PowerShake: Power Transfer Interactions for Mobile Devices

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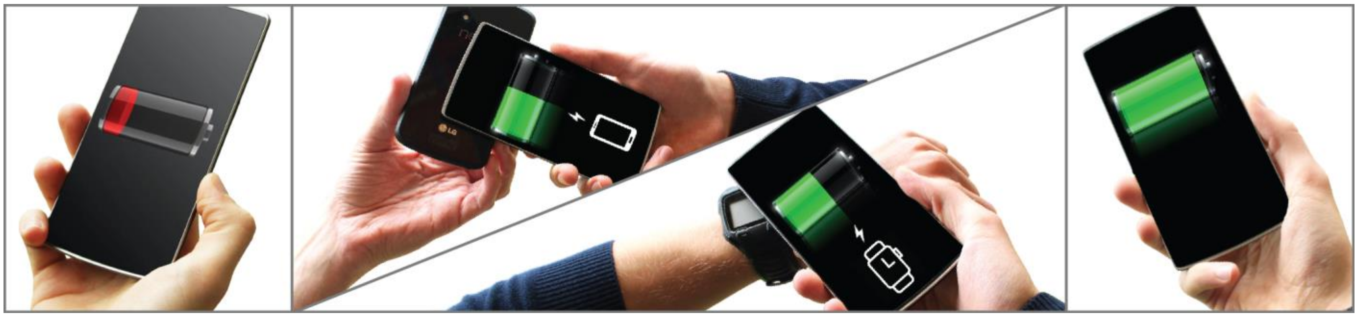

Figure 1. PowerShake enables power transfer interactions on mobile devices. In this envisioned example, as battery depletes (left), it can be transferred from other devices, such as your own watch or another's phone (center), allowing ongoing usage (right).

ABSTRACT

Current devices have limited battery life, typically lasting less than one day. This can lead to situations where critical tasks, such as making an emergency phone call, are not possible. Other devices, supporting different functionality, may have sufficient battery life to enable this task. We present PowerShake; an exploration of power as a shareable commodity between mobile (and wearable) devices. PowerShake enables users to control the balance of power levels in their own devices (intra-personal transactions) and to trade power with others (inter-personal transactions) according to their ongoing usage requirements.

This paper demonstrates Wireless Power Transfer (WPT) between mobile devices. PowerShake is: simple to perform on-the-go; supports ongoing/continuous tasks (transferring at ~3.1W); fits in a small form factor; and is compliant with electromagnetic safety guidelines while providing charging efficiency similar to other standards (48.2% vs. 51.2% in Qi). Based on our proposed technical implementation, we run a series of workshops to derive candidate designs for PowerShake enabled devices and interactions, and to bring to light the social implications of power as a tradable asset.

Author Keywords

Power Transfer Interactions; Safety Compliance;

INTRODUCTION

In the 2011 motion picture *In Time* [30], time has become the principle commodity. People wear their time as an observable balance on their wrists. When their balance runs out, the wearer dies. Thus, the population frantically hurries around to complete work and recharge their balance before it depletes. Although an extreme commentary on today's society, there are parallels between the temporal pressures of *In Time* and the battery pressures of today's widespread usage of mobile devices.

An increasing eco-system of wearables and mobile devices are available (e.g. smart-watches, smart glasses, GoPros, etc.), and eagerly adopted by more and more people. These devices support new functionality, complement other devices' capabilities (e.g. smartwatches extending smartphones) and act as portals to our digital life. Thus, users become increasingly used to and reliant on them.

However, mobile devices struggle to reconcile their increasing usage demands (e.g. email on-the-go, always-on camera, frequent web-searches) and capabilities (e.g. depth cameras, inter-device communication) with their battery lives. As such, many mobile devices last for only a day under moderate usage [22].

This issue has been highlighted by the research community. For example, Ferreira *et al.* [12, 13] analysed the charging habits of mobile phone users. Their work identified two key findings. Firstly, users are unable to predict the usage supported by their current battery state, resulting in battery anxiety. Secondly (and maybe as a consequence), a significant majority of users adopt opportunistic charging practices: with charging cycles of less than 30 minutes, topping up their battery levels on an ad hoc basis. IDC's ConsumerSpace 360 reports reflect this anxiety, with battery life as the most valued feature in existing smartphones [4, 8]. A survey of 1000+ participants released at CES this year reveals battery life is also the most demanded feature for future wearable devices [29].

Due to the vast range of different capabilities and form factors, we typically distribute our usage across several devices according to task requirements, ongoing simultaneous activities and environmental requirements. Thus, our devices' battery lives rarely deplete uniformly and we may find ourselves wanting to record our heartrate with no watch battery but (what would be) sufficient camera battery or needing to make a phone call, with no phone battery but near-full watch battery (for example).

So, although our individual devices have limited battery lives and we might not have access to charging facilities when needed, we very rarely find ourselves with no power across our multiple devices or in a group where no other person has power.

In this paper, we present PowerShake; power transfer interactions for mobile devices. PowerShake enables on-the-go, fast, Wireless Power Transfer (WPT) between mobile devices. This allows users to rebalance the power level of the devices they carry opportunistically, according to their current needs (e.g. recharging a smartwatch from a phone, as in Figure 1), and to trade power with other people. Power thus becomes another mobile commodity, subject to the same opportunities and social practices as other tradable goods.

This paper presents two main contributions. First, we revisit WPT from a new perspective, paying special attention to safety and mobile form factor. PowerShake prototypes ensure compliance with international electromagnetic exposure guidelines, allowing WPT to remain safe even for continuous usage or in close proximity to the body (e.g. charging whilst talking on a mobile phone). Our prototypes also present mobile form-factor WPT, including flexible coils (i.e. to integrate WPT in wearables, watch straps, etc.), reduced thickness (<1.5mm) and docking aids for usage on-the-go (e.g. charging a watch while walking). Across these constraints (safety and form-factor), PowerShake maintains high power transfer (~3.1W) sufficient to charge and support even power hungry tasks. Secondly, we explore power transfer interactions through a series of workshops, involving both designers and a broader audience. In the first workshop we explore different coil arrangements on mobile devices (phones and watches), reflecting on how this impacts WPT interactions (e.g. transfer power to our watch; share it with someone while he talks on the phone) and identifying relevant factors for the design of WPT devices. The second workshop allows us to reflect on the impact of this technology in our everyday lives and on the social considerations of power as a tradeable commodity.

