

Toward Environmentally Sustainable Mobile Computing Through an Economic Framework

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ABSTRACT Amid the plethora of initiatives and research endeavors targeting the minimization of power and energy consumption of information and communication technologies, what has been largely missing is an effort to reduce the energy consumption and electronic waste generated by the rapidly growing segment of mobile computing and communication devices. Prior work with energy efficiency in mobile devices has primarily focused on the goal of maximizing battery life of these devices and not on the broader concept of environmentally sustainable mobile computing. This paper provides an overview of the concept of environmentally sustainable mobile computing and identifies reduction in manufacturing energy costs and electronic waste generated as two important outcomes that can be achieved by increasing device lifespan. Increased device lifespans, however, are possible only if the underlying market forces support such a paradigm shift. This paper develops an analytical economic framework as it applies to mobile phones by analyzing a market scenario of two firms competing under a differentiated Bertrand duopoly model. The framework and its analysis helps verify intuitions about the reasons that affect a firm's decision to offer an environmentally sustainable choice for consumers and considers the feasibility, possible benefits, and challenges in increasing device lifespan, including technical challenges. The results of this paper also provide guidance on the relative impacts of various factors involved on device lifespan such as user-experience, subsidies, and differences in underlying costs to providers.

INDEX TERMS Mobile computing, electronics and the environment, economics, product life cycle management.

I. INTRODUCTION

Computing devices are increasingly pervasive and play different roles in server farms, data centers, office equipment, among others. With the increased awareness in how the world consumes energy, and its impact on the planet, it is natural to thus think about the impact of computing on global energy consumption. There have been many studies that document this impact looking specifically at information and computing technology [1]–[3]. The world, however, is changing the way it accesses the Internet, and does computing in general. The relevance of mobile, battery-operated devices¹ in how we handle computing and communication tasks is increasing.

¹In this paper we will refer to mobile, battery-operated communication and computation devices simply as 'mobile devices'. These devices could include laptops, netbooks, tablet PCs, mobile phones (including smart phones), personal digital assistants (PDAs), and similar devices.

The increased role of mobile devices has resulted in recent work advocating environmental sustainability in mobile computing [4], [5]. The work in [5] and [6] found that computing devices, including data centers, server farms, desktops, and mobile devices (laptops and mobile phones), accounted for about 3-7% of the global electricity usage. Surprisingly, mobile devices were responsible for 10-20% of this share, and this share is expected to grow as power-hungry smart phones proliferate the market. When it comes to looking at energy efficiency and the concept of sustainability in computing, the focus has invariably been on data centers and mobile infrastructures like cell towers, as they have been considered the power hogs within the computing sector (e.g. [7]–[10]).

When considering energy consumed by mobile computing devices, it becomes imperative to consider their manufacturing/production energy consumption along with the traditionally considered use phase energy consumption.

Mobile devices have very short lifespans compared to those of desktops and other network infrastructure. Thus, the overall energy spent in producing these devices is a very significant share of the energy consumed during their entire life cycle (57% as reported in [11]). The problem of electronic waste is also an important one with less than 10% of mobile handsets globally being recycled [12]. Thus, for mobile computing to be energy-efficient and environmentally sustainable, it is important to consider *increasing device lifespan* to reduce electronic waste and cut life cycle energy consumption due to manufacturing.

This paper studies the increase of device lifespan as it applies to contract-based² mobile/cellular phones, one of largest segments of the mobile device market. Two reasons why contract-based mobile phones have a short lifespan are (i) newer models typically provide a better user-experience with increasing capabilities demanded by applications, and (ii) contracts with carriers last only a few years after which there is little incentive for consumers to keep older handsets. Cellular phone carrier contracts in the U.S. last for two years after which customers typically upgrade to newer devices, if not earlier. These new devices offered are heavily subsidized conditional on the signing of a new contract; however, such consumers on contract typically pay a higher price monthly to reflect device cost and service. The novel economic framework developed in this work studies the scenario of a firm introducing a sustainable choice (called Firm 1) where consumers sign a longer contract in exchange for a possibly cheaper combination of device and service plan, which can be supplemented with software upgrades and service to improve user-experience over time. By comparing the demand for Firm 1 in a Bertrand duopoly competition (see [14]) with a firm (Firm 2) that offers only a shorter duration contract, but possibly newer, better hardware more frequently, a better understanding of the feasibility and challenges in consumers adopting a sustainable choice (offered by Firm 1 in this case) can be gained.³ Prior work in computer science and engineering has not looked at how economic factors and incentives can help guide future sustainable product offerings and aid system design in the emerging mobile computing area.

In this paper we propose a novel economic framework to analyze the lifespan of mobile phones and how it can be increased over current scenarios. The specific contributions from this work are the following.

- 1) Development of a conceptual economic framework to understand and make progress towards environmentally sustainable mobile computing as it applies to contract-based mobile phones.
- 2) A study of the impact of user-experience, underlying carrier costs, and subsidies on incentivizing consumers to adopt the environmentally sustainable choice.

²In the U.S. mobile phone market, 77% of users are in contracts with their carriers [13].

³The two-firm scenario used in this paper is easily extensible to a n firm scenario.

- 3) A metric to quantify the benefits due to an increase in lifespan of mobile devices and how it can be used in future system design.

Specific objectives of this work are the following.

- 1) *How competitive will a firm be that provides a sustainable choice for consumers?* This objective considers currently existing scenarios where the sustainable choice may not necessarily be the popular choice.
- 2) *What impact can providing subsidies have on greater adoption of the sustainable choice by consumers, and what areas should progress be made?* This objective relies on analysis from the economic framework to understand the impact of various parameters involved, including subsidies and user-experience from old and new hardware.

II. BACKGROUND AND MOTIVATION

There is increased realization of the fact that the energy consumption and carbon footprint of ICT is significant, and techniques need to be developed for greater power and energy efficiency [1]–[3]. Thus, understandably, when it comes to examining energy efficiency and the concept of sustainability in computing, the focus has invariably been on data centers and mobile infrastructures like cell towers, because they have been considered the power hogs within the sector [7]–[10], [15]–[17].

The relevance of mobile, battery-equipped devices in how humans handle computing and communication tasks is increasing as well. The increased role of mobile devices has resulted in recent work advocating sustainability in mobile computing [4], [5]. The study in [5] was the first to examine overall energy consumption of mobile devices, and showed that energy consumed globally by such devices can be significant. This study found that computing devices, including data centers, server farms, desktops, and mobile devices (laptops and mobile phones), accounted for about 3-7% of the global electricity usage. Surprisingly, mobile devices were responsible for upwards of 10% of this share due to their large scale, and this share is expected to grow as power-hungry mobile devices proliferate the market.

Energy-related research in the mobile computing area, unfortunately from an environmental perspective, has been focused primarily in addressing only the battery-lifetime issue (e.g. [18]–[30]). While optimizing battery lifetime can be useful in reducing the overall energy costs of mobile devices, it only considers energy consumed to operate these devices, neglecting the energy consumed to manufacture and recycle them. Recent studies by Nokia (as shown in Fig. 1(a)) show that use phase energy consumption is only a small fraction of the overall life cycle and broader efforts are required to move towards sustainable mobile computing that includes cutting down the amount of devices manufactured, and hence, eventually recycled as well.

