Effects of Components on Ecosystem Value: The Case of the iPhone and Mobile Broadband

February 28, 2021

By MARK A. JAMISON AND PETER WANG [†]

We examine how component changes affect network value. Theory indicates that increased component value can increase sales for network access. Using a panel of countries from 2003-2017, we test this by analyzing how the iPhone's introduction in 2007 affected mobile broadband adoption. We find the iPhone and its imitators explain 60% of the average rise in mobile broadband's growth rate. Per capita GDP mattered in developed, but not developing countries. The quality of government mattered in both types of countries, but regulation mattered more in developed countries, while rule of law mattered more in developing countries.

Keywords: platforms; network effects; innovation; competition
JEL codes: L13, L15, L51, L86

[†] M. Jamison: Public Utility Research Center and Digital Markets Initiative, Warrington College of Business Administration, University of Florida, 205 Matherly, Gainesville, Florida 32611 (mark.jamison@warrington.ufl.edu); and P. Wang (corresponding author), Digital Markets Initiative, Warrington College of Business Administration, University of Florida, 205 Matherly, Gainesville, Florida 32611 (peter.wang@warrington.ufl.edu). The authors thank the Digital Markets Initiative for financial support and participants in the Western Economic Association 2020 annual conference for their helpful comments. The authors are responsible for all errors and omissions.

I. Introduction

Economic studies of networks generally focus on value created by direct or indirect network effects. (Shy 2011) In their seminal work in economic theory, Rolfs (1974) and Katz and Shapiro (1985) each formally model a network whose value to a potential customer is determined in part by the potential customer's valuation of access to other members of the network. Rochet and Tirole (2003) develop a more general concept called platforms that mediate transactions and create economic value by interactions between buyers and sellers.

Empirical work supports these theories of network effects, according to Birke (2009) who provides a useful survey. Theory often assumes that rival networks are symmetric in their network effects, but Shanker and Bayus (2003) find asymmetries between rival platforms in the home video game industry. More closely related to our research, Garcia-Swartz and Garcia-Vicente (2015) estimate indirect network effects on the iPhone platform. Chan-Olmested et. al. (2009) examined how income and competing standards contributed to the diffusion of mobile broadband communications.

Largely missing from the literature are studies of situations where individual components of networks provide utility to users, affecting overall system value and demand for access. There are numerous examples of such situations. Increased baggage screening after the 9/11 terrorist attacks diminished flyers' airport experience, leading to a decrease in the demand for flying. (Blalock, Kadiyali and Simon 2007) Advances in personal computer technology increased the usefulness of the internet.[1] Anchor tenants in shopping malls create value for other tenant stores. (Pashigian and Gould 1998)

[1] PC microprocessor clock speed increased nearly 70-fold from 1999 to 2016 (from 0.41 gigahertz to 28.75 gigahertz). This increase in performance helped fuel a 14-fold increase in internet users worldwide over the same time period (from 248

We add to this literature by examining the effect of the introduction of the iPhone and Android phones on subscriptions to mobile broadband. Apple introduced the iPhone in 2007 with much fanfare. According to The Wall Street Journal (2017), within 10 years of the phone's introduction, Apple's revenue had climbed more than tenfold, the iPhone made up nearly two-thirds of the company's revenue, and the number of Apple employees had increased over five-fold. The iPhone arguably had impacts across companies, industries, and countries. The market for smartphones worldwide increased from $120 million in 2007 to $1.5 billion in 2016. Global shipments of cameras – smartphones incorporate camera features – dropped from 101 million units at the time the iPhone was introduced to 24 million by 2016. Mobile broadband subscriptions increased from 268 million worldwide in 2007 to 4.7 billion in 2017. (Statista 2020)

