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Human Generated Power for Mobile Electronics

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1 Introduction

Since the 1990's, mobile computing has transformed its penetration from niche markets and early prototypes to ubiquity. Personal Digital Assistants (PDAs) evolved from GRiD's PalmPad and Apple's Newton in 1993 to the Palm, Handspring, and Microsoft-based models that support the multi-billion dollar industry today. While BellSouth/IBM's Simon may have been the only mobile phone to offer e-mail connectivity in 1994, almost every modern mobile phone provides data services today. Portable digital music players have replaced cassette and CD-based systems, and these "MP3 players" are evolving into portable repositories for music videos, movies, photos, and personal information such as e-mail. Laptops, which were massive and inconvenient briefcase devices in the late 1980's, now outsell desktops. Yet all these devices still have a common, difficult problem to overcome: power.

This chapter will review trends in mobile computing over the past decade and describe how batteries affect design tradeoffs for mobile device manufacturers. This analysis leads to an interesting question: is there an alternative to batteries? Although the answer has many components that range from power management through energy storage [142], the bulk of this chapter will overview the history and state-of-the-art in harvesting power from the user to support body-worn mobile electronics.

2 Technology Trends in Mobile Computing

Mobile phone companies often sell more batteries than phones to consumers. The phones sold to users include a rechargeable battery so that the device is immediately useful, but a certain number of consumers are expected to own more than one battery during the life of their phone. The same can probably be said for laptops and camcorders. Yet, there is little incentive for consumers to buy new batteries except for when they fail or when the consumer feels the need for a larger battery. Unlike other areas of mobile computing that benefit from exponential improvements in performance, battery energy density (as measured by joules per kilogram or joules per cubic centimeter) changes slowly so that there is little pressure for consumers to upgrade.

3 Power from Incident Radiation

3.1 Catching the Ambience

With so many RF transmitters of various sorts distributed throughout today's urban environments, one might consider back-ground RF as a potential power reservoir for mobile devices. Electronic systems that harvest energy from ambient radiation sources, however, tend to be extremely power-limited and generally require a large collection area or need to be located very close to the radiating source. A classic example can be found in old-fashioned crystal radio kits [106] that draw their power directly from AM radio stations, which play audibly through high-impedance headphones without needing a local source of energy. The size of the required antenna, however, can be prohibitive for wearable applications unless the bearer is very close to a transmitter, and access to a good ground is usually required. Even so, the received power is very limited in a standard crystal radio, where set builders typically see received powers on the order of 10's of W, approaching a millliwatt for proximate stations. An interesting adaptation of a crystal radio set is described in US Patent# 2,813,242 [56], where a resonant tank circuit tuned to a strong, nearby station provides enough power to run a single-transistor radio with a small loudspeaker that can be tuned to other stations. An analysis of RF power scavenging at higher frequencies by Yeatman [194] crudely approximates the power density produced by a receiving antenna as , where is the radiation resistance of

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free space (377 Ohms). An electric field (E) of 10 V/m thus yields 26 at the antenna. Field strengths of even a few volts per meter are rare in habitated environments, however, except when very close to a powerful transmitter [123]. In a related note, power can also be extracted from the earth, across a large ground loop, tapping the AC potential difference between grounds at different locations. A harvest of 1.4 mW has been reported using a pair of grounds separated by 50 feet [169].

An example of ambient RF power harvesting in the mobile sphere at higher frequency is found in aftermarket modules that flash LED's when your cell phone rings. Several of these designs are batteryless, but need to be extremely close (or right against) the cell phone's antenna to work, as they draw their energy through near-field capacitive or inductive coupling. Perhaps another mobility example, much further afield, comes from the strange, scattered and usually anecdotal reports of people receiving strong, nearby radio broadcasts from spontaneous detectors formed by loose fillings in their teeth [86, 40], and the passive, implantable receiver design that this has inspired [152, 7].

Higher up in the electromagnetic spectrum, it's not uncommon to see very low power consumer items, such as simple calculators, run off photovoltaics with ambient illumination. The energy conversion efficiency of easily available and rel-atively inexpensive crystalline silicon solar cell modules (without going to IC-grade silicon or stacked junction structures) is generally below 20%, and closer to 10% for flexible amorphous silicon panels [26]. Accordingly, mobile applications, which generally imply limited surface area, tend to be constrained, especially in scenarios without strong and consistent sun-light (standard solar cells produce roughly 100 mW/ in bright sun and 100 in a typically illuminated office). Nonetheless, products like solar battery chargers for cell phones that purport to produce up to 2 Watts of power [117] and PDA's that run off a panel of solar cells lining their case [164] currently exist, and researchers continually strive to refine solar cell materials [92, 26] and technologies [27] to increase efficiency [78], as well as explore unusual form factors, such as flexible photovoltaic fibers [97], that promise to be more amenable to wearable implementations.

3.2 Get on the Beam

Rather than relying on the limited energy that can be scavenged from ambient radiation, other approaches actively beam power from a transmitter to remote devices. The wireless transfer of power originates with Heinrich Hertz who, ushering the dawn of radio in the late 1800's, induced sympathetic sparks across a gap interrupting a resonantly tuned ring placed several yards away from a transmitting antenna that was directed with a parabolic reflector [178]. The dream of wirelessly broadcasting power to an urban area dates back to the turn of the 20'th century and Nicola Tesla [180], who experimented with grandiose concepts of global resonance and gigantic step-up coils that radiated strong, 150 kHz electromagnetic fields able to illuminate gas-filled light bulbs attached to a local antenna and ground at large distances [50]. Wireless power research continued with the work of H.V. Noble [38], who in the early 30's at the Westinghouse Laboratory, demonstrated the transfer of several hundred watts between 100 kHz antennas separated by 25 feet, leading to public demonstrations of this technology at the Chicago World's Fair in 1933. The development of radar [39], hence powerful microwave transmitters, enabled further work in directed energy transmission, a highlight of which was the wireless powering of a small helicopter by William C. Brown in 1964 [38]. Microwave-to-DC converters, termed "rectannas" can be extremely efficient; efficiencies of over 90% have been produced in laboratory experiments and 30 kilowatts have been transferred across more than a mile at 84% efficiency [38]. This has led to proposals for beaming massive amounts of power to earth from solar collectors in space [75] and remotely beaming propulsion to interstellar probes from an earth-orbiting 10 gigawatt transmitter [69].

