An Approach to Improving The Power Management System in Electronic Devices

by

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Abstract

The current power management technology baseline does not address the increasing gap between system charge performance and functionality needs in a smartphone. This gap can eventually inhibit further increases in functionality and develop a balancing loop effect that reduces smartphone growth rates. Longer smartphone operation duration between recharging is currently being addressed with the introduction of low power circuit chips, low power displays and power management software. This thesis explores options that improve overall power management by looking at the power source and recharging methods. This thesis also explores technology transitions and management strategies that address the different multi-mode interactions between technology transitions.

Thesis Advisor: James M. Utterback

Title: David J. McGrath Jr. (1959) Professor of Management and Innovation

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To all my friends that I have made in the SDM program, I wish you the best of luck in your future endeavors. I know that, with the breadth of experience we have gained from the SDM program, you will succeed at your goals.

Finally, I would like to thank my family for their patience and support. They have encouraged me to seek my dreams, even if it means sacrificing my time with them. For that I am eternally grateful. Tracey, I cannot thank you enough for your support, encouragement and wearing multiple hats in the house. Aaron, daddy will now have more time to spend with you. To my parents, words cannot express the sacrifices you made to give me a great life.

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1. Introduction

Sales of electronic gadgets such as mobile phones, cameras, audio players and laptops continue to grow year over year. According to the Global Market Information Database (Global Market Database), 1.4 billion portable consumer electronics were sold in 2008, while in 2005 close to 1.0 billion portable consumer electronics were sold. It is expected that each of the gadgets sold came with a lithium ion battery and a corded power adaptor. The International Energy Agency (International Energy Agency) reported that an additional 280 gigawatts (GW) of new generating capacity will be needed between now and 2030 if policies that require energy efficiency in all consumer electronics are not implemented.

1.1 Mobile Phones Through the Years

Mobile phones, primarily smartphones, will be the focus of this paper. Mobile phones, which initially started with just voice, have evolved into a portable device with capabilities that mimic a personal computer. These new devices are known as smartphones and have fully integrated communication with voice, images and text. One of the key components in smartphones that has not seen vast development or breakthrough is the battery and recharging system. These fully integrated communication capabilities have significantly increased demand for improved battery system performance. Despite the recent publicity of wireless power transfer technology using magnetic induction techniques resulting in the availability of conduction mats, I have my doubts as to the significance that this technology will have in the consumer electronic space.

The intent of this work is to assess, from a system perspective, options to improve battery performance and recharging methods for mobile phones. I will also explore management issues in managing the integration of this new technology into the current system.

2. Motivation

How many times do you recharge your smartphone each day? Many times a day, I find myself recharging my iPhone using the Apple provided USB connection to my computer or the power adaptor. I do so because my current iPhone does not have a sufficient amount of charge to keep up with my habit of web surfing, watching videos, listening to music, and making phone calls throughout the day.

2.1 Battery System Trend

Despite advancement in the number of capabilities of a mobile phone, one area that is lacking is the battery system. In an environmental scan of phones with respect to energy charge, smartphones with full screens such as iPhone and Google Nexus One can be seen hovering at the higher end of energy charge requirements. Furthermore, through the years the strategy of increasing the overall battery system charge has been applied to enable newer and more powerful communication devices to be functional. Unfortunately, a significant increase in operating time has not been observed with the higher charge battery systems.

Figure 1 tabulates the chronological trend of battery charge capacity for mobile phone devices. As you can observe, the multi-functional devices with large screens are hovering at the higher end of the battery charge needs. This table further stresses the point that the only advancement in battery systems is in increasing its charge. Furthermore, despite power management devices and software that have been incorporated, overall phone operation time has not improved.

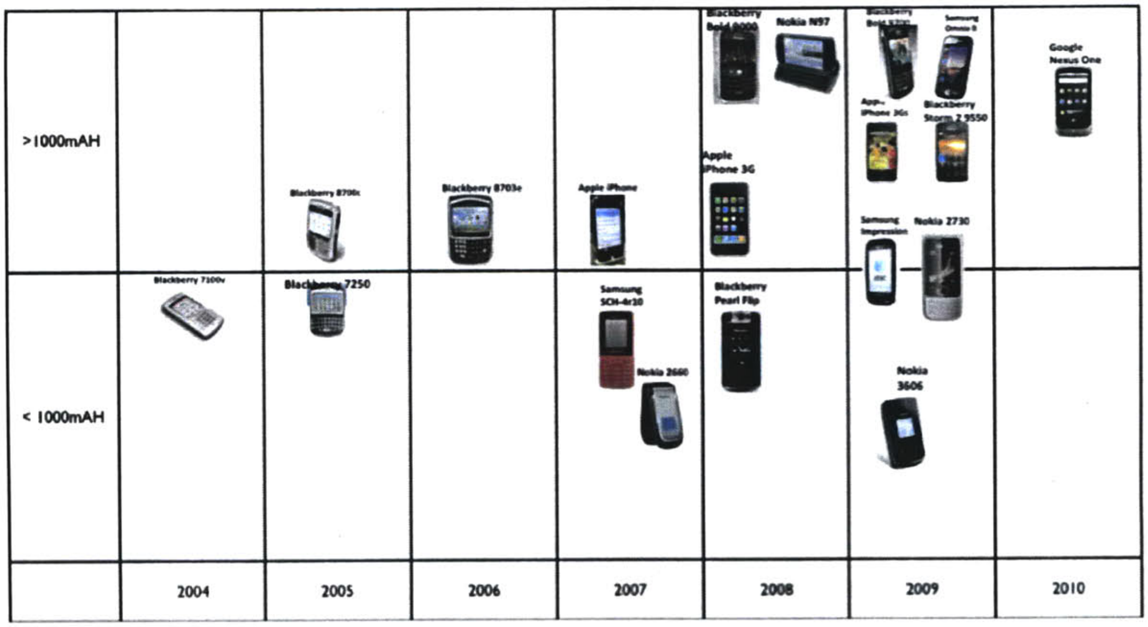

Figure 1 Battery Charge Capacity for Mobile Phone Devices

It is time to review what changes should be applied to the overall battery system to accommodate a significant leap in overall operating time, overall functionality and recharging method. There have been significant investments in newer energy technologies, but many recent announcements, such as from ARPA-E (Advanced Research Projects Agency-Energy), have been focused on large engineering systems such as transportation, carbon capturing and etc. I hope this paper will trigger some thought and debate about options for handset battery systems and provide insight into a new architecture that can address energy consumption and energy wastage from a bottom up perspective instead of top down.

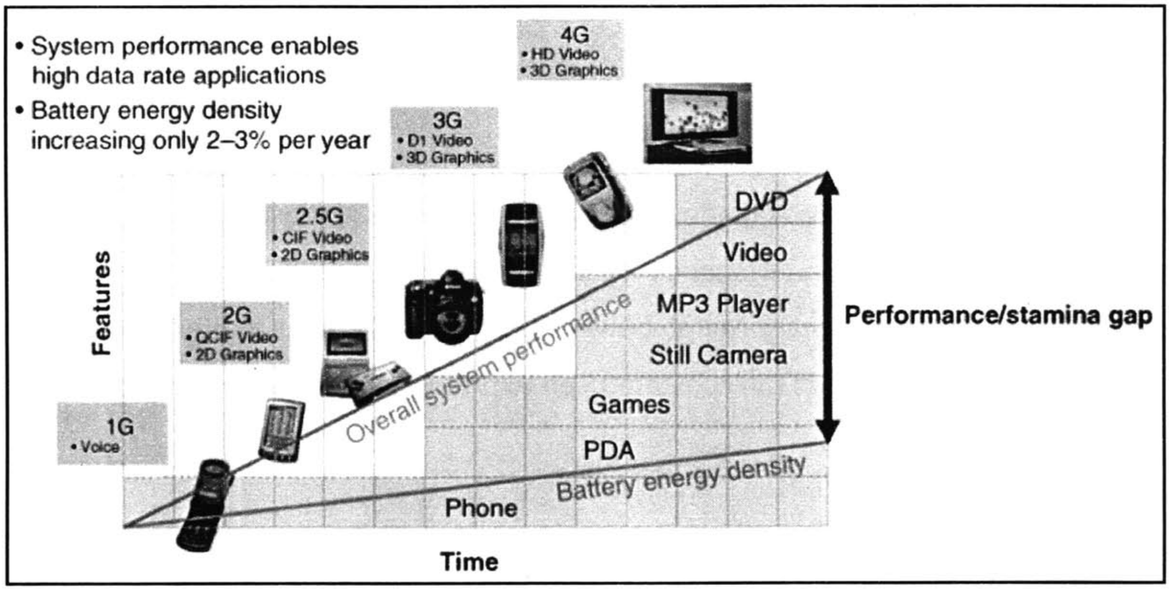

Figure 2 Gap Between Battery Energy Density and Overall System Performance

(Source: Shearer)

Figure 2 from Shearer (Shearer) illustrates the increasing gap between battery energy density and overall system performance. Despite an increase in functionality and device capability the battery charge density performance is only improving at a dismal 2-3% rate.

3. System Description

The mobile phone system is made of several sub-systems represented by concentric circles in Figure 3. The innermost circle is the smartphone system that comprises four main components that provide power efficiency and power to the system. The arrowed circle represents the constant need to fulfill the needs of consumer usability.

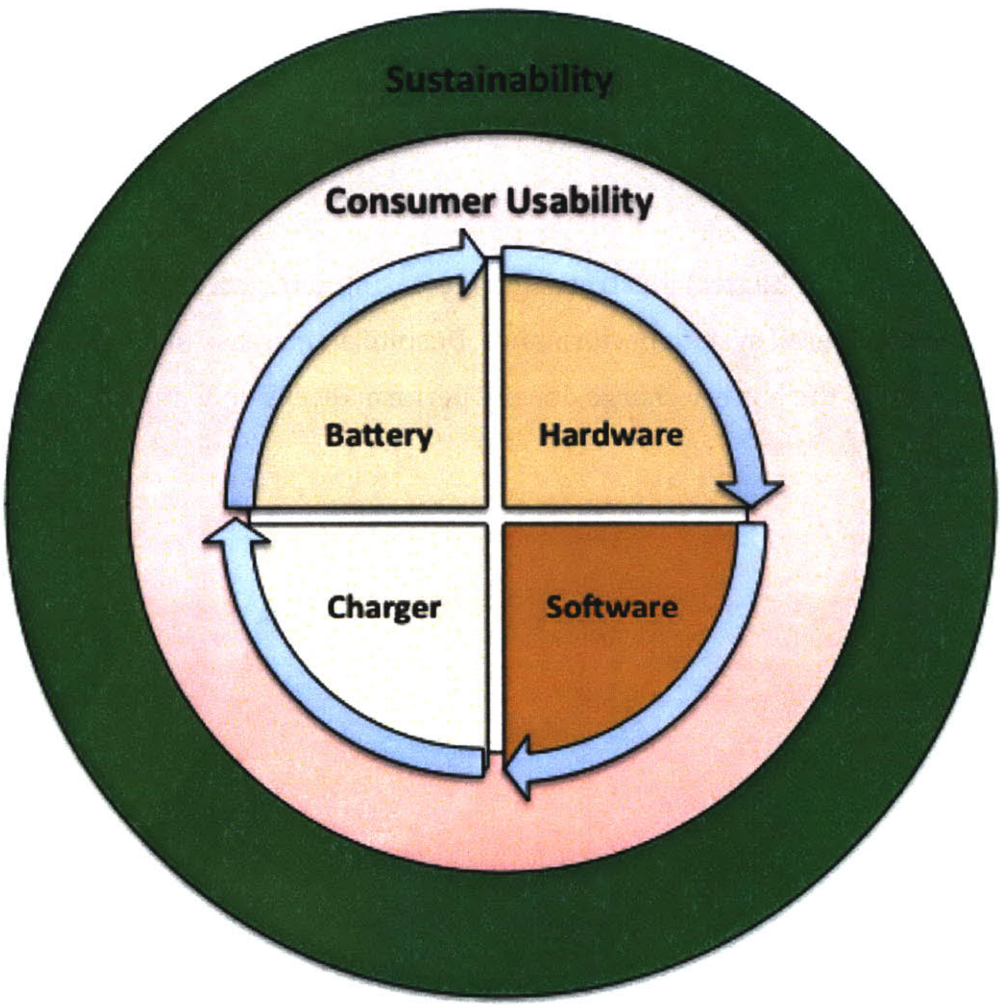

Figure 3 The Mobile Phone System is Part of a Larger System

The four components are hardware, software, battery and charger.

- Hardware includes the application processor chip, memory chip, liquid crystal display, and power management chip.
- Software includes the operating system, software optimization between the application processor and other related chips, and timing and software efficiencies to reduce operation during an execution.
- The battery provides the power to operate the device and can come in various forms such as a standalone device, like a lithium ion battery, or a combination of various other battery options.
- The charger is the standard adaptor that is shipped together with the smartphone and includes other options such as wireless charging methods.

Consumer usability needs is the need to provide a fully functional device or system that will provide constant access to the full range of smartphone applications. As with any smartphone, mobility is a key component. The user cannot have constraints, such as having to constantly look for a power outlet or a computer in order to recharge. One can estimate that the consumer needs at least a day's worth of power because an average consumer leaves their home during the day and returns to it at night, or a traveler leaves their hotel in the morning and ends up at another location to call it a day. The capability to provide power for full functionality for more than a day is more of a desire than a current need due to reasons explained earlier.

Sustainability is an important aspect of a system and covers a multitude of different components of a system. A smartphone system requires a sustainable solution for power management where the solution can be fabricated in high volume and over an extended duration. Furthermore, as more functionality is crammed into the smartphone, the solution has to be expandable to cover future needs through technology innovation, aside from the traditional process improvement for incremental improvements. Design modularity is a key design feature that enables a solution to be scalable at an effective rate. Modularity aims for flexibility and applicability across various product lines. Modularity here also requires some form of industry standardization in design and in interface.

4. Battery System Architecture

Figure 4 shows the Blackberry smartphone's block diagram from Phonewreck (Phonewreck). This figure shows the lithium ion battery connected to a power management chip, which is then connected to a processor. The processor is the brain behind the device. The lithium ion battery is a strong charge density device, and is controlled by a power management device to supply the necessary power to run the smartphone.

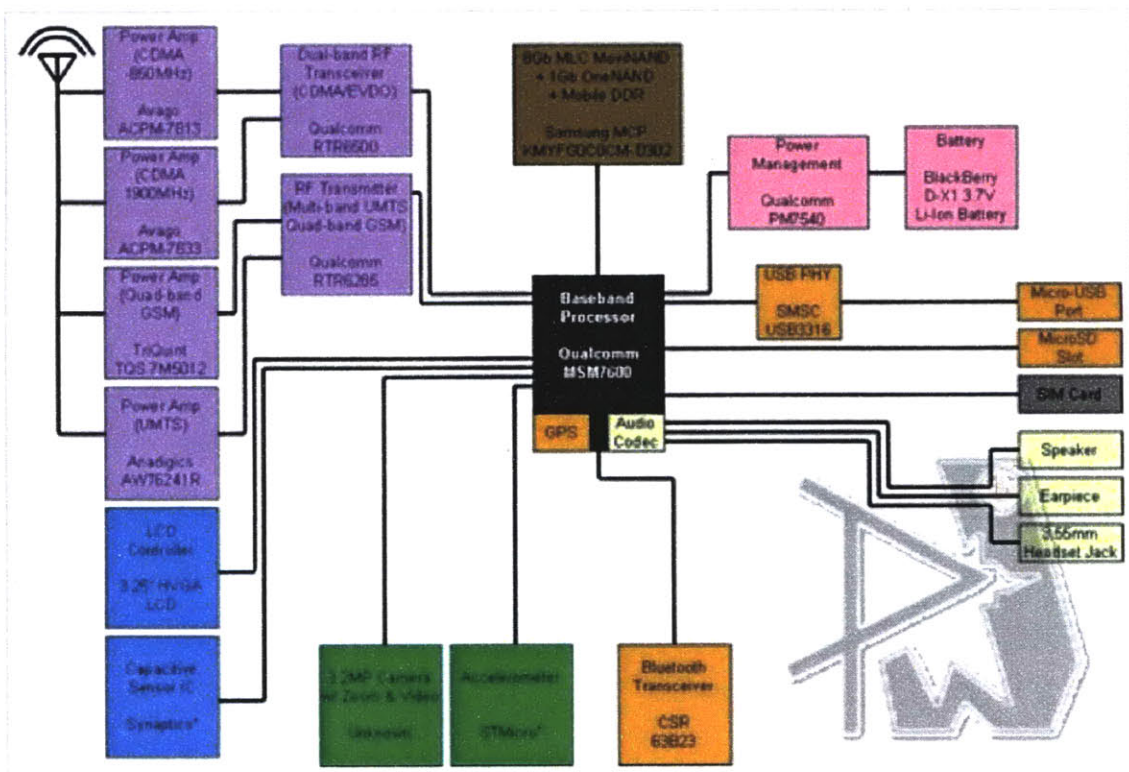

Figure 4 Blackberry Phone Block Diagram (Source: Phonewreck)

In the Apple iPhone's 3G technical specifications (Apple) the system uses a rechargeable lithium ion battery and has talk time of five hours and internet use time of five hours in 3G mode. All these results were collected from evaluations that were conducted in a controlled environment (Apple) where certain features were disabled and tests were conducted solely for the purpose of certain parameters. Additionally, in the footnote of the website, Apple disclosed that the performance may vary and is dependent on various other factors. In the Google Nexus One's technical specifications (Google) the system uses a 1400 mAH battery and has talk time of seven hours and internet use of five hours in 3G mode.

Table 1 is a list of specifications for different phone devices sold on the market.

Table 1 and **Figure 1** illustrate that higher energy charge lithium ion batteries are being used for newer devices and that there is a progressive increase in lithium ion energy charge with respect to the multi-functionality of the devices; increasing functionality such as larger screens require higher energy charge lithium ion battery.

