Provision and Storage of Energy for Pervasive Computers

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Abstract. Soon, pervasive computers will enormously outnumber humans. Devices requiring sufficient energy to operate maintenance-free for periods of years and beyond render today's technologies insufficient. With the gap between energy requirements of embedded systems and achievable levels of harvested power reducing, viable hybrid energy and power management subsystems have emerged that combine harvesting with finite, rechargeable energy buffers. Coupled with advances in wireless power transfer and energy storage, we propose that an *energy design* space is emerging. There are, as yet, no tools or systematic methods for design space exploration or engineering in this context. It is important to develop such a methodology, and critical to link it with methodologies for system design and verification. We discuss the key factors such an energy design methodology should incorporate, including size, weight, energy and power densities; efficiencies of harvesters and buffers; time between charges, (dis)charge speeds, and charge cycles; and availability and predictability of harvestable energy.

Introduction. As Weiser's vision of ubiquitous computing continues to become reality, significant technical challenges remain. Chief among them is achieving autonomous and long-term operation without the use of wires or 'tethered' interfaces. From a communications perspective, solutions have emerged quickly: cellular, Wi-Fi, Bluetooth, RFID, IEEE 802.15.4, and LoRa, to name a few. However, there is growing interest in providing sustainable energy for pervasive computers using wireless interfaces – to increase autonomy, reduce clutter, reduce maintenance requirements and expand application potential. Given increasing acceptance in consumer electronics of the dedicated transmitter-receiver model, whereby power is intentionally transferred from a source to one or more receivers (e.g. Qi), it is worth investigating the model's applicability in complementary pervasive computing scenarios, such as applications using embedded sensors and actuators. This raises interesting design questions in terms of: the range of transmission of energy; the physical size of transmitters and receivers; how to efficiently manage on-board conversion, storage and management; and how to tackle heterogeneous mobility patterns where receivers may be in contact with sources for limited periods of time - due to being mobile devices themselves, or because they use mobile energy sources. There are also cases where both source and receiver(s) may be static, or both mobile (Fig. 1). The *energy design space* is growing, and wireless energy transfer is a promising candidate where recharging is necessary and feasible.

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Energy and mobility in pervasive computing. Smartphones are ubiquitous in modern society, typifying mobile devices with static wireless connectivity points and tethered recharging, lately supplemented by 'wireless' charging (using *Qi* chargers that exploit magnetic induction and resonance). This holds for tablets and notebooks in their typical use. Thinking about the power requirements of these devices, the range is typically 1-30 watts, with smartphones on the lower end and powerful notebooks on the upper, and instantaneous power varying depending on the task(s) performed. We tend to carry these devices with us most of the time, and accept regular charging as a fact of life. Most of these devices are mass-market consumer products, and often use 'battery life' as a marketing tool. With the recent emergence of high performance 'wearables', such as smart watches, it has become common to discuss how much utility can be had for so many minutes charging! Quantifying performance versus user acceptance in these terms is difficult and subjective, but many companies and consumers accept that for moderate use, one day between charge cycles is reasonable. Simultaneously, charging times are improving, but are also difficult to comparatively analyse due to battery capacity variations; although typical batteries cannot be charged in less than 30-60 minutes as a compromise between charging speed and rate of capacity degradation. Today's high-end devices typically charge from empty to full in 1-3 hours, and as they mostly use Lithium-ion batteries, have around 300-500 charge cycles before they need to be replaced (~2 years).

Figure 1: Mobility scenarios in contemporary pervasive computing

Distributed, embedded wireless sensor (and actuator) networks (WS(A)N) have many mixed-mobility scenarios, and were initially considered constrained in practical utility by finite energy supplies (batteries). Lack of acceptance of the associated maintenance requirements led to research efforts focussed on energy efficiency across a spectrum of related themes, most notably communications protocols and associated algorithms. WSN applications are diverse in scope, but typically consist of static devices deployed across a sensing field where data is transmitted across one or more hops toward a sink/gateway. Alternatively, data are collected via 'muling' with a mobile sink, an example of delay-tolerant networking (DTN).

Improvements at silicon level, low power RF and processor design, monolithic system-on-chip (SoC) integration, and energy-efficient communications protocols, have all facilitated good progress in making energy harvesting – particularly from solar and air flow sources – viable options in the last ten years for WSN scenarios [4, 5]. Many examples have emerged that exploit hybrid harvesting and storage approaches, often using multi-source harvesting and multi-storage configurations typically comprising supercapacitors and lithium batteries [5]. The devices typical of these applications require tens to hundreds of microwatts in active operation, while ultra-low power modes can facilitate 'sleeping' in the

tens of nanowatts range, often exploiting maximum power point tracking (MPPT) techniques to optimise switching between buffers (or charging) based on real-time available energy [5, 6].