RELATED WORK

Our work draws on related work in: mobile device battery usage; battery extension and charging techniques; and wireless power transfer.

Mobile battery usage

Understanding mobile power is an active research area during the last years, that indicates anxiety around battery life and opportunistic charging behaviors have increased through the years.

In 2007, Banerjee *et al*. [3] conducted a study of user charging habits for 56 laptop and 10 mobile phone users. Their results highlighted the large variations in user charging habits, including how users would often recharge their device when they still had high charge levels. In the same year, Rahmati *et al*. [33] identified different charging profiles; with half of the participants presenting opportunistic charging behaviors, even if their batteries were still not empty.

In 2013, (i.e. when mobile device's power demand and our dependence on them became arguably bigger), Ferreira *et al*. [13] found that, from 12 smartphone participants, all experienced a period of time where the device was without power, and most displayed opportunistic charging behaviours [12]. Dhir *et al*. [10] report similar battery life anxiety from a series of focus groups of 27 users in Alice, South Africa, with several participants experiencing significant frustration at running out of battery on their mobile phone and carrying around phone chargers to avoid this situation.

PowerShake draws on this trend in charging habits and the challenges of running out of power, providing an alternative technique to support opportunistic charging as a potential to alleviate users' anxiety around battery life.

Battery extension and charging techniques

Several approaches have appeared as a response to this increasing stress around battery life.

Efforts have been made to introduce intervention systems to help prolong smartphone battery life. Metri *et al*. [26] developed a mobile power management tool, reporting savings of up to 20% for video download and streaming on a mobile device. Metri *et al*. also report on a number of commercial applications available for mobile devices that serve to reduce power consumption. Jalal *et al*. [21] developed a system called MoBELearn to allow users to tailor content delivery in a learning environment and reduce battery consumption.

Beyond power management software and techniques, several commercial products have recently appeared to increase the raw amount of power available to the device. Power packs [32] have become a popular way of storing more power (at the expense of extra size and weight). Charging cables [25] can transfer power from one device to another, and mobile hand generators and solar cells [11] can produce limited amounts of power. These products require external hardware, which are not always to hand and suffer from standardization issues (for example, the incompatibility of Apple and Samsung charging cables). WPT has the ability to overcome these standardisation issues and the requirement for separate hardware, allowing for spontaneous power transfer.

Wireless Power Transfer

Most WPT approaches use the concept of inductive charging through electromagnetic resonant coils [23]. The transmitter and receiver each contain a coil and a band-pass filter (LC circuit) that make those circuits especially sensitive to a specific resonant frequency. This allows efficient transfers for close coil proximity, dropping quickly as distance increases [36].

Although the applications of WPT were traditionally limited (i.e. toothbrushes or surgical implants [6]), it has received increasing attention from mobile manufacturers in recent years. Two main wireless power standards exist in the commercial marketplace today; the merged Alliance for Wireless Power (A4WP) & Power Matters Alliance (PMA) standard [1] and the Wireless Power Consortium (WPC) Qi standard [38]. Support exists for both standards; IKEA recently launched a line of products embedding WPC's Qi chargers in their furniture [17] and Starbucks began including PMA chargers in their cafes in 2015 [35]. Additionally, Microsoft prototype wearables with built in Qi chargers, through a pair of wireless charging trousers [19, 27].

Experimental approaches allow unidirectional transfer over bigger distances. Magnetic MIMO [20] embeds an array of coils in a desk allowing for energy transfer while the user is sitting. Deyle and Reynolds [9] enclosed a charging element in a backpack allowing power transfer to devices carried inside. Zeine [40] patented a technique making use of a phased array of coils that allows charging a device over long distances (i.e. 100 feet), but with an overall transfer efficiency of 10%.

The concept of bidirectional WPT has gained increasing attention. Schuessler [34] describes a technique where a coil can be used to both charge and discharge devices. Mikkonen *et al*. [28] extend this approach, applying it to the fast prototyping of wireless wearable devices. Fulton Innovation presented eCoupled [31], a technology enabling bidirectional power transfer between mobile or wearable devices, and they also envision any surface in our home or work environments (e.g., meeting tables and kitchen furniture) acting as charging surfaces.

The approaches aim to satisfy the user's need for opportunistic and seamless charging, as a way to overcome the limited battery life of mobile and wearable devices. However, none of these approaches are intended to allow safe WPT while the devices are in close proximity or in contact with our skin. PowerShake enables WPT according to electromagnetic exposure regulations (ICNIRP'98 and IEEE C95.1-2005), even in these conditions, which are essential given our mobile and opportunistic usage scenarios.

POWERSHAKE – WEARABLE POWER TRANSFER

PowerShake enables the sharing and trading of power as a commodity between mobile devices. This allows a user to spontaneously control the balance of power levels in their own devices - *intra-personal transactions* - and transfer power with other users - *inter-personal transactions* - according to ongoing usage requirements.

This vision made us revisit the concepts behind WPT from a new perspective. Traditionally, the sending circuit is fixed in a static location [17, 35]. Also, commercial WPT standards, such as Qi, are mostly focused on allowing efficient transfers. In our case, depicted in Fig. 2, both sender and receiver become mobile. They can be integrated in wearables and mobile devices, and transfer might happen in close proximity to the body. As a result, safety and form factor (i.e. thickness, weight, bendability, etc.) become just as important as power throughput.