Table 1 Mobile Phone Specifications

Phone	Release Year	Phone Type	Screen	Rechargable Battery Type	mAH	Talk Time (hours)	Standby Time (hours)	Internet Use (hours)	Video Playback (hours)	Audio Playback (hours)
Google Nexus One	Jan-10	Smart phone	Full	Li-Ion	1400	7	250	5	7	20
Apple iPhone 3Gs	Jun-09	Smart phone	Full	Li-Ion Polymer	1219	5	300	5	10	30
Apple iPhone 3G	Jul-08	Smart phone	Full	Li-Ion Polymer	1150	5	300	5	7	24
Apple iPhone	Jun-07	Smart phone	Full	Li-Ion Polymer	1400	8	250	5	7	24
Samsung Omnia ii	Nov-09	Smart phone	Full	Li-Ion	1500	10	430	-	-	-
Samsung Impression (SGH-a877)	Mar-09	Smart phone	Full	Li-Ion	1000	3	250	-	-	-
Samsung SCH-r410	2007	Non smart phone	Half	Li-Ion	800	2.5	200	N/A	N/A	N/A
Blackberry Bold 9700	Oct-09	Smart phone	Half	Li-Ion	1500	6	504	-	-	38
Blackberry Storm 2 9550	Jul-09	Smart phone	Full	Li-Ion	1400	5	305	N/A	N/A	N/A
Blackberry Pearl Flip 8220	Sep-08	Smart phone	Half	Li-Ion	900	4	336	N/A	N/A	N/A
Blackberry Bold 9000	Aug-08	Smart phone	Half	Li-Ion	1500	4.5	324	N/A	N/A	N/A
Blackberry 8703e	Nov-06	Smart phone	Half	Li-Ion	1100	3	480	N/A	N/A	N/A
Blackberry 7250	Feb-05	Smart phone	Half	Li-Ion	960	3.3	192	N/A	N/A	N/A
Blackberry 8700c Electron	Nov-05	Smart phone	Half	Li-Ion	1100	4	384	-	-	-
Blackberry 7100v	Oct-04	Non fully smartphone	Half	Li-Ion	960	-	-	N/A	N/A	N/A
Nokia 2730	May-09	Smart phone	Half	Li-Ion (BL-5C)	1020	7	360	-	-	-
Nokia 3606	Mar-09	Non smart phone	N/A	?? (BL-4B)	700	3.5	264	N/A	N/A	N/A
Nokia N97	Dec-08	Smart phone	Full	Li-Ion (BL-4D)	1500	9.5	432	-	4.5	40
Nokia 2660	May-07	Non fuly Smart phone	N/A	Li-Ion	700	7	312	N/A	N/A	N/A

5. Mobile Phone Power Consumption

Simulation of mobile phone power consumption during operation has shown power consumption to fluctuate depending on state of operation. According to simulations by Portalligent (Portalligent) on a Samsung SPH-W7900 smartphone, power fluctuated between 0.2 watts and 2.6 watts during a phone call, power peaked close to 6.0 watts during a camera flash operation, and multiple power peaks were observed throughout gaming mode. Simulations are shown in Figure 5 to Figure 7.

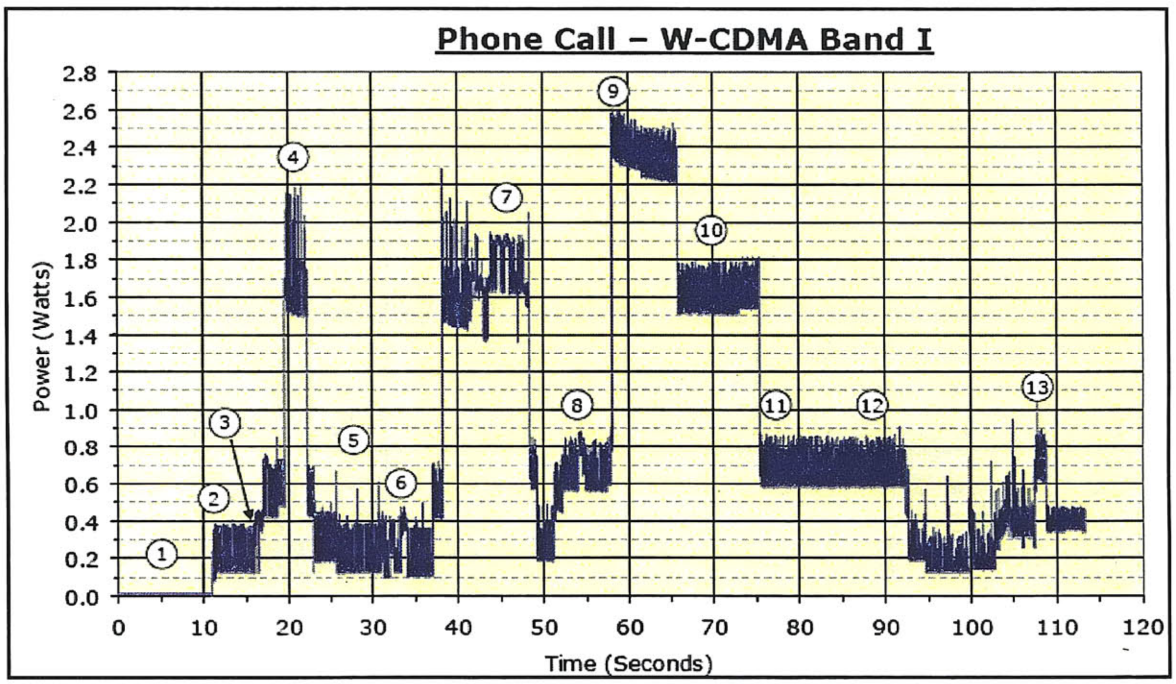

Figure 5 Power Consumption Simulation for a Phone Call (Source: Portalligent)

In Figure 5, during a phone call simulation power fluctuations were observed and fluctuated from 0.2 watts to 2.6 watts depending on the operation and function during the phone call.

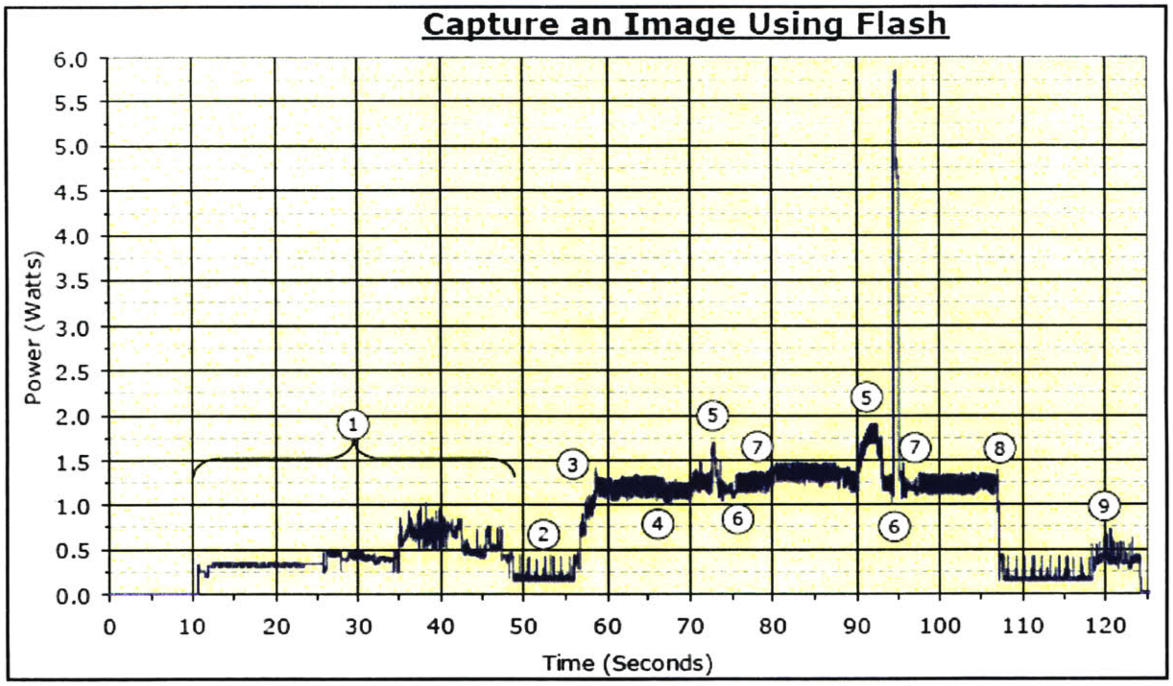

Figure 6 Power Simulation When Flash is Used (Source: Portalligent)

In Figure 6, during an image capture process with the flash turned on power peaked at 6.0 watts, whereas during the regular camera operation power hovered around 1.0 watts to 1.5 watts.

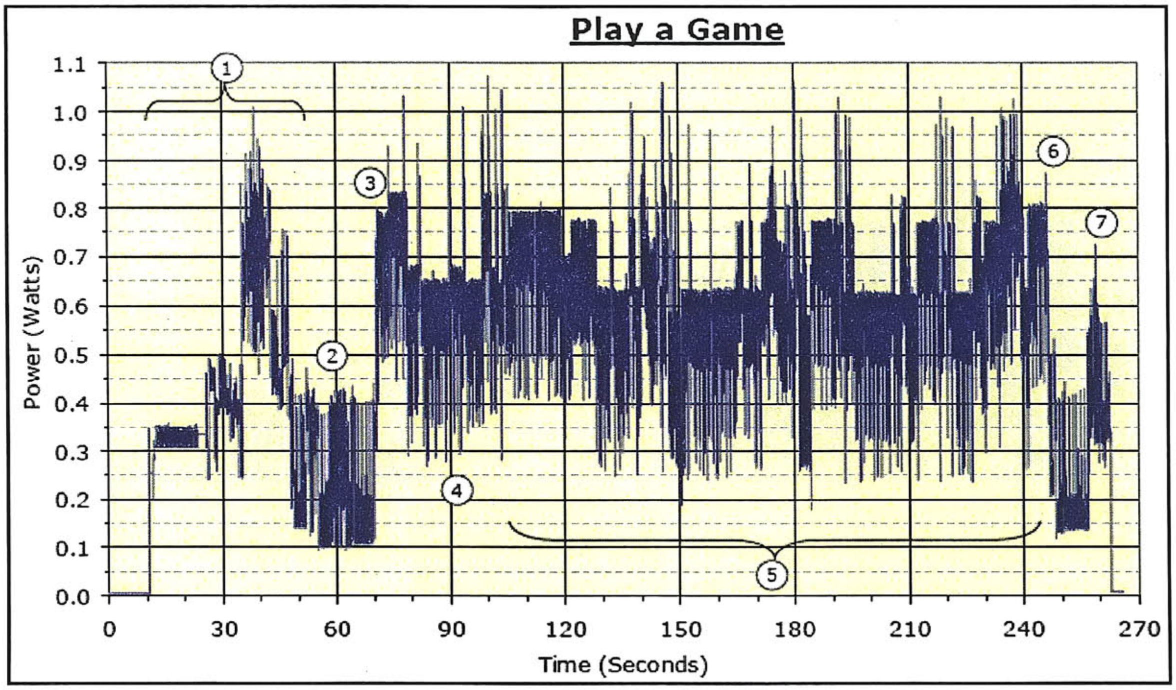

Figure 7 Power Simulations While Playing a Game (Source: Portalligent)

In Figure 7, when the phone is in gaming mode significant fluctuations were observed throughout the phone operation. The need for power density is significantly higher compared to other operations.

Throughout a phone operation the entire phone system is supported by a single battery system, which is usually a lithium ion battery. Lithium ion is mostly known for its energy capacity per unit volume and weight (energy density and specific energy) rather than its power density. Energy density is characterized as the amount of energy stored. The higher the energy density the more energy is stored for the same amount of mass. Power density, on the other hand, is the rate of energy discharge. The higher the rate of discharge the faster energy can be transmitted. Hence, high power density is more suitable to address power fluctuations whereas higher energy density is more suitable to address stable power consumption.

6. Energy Storage Technology Comparisons

Figure 8 through Figure 11 are from the Electricity Storage Association (Electricity Storage Association) and show the different energy storage systems with respect to different performances. Lithium ion batteries have significant advantages in its small form factor, light weight and long life efficiency, but its disadvantages are in its low power density, high discharge time and higher cost relative to other storage devices.

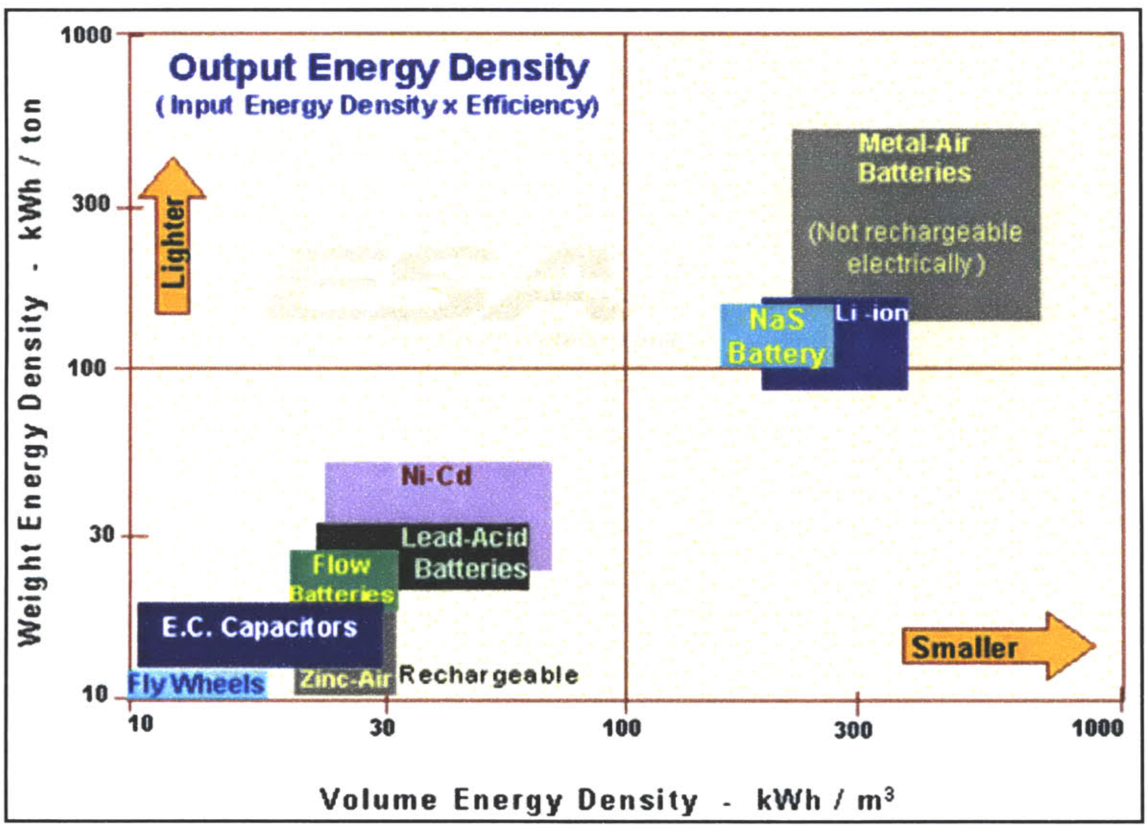

Figure 8 Relative Comparison of Volume and Weight Energy Density Between Storage Devices (Source: ESA)

Figure 8 compares energy storage capability versus weight and energy density. Lithium ion has a significant form factor advantage to meet energy density requirements.

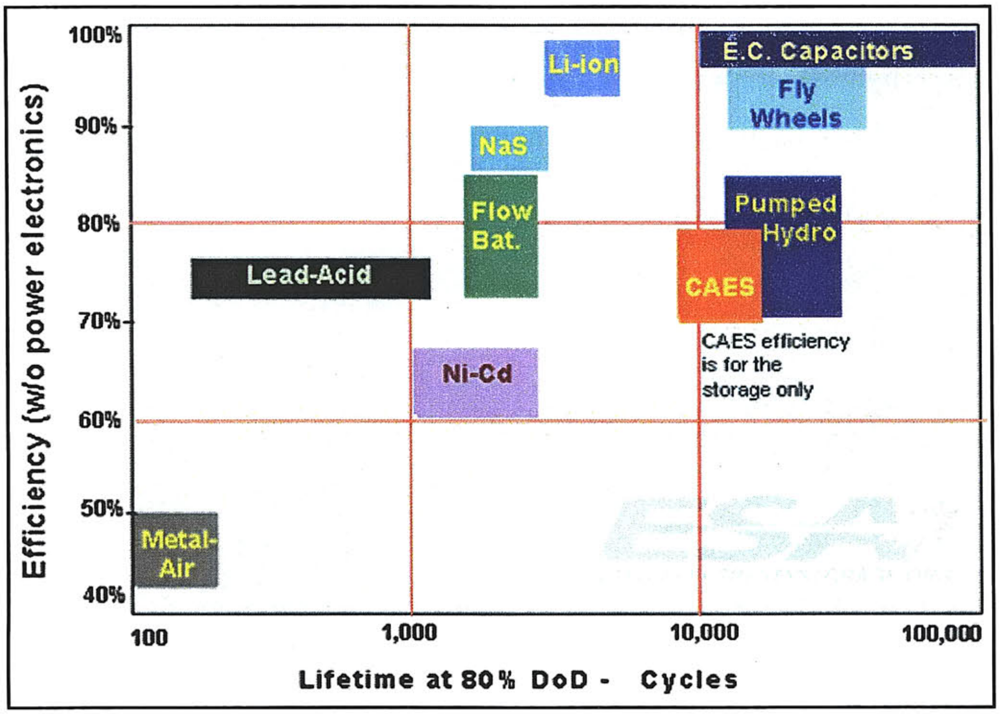

Figure 9 Energy Storage Efficiency (Source: ESA)

Figure 9 compares the energy efficiency between different storage capabilities. Lithium ion and ultracapacitors have some of the highest efficiencies. This is critical in assessing the overall speed to discharge.

