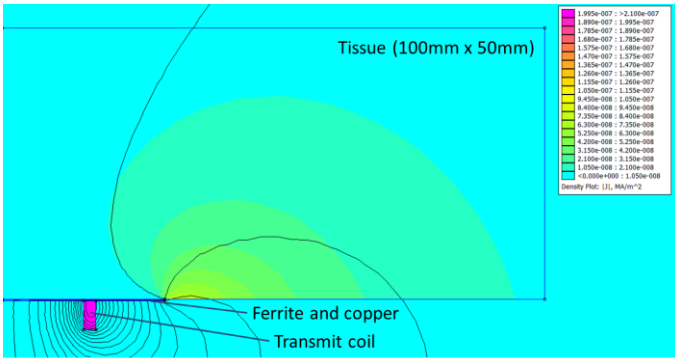

Fig. 9. FEMM model of transmit coil and shielding (ferrite and copper) demonstrating compliance with ICNIRP 1998 current density of less than 0.198 A/m^2 RMS at 99 kHz.

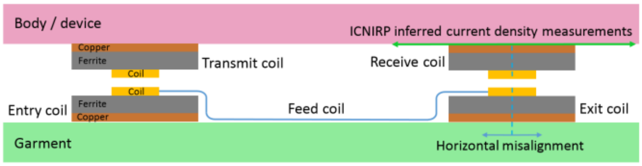

Fig. 10. Cross-section of power sharing system, indicating the horizontal misalignment, which can occur due to garment or device movement and ICNIRP inferred current density measurement line.

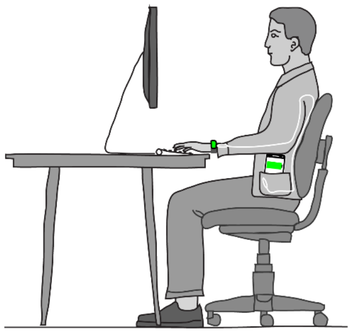

Fig. 11. Exemplar power sharing where a user is charging their wrist-worn fitness tracker from their mobile phone.

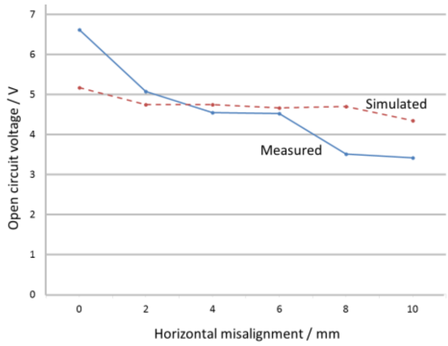

Fig. 12. Open circuit voltage at the receiver variation with horizontal misalignment of the feed coil across the designated transmit and receive coils.

Fig. 12 demonstrates the significant impact on the open circuit receive voltage for misalignments between the designated transmit or receive coils and the feed coil, which could be caused by garment movement. To mitigate the effect of a varying receive voltage a 5V output buck/boost converter based on the Texas Instruments TPS63061 was used at the output of the designated receive circuit.

VI. Power Sharing Experiments

Having established garment level power sharing by inductive power transfer can remain within ICNIRP 1998 guidelines for on-body use, we conducted three experiments to characterise and assess the feasibility of our proposed system. For the experiments, two bi-directional inductive power transfer circuits, shown in Fig. 5, were constructed in a mobile form factor, see Fig. 13.

Before the feed coil was used on the body the original feed coil, Fig. 3, constructed from 24 SWG wire with 18 turns was redesigned. The original feed coil is fixed into a cylinder using a coil adhesive. This rigidity helps to maintain a constant inductance of the coil but when placed on a garment could interfere with the body's natural movement, an important parameter for assessing the comfort and adoption of wearable technologies [18]. A new flexible spiral planar coil was produced from copper tape using a craft cutter, as shown in Fig. 3. The 9 turn spiral measures 43mm in diameter, matching the Qi coil dimensions used for the 24μH coil in Fig. 5, and comprises of 4 layers each insulated from each other by polymide tape, giving an approximate total coil profile of 0.51mm. With shielding the total flexible feed coil profile is 1.02mm, allowing for easy garment integration. A 90° deformation of coil and shielding changed the inductance from 30.32μH when planar to 32.38μH (6.8%), demonstrating a small inductance change over large deformations, and allowing the system to remain in resonance. The flexible feed coils are attached using Adafruit 1168 conductive fabric with a 5mm thickness, 634 mm length and a measured DC resistance of 2.7Ω. The flexible coil geometry was simulated in FEMM with the aforementioned shielding arrangement with a simulated maximum current density of 0.13001 A/m^2 RMS and a measured current density of 3.5472×10^{-3} A/m^2, both within ICNIRP 1998 basic restriction guidelines of 0.198 A/m^2.

A. Test 1: Bi-directional circuit characterisation

The first experiment consisted of characterising the bi-directional inductive power transfer circuit without a feed coil present. The transmit circuit was powered from 3 lots of 1.2V 2400 mAh Duracell® Recharge Ultra rechargeable NiMH batteries and used a Texas Instruments TPS55340 based switching regulator to provide the required 7.7V from the approximate 3.6V NiMH battery array. All batteries were fully charged using a mains based NiMH charger before the test. A Samsung Galaxy GT-S5360 smartphone was attached to the output of the designated receive circuit, via the 5V TPS63061 buck/boost converter, and a micro USB connector. Two ACS712LC 5A current sensors were used to output a voltage proportional to the current drawn from the battery array and current input to the smartphone. The input voltage from the NiMH battery pack, output voltage to the smartphone and two voltage based ACS712LC current sensors were sampled using an Arduino Uno at 10Hz. The data was read and stored in a CSV file from the Arduino Uno using a Python script running on a Raspberry Pi Model B powered from a 12000mAh 3.7V portable power pack, ensuring the test setup could be fully mobile. The Arduino's used for the 99 kHz square wave and serial communication were also powered from the power pack. The indicated battery state was logged during smartphone charging. The first experiment was carried out on the bench and run for a 3-hour duration. The results act as a baseline and set an upper bound of performance for the circuit. The results of the test are shown in Table 1. The battery started at an indicated 61% and ended at 77%.