Closer to home, FCC and safety regulations (e.g., IEEE/ANSI C95.1) along with public perception [70] have restricted the beaming of any significant amount of power in the proximity of people. Nonetheless, researchers have experimented with microwave transmission of power in domestic environments, transferring several mW across meters to sensors for ubiquitous and wearable computing applications [19]. At much lower power levels, short-range wireless power transmission is now com-monplace in passive Radio Frequency Identification (RFID) systems [65], which derive their energy inductively, capacitively, or radiatively from the tag reader. As most RFID chips talk back to the reader by dynamically changing their impedance or reflection coefficient, they require minimal power, generally between 1 and 100 W, depending on their implementation and operating frequency (lower-frequency, magnetically-coupled tags consume less power). Today, people commonly carry RFID transponders, most often for keyless entry systems. Simple resonant RF tags that change their tuned frequency or Q as a function of a local or environmental parameter have been used as passive sensors in several applications [155, 99]. Ex-amples include LC (inductive-capacitive) tags for wireless displacement and pressure sensors in human-computer interfaces [143], measuring tire inflation with pressure-varying backscatter from crystal bulk resonators [24], tracking tire strain with surface-acoustic wave (SAW) devices [149], and proposed studies for using such SAW sensors as implantable blood pressure monitors [129].

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Researchers, however, in wearable and ubiquitous computing have adapted reader circuits to identify tagged objects when handled with reader-integrated gloves [165, 146] or put into coil-lined pockets [94], and small, single-chip readers are now becoming available by companies like EM Microelectronic and Innovision Research & Technology for very short-range, lower-power applications [6].

4Power from the People

Potentially, there is a way around the limitations of batteries and the very restricted amount of energy available to siphon off common ambient environments: scavenge power from the user [175]. The human body is a tremendous storehouse of energy. Just one gram of fat stores nine dietary Calories, which is equivalent to 9000 calories or

per gram of fat

An average person of 68 kg (150 lbs) with 15% body fat stores energy approximately equivalent to

Thus, if even a small fraction of this stored energy could be scavenged, a mobile device would have a large and renewable resource to draw upon. That said, the devil is in the details. Although researchers are working to develop in-vivo fuel cells

[105] that oxidize blood glucose to provide a very small trickle of energy (circa a milliwatt) to power low duty-cycle implants (e.g., a valve to aid incontinence, efficient biomedical sensors, or low-power transmitters for tracking animals) [29, 157], tapping directly into the biological processes that turn fat into energy is beyond currently available technology. On the other hand, power might be scavenged indirectly from the user's everyday actions or might be intentionally generated by the user. Indeed, products (flashlights, radios, watches, etc.) have been on the market for years that operate in this mode, and researchers are driven to leverage other devices into this niche, while finding alternative ways to tap excess energy from human activity [104, 54]. Table 1 provides a perspective on the amount of power used by the human body during various activities. Everyday human activity consumes power at a rate of 81-1630W, a factor of 20 in energy use. Bearing in mind that any technique that parasitically harvests background energy from unrelated human activity must be totally unobtrusive to be commonly adopted, perhaps a couple of watts might be scavenged somewhere for a mobile phone or on-body computer without putting an onerous load on the user. The following sections examine this possibility with respect to power recovery from body heat, breathing, blood pressure, typing, arm motion, pedaling, and walking. A summary of the potentially scavengable power and the total power from various body-centered actions is provided in Figure The reverse, where people carry the reader to interrogate tags in the environment, is not as feasible, since the readers tend to be power hungry and large (e.g., several orders of magnitude more massive than the tags). 2. Note, however, that energy harvested from the user may require considerable conditioning (storage, voltage/current or impedance conversion, etc.) before it can be used for an application. Although we touch on a few important issues in conditioning power for piezoelectric generators, Chapter 7 of Edgar Callaway's "Wireless Sensor Networks" [44] provides an introduction to this topic specific to energy harvesting systems, and several other references on power conditioning are provided for the reader's convenience [46, 140].

5 Hot Bodies: Power from Body Heat

Since the human body emits energy as heat, it follows naturally to try to harness this energy. However, Carnot efficiency puts an upper limit on how well this waste heat can be recovered. Assuming normal body temperature and a relatively low room temperature (C), the Carnot efficiency is In a warmer environment (

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6 Conclusion

In the design of mobile electronics, power is one of the most difficult restrictions to overcome, and current trends indicate this will continue to be an issue in the future. Designers must weigh wireless connectivity, CPU speed, and other functionality versus battery life in the creation of any mobile device. Power generation from the user may alleviate such design restrictions and may enable new products such as batteryless on-body sensors. Power may be recovered passively from body heat, arm motion, typing, and walking or actively through user actions such as winding or pedaling. In cases where the devices are not actively driven, only limited power can generally be scavenged (with the possible exception of tapping into heel strike energy) without inconveniencing or annoying the user. That said, as detailed elsewhere in this volume, clever power management techniques combined with new fabrication and device technologies are steadily decreasing the energy needed for electronics to perform useful functions, providing an increasingly relevant niche for power harvesting in mobile systems.

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