The iPhone appears to have triggered a rapid and substantial improvement in smartphone technology, but in terms of physical units, the iPhone makes up only a fraction of smartphone sales. In 2007, smartphone operating systems were largely supplied by Symbian, Microsoft, and Research in Motion (RIM), the maker of Blackberry. By 2016 these operating systems had largely disappeared, being replaced by Apple, which provided 15% of the operating systems worldwide, and Google (now Alphabet), whose Android operating system served almost all the rest. (The Wall Street Journal 2017)

Isolating the effect of the iPhone on the value of mobile broadband is complicated by the introduction of the Android operating system. Campbell-Kelly et al. (2015) explain that the iPhone design was revolutionary and that Android phones largely imitated the iPhone features. But the number of Android phones exceeded the number of iPhones by 2010, which was the first full year of production for the first

million to 3.7 billion). Internet users buying these improved computers had a better internet experience than did users of the older technologies. PC data from Singularity.com (2020) citing data for 1976–1999 from Berndt, Dulberger, and Rappaport (2000) and for 2001–2016 from ITRS (2002 updated). Internet data from World 2020 Stats (undated).

successful Android phone, the Motorola DROID. Given these rapid changes and apparent interactions, we are unable to statistically distinguish between the iPhone's direct effect on the value of mobile broadband and its indirect effect through its influence on Android phones. So, we say that we are estimating the effects of iAPs, or iPhone-Android smartphones.

Our analysis considers both theory and empirical estimates. In our theory section, we extend Katz and Shapiro (1985) to examine how an innovation in network devices might affect demand for network services. In our model customers form expectations about network sizes that are fulfilled in equilibrium. Device providers compete in a quantity game, and then so do network providers. We find that an innovation in devices can stimulate output for network access in two ways. One way is to increase the number of device manufacturers. In Section II we provide data supporting this as a possibility. The second way is to increase device value by adding features and creating network effects within these features. This appears to have happened as well.

We then test this theory using data from the International Telecommunications Union's (ITU) World Telecommunication/ICT Indicators Database (WTIID) (ITU 2019). We examine the adoption of mobile broadband across 34 countries.[2] We estimate results for all countries and provide separate estimates for Organization for Economic Cooperation and Development (OECD) counties and for non-OECD countries. Our pooled results find that the introduction of iAPs increased sales the growth rates in sales for mobile broadband. Only the increased growth rate remained statistically significant in the separate OECD and non-OECD estimates, probably because separating the countries decreased the number of observations in the separate estimations. Time as an explanatory variable was statistically

[2] We define mobile broadband as third generation (3G) mobile technology. We explain this in Section II.

significant only for OECD countries, implying that iAPs accounted for nearly all the growth rates increases for non-OECD countries.

Our analysis finds interesting differences between OECD and non-OECD countries. Fixed broadband appears to compete with mobile broadband in OECD counties, but a complementary effect in non-OECD countries. Per capita GDP has a positive impact on 3G penetration in developed countries, but not in non-OECD countries. The effects of legal frameworks also differed between OECD and non-OECD countries: Regulatory quality, as measured by the World Bank's World Governance Indicators (World Bank 2020), is positively correlated with mobile broadband development in OECD countries, but not in non-OECD countries. A closely related yet broader governance indicator, rule of law, is positively correlated with mobile broadband development in non-OECD countries. Both governance variables are based on citizens' perceptions, so it might be that these two variables are both indicators of citizens' confidence in the legitimacy of their governments, with the differences being citizens' attention to government bureaucratic institutions versus elected bodies. We explore this further in section V.

The remainder of this paper proceeds as follows. The next section provides industry background and summarizes the literature. Section III develops our theoretical foundations and Section IV presents our data. Section V provides our empirical results. Section VI is the conclusion.

II. Background

A. Brief History of Mobile Broadband

Cellular telephony was technically feasible in the late 1960s and early 1970s, but the technology to not be commercially available the United States until the 1980s. Technologies for cellular telephony changed over time. The first generation (1G) technologies, first launched in Japan in the late 1970s, used analog signals. NTT deployed 1G throughout Japan by 1984, which was the year after the Federal Communications Commission (FCC) issued its first 1G license. Canada and the UK introduced 1G within a few years.