One avenue of cutting down energy costs for the non-use phase is greater efficiency in the processes employed such as

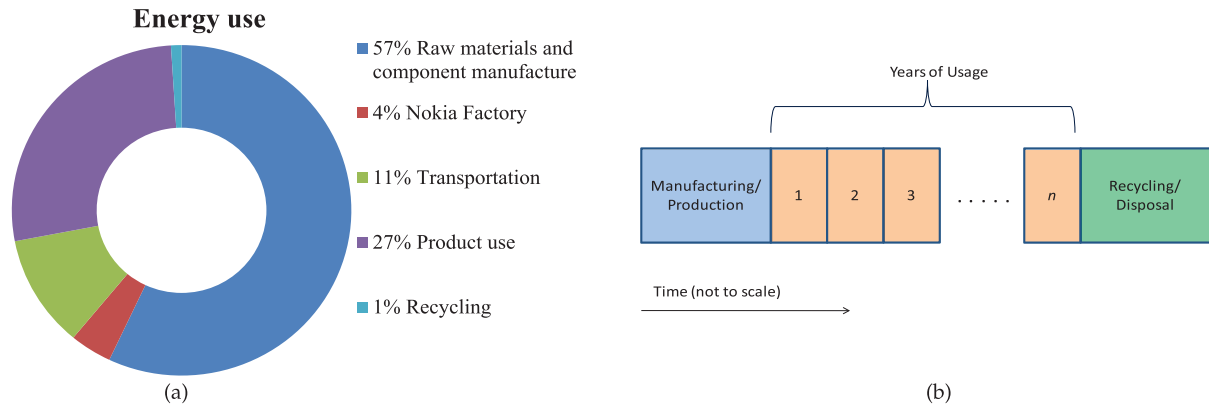


FIGURE 1. Motivation for moving towards sustainable mobile computing. (a) Energy consumption breakdown over the life cycle of a mobile phone as originally illustrated in [11]. Current approaches focus on minimizing use-phase energy neglecting the much larger manufacturing phase. (b) A life cycle perspective of mobile device energy consumption. Greater lifespan can reduce annual life cycle energy costs by amortizing non-use phase energy costs over greater number of years of use.

in manufacturing, transportation, and recycling. This option is an ongoing process employed by corporations currently to not only cut energy costs, but also overall monetary costs. Another avenue would be increasing the lifespan of mobile devices which would cut down energy consumed for tasks like manufacturing, transportation, and recycling across the entire spectrum of mobile devices. A longer lifespan would mean that the energy consumed by a device during the non-use phases would be amortized over a longer use-phase (see Fig. 1(b)), in turn reducing the overall energy consumed by the mobile device segment. The increase in lifespan option is expected to also have a more immediate impact and complementary to the ongoing search for efficiency in manufacturing, transportation, and recycling and will further assist cutting down the rate of generation of electronic waste through reduced device replacements.

Increase in mobile device lifespans can be achieved only if consumers retain their devices longer. From a technical perspective, this would probably require greater emphasis on software features that can be updated as opposed to hardware features which necessitate replacements. Additionally, educating consumers about the environmental impact of frequent device replacements may help. *However, by and large, an increase in mobile device lifespans will not be easy to achieve by relying only on technological advances and educational efforts.* The existing mobile device market relies on frequent device turnover to sustain itself and changing that model to a more sustainable one (with greater device lifespans) would require a study of the underlying market economics and how it can be tuned to incentivize market players like consumers and vendors.

Thus, in this paper we propose a novel conceptual economic framework to analyze how the lifespan of mobile devices can be increased over current scenarios. The emphasis in this paper will be on mobile phones as they tend to have the highest turnover among mobile devices possibly induced as a result of frequently introduced hardware features and one or two year wireless carrier contracts. More general implications

that can be applied to all mobile devices will be discussed in Section VI. Apart from an emphasis on the underlying economics, special attention will be given to understand the technical capabilities needed from any environmentally friendly device option relative to a traditional device option.

III. ECONOMIC FRAMEWORK

The goal of developing a conceptual economic framework here is to better understand how consumers can be incentivized to keep their mobile/cellular phones for longer durations, which clearly does not seem to be happening under current market practices. As reducing energy consumed in manufacturing devices and decreasing environmental waste provides environmental benefits, governments or regulators could provide incentives for customers to keep their devices longer. For example, a regulator could pay a part of carrier service costs after a device has been used over a period of time. The incentive for the subsidy provider is that increasing lifespan has environmental benefits through reduced electronic waste, associated reduction in manufacturing and recycling energy costs, and carbon emissions. There has been some market movement in this direction by some 'Green' cellular carriers who offer customers the option to buy refurbished phones without contracts. A recent article in the Wall Street Journal discussed such an option by Sprint [31].

This section begins by describing the market scenario and models used to determine demand for mobile phones in a scenario where no subsidies are provided. Subsequently, the demand for phones where a subsidy is used to provide consumers a discount for willing to adopt the sustainable choice is presented. This section ends by defining a metric to quantify the benefit that can be obtained by consumers adopting the sustainable choice.

A. MARKET SCENARIO

We characterize the U.S. mobile market to be an oligopoly where a few firms dominate the market and have strategic

interactions with each other.⁴ The study of non-cooperative oligopolistic competition can be done using various models such as Cournot, Bertrand, Cournot-Bertrand, Stackelberg to name a few. Cournot and Bertrand competitions can be seen as extremes of oligopoly types, with the mode of competition dictated more by the type of good than by the choice made by the firm, i.e., whether firms want to compete in price or quantity. Under Cournot market structure each firm maximizes its output with the expectation that the other firm holds its output level constant. In contrast, under Bertrand market structure each firm maximizes profit assuming the rival firm holds its price constant. If the firms can adjust the capacity and output quickly, Bertrand type competition will ensue. If capacity decisions need to be made ahead of actual production, i.e., output cannot be increased quickly, Cournot is seen. In this work we consider a differentiated Bertrand model to explain firm behavior in our paper because the nature of the mobile industry is such that firms are likely to compete on prices and not quantities. A differentiated Bertrand model takes into consideration that offerings of firms are not perfect substitutes—consumers differentiate and may prefer a firm's offering over another firm. For interested readers, more details on these micro-economic models and their applicability and use can be found in the book [32].

For simplicity and intuitive results, we assume two firms characterize the market. The mobile industry is concentrated with few major players, so modeling two firms (duopoly) will capture the market dynamics.⁵

Firm 1 offers consumers a service plan (and a phone) with a contract of t_1 years, while Firm 2 offers a service plan and a phone with a contract for t_2 years, where $t_1 \geq t_2$. If Firm 2 represents the current practice of short duration contracts, then Firm 1 can be thought of as the firm offering an environmentally sustainable choice to consumers. In the rest of this paper, one of the objectives will be to study how competitive Firm 1 is found to be (or can be made) with respect to Firm 2 such that consumers choose the sustainable option and retain the hardware device longer. We use a duopoly model with only two competing firms for simplicity as is common in industrial organization research; the model and its results can be extended to n competing firms similarly.

Consumer preference is characterized based on the model of vertical product differentiation by Mussa and Rosen in [14]. In a vertically differentiated product space, all consumers agree over the most preferred mix of characteristics and, more generally, over the preference ordering. For example, a smaller and more powerful computer is preferable over a larger and less power one. At equal prices there is a natural ordering over the characteristic space [32]. This model is used in this work to explicitly account for differences in consumer attitudes towards mobile phone offerings that consist of a hardware communications device and a service plan of a fixed

⁴An oligopoly is a market structure form in which a market or industry is dominated by a few sellers (oligopolists).