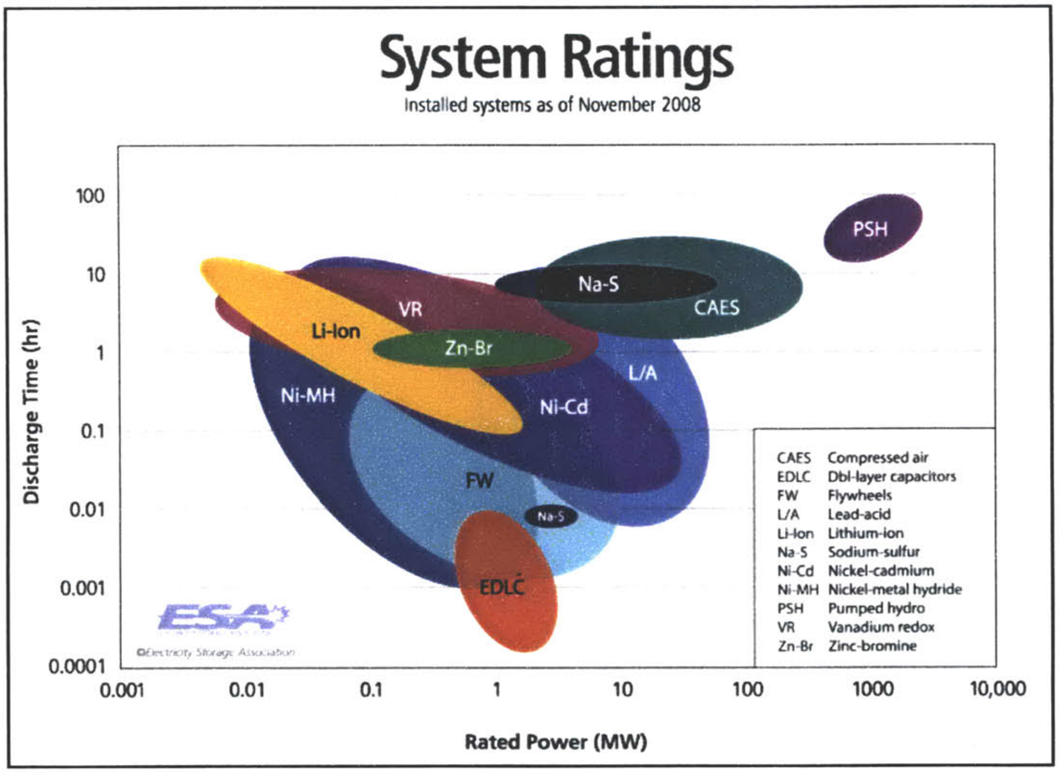

Figure 10 Energy Storage Comparison Between Discharge Time Versus Power Rating (Source: ESA)

As shown in Figure 10, ultracapacitors have an extremely fast discharge rate compared to other solutions for a comparable power discharge. Power rating solutions greater than an ultracapacitor is not necessary for consumer electronic applications. Furthermore, these solutions would not meet the form factor required for the consumer electronic industry.

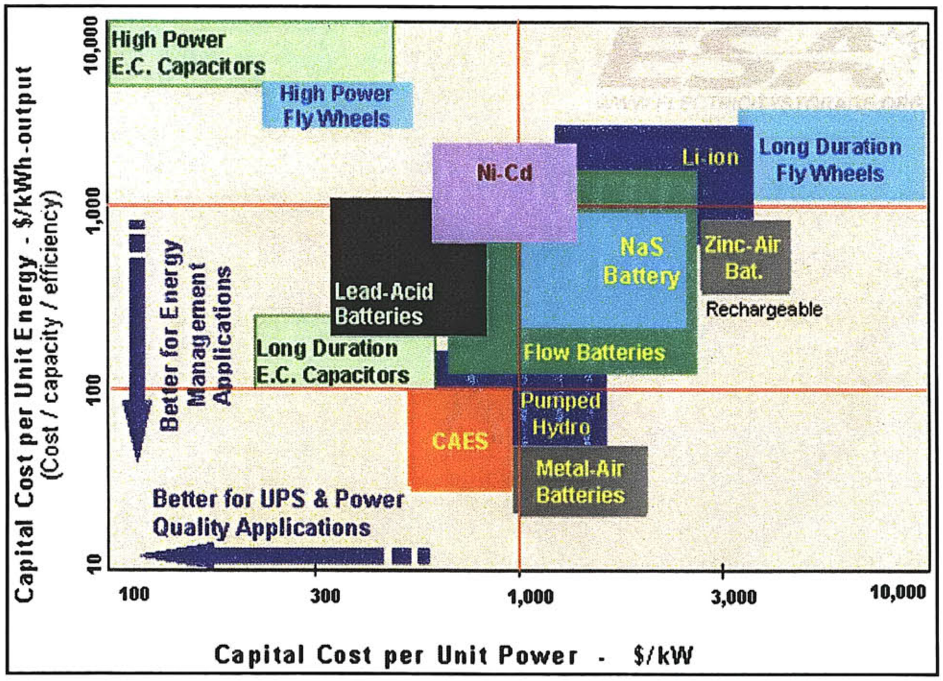

Figure 11 Capital Cost Comparison Between Energy Storage Devices (Source: ESA)

In Figure 11 the ESA shows that battery costs have been adjusted to exclude the cost of power conversion electronics, and the cost per unit of energy has been divided by the storage efficiency to obtain the cost per output (useful) energy. Unfortunately, total cost of ownership is not included in the charts despite it being a critical parameter, and much more meaningful for economic analysis. For example, while the capital cost of lead acid batteries is relatively low, they may not necessary be the least expensive option for energy management (load leveling) due to their relatively short life. A holistic system engineering approach is required to select a sustainable system that fulfills the need to meet the increasing functionality of smartphones, which require a battery system that handles both power fluctuations and stable energy output.

Based on Figure 11 from ESA, the storage technologies that have a high power density are flywheels, capacitors and nickel-cadmium batteries. These three storage options will be used later to assess suitable applications to address power fluctuations in smartphones.

Aside from commercially available storage solutions, there are technology breakthroughs with carbon nanotube ultracapacitors, micro fuel cells, and advanced batteries that have to be considered, but are still in the development stage. Concurrently, there are also continuous developments to improve existing storage solutions, such as Massachusetts Institute of Technology's Ceder Research Group (The Independent) that are looking into genetically engineered viruses to build fast charge lithium ion batteries, MIT's Prof. Horn's (Chandler) work on increasing electrode efficiencies in fuel cells by changing the surface morphology of the electrode and using methanol instead of hydrogen, and California based ZPower's work (Frost & Sullivan) on nanoparticle-enhanced electrodes which display twice the energy density of current lithium ion batteries.

According to Epcos (Epcos), several orders of magnitude of difference in energy density can be observed between commercial batteries and capacitors. Capacitor technology is improving over time and recently a new breakthrough from the Massachusetts Institute of Technology using carbon nanotubes in an ultracapacitor has exhibited energy density close to par with commercial batteries. Figure 12 from Epcos illustrates this performance comparison, and Figure 13 is the modified version of Figure 12 with the inclusion of the carbon nanotube ultracapacitor.

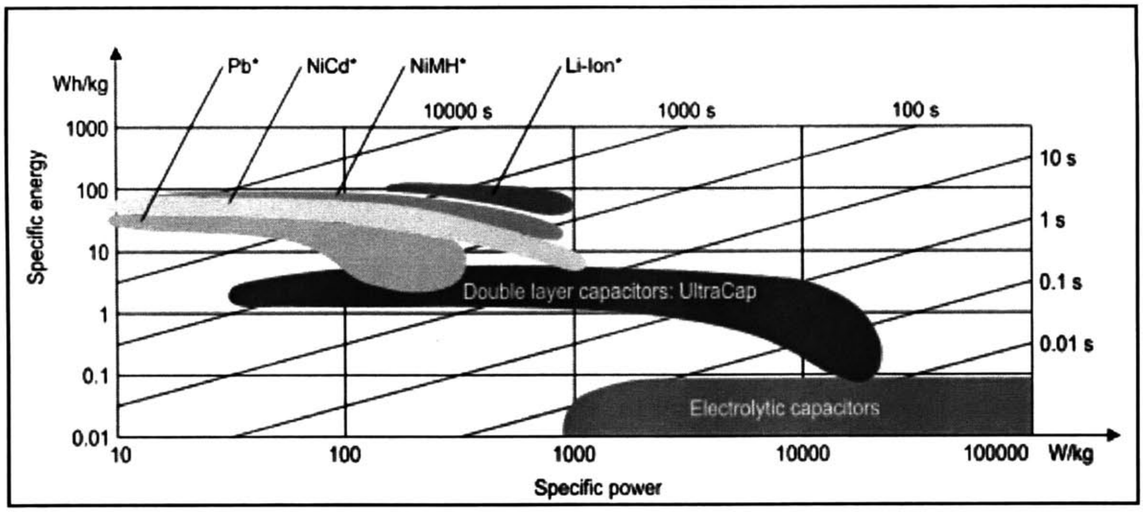

Figure 12 Specific Energy and Specific Power Density Comparison Between Different Energy Storage Devices (Source: EPCOS)

According to the MIT Laboratory for Electromagnetic and Electronic Systems, there is excitement growing around the NEU technology with its marked improvement in both energy density and in power density. The energy density is still lower than lithium ion, but the improvement is still significant. This comparison is shown in Table 3.

Table 3 Capacitor Performance Comparison (Source: MIT)

	Double Layer Capacitor (typical)	Li-Ion Battery (typical)	MIT NEU Expected Performance
Energy density (Wh/kg)	5.44	140	30-80
Power density (kW/kg)	5.61	0.2	40

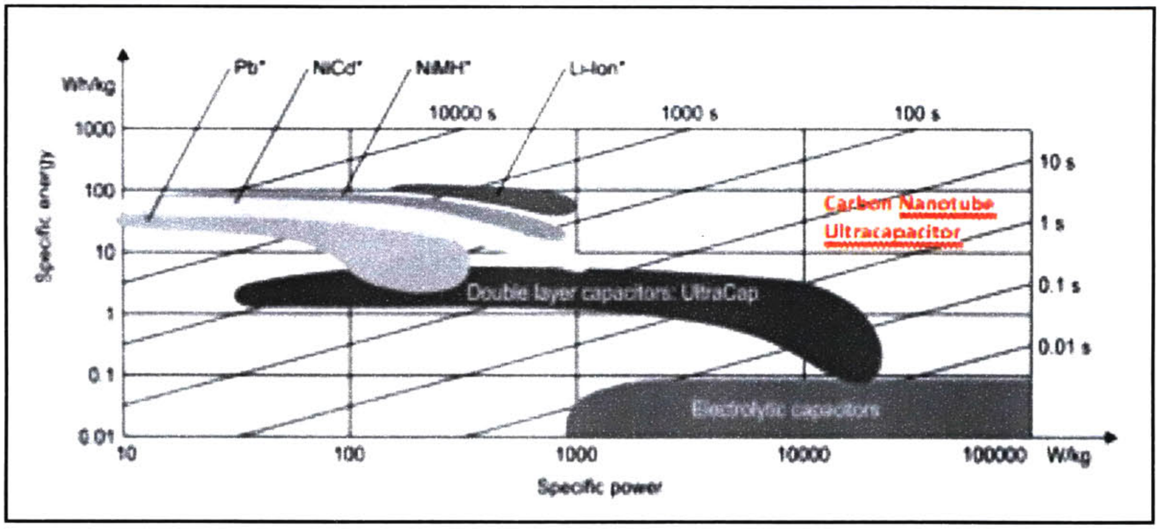

Figure 13 Carbon Nanotube Ultracapacitor Mapped Into Figure 12

Focus on battery system improvements has only increased recently. For example, according to Hoh and Magee (Hoh and Magee) dramatic improvements to capacitor technology with respect to energy density have shown capacitors to be slowly emerging as a competitive threat to the traditional chemical systems. Furthermore, the rate of technology improvement does not provide any indication that capacitors are approaching its technological limit.

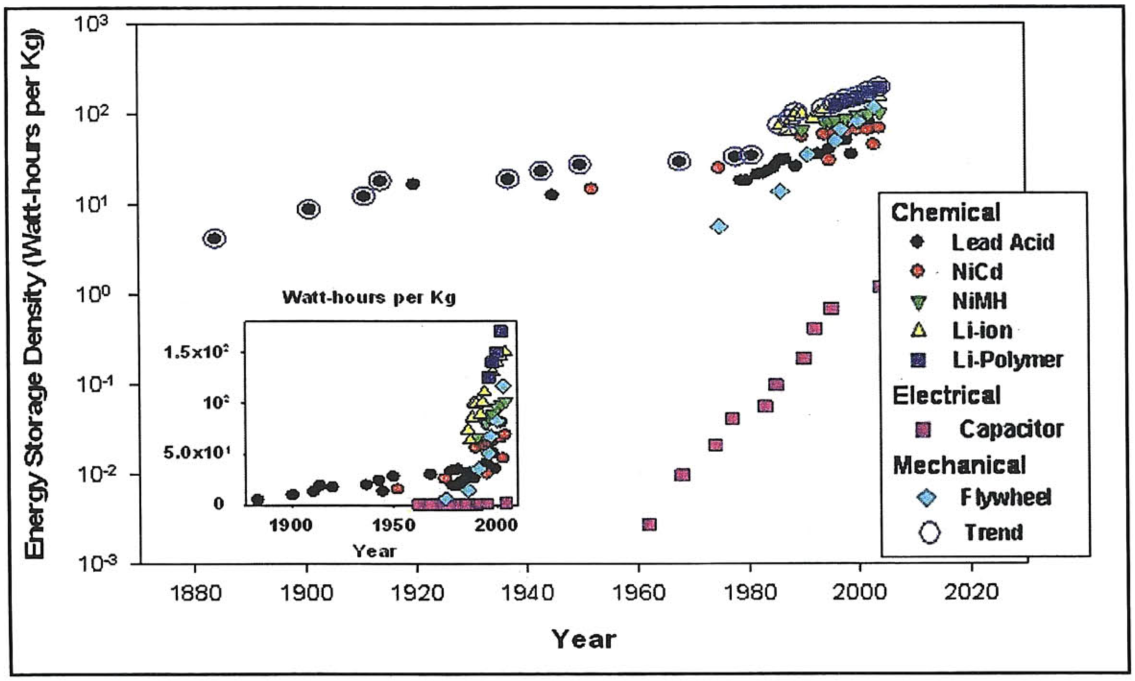

Figure 14 Energy Storage Density Improvements (Source: Hoh and Magee)

7. System Engineering Approach to Optimize Battery Systems

The Pugh method of Controlled Convergence (Hale) was used to define the possible options for the battery and charging system. This intent of using this method is to discover the advantages and disadvantages of each option with respect to a datum, which was assigned to the lithium ion battery, and to assess if there is a combination of options for the next round of selection. The second round of selection will involve ranking the characteristics in terms of its importance in order to provide a sustainable energy storage solution with the potential to meet current power and energy consumption demands.

The characteristics of a battery system for smartphones are the following:

- Energy density
- Power density
- Life efficiency: reliability
- Form factor: fit into a phone
- Charge and discharge rate
- Safety
- Recharge duration
- Availability: technology readiness for deployment
- Consumer behavior change: assesses if the options are transparent to the consumer and if it is visible to them

The possible options for energy storage are the following:

- Lithium Ion (Panasonic)
- Flywheels

- Electrochemical double layer capacitor
- Nickel-Cadmium
- Nickel-Metal Hydride
- Metal-Air batteries
- Microfuel cells
- Carbon Nanotube Ultracapacitor
- Ceder's new Lithium Ion or any equivalent Li-Ion improvement

Several candidates for energy storage were immediately eliminated due to reasons such as infeasibility to fit in the form factor and size required to be in a mobile phone and presence of hazardous materials that would not pass increasingly stringent safety and environmental regulations.

Table 3 shows the clear distinction in the progress of capacitors where improvements are seen in power density, but still an order of magnitude lower in energy density. Two paths were considered in terms of increasing the likely options for the Pugh's method of convergence (Hale) One was through a combination of strength in energy density and power density, and the other was through using a standalone energy density device. The former would be a strong combination and would serve the consumption of the smartphone, and the latter would require a significant leap in energy density and would align with the current practice of system designers where higher energy density batteries are deployed to manage the higher consumption of smartphones, as illustrated in **Figure 1** and

Table 1.

Table 4 is the for the Pugh method where the different available options were rated relative to the datum of the lithium ion battery. Several cells were highlighted within the table to illustrate the advantages within the critical characteristics, these highlights are critical for the iteration of the Pugh method.

Table 4 Pugh Matrix Selection of Energy Storage Solutions

Characteristics	Lithium Ion	EDLC	Ni-MH	NEU	Micro Fuel Cells	Nano Enhanced Li-Ion
Energy density	Datum	-	-	-	+	+
Power density		+	0	+	0	0
Life efficiency		+	-	+	+	+
Form factor		+	0	+	+	+
Charge / discharge rate		+	+	-	-	+
Number of deep charge / discharge cycles		+	-	+	+	+
Safety		+	0	+	-	0
Availability		0	0	-	-	-
Environmental Impact		+	0	-	+	0
Consumer Behavior Change		0	0	0	-	0
Replacement parts		-	0	-	-	0
Distribution Market		0	0	0	-	0
Sum (+)		7	1	5	5	5
Sum (-)		2	3	5	6	1
Sum(0)		3	8	2	1	6

Pugh's concept of controlled convergence involves convergence and divergence where, after each selection and scoring, the options available were narrowed and the strengths are combined to discover possible additional alternatives. The divergence path expands to include additional alternatives and the iteration of convergence and divergence continues. The Pugh iteration was stopped after the first iteration to account for possible near-term strategies and possible long-term strategies for adoption.

For mobile phones, the key characteristics are energy density, power density, form factor, number of deep charge/discharge cycles, expected customer behavior changes, availability, and distribution market. In the next round of selection, weights were assigned to key characteristics and individualized scores were normalized.

The ratings were grouped into 3 segments: greater than or equal to 0.2, between 0.1 and 0.2, and less than or equal to 0.1. The ratings were heavily weighted towards energy density, power density and consumer behavior change. This group was primarily focused on meeting and exceeding battery characteristics and the effects of the change to the consumer. The second group consisted of form factor, number of deep discharge and charge, and distribution market. The focus here was on deployment and the secondary factors for battery characteristics. Finally, technology availability was assigned to the last group, since deployment is broken into near-term deployment and long-term deployment.

Table 5 tabulates the result of the divergent, and the near term strategy of combining commercially available lithium ion batteries and capacitors should be further explored. For the long-term, as technology breakthroughs in lithium ion become commercially available, combinations with capacitors or pure standalone lithium ion batteries could be the interim long-term solution. According to Frost and Sullivan(Frost & Sullivan), the current lithium ion technology is only expected to see incremental improvements of 1% to 2% a year in power density, and energy density improvement is tapering off, hence a significant technology shift is required for lithium ion to undergo a leap in energy density. Nano enhanced electrodes in lithium ions are currently showing that promise to shift the technological trajectory.