1G had problems with signal quality and interoperability across networks. A lack of interoperability meant that it was hard or impossible for customers to roam across different network operators' networks. Second generation (2G) technologies were digital and designed to help solve these and other problems and became commercially available in the early 1990s. There were competing 2G technologies and the United States was one of the few countries to allow operators to choose their technologies. Most countries followed Finland's lead and required operators to adopt the GSM technology. U.S. carriers began deploying 2G following the FCC's radio spectrum auctions in 1994 and adopted different technologies, including GSM, TDMA, and CDMA. Although 2G technologies used digital signals, they were limited to traditional voice communications and small amounts of data. (Padgett, Gunther, and Hattori, 1995; Hommen and Manninen, 2003)

The first widely used cellular broadband was 3G, which is the popular term for ITU standard IMT-2000. Japan was the first to deploy 3G and did so beginning in 2001. 3G was designed to provide greater data transmission and multimedia services, up to 4 times faster than 2G. This allowed for innovations, such as video conferencing, video streaming and voice over internet protocol. These over-the-top services competed with traditional mobile companies' traditional voice services. (Zaber and Sirbu 2012; Roche 2003; Hui and Yeung 2003; Frattasi et al. 2006)

The next mobile technology evolution, 4G, provided additional bandwidth, which enabled more streaming services (Govil and Govil 2008). Unlike the transition from 2G to 3G, which required nothing more than a change in SIM cards for phone devices, 4G required a different kind of handsets than did 3G.

B. Mobile Device Evolution and Manufacturing

Phone device technologies evolved with the network technologies. The early 1990s saw the emergence of specialized consumer electronics devices, such as mobile phones, media players, digital cameras, and global positioning systems (GPS). These soon evolved into feature phones that provided integrated bundles of capabilities that were hardwired at the time of manufacture.

Smartphones emerged in the late 1990s. Rather than being single-purpose or multi-purpose hardwired devices, they were handheld computers that incorporated telephone functionality and could run software programs, later called apps. (Campbell-Kelly et al. 2015)

Prior to the introduction of the iPhone, Nokia, Ericsson, Motorola, and RIM were the primarily providers of smartphones. The Nokia, Ericsson, and Motorola phones worked on the Sybian operating system and first hit the market in 2001. RIM's first smartphone, the Blackberry 5810, was introduced in 2002 and was popular with business users. (Campbell-Kelly et al. 2015)

Apple started exploring developing an Apple phone in 2002, soon after the introduction of the iPod MP3 player. One of the key problems consumers were facing in the early 2000s, and especially after the iPod was introduced, was the proliferation of personal devices, meaning that some people carried a personal digital assistant (PDA) that would handle calendars, email, etc.; a phone; a music player (such as MP3); and a digital camera. Soon products began appearing that combined many functions in one device. The Palm Treo 600, for example, combined a phone, a PDA, and email capabilities. (Garcia-Swartz and Garcia-Vicente 2015)

Apple leveraged its iPod music player technology to create the iPhone. Steve Jobs' introduced it this way: "We are introducing three devices today: a phone, an internet communicator, and a portable music player ... get it?" the iPhone's screen-based user interface changed dynamically, allowing it to be a number pad, a keyboard, viewer, and the like as the device leapt from function to function.