⁵Once the results of such a market are mature and well understood, future work could look at n -player markets to study aspects that remain uncovered.

duration contract, with a device replacement offered after the contract expires.⁶

A consumer has the following preferences:

$$\mathcal{U} = \begin{cases} \theta k_1 - p_1, & \text{chooses Firm 1 with longer contract} \\ \theta k_2 - p_2, & \text{chooses Firm 2 with shorter contract} \\ 0, & \text{chooses no service} \end{cases} \quad (1)$$

where $k_1 \leq k_2$. \mathcal{U} can be thought as the utility derived from the use of the mobile phone. k_1, k_2 are positive real numbers that describe the average user-experience provided by a firm's offered phone over the entire contract duration.⁷ p_1 and p_2 are the prices paid by the consumer for each of the options respectively. The utility is separable in user-experience and price.

The user-experience value of a device being offered by the i th firm, k_i , will take the duration of contracts offered into consideration. For example, a larger duration of t_1 can be expected to have a smaller value of k_1 as this requires the consumer to retain an old device longer. The popularity of a particular device brand or manufacturer can be similarly incorporated in the user-experience parameter. θ , again a positive real number, is a taste parameter. All consumers prefer higher user-experience for a given price; a consumer with high θ is more willing to pay for higher user-experience. θ can be modeled as a distribution of tastes in the economy according to some density $f(\theta)$ with a cumulative distribution function $F(\theta)$.

Under this model, consumers with a taste preference $\tilde{\theta} \equiv \frac{p_2 - p_1}{k_2 - k_1}$ choose the mobile phone offering that involves a shorter contract (implying a new device is obtained at more frequent time intervals), since $\theta k_2 - p_2 > \theta k_1 - p_1 \Leftrightarrow \theta \geq \tilde{\theta}$.

Thus, demand for the shorter contract service by a single consumer⁸ can be expressed as

$$Q_2(p_1, p_2) = 1 - F\left(\frac{p_2 - p_1}{k_2 - k_1}\right) \quad (2)$$

Consumers with a taste parameter lower than $\tilde{\theta}$ but greater than p_1/k_1 buy the longer contract service. Demand for the longer contract service is then

$$Q_1(p_1, p_2) = F\left(\frac{p_2 - p_1}{k_2 - k_1}\right) - F\left(\frac{p_1}{k_1}\right) \quad (3)$$

Then, finally there are consumers who decide to choose no service given the options available to them and the demand for this option is just $Q_0(p_1, p_2) = 1 - Q_1(p_1, p_2) - Q_2(p_1, p_2)$.

⁶To the best of knowledge, such a framework has never been used to model and understand mobile device offerings, bringing together the disciplines of computer science and engineering, and economics.

⁷It can be expected that user-experience could degrade over the duration of the contract, being highest in the first year and lowest in the last year as the hardware and software become more outdated. Thus, an average value over the contract duration is taken in this work to keep the model simple.

⁸Demand in the case of N consumers is simply N times the demand of one consumer.

B. DEMAND UNDER EQUILIBRIUM CONDITIONS

Given the demand functions computed above, to determine the equilibrium quantity and prices of service desired, we first solve the profit maximization problem for Firm 1 and Firm 2. We will assume a uniform distribution in the interval $[0, 1]$ for the taste parameter θ . This is the most commonly used distribution in literature, but any other distribution could be applied here as well.

The profit maximization function of Firm 2 when both firms compete on price is

$$\max_{p_2} \Pi = [p_2 - c_2]Q_2(p_1, p_2) \quad (4)$$

where p_2 is price charged for Firm 2's service and c_2 is the cost per unit device to the firm to provide the service including device costs.

Firm 1's profit maximization similarly is

$$\max_{p_1} \Pi = [p_1 - c_1]Q_1(p_1, p_2) \quad (5)$$

where p_1 is the price charged for Firm 1's service.

The first order conditions give the quantity demanded and price for each firm's service at equilibrium.

Firm 2's demand can be expressed as

$$Q_2 = \frac{c_2(k_1 - 2k_2) + k_2(c_1 - 2k_1 + 2k_2)}{(k_1 - 4k_2)(k_1 - k_2)} \quad (6)$$

while the price it charges a consumer can be expressed as

$$p_2 = \frac{k_2(-c_1 - 2(c_2 - k_1 + k_2))}{k_1 - 4k_2}. \quad (7)$$

Similarly Firm 1's demand can be expressed as

$$Q_1 = \frac{k_2(c_1(k_1 - 2k_2) + k_1(c_2 - k_1 + k_2))}{k_1(k_1 - 4k_2)(k_1 - k_2)} \quad (8)$$

while the price it charges a consumer can be expressed as

$$p_1 = \frac{k_1(k_1 - c_2 - k_2) - 2k_2c_1}{k_1 - 4k_2}. \quad (9)$$

The impact of the underlying costs to the two firms c_1 and c_2 are of particular interest and will be modeled and studied in Section IV through numerical evaluations. These include the costs for both firms to provide the underlying service and handsets. For Firm 2 they also include the cost of subsidizing a new device at the expiration of the contract duration. For Firm 1 it could include costs for any maintenance plans and/or software updates and support to maintain or improve user-experience over a longer duration.

C. INCENTIVIZATION OF THE SUSTAINABLE CHOICE THROUGH SUBSIDIES

The impact of any subsidies regulators offer can be factored into this model by defining a new term s for the environmental cost.⁹ This could be a combination of costs incurred for manufacturing and recycling of a device, and dealing with

⁹This could be monetary value attached to the emissions and fossil fuels used up. Carbon offset costs in terms of planting new trees could be one way to perceive this term.

associated carbon emissions. By increasing lifespan, we are amortizing this cost over a longer duration that reduces the annual environmental costs. This reduction in annual cost can be passed along as a subsidy/annual cost saving to the consumer to help improve the chances of adoption.

With the addition of a subsidy s to the consumer, the utility function can be expressed as

$$U = \begin{cases} \theta k_1 - p_1 + s, & \text{chooses Firm 1 with longer contract} \\ \theta k_2 - p_2, & \text{chooses Firm 2 with shorter contract} \\ 0, & \text{chooses no service} \end{cases} \quad (10)$$

Under this new utility function, the demand functions can be computed similarly as above to arrive at the market share of each firm and the price they will charge. Firm 2's demand can be expressed as

$$Q_2 = \frac{c_2(k_1 - 2k_2) + k_2(c_1 - 2k_1 + 2k_2 - s)}{(k_1 - 4k_2)(k_1 - k_2)} \quad (11)$$

while the price it charges a consumer can be expressed as

$$p_2 = \frac{k_2(-c_1 - 2(c_2 - k_1 + k_2) + s)}{k_1 - 4k_2}. \quad (12)$$

Similarly Firm 1's demand can be expressed as

$$Q_1 = \frac{k_2(c_1(k_1 - 2k_2) + k_1(c_2 - k_1 + k_2) - (k_1 - 2k_2)s)}{k_1(k_1 - 4k_2)(k_1 - k_2)} \quad (13)$$

while the price it charges a consumer can be expressed as

$$p_1 = \frac{k_1(k_1 - c_2 - k_2 + s) - 2k_2(c_1 + s)}{k_1 - 4k_2}. \quad (14)$$

D. CONSUMER WELFARE

While we typically analyze the operation of markets by examining the movements of price or quantity, we may also be interested in asking broader questions about how much consumers benefit from consuming a certain good. This benefit is typically termed consumer welfare (also known as consumer surplus) and refers to the difference between what consumers are willing to pay and what they actually pay for a product. Consumer welfare is calculated by aggregating consumers' utility in purchasing a certain product with the number of consumers preferring that particular product.