Recent works propose the use of mobile charging ‘vehicles’ to provide wireless energy to static in-field devices, such as in [1] and the EU FP7 MOBESENS project. This is based on nonradiative wireless power transfer (WPT) [7]. Interestingly, the popularisation of drone technology could lead to drones as delivery vehicles and/or mobile devices requiring charge.

Home or office-based Internet of Things (IoT) devices are likely to be static, could benefit from mobile wireless energy, but will most likely exploit similarly static sources. In this case, coils could be built into walls or under flooring for inductive wireless power transfer. WiTricity (<http://witricity.com>) is developing products that do exactly this. For home/office IoT scenarios it is also possible to consider other wireless energy sources, such as electromagnetic waves (i.e. radiative sources). A commercial example of the RF approach is being developed by Energous (<http://energous.com>), whose system delivers wireless energy at a distance of approximately 5m from a transmitter to a receiver, maintaining charging while the receiver is in motion, for up to 12 devices simultaneously.

Acoustic energy transfer is another possibility that can potentially fit a combination of mobile and static transmitter and receiver scenarios. uBeam (<http://ubeam.com>) is a controversial start-up attempting to generalise wireless energy infrastructure based on ultrasonic energy transmission, despite widely publicised technical challenges and improbability of success [8]. There are numerous other efforts to demonstrate acoustic energy transfer, particularly where receivers may be otherwise inaccessible, e.g. subterranean pipelines, structural monitoring or body implants. For example, methods of ultrasonic and inductive power transfer for powering implanted devices through body tissue have been compared, finding that ultrasonics are preferable for longer distances when small receivers are used (e.g. over 1.5 cm for a 5 mm receiver) [9]. Recently, acoustic power transfer through solid structures has been demonstrated, and is a promising method in cases where beneficial geometries exist, such as beams, pipelines or panel structures [10].

Energy harvesting from infrastructure transmitters, such as broadcast signals, cellular base stations, even Wi-Fi routers, which create ambient RF energy for would-be scavengers, is another area of interest. However, such sources create power levels insufficient to energise contemporary devices (e.g. ranging from a fraction of a nanowatt (where a small antenna is used near a Wi-Fi router, for example) to tens of nanowatts (from GSM1800 from cellular base stations) per cm^2 on average, in urban environments) [11]. Additionally, bespoke, highly efficient omnidirectional rectennas (rectifying antennas) are required, probably in array configurations. Static or mobile devices in ‘energy rich’ areas could adopt this approach, although with significant variability in available supply.

Other examples of opportunistic harvesting that necessitate static deployment are known, such as thermoelectric harvesting exploiting temperature differentials over time, using phase-change materials,

for wireless sensor applications such as structural monitoring in aircraft [12]. Such harvesting approaches tend to be heavily optimised towards the targeted deployment scenario and the associated ambient available energy sources, rather than being general-purpose solutions.

Completing the mobility matrix, applications based on rendezvous scenarios between mobile sources and mobile devices/receivers are also possible – particularly if one considers advances in drone technology and swarm coordination, and historical approaches to in-flight refuelling in aviation. This is the least likely scenario to receive significant attention in the short to medium term for pervasive computing applications.

Considering mobility patterns relevant to modern untethered pervasive computers, the only scenario that does not require on-board energy storage is one in which the energy source and receiver(s) are static (or of limited mobility within the wireless energy transfer region of one or more transmitters), assuming no redundancy is required should the source(s) become unavailable. Numerous recent examples of instantaneous wireless power transfer, such as powering light bulbs (60 W) and notebooks (12 W) [13, 14], are demonstrative of this approach. If the source fails, so does the device, but on-board storage costs are reduced or eradicated and the device may be more compact.