It is commonly accepted that the iPhone changed the smartphone market significantly when it was introduced in June 2007 (Campbell-Kelly et al. 2015, Campbell-Kelly and Garcia-Swartz 2015, chap 11; Vogelstein 2008; Vogelstein 2013). In the United States the iPhone was exclusive to AT&T's wireless network because of a business relationship that Apple had established with the wireless company Cingular years before, which was acquired by AT&T in late 2006. Although the key innovation in the first iPhone was Apple's integration of the iPod, phone, and internet capabilities activated by touching the screen, (Thomas 2007) the introduction of the iPhone 3G in mid-2008 triggered the development of third-party apps. (Campbell-Kelly et al. 2015)

Google began challenging the iPhone soon after it was introduced. In contrast to Apple's strategy of controlling both the hardware and software for its phone, Google pursued an open architecture strategy and in November 2007 announced an alliance with T-Mobile, HTC, Qualcomm, and Motorola to form the Open Handset Alliance for the development of the Android operating system. T-Mobile released the first Android phone in late 2008, but the first successful Android phone was Motorola's DROID, which launched in October 2009. By the first quarter of 2011, Android was the leading operating system for mobile phones. (Campbell-Kelly et al. 2015)

The expansion of iAPs may have also changed the composition of the phone device manufacturing industry. In 2006 – the year before Apple introduced the iPhone – Nokia provided about 35% of the world's mobile phones, followed by Motorola at 21%, Samsung at 12%, Sony and Ericsson at 7%, LG at 6%, and "Other" at 19%. Motorola disappeared from the market by 2013 and Nokia dropped to 10% in 2014. Samsung rose to 21% of the market by 2014. The presence of smaller manufactures grew: In 2006 Gartner listed LG, Motorola, Nokia, and

Samsung as manufactures. By 2013 the listed manufacturers were Apple, Huawei, Lenova, LG, Micromax, Nokia, Samsung, Sony and Ericsson, TCL, and Xiaomi, but one-third of device shipments came from "Other." (Statista 2021) We cannot say whether there was causation, but this increase in the number of device manufacturers is correlated with the growth of iAPs.

C. Existing Literature

Rohlfs (1974) was perhaps the first to analytically model network effects. He considered a situation where customers varied in the value they placed on other subscribers, which led to a demand curve shaped like an inverted U. Katz and Shaprio (1985) analyzed network effects and issues of customer expectations of network size, compatibility, and sequencing of decision making, and the possible absence of equilibria. Economides and Salop (1992) develop a theory of fully compatible and complementary components of a system and show how prices might be affected by vertical and horizontal relationships. Rochet and Tirole (2003) develop a more general concept called platforms that mediate transactions. They illustrate how a platform must gain participation from both sides of a market and examine implications of governance structure.

Birke's (2009) survey of the empirical work on platforms concludes that it supports the basic theory. More relevant to our research, in a cross-national study using some of the same data that we use, Chan-Olmsted et al. (2008) examined the causal relationship between older mobile communications technologies and 3G deployment. Their study was limited by a low number of observations – 106 – but found that 3G served as a substitute for these older technologies. They did not find that it substituted for fixed broadband services. Zaber and Sirbu (2012) also examined 3G deployment, specifically considering the effects of government policies on radio spectrum management. They found that countries that mandated specific radio frequencies for 3G saw faster roll outs, but slower growth rates.

Lee et. al. (2011) found that rivalry in standards had a positive impact on mobile broadband deployment. They also found that higher population densities were also primary factors encouraging initial diffusion of mobile broadband services. Similarly, Sagbangsua et. al. (2015) used the Arellano Bond linear dynamic panel data estimation model to solve the auto-correlation problems existing in the dataset and found much of the same results. Shinohara et. al. (2015) used the Global Wireless Matrix database to look at whether the introduction of iPhone and Android phones in OECD countries, alongside carrier competition, influenced mobile subscriptions. They used the variable "mobile subscription", which measures the total number of mobile subscriptions. Though the authors claim these mobile subscriptions are the same as mobile broadband subscriptions, this variable should be a consistently upward biased measure of actual mobile broadband subscriptions since it included 2G subscriptions. In contrast to their work, the focus of our paper will strictly be on mobile broadband.

Griva and Vettas (2011) studied price competition in differentiated product duopoly in the presence of network effects, and MacCory and Shivendu (2014) studied smartphones as a Multi-layer Two-sided platform and the welfare implication of Apple's exclusive deal with AT&T.