Thus, based on the utility function in Equation 10, we can express consumer welfare CW as

$$CW = \int_{\theta_0}^{\theta_1} (\theta k_1 - p_1) d\theta + \int_{\theta_1}^{\theta_2} (\theta k_2 - p_2) d\theta \quad (15)$$

which can be solved using the values $\theta_0 = \frac{p_1}{k_1}$, $\theta_1 = \tilde{\theta} = \frac{p_2 - p_1}{k_2 - k_1}$, and $\theta_2 = 1$ to give the final expression

$$CW = \frac{k_2[A + k_1BC]}{2k_1(k_1 - 4k_2)^2(k_1 - k_2)^2}, \quad (16)$$

where A , B , and C are variables used to simplify the presentation of the equation. These variables are further expressed as: $A = k_2(c_1(k_1 - 2k_2) + k_1(c_2 - k_1 + k_2) - (k_1 - 2k_2)s)^2$, $B = c_2(k_1 - 2k_2) + k_2(c_1 - 2k_1 + 2k_2 - s)$, and $C = 2c_1k_1 + 3c_2k_1 - 2k_1^2 - 3c_1k_2 - 2c_2k_2 + 2k_2^2 - 2k_1s + 3k_2s$.

E. METRIC TO QUANTIFY ENVIRONMENTAL BENEFITS THROUGH LONGER LIFESPAN

A longer lifespan for a mobile device results in reduced life cycle energy consumption and electronic waste. Thus, the metric adopted for evaluating progress towards environmentally sustainable mobile computing in this paper is the fraction of devices that will not have to be replaced with new ones manufactured to replace them.

Assume that t_1 is the longer contract duration in years while t_2 is the shorter contract duration. The benefits from adopting the sustainable choice can be quantified as a ratio of the lifespan increase over the sustainable choice contract duration times the fraction of consumers willing to adopt the former among all devices sold. Thus, the *lifespan benefit metric* can be expressed as

$$b_L = \frac{t_1 - t_2}{t_1} * \frac{Q_1}{Q_1 + Q_2} \quad (17)$$

where $t_1 \geq t_2$. The first term in Equation 17 quantifies the amount of reduction in devices that will have to be manufactured under a static analysis condition assuming no new consumers enter the market for a device. This term comes about due to the fact that $\frac{x}{t_2}$ and $\frac{x}{t_1}$ are the number of devices that would have been manufactured under the shorter and longer plan respectively if x consumers were looking to possess such devices. The fraction of devices that would not need to be manufactured then is the ratio $\frac{\frac{x}{t_2} - \frac{x}{t_1}}{\frac{x}{t_2}} = \frac{t_1 - t_2}{t_1}$. The second term provides the ratio of demand for Firm 1's devices to the overall demand for devices from both firms. Note that we do not include demand for the no service/device option as it provides consumers with no utility. For example, if $t_2 = 2$ years, $t_1 = 5$ years with demand $Q_1 = Q_2 = 0.5$, then $b_L = 0.30$ signifies that the presence of Firm 1 (with its given market share and contract length) results in a 30% reduction in the overall number of devices that will be manufactured (and eventually part of waste if not recycled).

IV. NUMERICAL EVALUATIONS

The first objective of the evaluations here is to gauge the competitiveness of a firm that offers an option for consumers that requires retaining their mobile phone longer (than another competing firm) and analyze the impact of economic incentives. This is because eventually the introduction of such a sustainable choice will depend on the market share it can gather. The second objective is to analyze consumer welfare. The third objective is to look at possible benefits in terms of reduced life cycle energy consumption that can be obtained if a firm were to offer a sustainable choice aimed at increased lifespan.

A. EXPECTED MARKET SHARE

The first step was to study the market share that could be achieved by the two competing firms. A consumer choosing between these firms has three options available: choose Firm 1 with a longer duration plan, choose Firm 2 with a

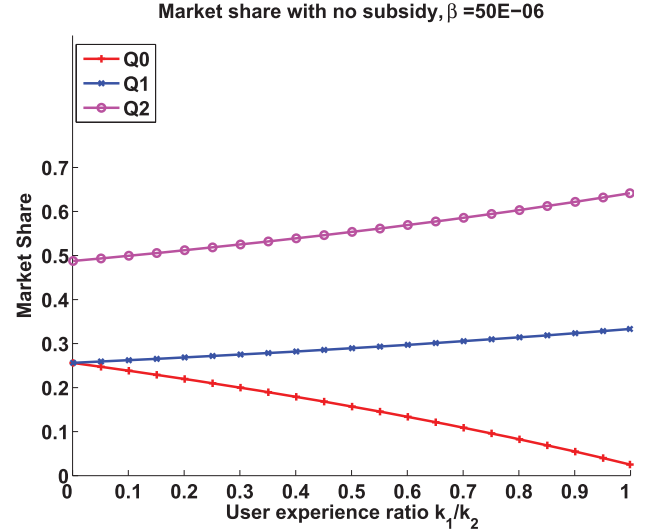


FIGURE 2. Market share for all three options available to a consumer for varying user-experience ratio $\frac{k_1}{k_2}$ with no subsidy provided. Q_0 here is simply $1 - Q_1 - Q_2$.

shorter duration plan, or decide against adopting service (and device) from either firm. The relative user experience ratio $\frac{k_1}{k_2}$ was set to various values between 0 and 1 in our experiment. The cost functions were modeled as $c_i = 0.5\beta k_i^2$, for $i = 1, 2$ where each firm's cost incurred is a function of the user-experience it provides with β acting as a scaling parameter. This is a commonly used form of modeling costs in economic theory [33], [34]. We use the values of $\beta = 50E-06$ and $k_2 = 1000$ in our experiments unless specified otherwise; these values along with θ (Equation 1), chosen from a uniform distribution $[0,1]$, ensure that the profit and quantity values stay positive and meaningful. With the ratio $\frac{k_1}{k_2}$ varied from 0 to 1, a small value of the ratio $\frac{k_1}{k_2}$ would imply a vast difference in user-experience making it more difficult for Firm 1 to compete with Firm 2. The point of interest was to look at what ratios Firm 1 is competitive. Later in Section VI, options to increase the ratio $\frac{k_1}{k_2}$ will be discussed.

Fig. 2 shows that initially when user-experience of the device from Firm 1 is low, Firm 2 captures about half the market with the remaining split between Firm 1 and the no device option. As k_1 increases, Firm 1 captures an increasing share of the market eventually gaining a third of the market, mainly at the expense of the no device option. Firm 2's market share also increases, at a rate slightly higher than Firm 1. A takeaway from this plot is that Firm 1 is reasonably competitive with over a quarter of market share at all times for the parameter values considered ($\beta = 50E-06$, $k_2 = 1000$); however, Firm 2 is always dominant. Though not shown here, Firm 2 stays dominant as shown until the cost scaling parameter β increases to above $665E-06$; from that point the cost structure begins favoring the no device option and to a lesser extent Firm 1 at the expense of Firm 2. Eventually if costs keep increasing, the no device option will capture the entire market as expected.