In Table 5, one observation to note is that, despite scoring high, the combination of a lithium ion battery with a carbon nanotube ultracapacitor was excluded from the near term strategy. The reason for the exclusion is the unavailability of commercial ready carbon nanotube ultracapacitors for the electronic industry. Based on commercially available readiness, it would be best suited for carbon nanotube ultracapacitor to be introduced with an improved lithium ion battery system instead of an available lithium ion system.

Hence for the near term, lithium ion batteries with an electrochemical double layer ultracapacitor will be a significant improvement compared to the current plain lithium ion battery. This combination will provide the power density to handle the multi-functional applications that are found in smartphones today. For a long-term strategy, the combination of an improved lithium ion battery with an ultracapacitor or carbon nanotube ultracapacitor, or even just an improved lithium ion standalone battery should be explored as possible options. The best technology may not win the race due to factors such as market timing, technology capability versus future needs, industry player strategy in going for higher value market segments, and etc. This is definitely a future area of focus.

Table 5 Pugh Matrix Expansions with Multiple Combinations

Characteristics		Li + EDLC		Li + NEU		Micro Fuel Cells Standalone		Micro Fuel Cells + EDLC		Micro Fuel Cells + NEU		Nano Enhanced Li-Ion Standalone		Nano Enhanced Li-Ion + EDLC		Nano Enhanced Li-Ion + NEU	
	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Energy density	0.25	3	0.75	3	0.75	5	1.25	5	1.25	5	1.25	4	1	4	1	4	1
Power density	0.2	4	0.8	5	1	3	0.6	4	0.8	5	1	3	0.6	4	0.8	4	0.8
Form factor	0.1	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4
Number of deep charge / discharge cycles	0.1	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4	4	0.4
Availability	0.05	4	0.2	1	0.05	2	0.1	2	0.1	1	0.05	2	0.1	1	0.05	1	0.05
Consumer Behavior Change	0.2	4	0.8	4	0.8	1	0.2	1	0.2	1	0.2	4	0.8	4	0.8	4	0.8
Distribution Market	0.1	4	0.4	2	0.2	2	0.2	2	0.2	2	0.2	2	0.2	2	0.2	2	0.2
Total Score			3.75		3.6		3.15		3.35		3.5		3.5		3.65		3.65
Rank			1		5		6		7		8		4		2		3
Continue (Y/N)?			Y		N		N		N		N		Y		Y		Y
Near-Term or Long-Term			NT		N/A		N/A		N/A		N/A		LT		LT		LT

8. Battery Charging Systems and Options

There is recent hype in the consumer electronics industry over displays of wireless power technologies showcased in the annual January Consumer Electronics Show in Las Vegas since 2007. This capability can be viewed as the last milestone into a truly mobile experience. Gadgets such as the Energizer accessory for recharging a Wii game controller, the Dell Latitude Z business laptop that can be recharged when placed on a stand, the Powermat mat charger, and Bosch power tools that can be recharged by placing them on a workshelf are some of the products that have been recently introduced into the market.

Wireless power transfer technology only became more significant due to the increased focus on mobility and increased functionality of electronic gadgets. This is evident in the competition's beachhead target, which is primarily mobile devices such as smartphones, although there have been some recent breakthroughs in power tools, laptops and kitchen appliances. Furthermore, in Portalligent's simulations, smartphone devices undergo various power and energy consumption cycles throughout its operation, and as a result the battery system installed needs to be recharged frequently since the system is not designed to meet those needs.

The combination of mobility and increased product functionality creates a perfect storm. Increased mobility requires a more flexible recharging method and an increasingly flexible recharging method reduces the ownership of power adaptors. The current norm is to use a power adaptor to recharge the battery system; power adaptors are already standard items in every electronic kit.

Following the technology adoption lifecycle proposed by Everett M. Rogers (Rogers), currently wireless power technology can be considered to be at the early adopter stage. There are many questions surrounding this new technology: is wireless power only a convenience, what is the industry standardization strategy, what is the marketing strategy to cross the chasm, what are the health implications, is this the permanent replacement for batteries, and what is the incumbents' strategy to address this attack?

From some initial data, Duracell's myGrid mat product is marketed as a convenience and an elimination of the cord. In contrast, Powermat suggested in their owner's manual that their power pad is more energy efficient since it "eliminates the power that is wasted when each adapter is left plugged into the wall." As such there is no industry standard perception of wireless power.

8.1 Wireless Power Technology Overview

The two methods of wireless power technology being considered are near field energy transfer and far field energy transfer.

8.1.1 Near Field Energy Transfer

The near field energy transfer method refers to the transmission of energy wirelessly at close-range and mid-range distances. Close-range distances are comparable or smaller than the size of the device, while mid-range distances can be equal or even few times the size of the device. Magnetic induction and magnetic resonant induction are two methods of near-field energy transfer. In magnetic induction, two coils are involved and when current is passed through the first coil, a magnetic field is generated. When the second coil is within proximity of the magnetic field, current is then generated on the second coil. The disadvantage of electromagnetic induction is the low efficiency of the transmitted energy when the distance between the two coils increases, so transmitted energy is wasted.

Magnetic resonant induction is capable of transferring energy at greater distances than magnetic induction. The physical difference between electromagnetic resonant induction and electromagnetic induction is the self-resonant coil used in the former. When two self-resonant coils are placed within transmission proximity and resonate at the same frequency, they achieve a higher efficiency due to less wasted transmitted energy. Hence, magnetic resonant induction has greater transmission distances. The amount of energy transfer here is also a function of the distance between the two coils. According to Kurs (Science Magazine), in systems of coupled resonances, there is often a general strongly coupled regime of operation. If one can operate in that regime in a given system, the energy transfer is expected to be very efficient.

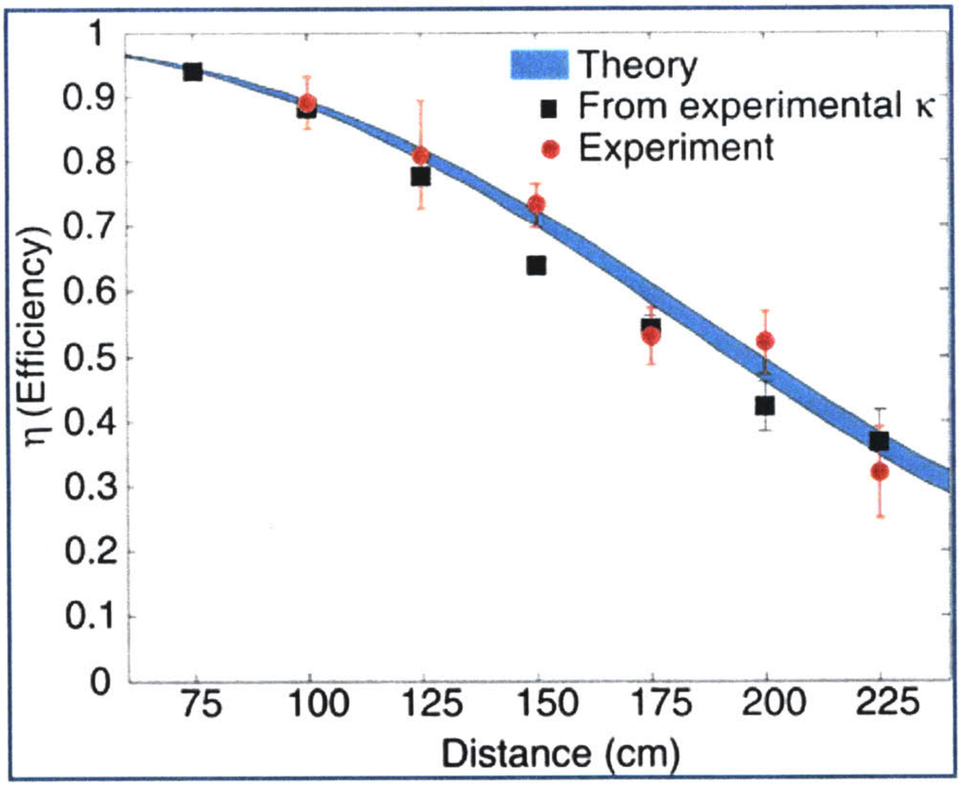

Figure 15 Electromagnetic Resonance Wireless Power Transfer Efficiency (Source: Kurs)

8.1.2 Far Field Energy Transfer

Far field energy transfer refers to wireless energy transfer at distances much larger than the size of the device, possibly up to kilometers in range. The technology enabling such transfer over long distances is mostly based on electromagnetic radiation. The energy is sent in the form of microwaves or radio waves from the transmitter to a special type of detector called a rectenna, a rectifying antenna, which enables the conversion of microwave energy into direct current. This transfer method will not be covered in this paper.

8.2 Wireless Power Technology Parameters

According to WiPower (WiPower), the parameters for wireless power technology are:

- Efficiency: Effective power received by device
- Range: Distance between power source and device
- Power: Charge capability
- Size
- Freedom of movement
- Cost

A technology envelope characterizes the technology limits where the technology can operate. Normally, within this envelope trade-offs between parameters occur. As illustrated in Figure 15, a trade-off between power transfer efficiency and distance is observed where efficiency decreases as a function of distance. This observation is found in all wireless power transfer methods. WiPower also accounted for the current competing technologies by distance in Figure 16.

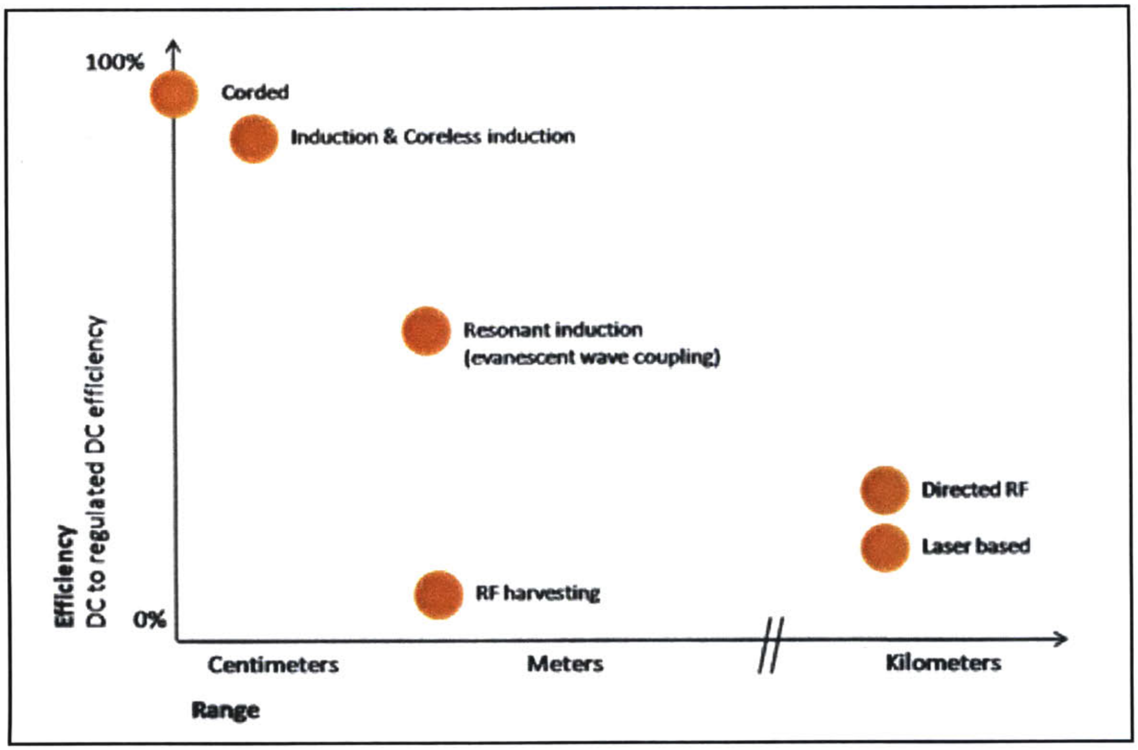

Figure 16 Wireless Power Transfer Methods by Distance (WiPower)

In Figure 16 and Figure 17 power cords have the highest power density, followed by induction and cordless induction. Losses from transfers through cords and from device efficiencies are not considered here.

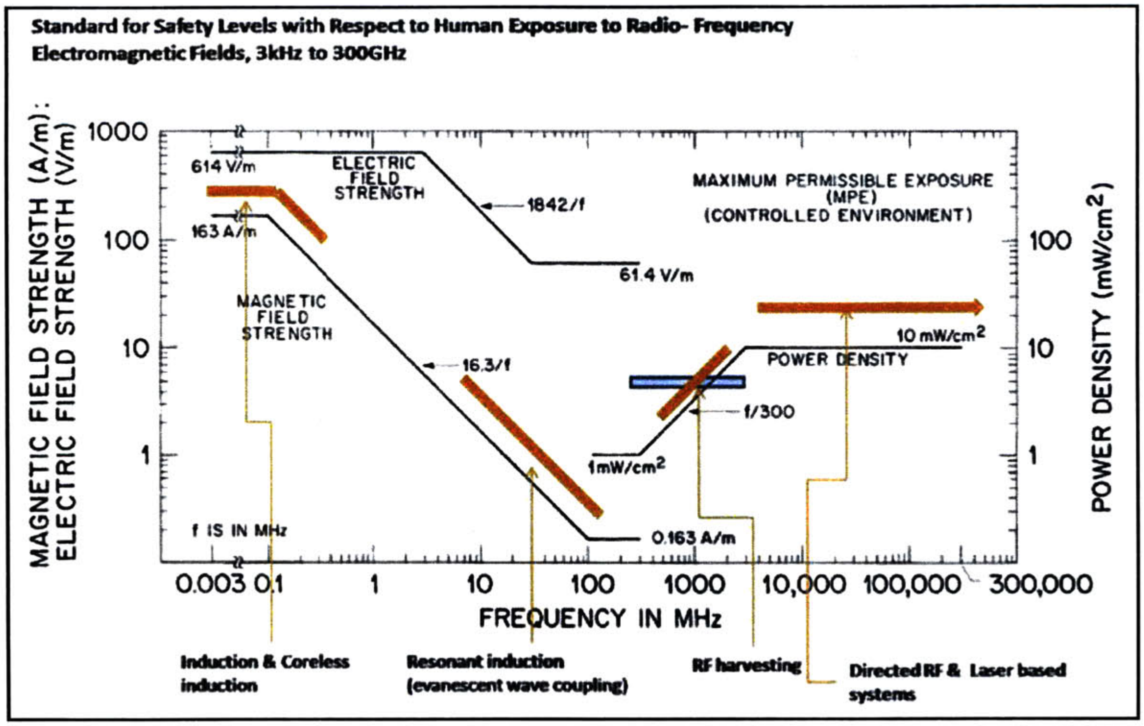

Figure 17 Power Density Comparison (WiPower)

8.3 Recharging Methods

A survey of players in the wireless power industry was conducted. A corded power strip was included into the comparison to establish the current technology baseline.

The existing practice requires consumers to attach their mobile phones to an interface or adaptor which is connected to a cord that is plugged into a wall outlet or a power strip.

From the survey of wireless power players, both magnetic induction power transfer and magnetic resonance induction power transfer use a transmitter and a receiver, and the difference lies in distance of contact allowance between the transmitter and the receiver. In both systems, the transmitter is attached through a power cord to a wall outlet or a power strip, and the receiver is a separate attachment that is attached to the mobile phone. In magnetic induction, the receiver and the transmitter have to be in direct contact, whereas for resonant magnetic induction there is a distance of separation allowed before transfer efficiency reduces significantly; no physical contact is needed.

There are also two approaches in the industry to bring these products to market. The first approach is to sell the transmitter and the receiver directly to the end users. The other approach is to partner with an original equipment manufacturer (OEM) and to incorporate the products into their product lines. The first approach has full design flexibility where these are only considered as add-ons. The second approach reduces the overall design flexibility and usability flexibility. For example, a hotel desk incorporated with a transmitter will not be of use to someone who does not have a phone that has the receiver. In both cases, power adaptors will certainly continue to be supplied. Mobile phone companies will certainly not limit phone usability with a battery system that is not considered to be their core technology.

8.4 Recharging Logistics

New technology introduction usually introduces changes to consumer behavior. A comparison between expected consumer behavior changes was assessed for wireless power, and the current method of using a power strip cord or wall outlet was included as a baseline.

Table 6 shows the comparison between the different recharging methods and its overall impact to consumer behavior.

Table 6 Recharging Logistics Comparison

Method	Cord	Transmitter	Receiver	Distance	Consumer Action	Change to Consumer Behavior
Current Practice	Y	Corded power strip attached to wall outlet	Adaptors supplied by manufacturers	Direct connection	Attach phone to adaptor	Neutral
Current Practice	Y	Wall outlet	Adaptors supplied by manufacturers	Direct connection	Attach phone to adaptor; attach to wall outlet	Neutral
Electromagnetic Induction	Y	Corded pads attached to power strip	Specific receiver matched to corded pad	Direct connection	"Attach" phone with receiver to pad	Minimal Change
Electromagnetic Induction	Y	Corded pads attached to wall outlet	Specific receiver matched to corded pad	Direct connection	"Attach" phone with receiver to pad	Minimal Change
Resonant Electromagnetic Induction	Y	Corded transmitter attached to power strip	Specific receiver matched to transmitter	Indirect connection	Close proximity to transmitter	Positive
Resonant Electromagnetic Induction	Y	Corded transmitter attached to wall outlet	Specific receiver matched to transmitter	Indirect connection	Close proximity to transmitter	Positive

According to John Gourville (Gourville) the rate of market adoption or customer acceptance is based on behavioral changes and perceived product benefits. When mapping the different technologies to the current practice the magnetic induction method would be equivalent to using a power strip since the pad is constantly attached to the power outlet just like a power strip, there is no consumer behavior change since all a consumer is required to do is place the electronic gadget onto the pad similar to placing the electronic gadget in an adaptor that is attached to the power strip.

On the other hand, in resonant magnetic induction where contact is not required, the consumer behavior change is a positive change and will drive for positive adoption. The benefits here are high since adaptors are eliminated and receivers can be integrated into the product similar to wifi, hence the additional step of having to physically connect or attach the device onto another interface is eliminated. Proximity is the only requirement.