Garcia-Swartz and Garcia-Vicente (2015) studied the indirect network effects between app developers and iPhone users. Using a cointegration approach, they find a positive relationship between the number iPhone shipments and the number of apps submitted to be included on the iPhone. Boik, Greenstein, and Prince (2017) examine how households allocate their attention when using the internet. Using click-stream data for U.S. households between 2008 and 2013, they found that households spent about the same amount of time online but allocated their attention away from chat and news towards video and social media.

Most recently, Fan and Yang (2020) and Yang (2020) studied smartphone markets. Fan and Yang studied the relationship between oligopolistic competition and the number of products in a market and found that welfare would be enhanced if there were more smartphone makers. Yang (2020) examined the relationship between the industry producing computer chips used in smartphones (called System-on-Chip or SoC) and the smartphone industry. He found that vertical integration can increase innovation and welfare, mainly by improving coordination for innovation.

III. Theory

Our empirical analysis tests whether iAPs led more customers to adopt mobile broadband than would otherwise. We do not claim to demonstrate causation, but we are testing whether the data would support or refute the idea.

The underlying theory is that iAPs increase the net consumer surplus of marginal customers of mobile broadband – customers who are indifferent between purchasing and not purchasing – leading more customers to purchase mobile broadband than would otherwise do so. To illustrate we extend the multistage game of network provision developed by Katz and Shapiro (1985). In the first stage, customers set expectations about network size and purchases of devices. Then in the second period, device providers play a quantity game to supply phones. In the third stage network providers also play a quantity game. Both device providers and network providers take customer expectations as given. Finally, customers complete their purchases. We simplify our analysis by only considering equilibria in which customer expectations are fulfilled. In a sense we are testing the effects of iAPs on system value and the presence of equilibria in which customers complete their expected purchases. We use subgame perfect Nash equilibrium as our solution concept.

A. Consumers

We examine a partial equilibrium oligopoly model in which consumers seek to maximize individual surplus. A consumer buys at most one device and one network service and buys either both or neither.

Consumers will base their purchase decisions on expected group sizes and the features that affect group value. A group is the collection of agents with whom a consumer can interact through a mobile network (in the case of network groups) or through device features, such as apps. Some apps enable groups across devices, while others do not. For example, an iPhone owner can FaceTime with other Apple product users but could not with users of non-Apple products until 2020, when FaceTime for PC was introduced. To date there is no FaceTime app for Android devices. In contrast Facebook is available for both Apple and Android devices, so a purchaser of an Apple device, for example, benefits from Android purchasers using Facebook. Device purchasers consider all the groups that the device makes possible. We assume networks are homogeneous and fully compatible, so networks make up a single group.

We assume a single market with three or more firms competing to provide devices and $m^n > 0$ network providers. No firm produces both devices and networks. Device $D_i = \{A, G, L\}$ is produced by device manufacturer i, where A is Apple, G is Android based, and L is any one of the legacy devices. Without loss of generality, let $m_A^d \geq 1$ represent the number of Apple device manufacturers,[3] $m_G^d \geq 1$ represent the number of Android manufacturers, and $m_L^d \geq 1$ represent the number of makers of legacy devices, each exogenously determined.

Consumers make their purchase decisions before actual group sizes are known. $x_i^d \geq 0$ is the number of customers that device provider i serves, $x_j^n \geq 0$ is the

[3] There is only one Apple manufacturer, but we use a variable expression to ease exposition.

number of customers that network provider j serves, $y^{n\,e} \geq 0$ is the consumers' prediction of the size of the mobile broadband network, and $y_{D_i}^{e} \geq 0$ is their prediction of the number of customers buying device D_i.