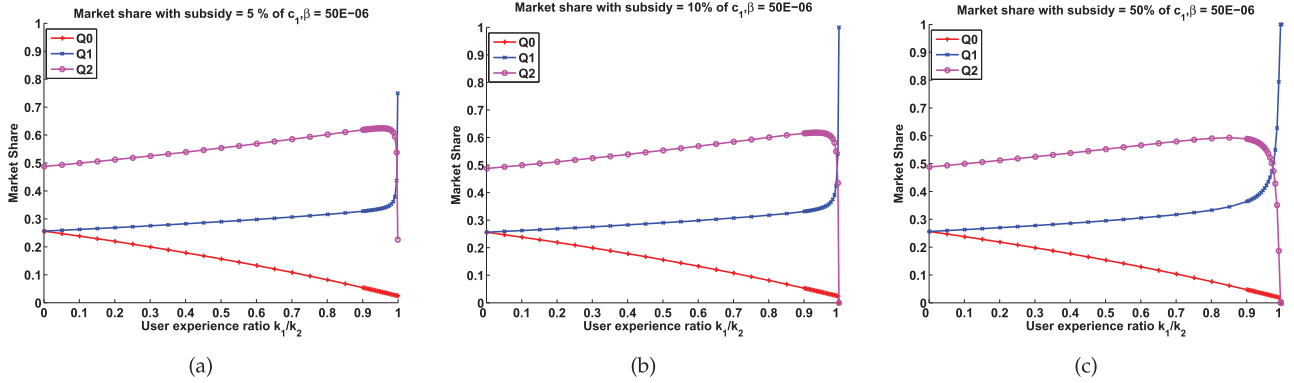


FIGURE 3. Impact of various values of subsidy on market share. Even a small subsidy makes the sustainable firm more competitive. For the given values, a subsidy of 10% of the cost c_1 or higher allows Firm 1 to capture the complete market share if the user-experience from its offering, k_1 , is close to the user-experience from Firm 2's offering, k_2 .

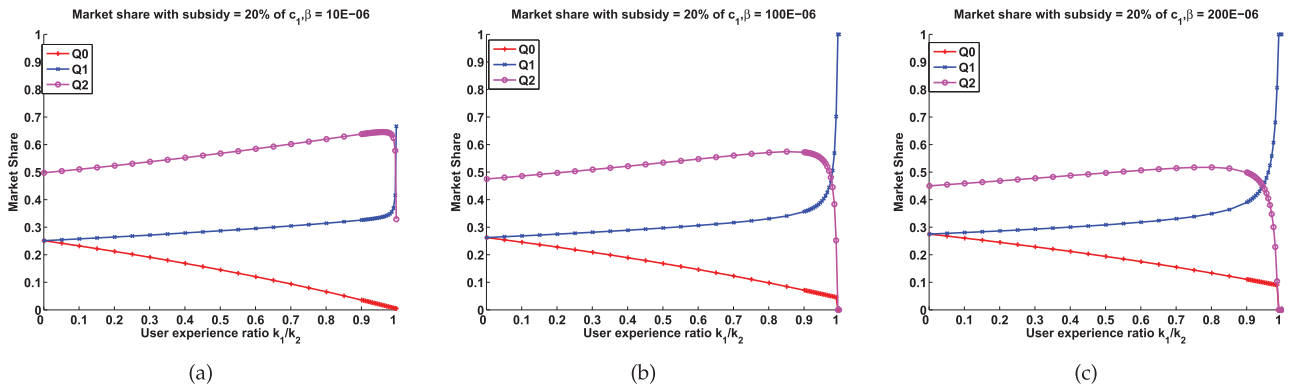


FIGURE 4. Impact of varying cost scaling parameter β on market share for a fixed subsidy of 20% of c_1 . A lower cost for Firm 1 (lower cost ratio) enables it to capture the entire market at a lower user experience ratio.

1) IMPACT OF SUBSIDIES

The second step was to study the impact of subsidies on how much market share the sustainable choice Firm 1 can garner, and whether the user-experience ratio needed differs significantly from the scenario above with no incentives. Subsidies were applied as a percentage of Firm 1's costs c_1 ; values considered were 5%, 10% and 50% of c_1 . As Fig. 3(a)–(c) show, adding a value of subsidy greatly benefits Firm 1 in terms of the market share it is able to capture from its competitors; in fact when k_1 is very close to k_2 for a subsidy equal to 10% of costs or greater, Firm 1 is able to capture the entire market. Additionally, even with small subsidies and a small user experience ratio $\frac{k_1}{k_2}$, an increase in relative market share can still be clearly seen for subsidies as low as 5% of carrier costs compared to the no subsidy outcomes.

2) IMPACT OF VARYING UNDERLYING COSTS OF FIRMS

Next we vary the cost scaling parameter β to study its impact on the relative market share that firms get for increasing values of the ratio $\frac{k_1}{k_2}$ with a fixed subsidy value of 20% of c_1 . A larger value of β increases the costs for a firm i to provide a user-experience k_i . The results in Fig. 4 suggests that an increasing value of β allows Firm 1 to capture the

market at lower user-experience ratios. This is because in the expressions for demand at equilibrium, Firm 1 with subsidies is less sensitive to an increase in the cost scaling parameter compared to a likewise increase for Firm 2. Thus, if the sustainable choice firm has an inherent cost advantage, it can leverage this to capture greater market share than other firms, even if user-experience is not as high. *Thus, overall, an environmentally sustainable choice can be reasonably competitive with adequate incentives provided. The proposed economic framework is useful in not just supporting this intuition, but also in providing the range of parameter values when this is possible.*

B. IMPACT ON CONSUMER WELFARE

Based on the expression in Equation 16, we plot total consumer welfare CW in Fig. 5 for increasing values of the user-experience ratio $\frac{k_1}{k_2}$ for four different values of subsidy as a percentage of c_1 and three different values of β . Note that consumer welfare is an aggregate value based on product choices a consumer has. The results indicate that consumer welfare increases as $\frac{k_1}{k_2}$ increases. Subsidies increasingly make a bigger difference to consumer welfare as β increases. This is because, subsidies allow the environmentally friendly option provided by Firm 1 to dominate the market at higher values of the user experience ratio $\frac{k_1}{k_2}$.

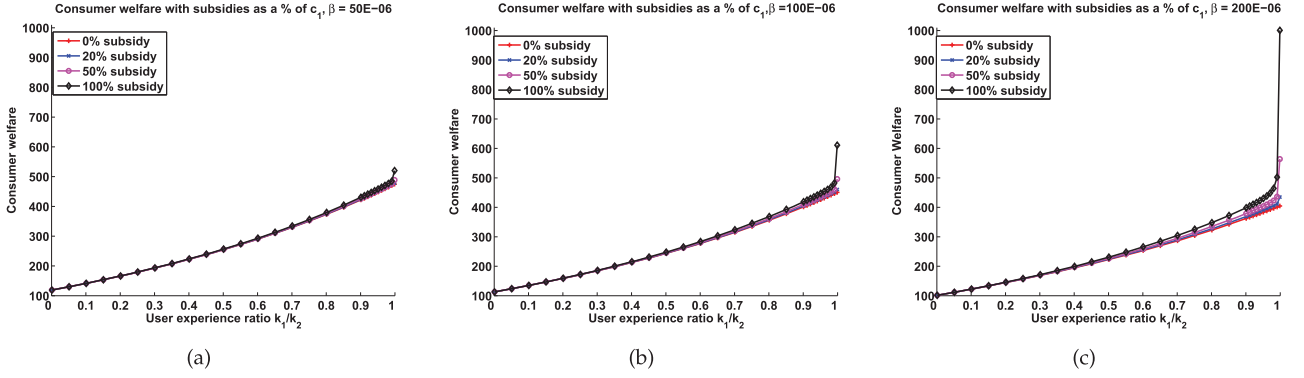


FIGURE 5. Consumer welfare as a function of varying cost scaling parameter β for a fixed subsidy of 20% of c_1 . Consumer welfare increases sharply as Firm 1 captures more of the market at higher values of the ratio $\frac{k_1}{k_2}$.