For magnetic induction consumers would have almost no customer behavior change, but will have to pay a hefty amount for the pads. The current going rate for a pad is approximately a hundred dollars, and each receiver is approximately thirty dollars. That is a handsome amount to pay considering that you can get a power strip for less than ten dollars.

Resonant magnetic induction, on the other hand, provides positive behavior change where one is not limited by distance by having to be in contact with the receiver to charge or to have a power supply. The cost factor for resonant magnetic induction is unavailable since there are no commercially available products to recharge a phone in the market.

8.5 Integration of Split Battery System with Recharging

There are two fronts that will clash in the future. On one front, there is the battery system - which is improving, albeit at a rate that is unacceptable unless there is a disruption, such as an ultracapacitor, that can spur both technologies to improve. On the other front, there is the battle between the different wireless power transfer technologies.

The rate of wireless power transfer adoption can be influenced by the rate of technological advancement in the battery system. The slower the technology advancement, the faster the wireless power transfer adoption rate will be. There are other factors that influence the adoption rate of wireless power transfer such as the effect of industry standardization, cost, consumer behavior changes, and etc.

The current offering of magnetic induction, although useful, has limited advantages compared to the current incumbent, which is the power cord. Power cord suppliers themselves should look into miniaturization to counter the concerns of encroachment by the magnetic induction players.

The integration of any battery system, hybrid or standalone, stand to gain significantly with resonant magnetic induction technology. Despite the consumer behavior change expected, it is a positive change and would be well received by early majorities. I view this change similarly to the advancement in wifi technology where consumers did not have to look for an outlet to attach their cable connection and had a greater sense of appreciation of mobility. In the later discussion, resonant magnetic induction will be coupled with the battery system and its management and transition strategies explored.

9. Future Power Management Systems

9.1 Split Battery System

The proposal here is to split the power and energy management between two devices; one device focusing on energy and the other device focusing on power. To enable such as split, at minimum a sensor and a fast switch is required. Further research and development is required to develop a new battery management system.

The role of the sensor would be to detect the surging need for power consumption, and to provide instructions to switch from battery to ultracapacitor, and vice versa. The sensor will be connected to a power management device, this link is required since the power management device will provide instructions to the switch to turn on and turn off. The power management device is connected to the processor, which is the brains behind the smartphone and provides instructions for the power management device.

There will be various sensors in the module; each sensor will be used to detect the different factors that are required for algorithm optimization. Factors that should be considered are, the rate of change of power consumption, the sensor connected to the processor to detect changes such as a flash operation in a camera, and etc. Software will have a part to play in the new module since the right amount of power burst needs to be provided. Depending on the operation that is being run, the various sensors will collect data and feed into a software program that will calculate the appropriate amount of power burst.

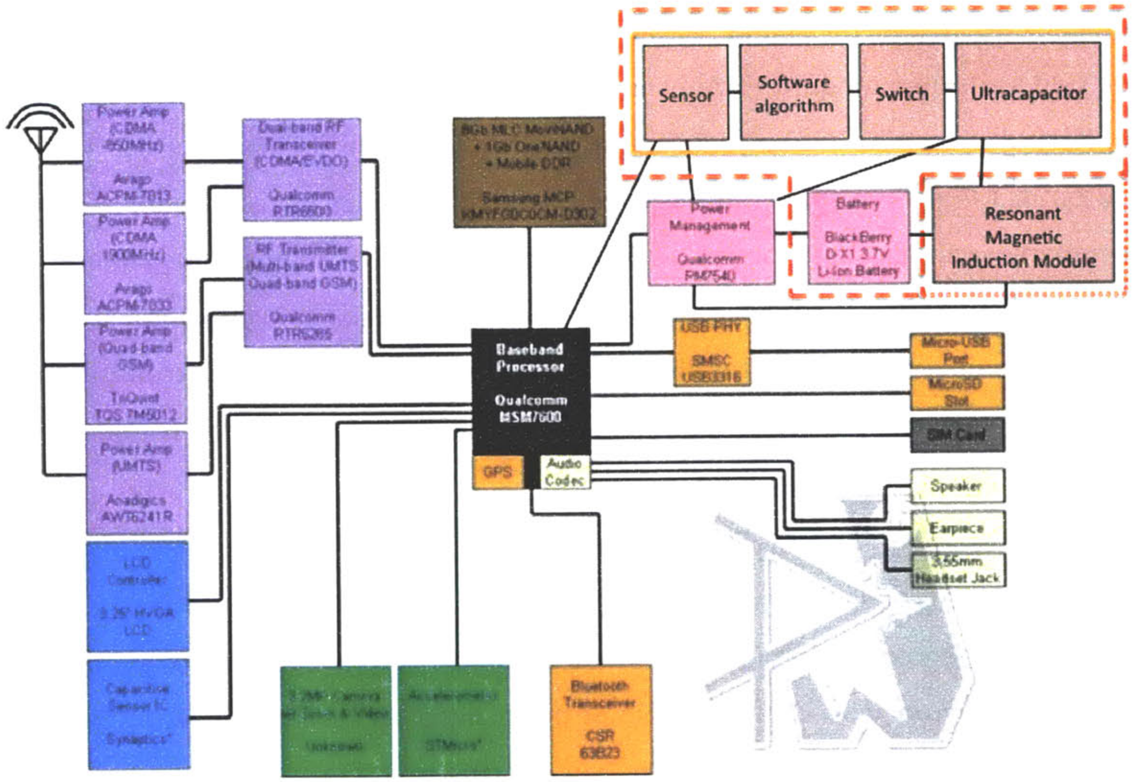

Figure 18 Split Management Architecture Proposal

Figure 18 illustrates the proposed architecture for the split management system. This is a modified version of Figure 4. The split management system includes a sensor, a switch, an ultracapacitor, and software algorithm. These new additions themselves can be a module or individual components, and parts can then be surface mounted onto the smartphone's printed circuit board. The new module can also be integrated with the current battery to create an integrated module. There is an additional option where the new components are individually surface mounted onto the printed circuit board, but that would be the option that has the most significant negative impact to the smartphone manufacturer due to the additional complexity in supply chain and in operations.

The box defined by the solid line can be managed by the ultracapacitor supplier and be sold as its own module. Furthermore, the module can be integrated with the battery system, which is enclosed in the dashed line. In either case, there is a potential for growth opportunities for either strategy since ultracapacitor companies can become more value added within the smartphone value chain. Battery manufacturers themselves can also be value added by providing a single solution point and providing breakthrough technology that is almost transparent in change to the smartphone manufacturers, hence reducing the overall complexity.

The concept of a split system is already deployed in the automotive industry. Maxwell Technologies (Smith), one of the industries' top ultracapacitor suppliers, has a split system with an ultracapacitor performing the duties of meeting peak power demand and as a secondary power source.

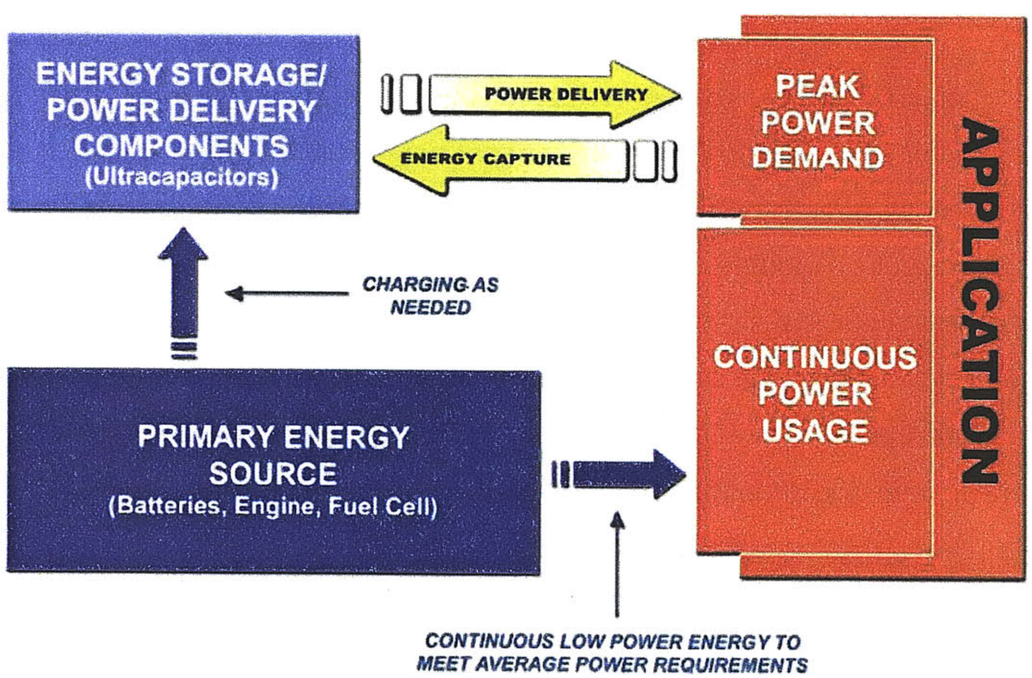

Figure 19 Split Power Management System (Source: Maxwell)

Figure 19 illustrates Maxwell's concept. The primary energy source continues to use the sources that have high energy density capability. The current application is only focused on a large-scale system, while our intent is to look at small-scale applications.

9.2 Recharging Integration

The earlier discussion pointed out that resonant magnetic induction is the wireless power technology that is best suited, and that has value add, within the system. Figure 18 provides an additional module to the new system architecture. This module has direct interaction with integrated circuits such as the application processor, power management, and battery. Constant charging of the battery is detrimental as all battery systems have an operation recharging life. Hence a software feature that sets a threshold or an on/off setting feature can be included into the overall system.

A preset threshold can be set to instruct the system to look for wireless recharging when the power level is reduced to a certain preset level. Predetermining the level using free information such as battery level is useful to prevent the smartphone from performing a non-value added task by constant recharging the phone. A constant recharge module is less attractive for total lifecycle cost due to shorter life and faster replacement cycles.

An on/off feature is another option, where the constant recharging and instructions or communication between the application processor and the new module can be eliminated. The on/off feature is similar in concept to the act of looking for a power outlet minus the physical action of looking for power outlets and hence improving mobility.

Industry level standardization is required to set the frequency band where wireless power can be deployed. The race for standardization is crucial at the onset of the technology, as companies need to ensure that they can transmit at an agreed frequency, test human safety considerations, and test for potential interactions with the other allocated frequency bands not just within the United States but globally.

Once a global frequency band is allocated questions will quickly arise over what the development and deployment strategy will be. As evidenced in Kurs' work transmission efficiency is a function of distance from transmitter. Development of the transmitter system should take place on two parallel paths. One path as individual boxes that can also function as signal boosters. The other path is to integrate it into stationary boxes such as cable routers, televisions, ceiling lights and ceiling fans.

Individual boxes can be plugged into an ideally suited power outlet. The user will have the flexibility to relocate the power source to the location needed. For travelers, an adaptor will be required to attach to the power outlet, but this is not an additional item since an adaptor should be carried anyway to recharge computers, shavers and etc.

Integration of the transmitter system into stationary appliances and furniture will spur market adoption aggressively. These devices are currently already connected to a power outlet, which will provide a constant flow of wireless power signals. Furthermore, the incorporation of this capability is a value creation and value added feature to internet router companies, television companies and the lighting industry as this technology provides an added dimension to their product offering.

9.3 Hardware and Software Improvements

Integrated circuit chips continue to improve their low power offering due to the many concerns highlighted in this paper. The transition to better semiconductor processing technologies contributes to less charge lost through operation.

Screen displays themselves are evolving. There is a transition now from liquid crystal to active-matrix organic light emitting diodes (AMOLED) which require lower power and have better display resolutions.

Software itself is playing a major role in smartphone processing algorithms. Mobility requires minimal idle time between execution and instructions. Hence, optimization in software is crucial to ensure that hardware such as application processors are not running extensively creating zero useful work and running down the battery source.

9.4 Battle From All Fronts

This chapter highlights the overall effort from a system perspective to improve the system battery performance. As hardware and software improvements, which are the focus areas of smart phone manufacturers, continue to progress, battery system and recharging technology play a significant role in enabling consumers to benefit and enjoy the full range of applications on the smartphone while fulfilling their mobility needs.

9.5 Performance Gap Bridging

I expect that there will always be a gap between performance to meet customer needs and performance that any system can provide. Figure 20 below depicts the expected gap.

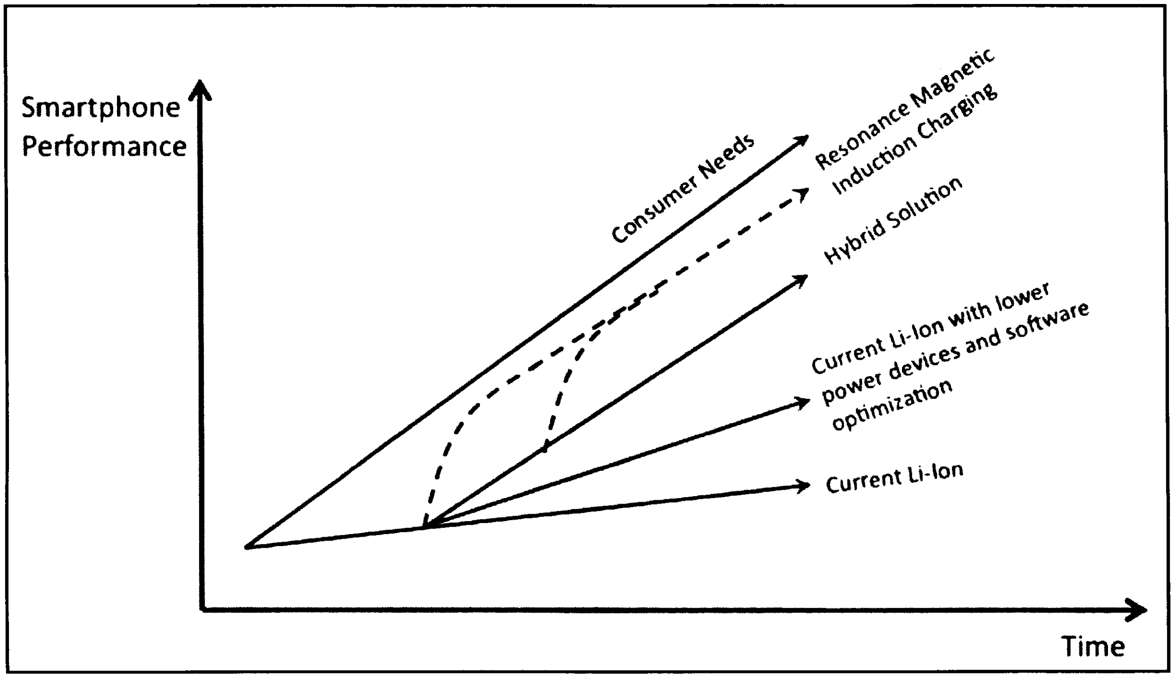

Figure 20 Charge Density Gaps Between Consumer Needs and the Different Methods to Improve the Current Performance

Current improvements with low power devices and better software optimization can improve the overall system performance, but it is not expected to match consumer performance needs. This gap can be attributed to various factors such as system inefficiency losses—no system can be 100 percent efficient—and modularity in design creating numerous additional interfaces and additional protocols required to execute a command.

A hybrid system with both ultracapacitor and battery can significantly improve the overall system performance, but it is not expected to meet the consumers' needs 100 percent. The reason for this is attributed to the low rate of improvements to the current system and the fact that the ultracapacitor only addresses peak loads. This duality option is complementary of each other and not a substitution for each other. As a result, as more functionality is added to the smartphone, there is always a significant performance gap expected.

Ultimately the closest to bridging the gap is to provide a situation where a smartphone is constantly powered up, similarly to being corded, but without losing the mobility factor. The concept of incorporating a resonance magnetic induction or the like, where mobility can still be honored to some degree, will provide a situation where the smartphone can constantly be powered on when in close proximity to a transmitter. The idea is similar to running the smartphone on a wifi connection where a transmitter at proximity is transmitting the signal needed to transmit and receive data. Figure 20 still shows a gap between the charging provided and consumer needs, since the constant charging of a battery system is detrimental as it shortens the life of the overall system. Hence, the concept of having an option to either set a threshold battery charge level or an on/off switch to detect available wireless recharging fulfills the goal of provide complete mobility and yet run the system at full performance.

10. Modular Architecture and Scalability

Modularity is already an ingrained concept in the mobile phone architecture. Devices from various suppliers are designed separately and produced based on an agreed set of design rules. Modularity should continue to be followed when incorporating split power management technology.

Based on the current business process the new device or new system can either come from a new player who will integrate various components and sell the module to the phone manufacturer, or from an existing battery manufacturer who can create value and capture value by internalizing the split function and selling an integrated component.

From a system architecture perspective, incorporation of additional functionality increases system complexity. In this case, a new set of design rules have to be developed to define the process window of the new device or the new function, and this new set of design rules will have to be agreed upon by the various stakeholders across the interface. For example, the sensor's sensitivity, speed of feedback and instructions, detection frequency, and maximum amount of power have to be considered between the different parties such as the sensor supplier, module integrator, ultracapacitor supplier, logic supplier, phone manufacturer etc. A new player in the ecosystem will increase the need for external coordination, whereas an existing player in the ecosystem will provide additional offerings without the additional need for system level integration.

To reduce the complexity, a battery manufacturer can either strategically partner with an ultracapacitor supplier or internalize ultracapacitor capability and technology. In either case the outcome is to provide a single solution consisting of both battery and ultracapacitor, and to gain the upper hand in terms of market penetration and market adoption.

Battery suppliers have already established communication channels and business processes within the existing ecosystem. This incorporation will be viewed as a product enhancement rather than as a separate module altogether. In a modular architecture the less the exposure and the less complexity that the phone manufacturer has to undergo, the higher the adoption rate will be.

Furthermore, a battery suppliers ability to create value and capture value by incorporating an ultracapacitor into their module and establishing a standardized module offering will provide reinforcing loops in market adoption. Battery suppliers are well versed in their own space in regards to standardization since most battery sizes come in certain dimension and with certain charge density. An extension of this concept should be adopted when incorporating the ultracapacitor's power management capabilities.

Standardization and modularization is the key to scalability where future needs can be met by either attaching multiple modules in series or by offering product extensions that can be established with fixed parameters of energy density, power density and dimensions. Standardization will improve the system level design and system level integration for various stakeholders.