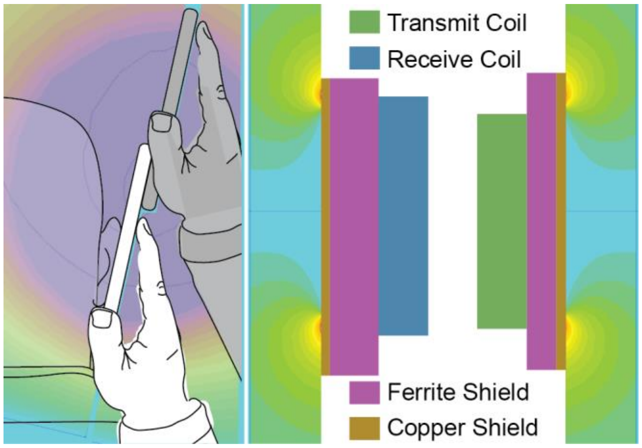

Figure 2. Left: PowerShake transfers can occur close to the body, such as during a call. EM radiation so close to the body could lead to health risks. Right: We add additional layer of shielding to the WPT coils, to reduce EM radiation entering the tissue, complying with safety regulations.

In the following sections, we explore the space determined by these three factors. We first describe our engineering technique (i.e. choice of frequency and transmit circuitry), which we use to demonstrate the feasibility of the power transfer envisioned. We then explore the trade-offs between power throughput, thickness and safety, gaining insight on its potential and limitations (e.g. power throughput achievable, efficiency, thicknesses, flexibility). These will help inform designers of the trade-offs they will need to consider when designing PowerShake-enabled devices.

Engineering safe power transfers

Time varying electromagnetic (EM) fields have known adverse health effects [18]. Many different metrics (e.g. Specific Absorption Rate – SAR – and current density) are currently used to assess EM field interactions with human tissue. However existing guidelines and regulations are not continuous and they characterize devices as either compliant with regulation or not, with specific thresholds and criteria that depend on frequency.

We chose to restrict our frequency to 97 kHz (sub 100 kHz) to allow other researchers to easily assess safety in their prototypes. At this frequency, both ICNIRP'98 [18] and IEEE C95.1-2005 [16] requires a current density measurement below 0.194A/m^2 Root Mean Squared (RMS) in tissue at 97kHz to ensure compliance (see basic restrictions in Table 4 of [18], we adopt the most conservative threshold for head and torso). This value of

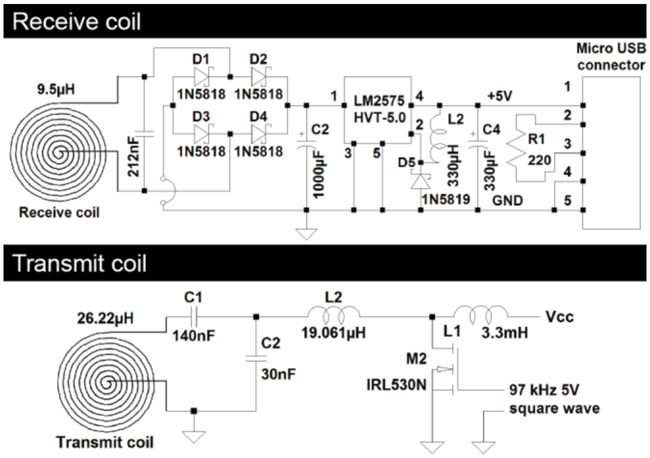

Figure 3: Asymmetric design of the receive (above) and transmit circuits (below).

current density can be easily inferred with an oscilloscope, as detailed in Worgan *et al.* [39]. If we had chosen a higher frequency (e.g. those used for Qi), SAR would also need to be measured, involving specialist modeling software [18].

To identify a viable approach for on-body WPT within safety levels, we created a model of a worst case scenario in FEMM (i.e. coils in contact with tissue). This revealed that, for a transfer similar to that of a Qi charger (at 175.1kHz where ICNIRP 1998 compliance calls for current densities in tissue < 0.3502A/m^2 RMS), tissue directly exposed to the coils would have a maximum current density of 6.497 A/m^2 RMS on the transmit coil side and 6.785 A/m^2 RMS on the receive side. We explored different techniques to include electromagnetic shielding to the back of our coils.

Firstly, we included a ferrite plate. Such plates are typically present in WPC chargers, to redirect magnetic flux and increase performance. However, this same effect would greatly decrease the amount of energy reaching the tissue behind the ferrite plate. We simulated FEMM models with increasing ferrite thicknesses. Although greatly decreased, current density still remained above 3.502A/m^2 RMS, even for thicknesses of 2 mm in the transmit side.

We modeled a Qi charging plate (2.4mm ferrite in the transmit and 0.2mm on the receive coil) as an example. Current density stays above the ICNIRP threshold behind the coil (i.e. in contact). Values do not comply with regulations until tissue is 69.3mm from the receive coil, leading to unusable form factors in a mobile context.

Thus, we also added a 0.1 mm layer of copper tape to the back of the ferrite shield, resulting in our proposed design in Figure 2, right. This copper layer transforms the remaining magnetic field through the ferrite into eddy currents within the copper, preventing the energy from reaching the tissue. The inclusion of this second copper layer allows compliance with ICNIRP with a thinner ferrite plate, but it also decreases the efficiency of the transfer (i.e. the energy is transformed into eddy currents).

Prototype circuitry

The design of our circuit (Figure 3) is simple and uses readily available electronic components, to facilitate reproducibility and encourage further exploration of the topic. We derived our design from the Qi standard, where different circuitry and coils are used to transmit and receive power [37]. The transmit circuit of our prototype uses a class E amplifier circuit, designed in accordance with the design equations given by Casanova *et al.* [7]. The receive circuit was designed in accordance with Figure A-7 in the Qi specifications [37].