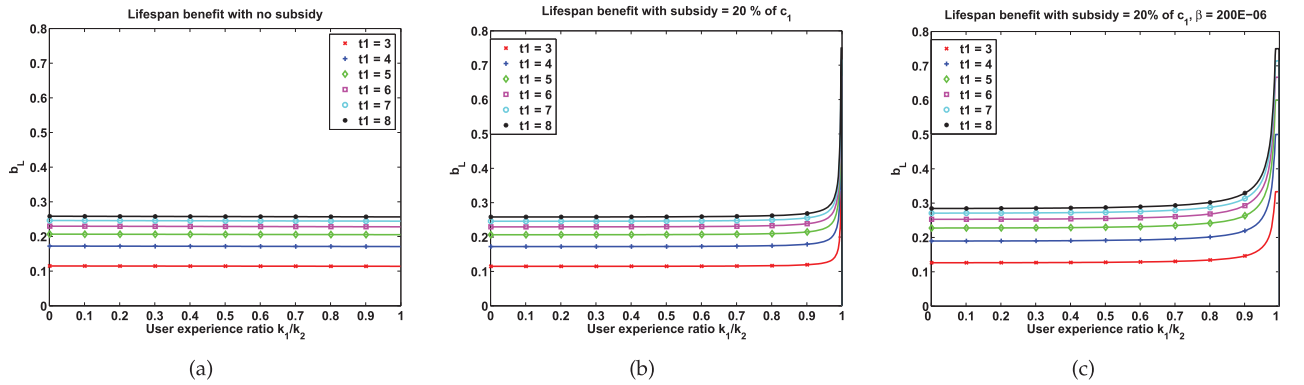


FIGURE 6. Lifespan benefit b_L for Firm 1 as a function of $\frac{k_1}{k_2}$ with $t_2 = 2$ years. A subsidy of 20% of c_1 was applied for Firm 1 for (b) and (c). The parameter β was set to $200E - 06$ for (c) while it was set to $50E - 06$ for (a) and (b).

C. IMPACT ON LIFESPAN BENEFITS

The second objective of our evaluations was to evaluate the lifespan benefit as defined in Equation 17 for varying contract durations of Firm 1, with Firm 2 duration kept fixed. The results obtained are shown in Fig. 6.

When no subsidies were applied the results in Fig. 6(a) show the relative benefits for varying contract durations t_1 . As expected, a larger t_1 results in greater benefit. Interestingly, even for $t_1 = 3$ years with $t_2 = 2$ years, the b_L value is greater than 0.1 (a 10% reduction in devices manufactured) for all values of k_1 . The value of b_L does not increase further until Firm 1 captures most of the market share when $\frac{k_1}{k_2}$ is closer to 1. The introduction of a subsidy for Firm 1 results in attaining a higher value of b_L at higher values of $\frac{k_1}{k_2}$. This trend mirrors the increase in market share for Firm 1 as seen in Fig. 3. When β is increased from $50E - 06$ to $200E - 06$, there is an increase in b_L at all values of $\frac{k_1}{k_2}$ due to Firm 1's advantages in costs compared to Firm 2.

V. IMPLICATIONS FOR SYSTEM DESIGN

Based on the results in the previous section, it is apparent that user-experience on a device, in addition to costs and incentives, plays a major role in determining whether consumers will adopt an old phone over a new phone. In this section we will study how cloud-computing can be leveraged to improve

the user-experience on older devices compared to newer devices as an example of how system design can be tuned for environmentally sustainable mobile computing. In terms of the analytical model presented earlier, this represents a case study of how the value of parameter k_1 can be brought closer to k_2 enabling an older device to effectively compete with newer devices in terms of computational performance. These user-experience parameters were shown in the previous section to be most significant in terms of which firm gathers greater market share, and hence are the focus of this case study as compared to other parameters of the model. Though computational performance is not a proxy for overall user-experience, it is certainly a major factor in terms of mobile phone user experience [35]. An older device's performance will be compared against a newer device to highlight why performance is one reason newer hardware is sought. Subsequently, we compare how a cloud-enhanced older device can compete well in terms of performance with a newer device that may or may not be cloud-enhanced itself.

A. CLOUD COMPUTING AND MOBILE DEVICES

Computing with mobile devices has always presented challenges in terms of storage, memory, processing, network connectivity, bandwidth, and battery lifetime in comparison to their static counterparts like desktop computers. With

the technological advances in recent years improving ubiquitous connectivity and bandwidth, cloud computing has become feasible allowing these constrained devices to utilize the greater storage, memory, and processing capabilities of powerful remote servers. Cloud computing is typically a client-server architecture, where the client can be any mobile device like a laptop, phone, browser, or any other operating system-enabled device. Due to benefits of cloud services, many mobile devices increasingly act like dumb terminals with most of the computing functionalities provided by the remote cloud servers.¹⁰ For many advanced applications (e.g. face recognition) powerful cloud servers are more preferable [37], [38]. Better network connectivity and performance aids this trend. In such scenarios mobile devices need limited hardware functionality with most of the functionality provided through software. Software can be easily upgraded periodically requiring no hardware upgrades. Under such scenarios newer hardware may provide little additional benefits allowing the ratio of $\frac{k_1}{k_2}$ to be close to one.

B. EXPERIMENTAL METHODOLOGY

The comparison of the older device's performance against a newer device will be done by executing a task locally on both, and also on a server emulating a cloud. The offloading of the task to the cloud involves running a client-server program on the device under test (the client) and the cloud server. Our experimental methodology can be divided into devices used for the experiments, the task performed, and the performance metric used.

1) DEVICES

The server device used was a Sony VAIO laptop with Intel i5-3210M CPU and 2.50 GHz processing speed. It had 6 GB RAM and was running the Windows 7 platform. A HTC Desire phone with a 1 GHz Scorpion processor was used as one of the mobile devices under test. It had 512 MB of RAM and was running Android v2.2. The second mobile device under test as the Samsung Galaxy Note N7000 with a dual core 1.4GHz processor ARM cortex A9. It had 1 GB RAM and was running on Android v2.4 platform. These two phones were introduced at least two years apart from each other, and thus, served as ideal devices¹¹ for the comparison between a newer and older device. They both used the Wi-Fi interface for communication with IEEE 802.11g/n capability.

2) TASK

The task considered was to sort a file containing $N = 100$ random integers repeatedly 200,000 times using the common

¹⁰The Google ChromeBook could be cited as an example of such a device that runs mainly off cloud servers with limited local hardware capabilities on the device itself [36].

¹¹We also ran these tests on a third mobile phone Samsung Galaxy S3 running a newer version of Android, Android v4.1. Its specifications are similar to the Samsung N7000, but with a faster processor and using a newer OS. The performance of this phone was better than the N7000, but not better enough to add any significant value in presenting as a separate result.

insertion sort algorithm. Sorting is a task whose computation intensity and execution time can be easily varied by varying N making it very useful for the problem under consideration to study relative performance. Many common applications execute tasks resembling sorting in complexity; examples include image processing, face recognition, search, scheduling. Insertion sort is a commonly used sorting algorithm that is well-understood. Note that the particular sorting algorithm used could be easily changed and will not have any bearing on the conclusions drawn. Experiments were also conducted to understand the impact of task complexity on the results by increasing the value of N to 1600.