Ultracapacitor suppliers themselves can try to penetrate the industry. The traditional capacitor technology is not new to this industry and many can be found within the phone. A quick survey into several capacitor company such as AVX(AVX), Vishay (Vishay) and Kemet (Kemet), show that only AVX has an ultracapacitor—albeit limited—as a product offering. The opportunity to add value and to value capture can also be observed from the viewpoint of the capacitor or ultracapacitor suppliers. They would have the core competency to develop new breakthroughs in capacitors, which according to Hoh and Magee (Hoh and Magee) is still at its infancy of technology development, and hence would be enticing to increase its penetration into the overall smartphone bill of material.

According to Baldwin (Baldwin and Kim), modularity-in-design is complex and design rules integrate the different sub-systems. This complexity disperses the value and creates value within the ecosystem since companies separately can build technological core competency in parallel and decision-making is decentralized. These dual roles spur the rate of innovation. Baldwin (Baldwin and Clark) also describes that modularity is designed independently but functions as a whole.

Therefore, modularity is key to the success of adoption by the smartphone manufacturers and in operation scalability. Modularity concepts should be adopted from the start and seamlessly integrated into the business processes of the current smartphone business process flow. A deviation from the current norm will be detrimental to the adoption process.

11. Potential Market Growth Opportunities

The ideal space for this module is one that requires both power bursts and stable energy consumption. Power bursts reflect the constant fluctuation in power usage and thus require fast on/off switching. Stable energy consumption functions well with lithium ion or similar technology since the usability is more predictable. This concept is similar to the demand response concept in the large-scale energy sector, except that this is at a micro scale level.

In energy demand response, fluctuations in daily energy demand require energy storage devices to be installed to supply the peak demand. Likewise, in a smartphone as a result of fluctuations in consumption, ultracapacitors can be used to support the peak loads and lithium ion batteries used to support stable consumption.

Mobility is also another key factor that is crucial for this system. A stationary device will not require a dual system since the device can be plugged directly into a power outlet. In this case the battery system itself is a minor component in the entire system.

Hence, products that are mobile and have high fluctuations in power and energy consumption would be a good fit. Based on these criteria the following are several examples of industries or applications that can utilize this capability, in addition to smartphones:

- Gaming applications such as game consoles, hand controllers such as the Wii controller

- High end laptops catering to the gaming enthusiast
- Cameras (digital still cameras and SLRs)
- Children's toys
- Portable audio video recording devices

Figure 21 through Figure 24 are power measurements of a Nintendo DSi from Portalligent (Portalligent) and show the similarity in power fluctuations and power needs thorough its operations. Nintendo DSi is a handheld digital video game system. The figures clearly illustrate significant power fluctuations through simulated operation of the device during various functions such as downloading, copying, recording and during gaming. These figures provide an insight into potential opportunities as mentioned above, since all the potential applications require functions similar to Nintendo DSi.

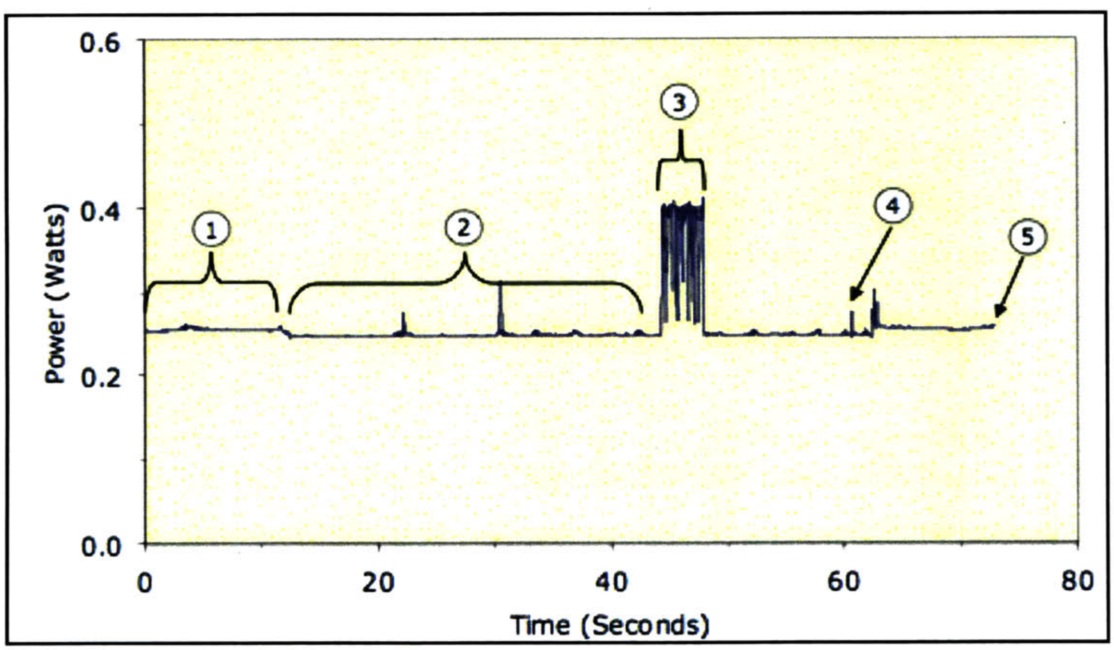

Figure 21 Nintendo DSi Power Measurement When Copying Photos From System Memory to SD Card (Source: Portalligent)

In Figure 21 the download function requires a peak power consumption to read and write data. The power fluctuated by approximately thirty three percent.

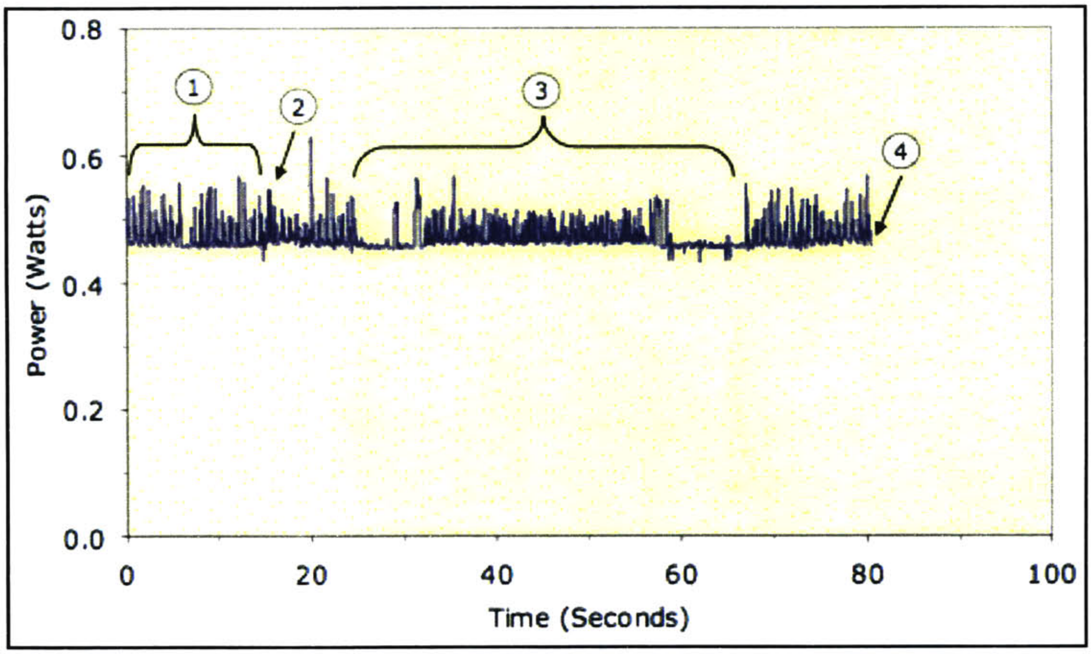

Figure 22 Nintendo DSi Power Measurement When Downloading a Game (Source: Portalligent)

In Figure 22, during gaming mode, up to twenty five percent power fluctuation is observed and rapid fluctuation is also observed. Rapid fluctuations are the ideal situations that require an ultracapacitor system.

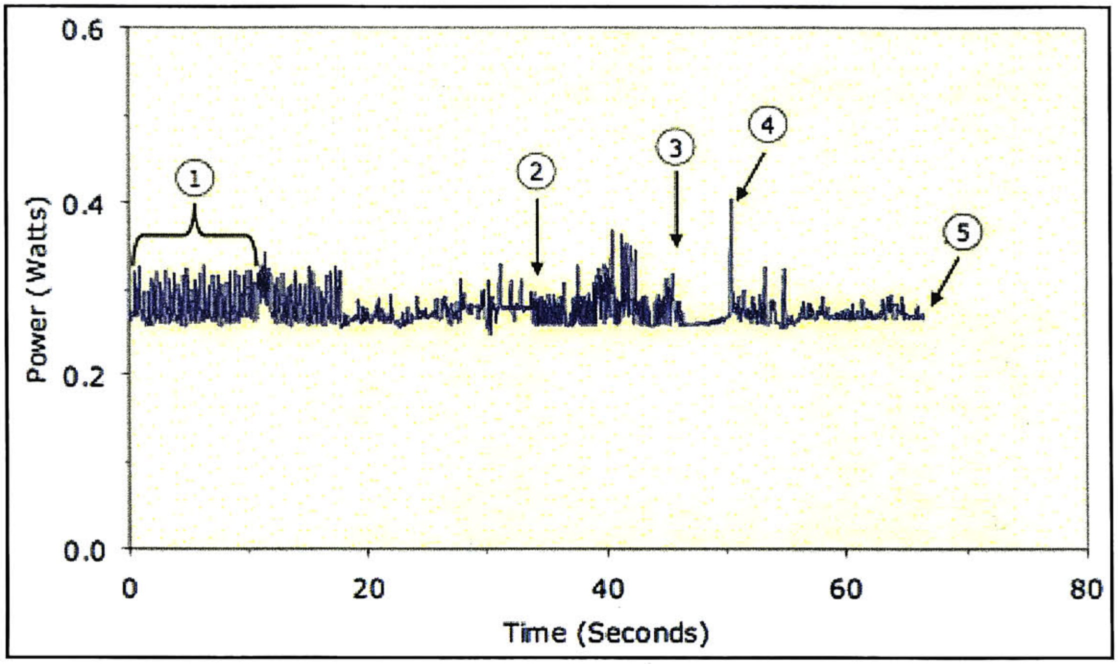

Figure 23 Nintendo DSi Power Measurement When Playing Games With Music Turned On (Source: Portalligent)

Figure 23 and Figure 24 are very similar to gaming mode where rapid power fluctuations are observed and are another good candidate for ultracapacitor deployment.

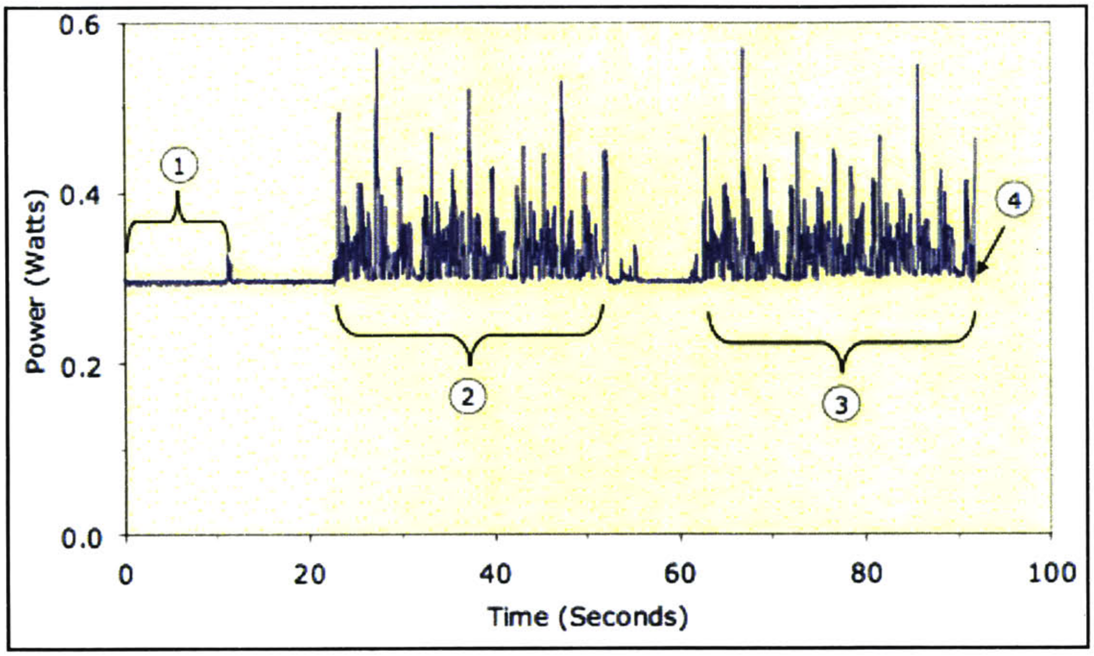

Figure 24 Nintendo DSi Power Measurement When Recording Audio With Internal Microphone (Source: Portalligent)

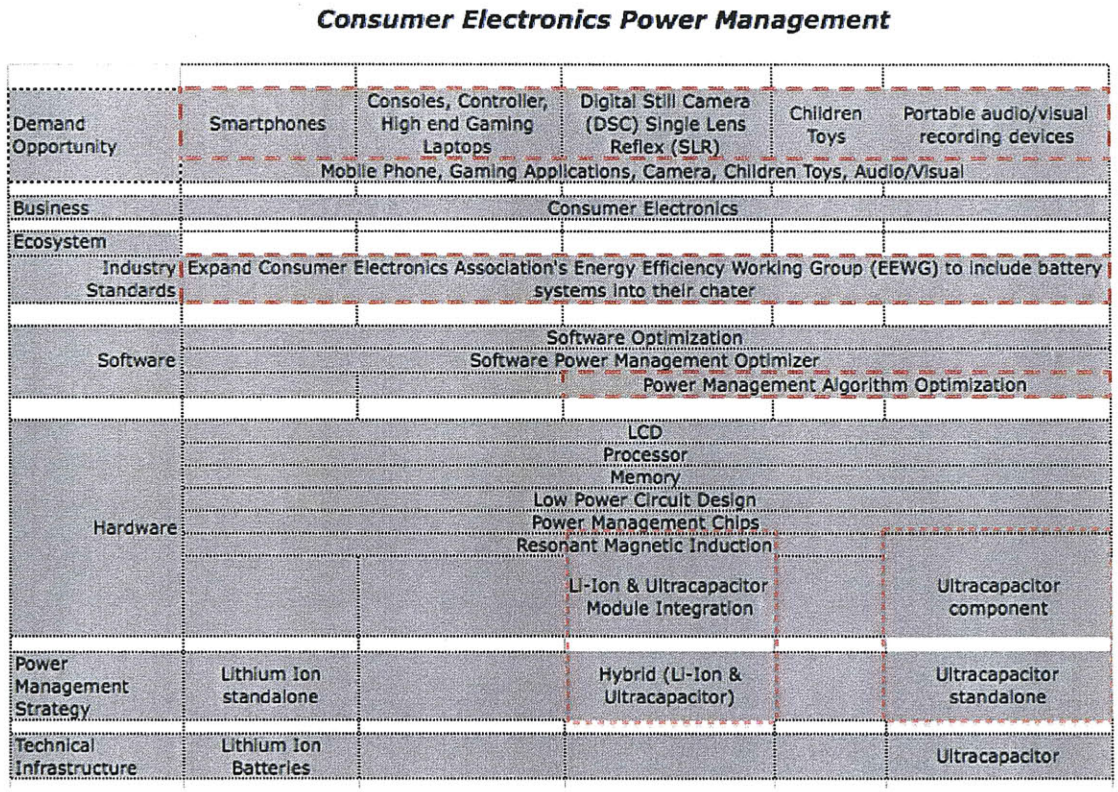

Figure 25 Consumer Electronics Power Management Value Creation and Value Capture

Figure 25 illustrates the demand opportunity for both hybrid, standalone and coupled with resonant magnetic induction. The dash in the figure shows the area that is value created and value captured depending on the strategy that is decided upon by the company. Resonant magnetic induction is the only wireless power technology included here. This technology will provide significant value creation and value add across various industries.

Regardless of strategy, there should be an industry standardization effort to consolidate and to agree upon a set of design rules that the hardware and software interfaces will require. The Consumer Electronic Association's Energy Efficiency Working Group (EEWG) should assume the leadership role in this task. This working group should also focus on determining the industry standard wireless power transfer transmission frequency.

In terms of the demand opportunity, this solution can be expanded across the various market segments highlighted. This becomes a highly attractive market segment to break into since each demand opportunity amounts to millions, if not billions, of units sold. The expected attach rate is one per application and amounts to a significant amount of revenue and profit. The main considerations are choosing the right technology strategy and managing its technology evolution.

12. Market Adoption Dynamics

The dynamics of market adoption is influenced by several factors and is illustrated in Figure 26.