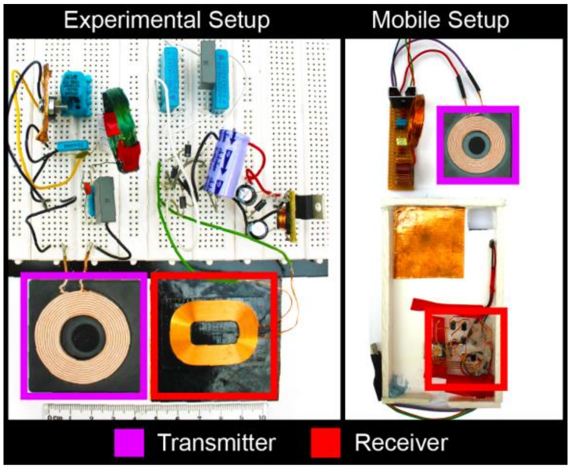

Figure 4. PowerShake electronic circuitry on breadboard (left) and in mobile form factor (right).

We used Qi coils in our own design, as they operate in a frequency range (110-210 kHz) similar to PowerShake, and their availability facilitates reproducibility of our experiments. We use a 44mm transmit coil (TDK WT525225-20K2-A1-G) and a 30mm receive coil (TDK WR483245-15F5-G). The asymmetric design (smaller receiver coil than transmit coil) increases system tolerance to lateral misalignment between the coils. This is a common technique for many WPT chargers, yet was considered especially important for PowerShake, as both the sender and the receiver are mobile, subject to use whilst walking or between different people. Any size of coil could be chosen provided they share similar electrical properties (in terms of coil current × coil turns ÷ coil area).

We implemented two prototypes circuits; a desktop, breadboard-based circuit, to support greater experimental accuracy in our benchtop studies, and a mobile circuit, through which to envision how PowerShake can be applied to mobile form factors (Figure 4). We tested various coil arrangements and shielding configurations as detailed in the following sections. Full schematics and assembly instructions are available on our webpage [5].

Exploring Throughput, Thickness and Safety

There are several elements that need to be considered when designing PowerShake devices. We describe them here, as well as their impact on throughput, thickness and safety.

Shielding the Transmit Coil:

As explained above, the proximity of the copper shield can have a significant effect on performance (i.e. eddy currents). Increasing the thickness of the ferrite plate helps to direct the field away from tissue behind the coil, aiding guideline compliance, but it increases the form factor of our WPT device. We performed a series of empirical measurements of power throughput and current density, varying the thickness of the ferrite plate on the transmit coil (Figure 2, right) from 0mm to 3mm (adding additional layers of 0.2mm, relative permeability of 230 at 97kHz). A 0.1mm layer of copper tape is used throughout. It is worth noting that changing the thickness of the ferrite plate affects the inductance of the coil. The circuit was re-tuned to 97kHz after each change, consistent with the circuit design equations given in [7]. We used the TDK WR483245-15F5-G receive coil, taking three measurements at each step.

Figure 5 shows the impact of thickness on power transfer and safety for a reference device (LG E610V smartphone). Performance is severely affected below 0.4mm, reaching a plateau at 0.8mm, with very little improvement thereafter. Current density falls within safety levels above 1 mm of ferrite shielding.

Shielding the Receive Coil:

Although a significant part of the EM field is turned into a current by the receiver, shielding is still necessary (and still impacts transfer). Similarly to our exploration of the transmit coil, we measured the power throughput and current density to the back of the receive coil, whilst increasing the thickness of the ferrite shielding. We increased the ferrite shielding on the receiver's side in steps of 0.2 mm with a last layer of 0.1mm of copper tape, as before. The transmit coil was kept constant throughout and included a 1mm ferrite plate and 0.1mm copper tape (i.e. optimum safe form factor from previous experiment).

Figure 5 shows the tradeoffs between performance, thickness and safety for the receive coil. Throughput is significantly affected by thickness, attaining maximum power transfer of 3.1W (0.62A at 5V) above 0.6mm. It also ensures ICNIRP compliance (with an inferred current density of 0.085A/m^2 RMS behind the transmit coil and 0.171A/m^2 RMS behind the receive coil).

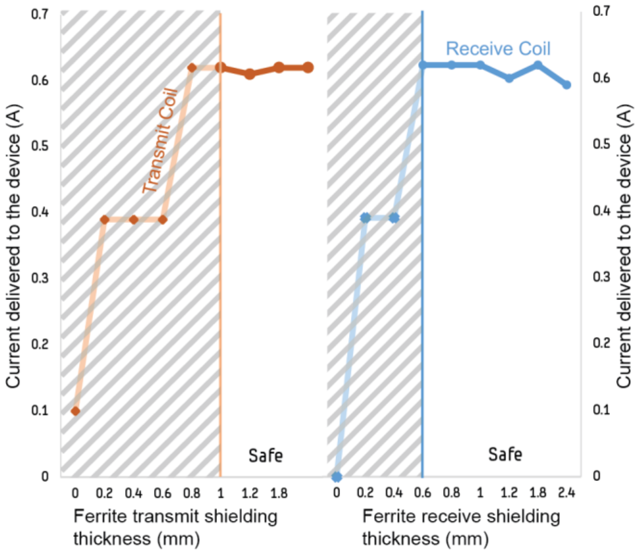

Figure 5. Impact of ferrite thickness on the power transfer for transmit (left) and receive (right) coils. Regions of non-safety compliance are indicated with grey lines.

As a baseline test, we compared this arrangement (safe shielding on both sides) with a commercially available GMYLE QI charging plate [15] and a DiGiYes MicroUSB Qi receiver [2], yielding similar results. With both coils coaxial, the Qi charger achieved a maximum DC current of 0.57A into the LG E610V with 51.2% DC-DC efficiency (but with a maximum induced current density of 6.12A/m^2 RMS for tissue by the receive coil). Our final shielded prototype (see below) has roughly similar performance (0.62A, 48.2% DC-DC efficiency, maximum induced current density of 0.171A/m^2 RMS behind the receive coil). At the same time, however, our design ensures easily-verifiable safety compliance.

Testing on Real Devices

The design proposed above allows for safe (ICNIRP 1998 compliant) power transfers, with a small form factor (1mm and 0.6mm shielding on the transmit and receive coils, respectively) and high power throughput (in-line with current commercial systems). However, in order to also test its ability to support the use cases envisioned (such as supporting ongoing calls), we tested our technique in a range of current mobile devices (2 smartphones and 2 tablets). We also analyzed how different amounts of horizontal misalignment affect the transfer.