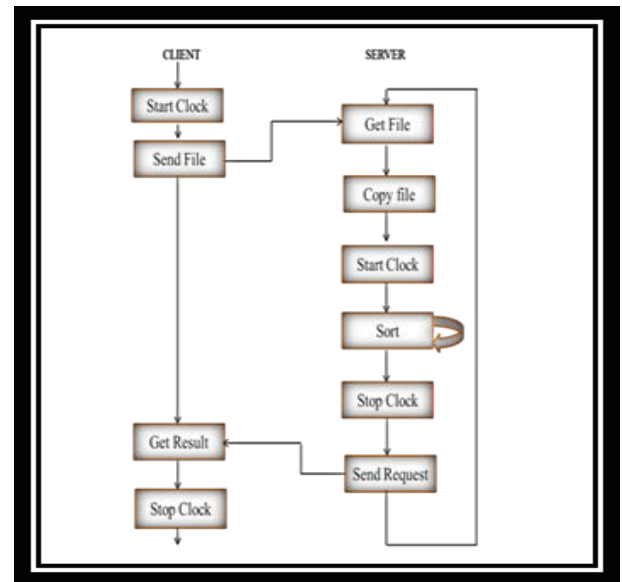


FIGURE 7. Methodology to measure execution time of the task at the server and client device.

3) PERFORMANCE METRIC

For performance metric, we use the latency to complete a specific task. We compare the time it takes for a device to complete the task. The task could be executed locally on the device or offloaded to a remote server over a communications network, executed, and the results brought back to the device. Fig. 7 explains how the insertion sort algorithm is used between the client (the mobile device) and the cloud server, and how we measure the time needed to complete the task at either the client or the server. The total time to perform the task at the server includes the time spent in the network, and the time to execute the task at the server itself. For our experiments involving offloading the task to the cloud and back, the server was on the same local area network as the client; thus round trip network delay was typically less than 50 ms. In a more practical scenario the server could be anywhere. Thus, one may need to add anywhere from 50-400 ms of additional round-trip delay due to the network depending on server location; the reader may refer to [39] for a list of common network latencies across geographic regions.

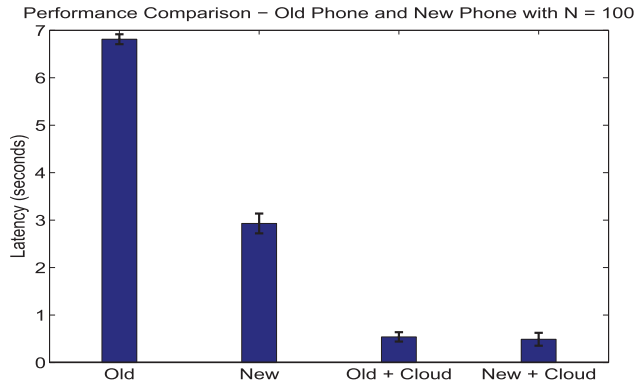


FIGURE 8. Performance comparison between an old phone (with and without cloud-enhancement) and new phone (with and without cloud-enhancement) for sorting a set of $N = 100$ integers.

We will discuss this additional worst-case delay when we present our results next.

C. RESULTS

Fig. 8 shows the latency to execute the sorting task locally on both the old phone (HTC Desire) and the new phone (Samsung N7000). The figure also shows the latency to execute the task by leveraging a more powerful cloud server. The task size was set to $N = 100$ integers for this experiment. The data points plotted are the mean of 10 different experiments; error bars shown indicate the standard deviation over these 10 runs. As expected the old phone takes more time (as much as 3 seconds more) to sort 100 integers compared to the new phone. When the old phone leveraged the server to complete the task, it was able to do it significantly faster due to the greater capabilities of the server. The new phone also benefits similarly by using the cloud. *The result of interest, however, is not only that both devices benefited significantly from the cloud paradigm, but also that the performance advantage of the new hardware was rendered inconsequential.* It can be argued that if the server were far away from the devices under test, the cloud-based execution would have incurred greater delays. This is true, but, it would have added only a few hundred milli-seconds to the overall latency, much less than the performance gap for cloud vs. local execution. Further, network delays would equally impact both devices when they leverage the cloud.

The experiment was repeated for a more computationally-intensive task by increasing N to 1600. The results are shown in Fig. 9. For a task requiring greater computational power, the difference in performance between the old and new phone is greater for local task execution. However, when the cloud server is used, the difference in performance again vanishes. In fact, the old device can even do better than the new device if its network interface is comparable to that of the new device, or more compatible to the existing network. This was the case in our experiment where the network interface on the old device seemed to perform better with slightly,

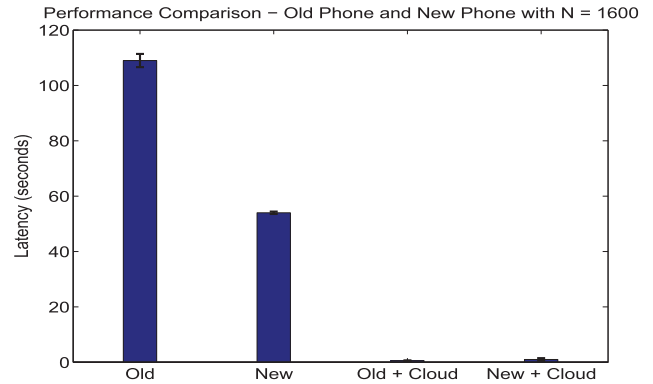


FIGURE 9. Performance comparison between an old phone (with and without cloud-enhancement) and new phone (with and without cloud-enhancement) for sorting a set of $N = 1600$ integers.

but consistently, lower network latencies than the interface on the newer device.

The take away from the experiments in this section is that it is possible under some conditions to bring the user-experience, k_1 in the economic framework, of old devices closer to that of newer devices, k_2 , by relying on primarily software technologies. Cloud-computing is primarily a software technology relying only on a centralized hardware infrastructure. It is much easier to plan and design green data centers due to their centralized nature than “greening” distributed computing hardware on a large-scale like mobile devices. Of course, user-experience depends on other factors as well, and newer hardware may have an edge over older devices in other categories. However, based on the results of this paper, any improvements in user-experience in older hardware (k_1) would require less economic incentives for a similar adoption rate, making it more feasible.

VI. DISCUSSION

In this section three interesting questions that need to be explored further are discussed. These questions have come about mainly as result of the exploration of the framework; hence, the generation of such questions and identification of future pathways for additional research on environmentally sustainable mobile computing can itself be considered as an additional contribution of this paper. We begin with a summary of the analytical results and discuss what they mean in the context of the problem discussed.

A. OVERVIEW OF ANALYTICAL RESULTS AND THEIR IMPLICATIONS

The overall goal of the work was to further sustainable mobile computing by exploring whether a firm providing environmentally friendly options would be able to compete in the marketplace and under what conditions. As economic principles and market forces often dictate future technical directions, our work tries to link the two in understanding what factors need to be looked in moving towards greater environmental sustainability for the mobile computing paradigm.

Some of the results seen in the previous section help answer the following specific objectives of this work.

- 1) *How competitive will a firm be that provides a sustainable choice for consumers?* In our model, demand for a firm's offering at equilibrium was quantified by equations 11 and 13 for the case with subsidies. Our results [Figs. 2 and 3(b)] indicate that with no subsidies a firm providing a sustainable choice with less frequent device replacements will lag behind a firm that offers more frequent device replacements. However, with the addition of a 10% or more subsidy that reduces the price paid by consumers for the sustainable choice, such a firm can become much more competitive in the market. In fact, such a firm offering a sustainable choice can garner the whole market share when offered user-experience is close to that of the other firm employing shorter contracts.
- 2) *What impact can providing subsidies have on greater adoption of the sustainable choice by consumers, and what areas should progress be made?* From a consumer perspective, results from the economic framework helps understand the impact of various parameters involved, including subsidies and user-experience from old and new hardware. In addition, two other metrics are used to quantify the impacts of adopting devices with increased lifespans: consumer welfare (derived in Equation 16) and the lifespan benefit (Equation 17). Subsidies were shown to increase consumer welfare indirectly by enabling the firm offering the sustainable choice to be more competitive (as seen in Fig. 5). Similarly, subsidies help increase the lifespan benefit metric when market share of the sustainable choice firm rapidly increases (as seen in Fig. 6). In both cases, a firm offering a sustainable choice needs to ensure a user experience k_1 closer to that of a frequent device replacement option k_2 . In Section V we looked at a case study of how emerging technologies such as cloud computing could be leveraged by a firm offering a sustainable choice to make k_1 closer to that of k_2 .