- Exogenous factors such as standardization and modularization that can influence adoption or abandonment, but is independent of the desire to bridge charge gaps or customer needs
- Reinforcing loops positively influence and increase the adoption rate
- Balancing loops counter the adoption rate and strives for a plateau or decline in growth rate

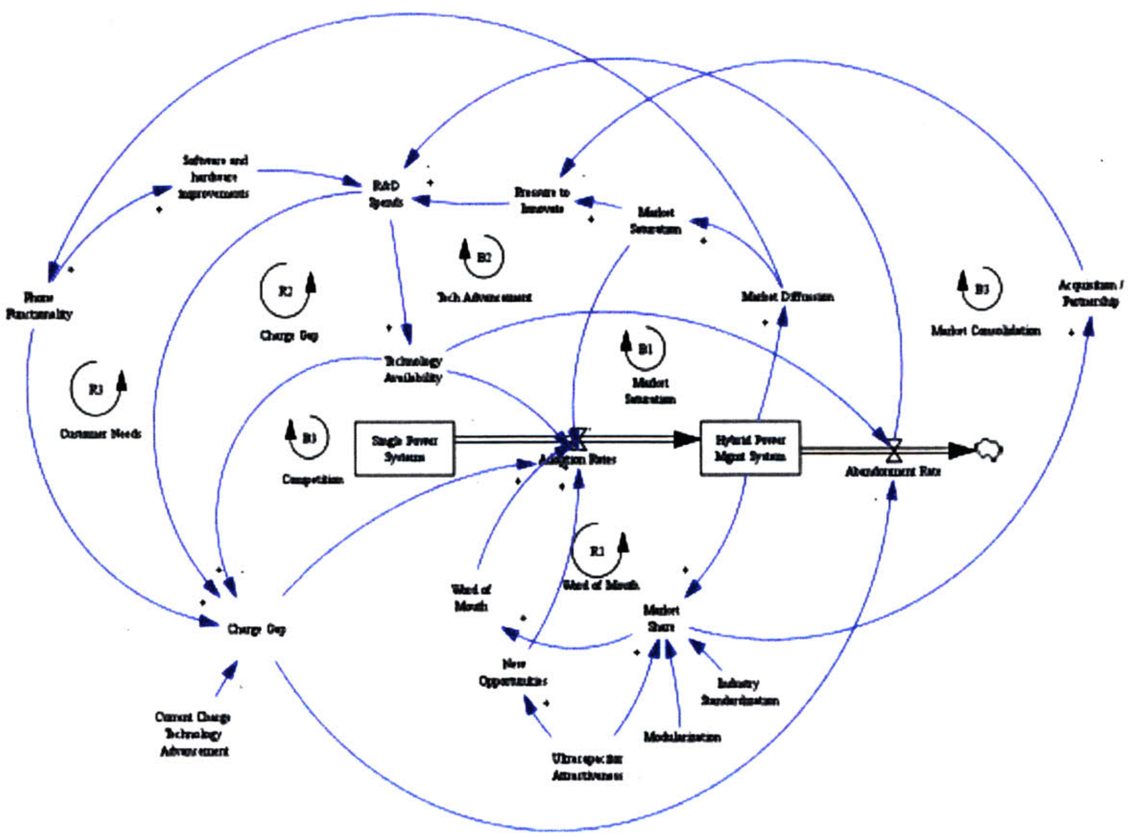

Figure 26 Market Dynamics Causal Loop Diagram

12.1 Exogenous Influence

Exogenous factors such as modularization and standardization significantly influence the sustainability of the technology in becoming a dominant player in the industry.

12.1.1 System Modularization

Modularization influences scalability, product reach, cost, design rules, system complexity, and system interfaces.

There are two potential options in modularization here. One option is the integration of the new system with the current battery system into a single solution. The other option is separate systems that interface, but are not incorporated. Both options have their advantages and disadvantages. At a micro level, the system here will encompass components such as lithium ion, ultracapacitor, resonant magnetic induction, and its supporting components. In a worst-case scenario, all components are supplied from different suppliers. The rate of technology readiness is a function of the number of interactions or interfaces that the system has to go through.

The optimal scenario is a single module that addresses the entire system where lithium ion, ultracapacitor and resonant magnetic induction can be integrated together and provide a single solution to the smartphone manufacturers. This solution point provides a faster development cycle through centralization in design and decision-making, provides fewer interface points with the other systems within the smartphone, and provides a more efficient overall system from cohesive development. A single module will foster competition between components and by maintaining centralized design and decision-making, the other systems are shielded from the battle between the players within the module. To the major system, there is a set of design rules and design requirements that have to be met regardless of the form, fit and function of the system. The true test will be the transition in leadership in the module. It is expected that the current leader integrating the module would be led by the lithium ion suppliers due to their entrenched relationship within the smartphone industry. As technologies evolve, a changing of the guard scenario may occur depending on the differential in rate of technology advancement.

The disadvantages of modularization are the creation of an inefficient system component and creation of an inefficient production system. In a module components are not optimized in part but optimized in whole. An analogy to boat rowing can be visualized where the rowers have to be synchronized, otherwise the net effect is a slower rowing pace. In production this results in additional part numbers or stock keeping units (skus). This results in higher operations cost, which inadvertently slows adoption rate due to expected pass through cost from supplier to customer.

The degree of modularization within the system and within the sub-system needs to be assessed. Industry players need to evaluate their internal core competencies and decide on partnerships, acquisitions, or internal development to manage modularizing the overall battery system.

12.1.2 System Standardization

Standardization is required in many areas within the system in order to drive market adoption. A standard design rule goes a long way when it comes to different systems delivering and anticipating a predetermined set of deliverables and targets. The resonant magnetic induction system should start charging the system upon degrading to a preset threshold, and recharging should stop when a preset charge capacity is achieved. A standard communication, instruction, and execution protocol between the processor, power management unit, lithium ion, and ultracapacitor should be developed to optimize the overall system. The system should identify the triggering mechanism that switches on a different powering system, and detect the need for the switch.

A defined standard will drive compliance across system components and drive for faster development time. The EEWG should be the governing body to deliver a cohesive standardization strategy since the key players in the industry should already be actively engaged in the organization.

The race for standardization is a crucial battle. The most technologically capable or technologically superior solution is not guaranteed to win this battle. History has shown this to be the case time and time again, such as between Beta and VHS. Alignment between partners within the ecosystem, the rate of introduction of an integral solution, and the degree of change transparency to the existing norm plays an even larger role than technological strength.

Industry players should assess the ecosystem to define the right partners with the appropriate business strategy, focus, corporate goals, and business operations. The standardization battle can be won by delivering a system that allows the customer to benefit, albeit not a maximum benefit as a result of a lesser superior technology, but one that provides a full transparent change to the stakeholders within the system.

12.2 Reinforcing Loop Influence

Several reinforcing loops were modeled in market dynamics for this system and they are designated by counterclockwise loops in **Figure 26.** Reinforcing loops drive market adoption because the more the influence of the elements, the faster the adoption is exhibited.

The word of mouth loop shows that when market share increases, there will be an increase in word of mouth, and an increase of adopters is observed. Word of mouth is the best strategic advertisement there is. When a trusted person recommends a product the recommendation carries more weight compared to a recommendation from a random person. This can be the mechanism to cross the chasm between early adopters and early majorities. From a manufacturer's perspective, there will be a transparent change due to the effects of modularization and an initial partnership with a known supplier builds change credibility and eases the transition. From an end customer perspective, the new system meets the desire of customers for more mobility and an increase in charge capacity between recharges, hence barriers to adoption are reduced.

In the customer needs reinforcing loop, as more functionality is packed into the phone, the charge gap is expected to increase since the rate of improvement of the lithium ion battery is at a dismal 2-3%, as reported earlier. The increase in charge gap will increase the adoption rate for a hybrid system. As the adoption rate increases, market diffusion increases, and with the newer capabilities the desire to have more capabilities increases, which further results in an increasing customer need to bridge the charge gap.

Another reinforcing loop can be observed where the increasing expenditure in research and development increases the new system capability. The increase in functionality increases the charge gap again and further spurs adoption. An increase in adoption increases sales and revenue, which enables more funding to be allocated for research and development.

12.3 Balancing Loop Influences

In **Figure 26** balancing loops illustrate the counter effect that reduces the adoption rate. Balancing loops can be influenced by technology growth rates, market growth conditions and situations, and corporate strategies.

An increase in the market adoption of hybrid system drives an increase in sales and revenue, which then increases spending in research and development. The more money that is poured into research and development, the more alternative options should be available. The wider the availability of options in addressing charge gap, the slower the adoption rate for hybrid battery systems. The wider availability of options increases competition and drives the slower adoption of hybrid systems.

Market consolidation is also a factor in balancing loops. When the adoption rate increases the total market share increases, and the increased market share prompts acquisitions or partnerships. Consolidation via acquisition or partnership will reduce the pressure to innovate since there are fewer competitors, which results in reduced spending in research and development. Reduced spending in research and development results in fewer newer technologies being available and hence reduces adoption rates. When there is less competition there are fewer risk takers, as the pressure to push for technology innovation is reduced. As a result, radical leaps in performance will not be fostered, but marginal steady state improvements will continue. The abandonment rate can potentially increase as a result.

Market saturation is also a balancing loop where the total available market decreases as the adoption rate increases. This is alleviated by expanding to newer market opportunities, such as those covered in the previous chapter. The danger of market saturation is observable when the cumulative annual growth rate decreases and the product is only following a refreshing cycle. Hence, venturing into other market segments or increasing product segmentation to capture market share in the upstream and downstream value chains are mechanisms for prolonging the market saturation effect.

An advancement in technology that creates alternative options can have a balancing effect on adoption rates. As the adoption rate increases, more revenue will be channeled into research and development, which results in the creation of innovative breakthroughs and drives the reduction of hybrid system adoption as a newer solution can potentially function to charge the entire system. The initial hybrid management system is a symbiosis relationship, but as technology gap capabilities start to decline, the newer technology can become a predator to replace the existing system. Finally, unless the lithium ion battery achieves an innovative breakthrough, further advancement in ultracapacitor technology will create a pure competition scenario. This transition will be further explained later.

12.4 Everett M. Roger's Market Adoption Perspective

There are other factors that are not shown that have an influence on market adoption. These are primarily endogenous factors. Everett M. Rogers (Everett) proposed at least five factors that can influence market adoption rates. These factors are relative advantage, compatibility, complexity, trialability, and observability.

Roger's work uncovered that all attributes except for complexity have a positive correlation to market adoption. For example the more relative advantage an innovation is perceived then the faster the rate of adoption, whereas the more complex the innovation is perceived the slower the market rate of adoption.

12.4.1 Relative advantage factor

Relative advantage can come from the comparison between new system and current system; a longer duration between charges is a strong advantage and drives for faster adoption rate. There is also a ceiling limit to relative advantages. When duration between charges improves from hours between recharge to days between recharge, the improvements may exceed the customer needs. When improvements exceed customer needs then adoption rate will decrease; the new current state of art is sufficient. For example, I would perceive that charge duration longer than a full day period is excessive since I can charge my devices once I arrive at my final destination.

The delivery of a seamless change to the end user is a strong relative advantage. If change is inevitable then a positive change to the stakeholders will definitely increase market adoption. In the recharging example, there is perceived to be little relative advantages between recharging using a power strip and recharging using the new magnetic induction mat charges. In both cases, mobility is limited and the mechanics in recharging is about equivalent; when using a power strip one would attach the device to an adaptor which is connected to the power strip, and when using a power mat the mobile devices would require a receiver attached to the phone and then physically place the phone on top of the transmitter. On the other hand, when using resonant magnetic induction as the wireless power transfer, one is not limited by mobility and devices can be charge as long as it is in proximity. The net increase in mobility becomes a positive relative advantage and will spur market adoptions.

12.4.2 Complexity factor

Designing using modularity reduces the complexity of the new architecture. The initial work invested in determining the design rules plays a significant role in reducing system complexity. The design rules within each interface governs the delivery expectations to other modules it interfaces, and it also governs receiving expectations from other modules. This clear expectation ensures that each module is designed to deliver and receive the appropriate specifications. Design, manufacture, and test can be done in parallel, and system integration can be done at the final stage. No change to the current business process and business operation is expected aside from potentially managing additional suppliers.

The norm in qualifying adding a new module to the current system requires the standard cycle of proof of concept, test vehicles and full qualification cycles. Each step has its gates that are needed to be passed, and risk mitigations and reruns if failures are observed. This extensive trialability of the norm process provides the required data prior to adoption.

It is expected that the new architecture will provide a positive experience for end users. Gone are the days when one has to look for a power outlet after several hours of handset operation. This change is deemed a positive change, and will spur the adoption of the new architecture. A longer duration between recharging will increase the word of mouth effect, which will further drive market adoption.

12.5 Customer Behavior Change Influences Market Adoption

John T. Gourville's framework (Gourville) on capturing value from innovations provides a good insight into product adoption from change resistance based on behavior change. The new module can be considered a smash hit since it offers a significant product change with longer overall battery life and limited behavior change. Gourville also mentioned in his article that companies create value through product change, and capture value best by minimizing behavioral change. Regardless of how limited behavior changes are, behavioral changes still exist, and it is up to the management team to manage the resistance to change. Recommendations, such as striving for an improvement by a factor of ten over the current state of the art and making a behaviorally compatible product, were also advised.

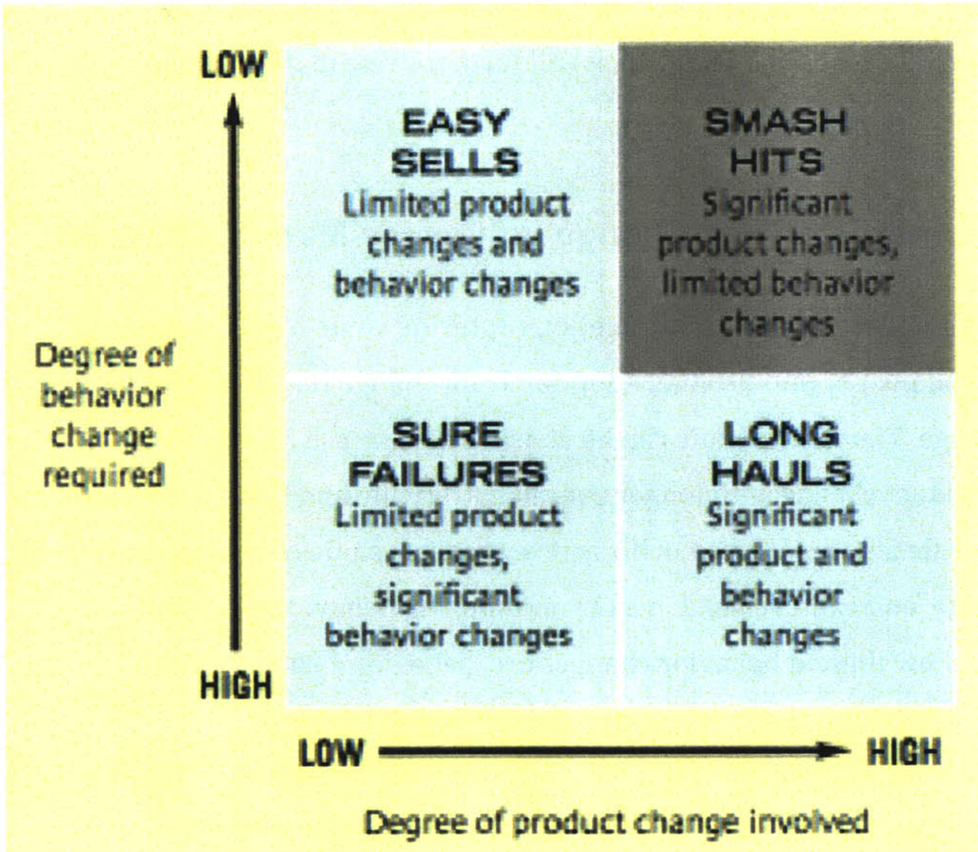

Figure 27 Capturing Value from Innovations (Source: Gourville)

These will be the goals for the new product introduction where consumers will no longer need to look for power outlets every several hours and the new innovation will have a seamless change to the end customer, aside from being able to run their phones longer with minimal disruption.

13. Technology Co-evolution

The partnership between ultracapacitor and lithium ion poses a challenge in technology transition management. Both technologies have their own strengths and weaknesses, and the differential in advancement rate can shift the nature of the partnership. Research and development money can be invested to uncover technology innovations in addition to process improvements. Market consolidation can shift the direction of a partnership, where a partnership in the beginning can become a competition at the end if one of the parties decides to bring in house its complementary technology.

Resonant wireless power transfer, on the other hand, is complementary to either technology or to the combined solution. A technology transition to incorporate a wireless power transfer technology should purely focus on technology incorporation rather than technology transition management. There is no expectation that a wireless power transfer will substitute for any battery system.

Lithium ion can be categorized in the mature stage and ultracapacitor can be categorized in the emerging stage. This categorization is based on the findings of Hoh and Magee on the rate of energy density improvements. In this chapter we will explore the interactions between the two technologies. Figure 28 illustrates the trajectory performances of the two systems, its interactions and response.

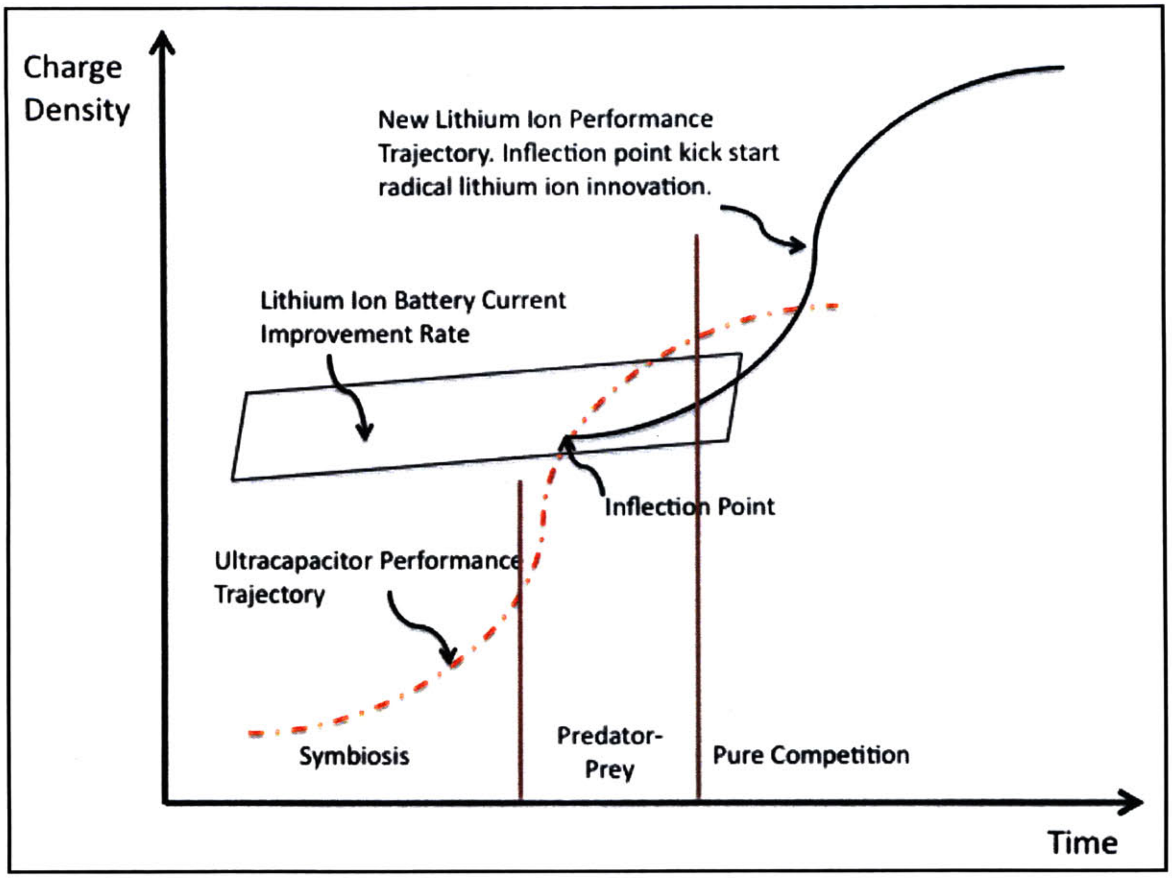

Figure 28 Performance Trajectory and Multi-Mode Interaction

Pistorius and Utterback (Pistorius and Utterback) proposed a multi-mode interaction among technologies and suggested that there are temporal shifts between modes based on changes to the ecosystem landscape. Furthermore they suggested that management monitor the dynamics of technological change, the nature of interactions among technologies, and develop strategies to deploy within each mode and during the transition between modes.