In the following, emphasis shifts from consumer electronics towards embedded monitoring and control systems synonymous with WSN, cyber-physical systems and IoT scenarios with high degrees of autonomy and ultra-long lived operational requirements. In particular, we are interested in where these systems intersect with the potential to exploit wireless energy transfer and harvesting. Nevertheless, heterogeneous mobility models, requirements and characteristics are unavoidable. Fig. 2 provides a general overview of the active power of a number of components and systems relevant to emerging pervasive computing systems and their evolution over time. Clearly, the power requirements vary over many orders of magnitude. The earliest generation of ‘mote’ class devices comprised some combination of ‘cheap’, energy efficient sensor(s), analog-to-digital converter, RFIC and microcontroller; active power is the sum of components’ active modes, and the primary energy cost is incurred during communication - typically in the tens of milliwatts range, irrespective of chip manufacturers. More recently, sleep or ‘low power modes’ of microcontrollers can operate in the sub-microwatt range, for example the NXP LPC1100L series based on the ARM Cortex-M0 architecture. SoC implementations, combining IEEE 802.15.4 radios and microcontrollers, e.g. TI-CC430 and NXP-JN5168, provide similar low-power modes and comparable RF power performance (~15-17 mA in TX and RX modes). There remains a convincing case to use duty cycling techniques (where permissible by application requirements) to minimise net energy consumption.

Figure 2: Indicative power consumption of various components & systems. NB: The presented data are shown as a reference for evaluating overall power demand. As the application objectives and performance levels of the systems presented here are very diverse, a comparison of low power electronics based on this graph should be avoided.

Energy Evolution. Application-level performance and operational requirements are fundamental considerations for energy design. Minimum performance and operational criteria are often stated in terms of availability, accessibility, throughput, reliability and security, and lifetime. Therefore, rather than being thought of as a constraint, ‘energy engineering’ can be performed at design-time for a given specific set of application-level requirements. This is particularly important in the case of sensor network application scenarios where autonomous field operation is required over long periods.

Consider an *ad hoc* wireless sensor network application tasked with periodically monitoring a phenomenon of interest, such as in long term structural health monitoring. An application designer may use aggressive duty cycles (DC) in each device in the network to minimise energy use over time, while attempting to balance this with meeting performance or Quality-of-Service requirements dictated by the application. The operation of a device in such a network can be modelled as a simple finite state machine, where average power is the weighted average of the active and sleep phase power. The active phase includes data acquisition, processing and transmission, and the sleep phase includes the time spent in low power modes and performing other tasks. Given a finite energy supply, it is easy to estimate the lifetime of a sensor node by dividing its capacity rating by average rate of consumption, taking into account self-discharge of the battery and environmental factors.

Such a model can be useful in determining when a sensor node(s) may require recharging, and could also inform the selection of suitable on-board storage at design time to satisfy an economically feasible maintenance schedule. However, a detailed model of the operational state machine and potential state space is first required to determine reasonable boundaries for the active phase. Factors such as position in the network affecting routing responsibilities, time-varying link qualities resulting in packet retransmissions, event detection or alarm threshold breaches, are among those which make effectively modelling a device's energy evolution a complex task. Modification of the energy model is also required for time-varying yet predictable ambient energy harvesting sources [5].

Energy Design. Harvesting is increasingly included in designs (e.g. EnOcean), and sensor network devices' energy subsystems are becoming more tightly engineered relative to the application and its deployment environment. Legacy philosophies wherein devices comprising sensor networks are thought of as being cheap and disposable are being dislodged by those which suggest that the resultant data are of enough importance to collect over long periods of time. This requires sustainable operation beyond the capability of many contemporary battery packages, while replacement of batteries continues to be seen as an unacceptable overhead, is potentially environmentally unfriendly at scale, and in some cases impossible due to device placement in inaccessible locations. Most WSN-type applications aim to achieve a sub-1% DC, which is essential to enable a long-lived application, and given the ultra-low current draw in modern components may mean that in many cases the limiting factor in determining lifetime of a node is the self-discharge rate of the battery.

Approaches to system level co-design are beginning to include energy as a primary element of the design space, although this is largely restricted to research projects. Thus, models of reasonably predictable ambient energy sources are under development and improvement. These are typically based on energy traces collected in the real world and subsequently introduced to simulation and emulation tools. Such efforts have led to useful advances including improvements in the predictability of short and medium term energy availability [15], integration of ambient energy models to contemporary simulators [16] and emulators [17], and informing of co-design for bespoke application scenarios [5]. As part of the design process, the ambient available energy from potential harvesting sources is determined using surveys, or estimated based on available data, such as prevailing weather conditions. There is a pressing need for more tools that enable realistic and consistent experimentation where renewable and time-varying sources of energy are part of the design space. Notwithstanding this, there are few application scenarios where the ambient harvestable energy is sufficient for energy autonomy in devices with strict performance criteria. Fig. 3 shows an illustrative cross-section of power density per surface area or volume for a number of potential harvesting solutions proposed in the literature over the years. Without a high degree of predictability of the ambient source it cannot be guaranteed that the system will operate as needed, thus it has been difficult up to now to justify including stochastic sources in the design space for practical, commercial applications.