B. WHAT IS A REASONABLE VALUE OF SUBSIDY AND WHO SHOULD PROVIDE IT?

The analytical study showed that at market equilibrium, even a 20% subsidy added to the cost of an environmentally conscious option can enable it to compete, if not dominate the market. Thus, the source and value of such a subsidy would be of great interest. There are two entities that could be the source of subsidies to the consumer. It could be regulators/lawmakers who are interested in a policy-driven shift towards sustainable computing. Funds could be allocated to incentivize such shifts by consumers in a manner similar to subsidies given for adopting electric vehicles or energy-efficient appliances. Part of these funds could be money that would otherwise have gone to deal with carbon emissions; through a shift towards environmentally sustainable mobile

computing, some of the expected carbon emissions would now be eliminated. For example, in the U.S., subsidies in the form of tax credits are provided worth USD 2500 to 7500 for plug-in electric vehicles, which is easily 10-20% of the initial cost of such a vehicle. Alternatively, the source of subsidies could be environmentally conscious cellular carriers. Many companies are adopting sustainability as a major theme for their businesses and they allocate some funds for such efforts which could be used as a source of subsidy. For example, Sprint (the third largest carrier in the U.S.) is known for its sustainability practices and puts significant efforts to meet its environmental goals. A reasonable value of subsidy then could be the sum from various such sources. Considering such sources of subsidies, it is not unreasonable to assume 0-20% of carrier costs per consumer to be passed along as subsidies. For example, Boost Mobile in the U.S. reduces the cost of its monthly plans by 10% every 6 months. Additional work that needs to be done in this area includes a more detailed quantification of subsidies possible from various sources.

C. WHAT IS THE INCENTIVE FOR DEVICE UNIT VENDORS TO HAVE LONGER LIFESPANS FOR THEIR DEVICES?

The analytical results earlier showed the benefits of increased device lifespan through lifespan benefit metric b_L . Hardware phone vendors would seem to have the least incentive for increased device lifespans. However, many such vendors increasingly have trade-in and recycling programs that have created a secondary market for phones. Thus, such vendors can still profit from their units being usable longer but not by a customer still retaining it longer. Also, these vendors are not the only players in the mobile market. It includes cellular carriers and regulators whose interests also impact vendor practices. The cellular carriers have incentives in terms of using consumer welfare as a selling point. For example, T-Mobile has recently begun offering no-contract options citing how it benefits consumers [40]. Regulators could be interested in the broader picture and enforce laws that govern vendor practices; similar examples abound in other industries such as automobile and energy where environmental concerns play an important role in vendor offerings or practices.

D. WHAT WILL BE THE RANGE OF USER-EXPERIENCE RATIO $\frac{k_1}{k_2}$ IN PRACTICE, AND HOW CAN THIS RATIO BE INCREASED?

This is a major consideration in determining how competitive an environmentally sustainable choice will be. For a longer device lifespan option, if the handsets lag far behind newer phones in user-experience as they get older, very few consumers will be willing to take on the former option in spite of cheaper pricing, as evidenced by the results of this paper. The firm offering a more environment-friendly option could spend some of their cost savings (by not offering subsidized new devices) on increasing the user-experience ratio by offering "maintenance" plans (possibly in conjunction with handset vendors) that could include (i) upgrading software like

operating systems and applications, (ii) replacing batteries, and (iii) upgrading some modular hardware features when possible. These options are in addition to leveraging cloud-computing as studied in Section V. Additional work needs to be done to quantify user-experience when using mobile devices. There have been some prior attempts such as in [41] and [42], but they have not necessarily focused on aspects like hardware features, network connectivity, social factors, all at the same time. Additional work required would include factoring in user surveys with appropriate statistical validation of the relative importance of various factors to users.

E. HOW DO THE RESULTS OF THIS PAPER APPLY TO A WIDER CLASS OF MOBILE DEVICES?

In this paper a linkage was made between the lifespan of a device t_i under a carrier i 's offering and the average user-experience k_i it may offer the consumer. This linkage was easier to establish under existing wireless carrier contracts (at least in the U.S), where once a contract expires, a consumer can get another new device at highly subsidized rate, and thus possibly improve user-experience. If we consider a scenario where contracts are not enforced (for example contractless phones or tablet PCs) device replacements happen more based on initial device quality or changing consumer needs or both, and it may not be as easy to distinguish between two firms in terms of environmental friendliness. Further, a contractless device could decouple wireless service from the handsets that are bought and shift the focal point of our analysis from wireless carriers to hardware manufacturers of handsets. In this case a vendor offering a sustainable choice could aid increased device lifespans by providing incentives for retaining devices as mentioned in the previous subsection. Without a longer, guaranteed contract with consumers to absorb some of these additional costs, such firms would have to pass those on to the consumer, possibly aided by subsidies, if they exist.¹² The economic framework presented in this paper would still be applicable under these scenarios and can be used to analyze these situations to understand market behavior and what level of user-experience may be needed from a sustainable choice before it can garner significant market share.

VII. CONCLUSION

One approach to environmentally sustainable mobile computing is for users to retain their mobile devices longer as a means to reduce life cycle energy costs and electronic waste. This paper studied the conditions under which market economics will support a firm offering a sustainable choice of cellular phone service to consumers considering the possibility of some losses in user-experience. The competitiveness of a firm that offers such sustainable longer duration service plans was studied in comparison to a firm offering shorter contracts, including the impact of subsidies to incentivize

the adoption of such plans. Addition of subsidies and any underlying cost advantages by offering a longer-term contract was found to aid competitiveness greatly, with the condition that user-experience over the lifetime of the device is close (not necessarily equal) to the other firm offering a shorter-term contract. A case study comparing performance of older and newer phones was done to demonstrate the potential of increasing the competitiveness of older devices by leveraging software-based paradigms like cloud-computing. This paper also presented a metric termed lifespan benefit that quantified the relative reduction in handset manufacturing that can be achieved by a firm offering a longer-term contract.

Though this work just scratches the surface on the broad area of environmentally sustainable mobile computing, the novel conceptual framework developed lays the foundation for additional research that incorporates social, economic, and environmental aspects. This work is highly relevant to the mobile computing community as it looks at both the causal factors and impacts that may eventually end up limiting the rapidly expanding paradigm. *Economic principles and market forces often dictate future technical directions and this effort tries to link the two in moving towards greater environmental sustainability for the mobile computing paradigm.* This work not only helps verify intuition of the challenges facing longer device lifespans, but also provides deeper insight, in the form of a specific range of parameter values, on the impact of some important factors such as user-experience, underlying carrier costs, and available subsidies. In addition to serving as a useful guideline to the mobile computing research community, these results are expected to be useful to firms when considering offering environmentally sustainable choices, and also to regulators considering policy options.

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¹²Environmentally friendly cars, for example, are offered under similar pricing mechanisms where their initial offered price is higher than comparable non-environmentally friendly options, but some subsidies may exist.

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