From this analysis, we provide example real-world performance data, giving an insight into PowerShake's potential.

Tasks supported and duration of WPT interactions

We compared our power transfer rates on real devices against typical task consumption rates of a Nexus 6 device [14] (see the vertical axis of Figure 6). As such, these rates are representative only and the specific consumption of other devices will vary slightly. All devices' batteries

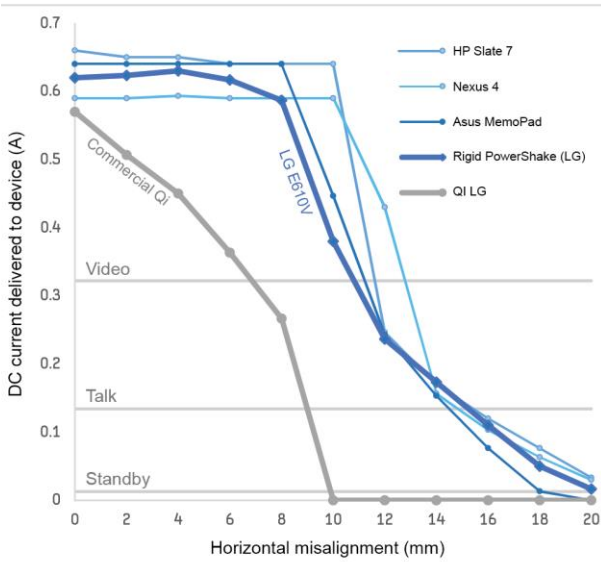

Figure 6. Impact of misalignments on throughput in Qi and PowerShake, using several real devices.

started at ~40% of their capacity, a best case scenario, right at the bottom of the linear charging rate of the batteries [24].

Figure 6 illustrates charging rates between 0.57A and 0.66A (2.85W-3.3W) with no horizontal misalignment between coils. The charging rate varies per device due to each manufacturer's unique power conditioning circuit. This rate allows charging ratios of up to 1:2.05 for video watching, 1:4.88 for phone calls and 1:51.24 for standby (display-on). So, for example, twelve seconds of charging will enable 1 minute of additional talk time, or two minutes of charging supports 4 minutes of video watching (approximately one music video). Thus, power transfer interactions can remain reasonably brief across a wider range of less demanding tasks. These transfer rates are not sufficient to enable charging during the most power-hungry long-term tasks (such as a business video conference), however they will support extended use. For instance, with a charging rate of only 1:0.5, PowerShake can still double the task duration supported by the battery (i.e. only 50% of the device's battery requirements will be drawn from the on-device battery during transfer).

Docking to Prevent Misalignments

We measured the impact of misalignments both on our PowerShake circuitry and the commercial Qi system. We started with the coils coaxial (0mm offset), and increase the offset in steps of 2mm, up to a maximum 20mm offset.

Misalignments have a very significant effect on power transfer. With PowerShake, a misalignment of 8 mm still allows ~86% of the power transfer, where Qi allows ~50%. This rate decays to ~30% at 12mm with PowerShake. (The Qi circuit includes sensing functionality that disables transfer above 10mm misalignment). The effect of misalignment is especially relevant given our mobile context, where we envisage power transfers occurring whilst on-the-go and alongside other tasks.

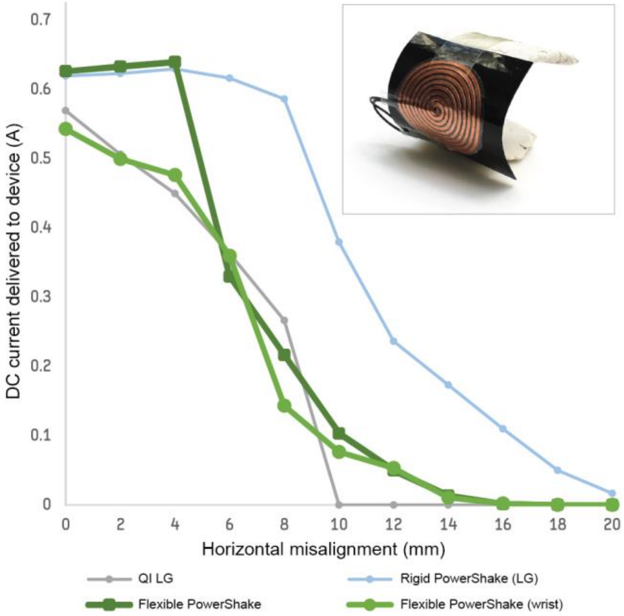

Figure 7. Impact of misalignment on throughput in flexible PowerShake, both when flat and bent over a wrist mold.

This motivates our advice to include a docking mechanism to maintain transmit and receive coil alignment under 8mm. Actually, the amount of movement allowed will require an equal amount of shielding around the coil, to maintain safety compliance, even if coils move. This factor deserves special consideration in smaller devices (e.g watches) or even smartphones, to avoid surface competition with other coils/antennas. Current sensing techniques (to stop transfer if out of alignment) should also be included for commercial devices.

Flexible form factors

We also explored the possibility of building flexible coils (see insert in Figure 7). This was actually based on observations from the participants in our first workshop (later in the paper) who wanted to explore coils that would bend to the curvature of a watch strap.

We created a custom transmit coil from three layers of copper tape with a diameter of 44mm (equal to the TDK Qi transmit coil) and a 9 turn spiral in each layer (to increase inductance). We used 1mm of flexible ferrite sheet and a layer of copper tape to ensure safety compliance. The coil had an inductance of 18.46µH, similar to the TDK Qi transmit coil. We reused the receive coil from our previous device (complete with our additional shielding) as it is already sufficiently flexible.

We tested the flexible coil's performance against our rigid PowerShake charger and the Qi charger (on the LG E610V smartphone). Figure 7 shows that for horizontal misalignments up to 4mm, the flexible transmit coil performs as well as the rigid PowerShake arrangement. Above 4mm, the flexible coil exhibits a sharper decline in current delivery. This is a limitation of the spiral design of the flexible coil. When misaligned, the receive coil does not cover all the turns in the spiral (and, thus, does not receive the magnetic flux from those spirals). Even as the power throughput drops, the flexible coil continues to perform similarly to the commercial Qi system.