Figure 3: Power levels for recent approaches to ambient environmental energy harvesting (indicative values are taken from the literature; power density by one unit of area (cm^2) or volume (cm^3) in the y-axis).

Wireless Power Transfer. Tracing back to Nikola Tesla’s experiments in the early 20th Century, the idea behind wireless power transfer (WPT) is mature, and has found significant application in contemporary consumer electronics in the form of electromagnetic inductive coupling, usually over very short distances (cm range or less). This involves generating a magnetic field by applying alternating current to a primary coil on the transmitter side, which induces voltage across the terminals of a secondary coil on the receiver side – acting as a transformer with the core removed. Safe and simple, in 2010 the Wireless Power Consortium (<http://wirelesspowerconsortium.com>) introduced the ‘Qi’ standard for wireless charging of devices, at very short range, at up to 5 W.

However, there is significant performance degradation in terms of energy transfer when the distance between transmitter and receiver exceeds approximately one coil diameter, due to the rapid reduction in magnetic field strength away from the transmitting coil (which is in the cm or mm range for typical electronics devices due to size and packaging constraints) and when misalignment occurs; a problem which can be solved using magnets to hold devices almost precisely in place. Charging electric toothbrushes, smartphones, watches, etc., in this way is practical in most cases, but is less than ideal where almost direct and aligned contact is impossible. WSN applications, for example, where distributed devices may be inaccessible or arbitrarily oriented, make wireless transfer using simple inductive coupling impractical.

If the transmit and receive coils are operated at a frequency to maximise their Q-factors, so as to minimise losses associated with the repeated energising and discharging of the resonant tank components, reasonable efficiencies can be achieved at greater distances. Kurs *et al.* showed that a link efficiency of around 40% could be achieved over a distance of 4 times the coil diameter, which is in a

region often called ‘mid-range’ [13]. The tuning out of the coil inductances with capacitors to both reduce the VA rating of the drive electronics and improve link efficiency has been long known, and most practical inductive power transfer (IPT) systems have employed this for some time [18].

Developing the principle, Kurs *et al.* showed that for mid-range applications it is possible to simultaneously power multiple devices, where the devices have much smaller surface areas than the source. It has since been demonstrated over greater distances in sensor system power ranges using smaller receivers, achieving around 10 mW received at 6 m stand off [19]. We summarise the key features of IPT devices for different size scales in Table I.

The benefits of IPT are numerous compared to other wireless energy transfer mechanisms, including short- to mid-range capability, high transfer efficiencies (difficult to achieve with radiative methods), and the ability to transfer power through many objects with low loss. Further understanding of the impact of external objects and environments is required, where certain materials in proximity may shift resonant frequencies or reduce the Q-factor, ultimately impacting upon transfer efficiencies.

Health effects of magnetic and electric fields must be taken into consideration. Standards for exposure to EM waves are set by different bodies in different countries based on the same basic principles, intended to limit both tissue heating and muscle and nerve stimulation effects. The World Health Organisation set guidelines based on IEEE and ICNIRP recommendations. Absolute levels for ICNIRP and IEEE differ, but are both based on basic restrictions: maximum allowed in-body magnetic and electric field strengths as a function of frequency. As these internal quantities are difficult to measure, a set of reference levels are described for outside of body measurements, which if adhered to, allow basic restrictions to be met. Typical specific absorption rate limits are 10-20 W/kg depending on where heating occurs, and less than 400 mW/kg across the entire body. As the limit values are more generous for low frequencies (in the 100 kHz range) than at higher frequencies used for IPT (e.g. ISM bands at 6.78 and 13.56 MHz), high power systems (for vehicle charging) tend to use lower frequencies than low power systems (which need to use higher frequencies to use small coils efficiently).