B. Test 2: Feed coil characterisation

The second experiment consisted of repeating the first experiment, but this time placing the feed coil in a coaxial configuration with both the designated transmit and receive coil. This experiment was again run over a 3-hour duration on the bench and allowed the impact of the feed coil to be assessed. The results are shown in Table 1. The battery percentage indicated 67% at the start and ended at 81%.

Fig. 13. Participant wearing the on-body garment power sharing distribution system, transferring power from the designated transmitter in the jacket pocket to the smartphone based on the wrist.

Test	Input I / A	Output I/ A	Input P / W	Output P / W	Effici-ency / %	Total energy used / J	Total energy received / J
1	0.120	0.049	0.473	0.199	42.603	5158.044	2165.783
2	0.125	0.046	0.490	0.190	39.210	5316.769	2053.880
3	0.192	0.046	0.710	0.185	25.555	7793.941	2026.333

TABLE I. THE MEAN CURRENT (I), MEAN POWER (P), MEAN EFFICIENCY AND MEAN ENERGY USED OVER THE THREE HOUR DURATIONS OF EACH OF THE TESTS; WHERE TEST 1 ONLY USED TWO POWER SHARING CIRCUITS ON THE BENCH, TEST 2 USED A FEED COIL BETWEEN TWO POWER SHARING CIRCUITS ON THE BENCH AND TEST 3 USED A FEED COIL BETWEEN TWO POWER SHARING CIRCUITS ON A USER'S JACKET ON THE BODY.

C. Test 3: On-body garment power sharing

The third experiment consisted of placing the setup on a participant's body, with the designated transmit circuit placed in a jacket pocket, the feed coil going from the jacket pocket to the wrist and the designated receive circuit being placed on the participant's wrist, as depicted in Fig. 11 and shown in Fig. 13. The experiment was carried out over a 3-hour duration, so preliminary data on how user movement impacts power transfer could be assessed. The results of the experiment are shown in Table 1. The battery started at an indicated 59% and ended at 73%.

D. Results

The values given in Table 1 are comprised of the mean of 108,000 samples recorded over each 3 hour period. Table 1 highlights the variation in DC-DC efficiency of each of the experiments. With no feed coil present the system has a mean efficiency of 42.603%, using 5158.044J from the NiMH battery pack to transfer 2165.783J to the smartphone. The effect of inserting the feed coil coaxially between the designated transmit and receive coils can be observed in Test 2 by a DC-DC efficiency drop of 3.393% to 39.210% and using 5316.769J to deliver 2053.880J to the smartphone. As discussed previously in Section II, the feed coil introduces different reflective loads on the designated transmit and receive circuit, depending on the coupling between the coils, which is determined by the physical position of the feed coil relative to the designated transmit and receive coils. In Test 2 the feed coil introduced a loading on the transmit circuit, essentially requiring 158.725J (3.08%) more in the transmit circuit over Test 1 to deliver 111.903J (5.17%) less to the smartphone. When placing the feed coil on the body the DC-DC efficiency of the system drops to 25.555%, using 7793.941 J to transfer 2026.333J to the smartphone. One can see on comparison of Test 2 and Test 3 results, a similar amount of DC current and energy was delivered to the smartphone, only 27.547J less, however the transmit circuit has used 2477.172J (46.59%) more energy. This increase in energy use is owing to the variable nature of the on-body power sharing, where frequent disconnects cause an inrush of current in the designated transmit circuit when it is switched back on after a period of inactivity, which could be addressed by using soft start circuitry. The small difference in energy delivered to the smartphone between Test 3 and Test 1, 139.45J (6.44%), demonstrates the feasibility of power sharing between wearables and smart devices using the garment as a delivery system and acting to reduce the charging burden on the user by transferring significant amount of power to the receiving device. Furthermore, the indicated phone battery state changed by 16% in Test 1 and by 14% in Tests 2 and 3, again demonstrating the feasibility of our approach.

VII. Conclusions and Future Work

This paper has demonstrated garment-based power sharing between wearable devices in an effort to alleviate charging multipledevices separately. A novel coil architecture to achieve garment based power sharing was proposed and flexible form factor coils were developed to afford comfortable garment integration. We demonstrated the power sharing system complies with ICNIRP 1998 guidelines. The impact of human and garment movement has been experimentally quantified.

Further investigation into the human factors of wearable power sharing will enable a greater analysis of the technique and associated human factors. A smaller, integrated power sharing circuit would allow a long term deployment and evaluation of the technique. Efficiency improvements, such as reducing switching losses [19], to the bi-directional LCL circuit and improving the conductivity of the fabric used to connect the feed coil would reduce the power cost to the transmit device. Future work could explore multiple wearables devices on one garment power sharing network, allowing the user to select which devices are the transmitter and the receiver and investigating autonomous power sharing for balancing charge between wearables.

Acknowledgments

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