This flexible coil design supports the embedding of WPT circuitry in a greater range of devices (such as in a watch strap), but maybe not for other wearables (i.e. clothing).

DESIGNING POWER TRANSFER INTERACTIONS

Our previous experiments demonstrated the feasibility of PowerShake and helped identify technical opportunities and limitations. We envision PowerShake embedded into a range of mobile devices. In designing these devices, the coil layout plays a key role in defining the set of available WPT interactions (as the coils must be closely aligned). Once coils are positioned, the users can control the angle, orientation and ongoing activities of the coupled devices. To this end, we conducted a series of workshops to explore: a) ways to integrate coils into current wearable/mobile devices and; b) and to bring to light some of the social implications of battery life as a tradable commodity. Three researchers were involved. One researcher chaired the workshops, while the other two observed and took notes. The workshops were video-recorded and stills were taken (see S3) for later analysis.

Workshop 1: Designing Devices and Exploring Interactions

We conducted an initial design workshop and invited six interaction designers to participate. They had experience designing interactive technologies, but none had prior experience in WPT.

The workshop began with an **Introduction to PowerShake** (S1), in which we described the technique, emphasizing the results of our experiments; the charging times (12s ~ 1 min call), loss of power during transfer (~50%), impact of misalignment and the need for docking. Next, the participants **Explored Scenarios** (S2) in which they had run out of power including the context of their device usage and the task were trying to perform. The participants presented their scenarios to the group and placed sticky notes on a common wall. (These scenarios were revisited in a subsequent workshop).

Each participant was then given a phone, watch and circuit mock-up with which to **Design Prototype Devices** (S3) (i.e. determine coil placement) and their afforded interactions. They were asked to create device arrangements for a watch and a phone (Figure 8, left), considering phone-phone, watch-phone and watch-watch transfer interactions. Upon completion of each mock-up, the participants were asked to demonstrate their proposed interactions in front of a camera (Figure 8, right). Each participant then **demonstrated a device design** (S4) to the group, describing their design rationale and motivations. During this process, the participants demonstrated their interactions with another participant, to avoid pre-conceived ideas regarding how the interaction would work and to showcase how easy the interaction would be to 'learn'. Finally, the participants **voted** (S5) for their favorite three designs.

Figure 8: Mock-ups of a phone, watch and coils used for the workshop (left). Participants used these to design device arrangements and explore potential interactions (right).

Workshop 1: Analysis

We analysed the workshop in order to identify recurrent rationale, themes and considerations.

When does the Power run out? (S2)

The participants recorded a range of scenarios during which their phones had run out of battery (18). Of these, a number related to longer periods away from chargers (7), such as travelling (5), camping (1) and festivals (1). Other suggestions included more everyday locations, such as on the street (3), on public transport (2), on a night out (1) and in the gym (1).

The participants recorded what they were doing or attempting to do as the batteries ran out. This included the use of navigation aids (5), contacting friends (4), accessing travel documents (2), taking photos/video (4), listening to music (1), tracking activities (1) and passing the time (1).

What could PowerShake-enabled devices come to look like? (S3, S4, S5)

Our participants created 16 unique PowerShake-enabled prototype devices (S3), but only their six favorite designs were presented and discussed with the rest of the group. These considerations focused around: privacy, ergonomics, aesthetics, ease of use and social concerns.

Privacy (DC1). The participants likened PowerShake interactions to Near Field Communication (NFC) interactions and thus raised concerns regarding the clarity of exactly what was being transferred alongside power (i.e. files, contact information). While only the receiving device needs to be visible for intra-personal transfers (i.e. enable on-going tasks), they suggested that the transmitting devices must also be visible in inter-personal interactions (i.e. show exact amount of energy transferred, no other unwanted, simultaneous activities).

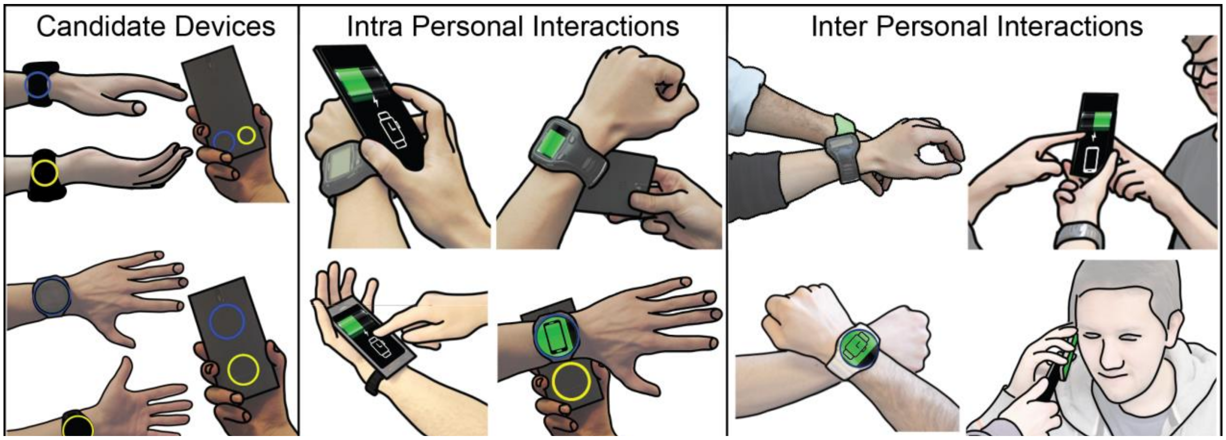

Figure 9. Sketches of the candidate designs from workshop 1 (far left) and some examples of the power interactions they explored

Ergonomics (DC2). One participant specifically emphasized ergonomics during the design of their device, both for intra and inter-personal transfers. Three participants discussed fixed device-docking (i.e. the transmitting device becomes securely attached to the receiving device) to support on-going tasks on the receiver. They also looked at the affordances that the coil could enable, such as a way to provide additional grip whilst holding the back of the phone. In one design the coil was secured to the device with a hinge. The coil could be used as a kind of keyring, enabling different styles of carrying and interacting with the device.