TABLE I
KEY FEATURES OF WIRELESS POWER TRANSFER DEVICES FOR DIFFERENT SIZE SCALES

Charger size range	Ø 2 – 10 mm	Ø 20 – 100 mm	Ø > 100 mm
Required proximity	< 10 mm	< 100 mm	< 1 m
Required alignment	± 1 mm	± 10 mm	± 100 mm
Power range	< 10 W	< 10 W	< 100 W
Resonance sensibility	±1%	±1%	±1%

Safety	Packaging for safety.	Packaging for safety User training.	Electromagnetic shielding User training Protective equipment
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On-board storage. Lithium ion batteries dominate in mobile electronics applications because of their high energy density. In these applications their relatively high cost, and limited number of charge-discharge cycles, are generally considered acceptable. However, as with other battery chemistries they have low power densities, which can be a drawback when the application has highly “peaky” power demand, and certainly limits the ability to do rapid recharging, as will be needed for the scenario of mobile power sources wirelessly recharging multiple devices in turn. Supercapacitors provide an alternative storage solution that looks increasingly attractive. Functionally occupying a middle ground between batteries and conventional capacitors, they offer charging times of 10s of seconds (Table II), but energy densities about 10x less than lithium batteries (Fig. 4). As a long-term storage solution, however, they fail because of their short self-discharge times of a few days. In a daily recharging scenario this is tolerable, but considering again the use of mobile power sources, e.g. for embedded sensors, what is really desirable is short charge times (a few minutes or less) combined with long periods between recharges (e.g. months). There would appear to be no way of achieving this with a single storage technology, without dramatic improvements in the state-of-art, e.g. in secondary battery design and fabrication [20].

A hybrid solution, with supercapacitors buffering batteries, can offer this combination of quick charging and long operational life. Efficient energy transfer circuits are available for this purpose; they drop dramatically in performance when the input (i.e. supercap) voltage falls below a few hundred mV, but if the battery voltage is, say, 3-4 V, then a residue of even 0.5 V in the capacitor represents only a few % of its energy. Furthermore, if a lifetime between charges of several months or more is achieved, the battery limitation of hundreds of charge-discharge cycles need not be a concern.

To decide whether the quick, infrequent recharge scenario is practical, the next consideration is whether a sufficient power rate can be delivered. If we target one 5-minute charge once a year, the ratio is 10^5 , meaning the charging power must be 10^5 times the device average power consumption. If the average power is 0.1 mW, charge power needed is thus 10W. For a wireless source of a size compatible with an autonomous carrier, especially an airborne one, transfer of 10W is probably near the upper limit. This suggests that a 10W charging rate will require high transfer efficiency, and thus, as discussed above, a proximity between charger and receiver of a few coil diameters or less [14]. If this is not achievable, for example if the wireless device is too deeply embedded in some structure, or because the delivery vehicle cannot practically approach so near, rapid charging becomes infeasible. In such a case, buffering of the battery with a supercapacitor probably offers no advantage.

Figure 4: Indicative energy and power densities of popular commercially available battery and supercapacitor models

Feature	Battery	Supercapacitor
Charge Time	1-3 hours	10-100 s
Capacity (kJ)	2 – 10 kJ	0.02 – 2 kJ
Self-discharge time to 50%	2 yrs	4-15 days
Powering an active 3 W SoC	5-30 mins	6 s – 10 mins
Powering an active 10 mW MCU	2 - 10 days	30 min - 2 days
Powering 10 μ W of sleep mode	Self-discharge dominated	

Outlook. State-of-the-art sleep modes of electronics and pervasive computing devices are now often below the self-discharging rates of batteries and supercapacitors. A typical Li-ion battery self-discharging at 0.1% per day means that a 0.1C power system (C is the capacity rating of the battery specifying the

maximum safe discharge rate), duty cycled at less than 0.1%, loses one third of its energy to leakage. Therefore, the self-discharge rate of a storage medium can be considered as a lower limit of beneficial duty cycling. Lithium primary batteries' self-discharge rates are significantly less than those of rechargeable chemistries (1% of nominal capacity per annum is typical of off-the-shelf packages), and are still one of the best solutions for applications that lend themselves to duty-cycled methods. The charging speed of supercapacitors is limited by wireless power transfer system state-of-art, as opposed to the battery case, where the limiting factor is the battery charging speed. Coupling these limitations with size, orientation and proximity constraints, IPT is not likely to be a widespread solution to energy provision in many application contexts.

The energy design space remains informal and subjective. There is no discernible methodological approach, and there are insufficient analyses in the literature concerning emerging battery and supercapacitor technologies with regard to their use in contemporary applications, beyond solar-supercapacitor systems that are now well known. Nevertheless, with the increasing need for long-lived autonomous operation of devices and the emergence of new harvesters, deliberate transmission and storage technologies, we argue that it is time to develop a systematic approach to energy engineering for the next generation of pervasive computing systems.

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