The combination of the current need for longer battery life and the feasibility of a split power and energy management system will allow for a symbiosis mode at the onset of the introduction. The ultracapacitor's advantage is in its power density, its energy charge density capability is still orders of magnitude lower than that of the lithium ion battery. The lithium ion battery's advantage is in its energy charge density, and there seems to be limited advancement in improving its power density. Hence, at the current stage, both technologies are complementary of each other to enable a single solution that meets an overall need. Furthermore the combination of both an ultracapacitor and a lithium ion battery can help to expand the combined market share and spur growth more so than individually. The potential markets are already illustrated in Figure 25.

It is expected that both technologies would have their own technology trajectory path. The key to this transition management is the charge difference between the two technologies as both technologies progress. Three potential scenarios, as shown in Figure 29, can occur depending on the rate of technological improvement in energy density.

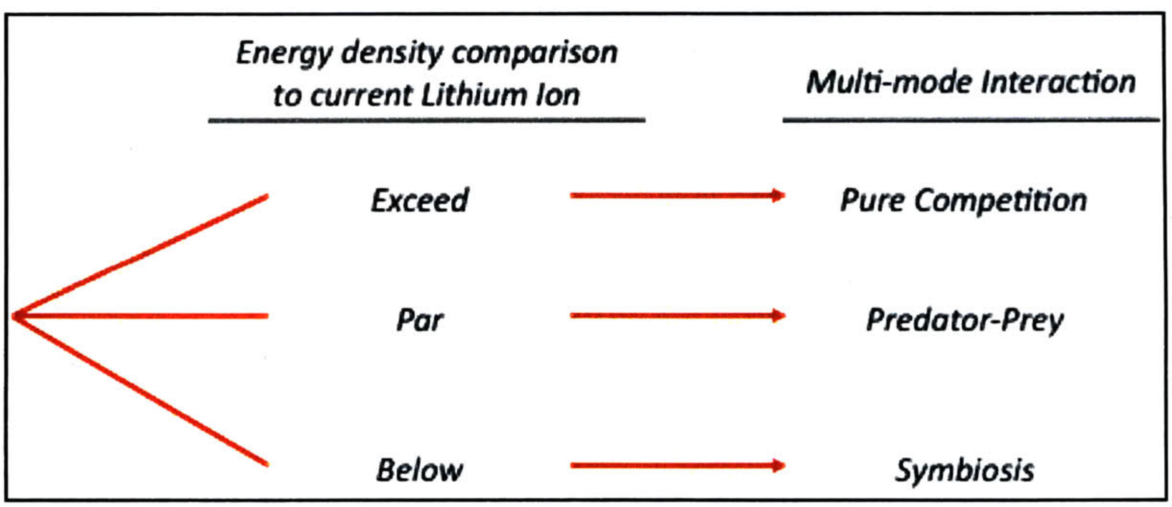

Figure 29 Ultracapacitor and Lithium Ion Technology Multi-mode Interaction Scenario Based on Ultracapacitor Advancement

13.1 Technology Transition Model

13.1.1 Symbiosis Play

If the ultracapacitor charge density remains inferior to that of lithium ion batteries, than a symbiosis mode will continue. Both technologies are complementary to each other and will not be capable of expanding their market share without a partnership.

At the initial stage there is a high degree of uncertainty. Product innovations are still occurring and driving marked improvements in its performance trajectory. In the emerging stage ultracapacitors are still gathering feedback on further product innovations from the consumer electronics industry. Product modularization is still in its infancy and the initial product portfolio will be more customized due to smaller initial market size and its inexperience in the consumer electronics industry.

Furthermore, aside from ultracapacitor technology itself, in the smartphone space there are marked numbers of interactions with software, integrated chips, and power management algorithms that ultracapacitors need to interface and respond to. Product changes are expected to occur throughout the initial stage. A symbiosis strategy is inevitable due to the consumer electronics industry's risk adverse mentality in areas that are not their core competency.

Market consolidation can occur at this stage and the discussion would be more focused on technology rather than management. Consolidation here would be more concerned with upside risk and upside potential, and focus on the future rather than immediate merger benefits. Market valuation at this stage would be more realistic compared to other stages. At this stage it would be still considered as being in the early market entrance stage but not quite in the seed stage, hence valuation risk is more than it is in an early market entrance but less than in a seed stage.

13.1.2 Predator-Prey Play

When the ultracapacitor's charge density is at par with lithium ion batteries', then the ultracapacitor becomes the predator and lithium ion becomes the prey. Ultracapacitors as the emerging technology will have a negative effect on the lithium ion battery growth rate; whereas lithium ion batteries will have positive influence on ultracapacitor growth since ultracapacitors can start to expand into the lithium ion battery market space and market share.

The "sailing ship" effect as highlighted by Utterback (Utterback) can be observed here. Lithium ion battery companies are likely undergoing process improvements which deliver only incremental improvements in their technology trajectory. As ultracapacitor technology advances rapidly, lithium ion battery technology will have to undergo a technological innovation that results in a shift to a newer technological trajectory path creating a new technological S-curve.

Market consolidation should be in internal discussion at this stage. Mergers and acquisitions can be in either direction; lithium ion battery companies can consider integrating ultracapacitor technology into their product portfolio, and vice versa. It is very unlikely that one will see consolidation between top lithium ion companies and top ultracapacitor companies, but more likely it would be the top company in one field merging a weaker player in the other field. Top companies would want to continue striving on their market domination or on their market growth, even though consolidation between the major companies makes sense technologically, but the concern is a management issue rather than a technological issue. It is unlikely that the management in the top companies would want to relinquish their controlling stake. Furthermore, the merging of top companies would require breaking the bank, resulting in a potential overvaluation of each other.

Hence, it is more likely to see consolidation between a top company and a lower ranked company where the top company will maintain the majority control in management and in technology. The top rank company would be confident that their own research and development team could provide the leadership to steer the integration and to deliver breakthrough products.

13.1.3 Pure Competition Play

When the ultracapacitor's charge density exceeds that of lithium ion batteries, then pure competition will occur. The ultracapacitor is no longer a complementary technology but a substitution technology. Lithium ion battery and ultracapacitor companies in partnership should closely monitor the advancement rate and decide at a certain juncture to bring in house its complementary technology.

Ultracapacitor companies have more to lose if they are slower to react to incorporate lithium ion batteries in house. The road to become a major component supplier in the mobile phone space is a rocky one. Lithium ion battery companies have a longer business relationship than ultracapacitor companies, and have a working model established between the different stakeholders within the ecosystem. This is one example of how perceived change can have a negative effect. For ultracapacitor companies, the barrier can be eased through acquisition of already renowned lithium ion companies.

For lithium ion companies the road to market domination is again smoother because of minimal perceived change to the end customers and to the stakeholders within the ecosystem. The lithium ion companies can internally manage the technology transition effectively. An internal technology transition barrier can be foreseen where the lithium ion companies' management is slow to identify the threat and refuse to acknowledge the ultracapacitor threat. A repeat of the Kodak management fiasco, where management were blinded by the threat from digital technology and continued to strategize around 35mm disposable films, will have to be avoided.

13.2 Technology Management and Leadership

The key takeaway is that technology changes are fluid and management should never rest on its laurels. No one can better describe this than Andrew Grove in his comment that only the paranoid survive.

The consumer electronic industry has multiple windows of opportunity for technology interception and change can come quite rapidly, especially when the components are related to their core competencies. Smartphone ownership durations are getting shorter, therefore the fast refresh rate dictates the need for fast technology interception and fast exits. Unlike the automotive industry where ultracapacitors are also entering, the consumer electronic industry's reliability requirements are shorter, safety requirements are not to the scale of automotives, and production is more flexible with lower inventory levels.

All these positive factors are added benefits and incentives for ultracapacitor technology to advance rapidly with high certainty of adoption and lower barriers to overcome.

Therefore, both lithium ion battery and ultracapacitor companies should be internally cooking a strategy of product innovations for radical improvements and deciding on a strategy for long term relationships with their complementary partner via long term partnerships or mergers and acquisitions.

14. Conclusion

This thesis explores options that improve overall power management by looking at the power source and recharging methods. This thesis also explores technology transitions and management strategies that address the different multi-mode interactions between technology transitions. In addition, this thesis also explores market adoption dynamics and identifies factors that will either spur or inhibit the proposed power management system's adoption rate. Finally, opportunities in other markets were identified for the new power management system to expand into.

Smartphones are now one of the best selling electronic devices in the consumer electronic market. Two key factors that have spurred smartphone adoption are mobility needs and functionality improvements. Mobility needs are spurred on by broader network coverage and faster data transfer rate. Functionality improvements and the increase in the number of applications is spurred on by higher computing power and larger storage capacity.

Unfortunately, not all the key components of the entire smartphone system are advancing or even keeping pace with advancement. Software and hardware have advanced but the overall power management system has fallen drastically behind. Users are demanding longer operation time between recharges and expecting minimal disruption throughout the day. The simple solution of increasing lithium ion charge density is plainly masking the problem. Current charge performance significantly lags the charge demand from more functionality, and hence creates a gap that will only further increase. Product innovations are needed to bridge the gap since process improvements can only provide marginal performance improvements.

14.1 Product Innovation in the Battery

A new power management system for the smartphone is inevitable. The charge gap, which is the difference between energy charge demand and current battery charge supply, continues to increase and will inhibit future smartphone growth opportunities. A combination of a dual battery system and wireless recharging system is the immediate solution to address the charge gap.

The dual battery solution combines a lithium ion battery with an ultracapacitor where the former supports stable charge needs and the latter supports peak demand needs. Drastic fluctuations in energy and power consumption within an application further drive the need for a dual system or otherwise the current system's operation duration will degrade further.

A wireless recharging system using resonant magnetic induction technology will provide power recharging without the power cord. Incorporating resonant magnetic induction technology into routers and lights will increase the number of wireless power accessible points and provide a total mobility experience.

The new dual battery system will include sensors, switches, software, and software algorithms to effectively and intelligently manage a dual system. Sensors will detect the rate of change of power consumption and will trigger switching from lithium ion to ultracapacitor and vice versa. In a circuit board layout, sensors will be in communication with the processor and power management device. The processor-sensor interface will provide fast response times that will trigger the mechanism to switch power supplies and the sensor-power management interface will provide instructions to shut off the lithium ion battery power supply. Switches will switch the power supply from battery to ultracapacitor and vice versa. As shown in Figure

18, a lithium ion battery and an ultracapacitor are connected to the power management device to deliver a single source. The parallel connection between processor, sensor, and power management delivers a single power source each time and with minimal time delay.

Software and software algorithms are critical components that provide an added dimension of efficiency to the new system. Software will provide instruction to the processor to trigger the sensor and switch. In parallel, software algorithms will calculate burst power amount required. The triangulation between hardware, software and algorithm will provide the power at the desired time and at the desired quantity.

The long-term solution is still fluid. Technological advancement in ultracapacitors with carbon nanotube and in nano-enhanced lithium ion batteries will potentially drive changes in how technologies in the future will interact, and drive changes in strategic directions within companies and between companies.

The Pugh method was used and increased the number of long-term technological battery solutions. We assessed various factors that spanned across technology, safety, operations, and consumer behavior. In the end, each solution has its strengths and weaknesses. The higher the performance trajectory leap, the greater the potential for market adoption, but we have to acknowledge that technology advancement alone is not sufficient to win the battle. Other factors such as change management, standards, and modularization are key factors that also influence market adoption.

14.2 Implementation of Resonant Magnetic Induction System

Minimal disruption to daily operation is another key end user desire. The current practice requires users to attach a smartphone to a recharging outlet via a cord, whereas the new system will eliminate the last cord. This implementation increases user mobility and eliminates the need to physically look for a power source. Features in smartphone can be incorporated to detect wireless power signals similarly to the current practice of looking for a wifi signal. Resonant magnetic induction technology adoption is independent of the battery system deployed and it is flexible enough to work with any system.

Wireless power transmission coverage can be increased if the wireless power transfer architecture can be integrated into the wifi architecture. Furthermore, this technology can extend its coverage by integrating into stationary points, such as lighting, to create value for other partners within the ecosystem.

A positive customer behavior change is expected since end users are no longer required to physically search for power sources, and instead the smartphone will either have software intelligence that triggers recharging after exceeding a charge threshold or have an on/off feature that manually recharges upon detecting wireless power transmission signals. This feature is critical for the longevity of the battery system since constant recharging decreases battery life.

14.3 Integration of New Systems Drive Complexity

Smartphone companies do not have the internal core competency to develop and to manage new battery systems. Therefore these companies will be risk averse to adopt this change. The early adopters can be specific product lines that are in dire need for a radical breakthrough system, but to cross the chasm it takes more than just technology to attract the early majority. We explored change management transparency, change management ownership, industry standardization, modularization, and scalability as factors that influence the adoption with the early majority.

Lithium ion suppliers should manage the initial system introduction. They already have a strong and established working relationship with phone manufacturers; hence the communication channels are well established. If the change can be kept localized to the battery system, and at near transparency to the other subsystems within the smartphone, then the barriers to adoption will be reduced. The fewer number of interaction interfaces between the new system and the current system, the faster the adoption.

The faster a technology becomes an industry standard the faster its adoption. Technology standardization helps in crossing the chasm by providing a technology platform where product modularity can be designed and developed. Standardization enables technology to be scaled in production to provide the most efficient operation at the lowest possible cost. Industry specification standardization is another critical element that formalizes the critical characteristics of the technology and defines a standard language between system interfaces. An agreed set of technology characteristics and standard language helps in design rule development and enables an efficient development system between different smartphone sub-systems.

Lithium ion companies and ultracapacitor companies should continue developing new breakthrough technologies that provide performance leaps. Furthermore, they should continue monitoring the progress of their counterparts and strategize how to combat competition.

14.4 Monitoring Performance Trajectories is the Solution to Longevity

Monitoring performance trajectories is a critical task for all technologists and product managers. The trajectory performance of lithium ion, ultracapacitor, and customer needs should be overlaid to assess the gap between technology and customer needs, and the gap between lithium ion and ultracapacitor. Both assessments are equally important.

Our goal is to deliver a system that provides sufficient charge supply to operate a full days worth with minimal disruption by using a new battery system. The assessment between the technology performance and customer needs ensures that technology development does not far exceed projected customer needs. A technology that far exceeds projected customer needs will subject itself to entrance and competition from a lesser superior technology, and one that improves and just meets customer needs.

Monitoring performance of other technologies is equally important. In this case, the current lithium ion improvements have reached a plateau but ultracapacitors are still rapidly improving. Therefore research and development spending should increase in order to discover new product innovations that will shift lithium ion systems to a higher trajectory path. The overlay of trajectory path should encourage active research and development and not create a reactive mode. Lastly, performance trajectory data provides companies with discussion points on corporate strategies in terms of partnerships or market consolidation.

14.5 Different Management Strategies to Address Different Multi-Mode Interactions

The impact of continuous technology improvements and performance shifts on trajectories are moving targets that all corporations have to constantly consider when strategizing their growth path.

Moving targets are dangerous in technology management. Differing technology trajectory paths force corporations in different strategic paths to be more value creation and more value add to the ecosystem. Moving targets force management to continuously assess the impact of multi-mode interactions between technologies and force management to consistently formulate strategies to address the different modes.

The symbiosis relationship is the first stage of co-evolution between lithium ion batteries and ultracapacitors. Each technology has its advantages and each technology is complementary to each other. This symbiosis relationship is suitable for the current state of technology, and as an integrated system it can gain market share and expand to future market growth opportunities better than as individual components.

This relationship will change depending on the performance gap between lithium ion and ultracapacitors. A predator-prey relationship will develop when ultracapacitor performance is close to at par with lithium ion batteries in charge performance. In predator-prey mode, ultracapacitors are the predator and lithium ion batteries are the prey. The continuous growth of lithium ion's market share and market growth positively influences the ultracapacitor's market share and market growth opportunities. On the contrary, the ultracapacitor's growth negatively influences lithium ion's growth. As ultracapacitor's charge performance nears or mirrors that of lithium ion batteries, an inflection point is observed where there is a transition from complementary technology to substitution technology.

Ultracapacitors will become a substitute to lithium ion batteries when its charge performance exceeds that of lithium ion. Unless lithium ion can shift its performance to a new technology performance curve, the dual system will evolve into becoming a single ultracapacitor system. Pure competition commences at the onset of superior ultracapacitor performance.

Corporations should strategize on market consolidation via mergers and acquisitions when ultracapacitors start to make inroads to capture more lithium ion market share. Lithium ion companies should delay market consolidation or decide to not consolidate if there is a high degree of certainty that a radical breakthrough in lithium ion product innovation will be delivered before the multi-mode interaction migrates away from the symbiosis mode. Ultracapacitor companies should decide on delaying market consolidation or decide not to consolidate if their performance trajectory surpasses lithium ion's current and future performance.

14.6 Ultracapacitor and Resonant Magnetic Induction Provides Second Wind for Smartphone Growth

The integration of a new system comprised of a dual battery system with resonant magnetic induction wireless power technology will provide the second wind needed for the smartphone to continue its projected growth. The continuous application of a single lithium ion system with current state of the art charge performance will inhibit smartphone growth. This new system will prolong the operation duration between recharges and enhance user mobility experiences. Charge performance trajectories, proliferation of wireless power transfer technology, and changing company strategies will determine the future of the smartphone charge ecosystem.

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