Aesthetics (DC3). One participant focused on aesthetics during the design and discussion of their candidate devices. This became especially pertinent in the design of the watch, suggesting that the coils need to carefully fit within any existing design (e.g. around the watch's face, in the strap).

Ease of use (DC4). A number of participants highlighted different factors affecting ease of use. Two participants suggested a single coil design, where power can be transmitted and received through one coil, as this represented the simplest solution. Another participant used the metaphors of the microphone and speaker as receivers and transmitters, to suggest that the coil positioned on the top of the phone (near the speaker) should always transmit.

Reflecting on designs and the interactions enabled

After introducing their favorite designs (S4) to the other participants, each participant voted for their three preferred configurations and the two most highly ranked designs were selected for further discussion (S5). It is possible to draw similarities between the two selected devices (Figure 9, left), which we believe reflect the designers' rationale.

Both phone designs use a symmetric coil placement (side-by-side or above-below), aligning with designers' plea for a standardized coil layout. They both support back to back docking, allowing both displays to be visible during the transfer in order to monitor any simultaneous activity. Additionally this facilitates handing the device to the recipient, so they can easily grip both devices and continue on-going tasks (e.g. browsing). Alternatively, both phone designs allow for a more "tip to tip" transfer (Figure 9, bottom, far right), avoiding proximity with the other person, which designers commented would be better for interactions with strangers.

Smartwatch designs show a top-bottom (Figure 9, bottom, far left) and side-to-side (Figure 9, top, far left) layout. Both allowed the receivers' display to remain visible during the transfer, but only the side-to-side design reflects the designers rationale to keep both displays available for inter personal transfers. Participants also commented this design reduced the risk of scratching the watch face during docking. The transfer interaction for the top-bottom design was reported as comfortable, while the side-to-side design forced uncomfortable positions and required the users to carefully consider which side pertained to the transmitter and receiver before docking. The top-bottom design also allowed the integration of the coils in the aesthetics of the device (i.e. watch's face and clasp). The possibility to integrate the coils within the smartwatch strap (side-by-side design) motivated our exploration of flexible coils (in the implementation section), which also allows us to envision PowerShake integrated in a wider range of devices.

Both smartwatch and smartphone designs allow for intra-personal interactions while keeping the receiver's screen visible. With the top-bottom watch design, the face can be rotated to the inner part of the wrist, allowing it to power a phone while talking or browsing (Figure 9, bottom, second from left). Participants commented the change on the grip of the phone felt uncomfortable and could make it easier for the phone to fall. However, they found the potential to extend a critical task could justify these interactions, considering their duration remains short.

Workshops 2: Exploring Social Interaction

Having conducted a workshop to derive candidate designs for PowerShake-enabled devices, we invited the original 6 participants back to consider the wider social implications of using PowerShake day-to-day (workshop 2). In order to engage with a more representative sample of participants, we also ran another instance (workshop 3) as part of a calendar of events hosted by a creative hub for artists and technologists. This event was attended by 24 participants from a wide range of backgrounds, including creative technologists, artists, technology policy makers and designers.

In these workshops, we re-introduced PowerShake, its opportunities and limitations and the PowerShake mock up devices. We then presented a series of scenarios, based on those collected from workshop 1, for the participants to roleplay. The purpose of this workshop was to generate open discussion around PowerShake's usage in real-world settings. As a result of this, the workshop was kept purposefully open-ended, allowing for the natural development of discussion within the group. The observations and discussions from these workshops are analysed together, based on recurrent themes, but we distinguish between participants in workshop 2 (D1-D6) and workshop 3 (P1-P24).

Workshops 2 and 3: Analysis

Context (SI1). During the workshops, the participants brought to light the importance of context in influencing the use of PowerShake. Many participants liked the idea of being able to share power with their friends or family. P16 remarked: "*I can see my family using this. One of us usually has a low battery!*" Another participant said they would use PowerShake "*amongst friendship groups*" (P12).

A number of participants brought to light the importance of shared experiences in influencing the use of PowerShake. One participant highlighted the suitability of PowerShake in a meeting space, where all attendees are engaged in a mutual activity. When role-playing hiking and camping, the participants suggested a greater willingness to ask anyone for power as a result of a shared activity or experience: *"When you are hiking, everyone is your friend."* (D1). In this way, the shared activity came to reduce social barriers that may otherwise prevent the use of PowerShake.

Conversely, in the festival scenario where so many people are engaged in the same activity (and typically with limited resources), these social barriers are not reduced and our participants demonstrated a greater reluctance to share and ask for power across a wide audience. Additionally, one participant remarked "*I would trust a friend with my power. I wouldn't trust a stranger."* (P6).

In workshop 3, only 10% of participants said they would be willing to transfer power to a stranger. 80%, however, said they would use PowerShake (indicating adoption amongst their own devices, or between friends).

Activity (SI2). The role-played scenarios included a range of different mobile activities, from locating a vehicle, to taking photos and making emergency calls. These different activities brought to life an implied scale of activity importance. When needing to make an emergency call, the participants (D1, D5) suggested they would prefer to ask to borrow a phone than to ask for power. This is partially influenced by the overall efficiency of PowerShake (where twice as much power needs to be transmitted as is required for the call). The participant taking photos (D6) said photos were not perceived as important and, as such, they felt they could only ask close friends for power.

The exploration of the importance of any activity also brought to light the perceived importance of any device. For example, the participants were more reticent to ask for power for a watch than a phone – suggesting that smart watches currently have a more leisure-based perception.

Interactions (SI3). The participants brought to light a variety of different factors impacting PowerShake interactions. Firstly, there was some discussion around the etiquette of how you negotiate a power transfer. This was impacted by both the context of the interaction (SI1) and the activity being supported (SI2). From this discussion, P8 suggested implementing pay-per-charge as an incentive for the transferer. P3 and P4 suggested a kudos-based system, where people could see other people's transmit/receive karma. This brings to light the consideration of mobile power as a commodity. Furthermore, as people build a history of PowerShake interactions, people may come to attribute more trust to them.

Other participants acknowledge other opportunities for social interaction during the interactions ("*it is perfect to show people your web-page or latest work. You have a captive audience*" (P3), or "*this could be an amazing flirting technique*" (P4)). This contrasts other participants wanting their screens to be blacked-out during transfers, to maintain privacy (e.g. block notifications from social media) or feeling uncomfortable about intimate interactions required to transfer power (e.g while role-playing an ongoing call: "*He has to put his hand on my head, and it's weird."* (D3)).

Participants also acknowledged the challenge of negotiating for power during an ongoing activity. P14 suggested that arranging a PowerShake interaction would be so disruptive to their phone call, that they would rather ask to borrow a device than borrow power (assuming data/contact details from his personal device were not needed). Other participants envisaged a common gesture set appearing for communicating the need for power (akin to a 'cupped hand' and a wrist flick suggesting: '*do you want a drink?*' (P15)), as WPT interactions become more common.

Finally, most participants felt comfortable during intra-personal interactions and explored back-to-back inter-personal docking, when social trust was not an issue. However, they also reported that the device designs led to tiring gestures during interactions. Particularly, many of them preferred to take off their watches, and dock them to the back of the device (i.e. while talking, watching videos), rather than modifying their usual grip on the device (P3,P4,P17,P18 and P19).

Safety (SI4). All of the participants acknowledged safety concerns with the use of PowerShake. These ranged from simply not wanting to make a stranger aware that you have a mobile phone, to concerns regarding the easy theft of your device during a charging transaction: "*We discussed if the smartwatch is attached to the wrist, then holding out your hand in public could be risky. It could be gently removed!*" (P7). Conversely, one participant, D5, specifically altered their behavior in acknowledgement of others' concerns, suggesting that the transferer should hold both devices during the interaction.

Many participants were more comfortable with receiving power than giving away power. P22 remarked "*This phone is my office. I would be reticent to lend it out!*" The participant went on to explain how their contacts and business was run from their smartphone and the pivotal role it played in their life. A colleague then asked the participant "*If the device is your office then wouldn't it make sense to accept power in a critical situation?*" (P21) with P22 remarking, "*Oh, that's totally different! Of course I would ask for power*."

DISCUSSION

After demonstrating the technical feasibility of our concept and identifying the potentials and constraints, we focused on the way this technology could be integrated in current devices (workshop 1) and the possible application contexts (workshops 2 & 3). Our participants unanimously suggested that they would be more willing to conduct PowerShake interactions when surrounded by others engaged in similar or sympathetic activities, or in specific contexts (such as office meetings, with the family and whilst hiking, for example). Safety was also a key consideration, with multiple participants suggesting discomfort with placing their devices near strangers, through a fear of physical or digital theft. We also saw participants reticent to transfer their power, yet happy to ask for power when needed.

What we see then, is a varying adoption of PowerShake across a scale of social context. People may be willing to transfer power between themselves and their immediate friendship circle, yet grow increasingly reluctant when considering strangers. In certain circumstances, the activity serves to level friendship barriers, with people willing to share power with strangers when hiking, for example. This is a complicated relationship, however. Given the efficiency costs of power transfer (i.e. the transferer 'gives' more than the receiver 'receives.'), some participants were willing to ask a stranger for power, where others preferred to ask to borrow a strangers' device. Participants alluded to a complex interplay of social connectedness, task importance and safety considerations, when deciding whether to use PowerShake in any given situation.

Across both of our workshops, 3 participants suggested different incentives, whether paying for power, or a kudos-based system. Participants also elaborated on the opportunities of social engagement that could be raised around PowerShake interactions. We envisage an app-based control system for PowerShake, allowing for different levels of social engagement (from privacy-preserving black screens to social media sharing). This app could facilitate power transfer etiquette, control amount of power to be transferred and include (monetary or social) incentives.

Across the workshops we observed four common stages of power transfer interactions; *negotiation*, *mutual orientation*, *transaction* and *termination*. Initially, a *negotiation* of the amount of power required by the receiver is undertaken. This frequently involved potential power recipients explaining their needs and expected durations, such as the length of the required phone call. The sender and receiver then *mutually orient* their devices to enable transfer. Next, the *power transaction* occurs. It was in this stage that our participants' security concerns came to light. Finally, the sender and receiver *terminate* the power transfer. This typically occurred verbally, yet we foresee this being automated through an app in the future. During *transaction* and *termination*, the participants were keen to be able to see their device's screen, for both transfer feedback and continued use.

Participants also demonstrated valuable, but limited usage of PowerShake – mostly in emergency situations with no access to charging resources. We believe this perception of PowerShake as a rare emergency charging technique, is closely tied to our current conceptions of power as a personal, precious resource. As WPT techniques become more pervasive (e.g. greater adoption of Qi enabled furniture) and static charging becomes easier, we envisage a changing perception from power as a precious resource, to a more open perspective. This new perspective could further encourage the usage of PowerShake for quick power-rebalancing, replacing the current use of power packs by the fact that each device can work as each other's battery.

CONCLUSION

This paper explored the concept of power as a tradable commodity that can be transferred between mobile devices. We proposed a shielding arrangement that allowed for safe WPT even for continuous on-body use. We performed experiments to characterize the scope of application of this technique, demonstrating safe power transfers with charging rates (throughput and efficiency) in line with commercial Qi chargers. PowerShake also allows thin form factors, flexible formats and it can be used to charge conventional tasks and extend the duration of on-going power-hungry tasks.

We also conducted several workshops that allow us to envision how PowerShake can be included in real devices, together with a range of higher level implications. These include the way power interactions could be conducted, scenarios where they could be applied and social implications enabled by the change of perspective that PowerShake enables, transforming power from a personal resource, to a social tradable commodity.

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