Consumers are heterogeneous in their basic willingness to pay for the products, but homogeneous in their valuations of network effects. More specifically, a consumer of type r's willingness to pay for i's device is $r^d + v^d\left(\omega_{D_i}, \boldsymbol{y}_{D_i}^{e}\right)$, where ω_{D_i} is a set of parameters, some of which are specific to device D_i, $r = r^d$, and $\boldsymbol{y}_{D_i}^{e}$ is the vector of expectations of device groups relevant to purchasers of i's product. r is uniformly distributed between negative infinity and $R > 0$ with density one. Hereafter we suppress ω_{D_i}.

Without loss of generality, we normalize v^d so that $v^d(0) = 0$. We take v^d to be twice continuously differentiable, with $\frac{\partial v^d}{\partial y_{D_i}^{e}} > 0$, $\frac{\partial^2 v^d}{\partial {y_{D_i}^{e}}^2} < 0$, and $\lim \frac{\partial v^d}{\partial y_{D_i}^{e}} = 0$ as $y_{D_i}^{e} \to \infty\ \ \forall i$. And $\frac{\partial^2 v^d}{\partial y_A^e\, \partial y_G^e} > 0$. Likewise, a consumer of type r's willingness to pay for a network separate from device is $r^n + v^n\left(y^{n\,e}\right)$. We normalize v^n so that $v^n(0) = 0$. We take $v^n\left(y^{n\,e}\right)$ to be twice continuously differentiable, with $v^{n\prime} > 0$, $v^{n\prime\prime} < 0$, and $\lim v^{n\prime} = 0$ as $y^{n\,e} \to \infty$. For analytical convenience, we assume that r^n varies linearly with r^d, i.e., $r^n = a \cdot r^d$ and $R^n = a \cdot R^d$, where $a \geq 0$.

Let p_i^d and p_j^n denote i's device price and j's network price, respectively. We can now express r's surplus from purchasing from i and j:

$$(1 + a) \cdot r^d + v^d\left(\boldsymbol{y}_{D_i}^{e}\right) - p_i^d + v^n\left(y^{n\,e}\right) - p_j^n$$

B. Firms

Let $s_r^d = r^d + v^d\left(\boldsymbol{y}_{D_i}^e\right) - p_i^d$ (conversely, $s_r^n = r^n + v^n\left(y^{n\,e}\right) - p_j^n$) represent r's net consumer surplus from its device (conversely, network service). In equilibrium, networks j and $\hat{j}$, $j \neq \hat{j}$ will each have positive sales only if:

$$p_j^n - v^n\left(y^{n\,e}\right) - s_r^d = p_{\hat{j}}^n - v^n\left(y^{n\,e}\right) - s_r^d = \phi^n. \quad (1)$$

Equation (1) implies equal prices for network services. Every $r^n \geq \phi^n$ purchases a network service such that $R^n - \phi^n = z^n$ is the number of network subscribers. This gives prices $p_j^n = R^n + v^n\left(y^{n\,e}\right) + s_r^d - z^n \ \forall j$.

We assume that production costs are the same for all networks (conversely, devices) and that these costs include a fixed cost, G^n (conversely, G^d), plus a constant marginal production cost, g^n (conversely, g^d). We take both fixed and marginal costs to be zero. We assume that the cost of compatibility, $F_i \geq 0$ for devices and $F_j \geq 0$ for networks, are fixed relative to output.

We can now express j's profit function as:

$$\pi_j \equiv \left(R^n + v^n\left(y^{n\,e}\right) + s_r^d - z^n\right) \cdot x_j^n - F_j. \quad (2)$$

Differentiating equation (2) with respect to x_j^n and rearranging terms, first-order conditions imply that the equilibrium sales levels $\forall j$ must satisfy:

$$x_j^{n*} = R^n + v^n\left(y^{n\,e}\right) + s_r^d - z^{n*},$$

which gives industry output:

$$z^{n*} = m^n \cdot \frac{R^n + v^n\left(y^{n\,e^*}\right) + s_r^d}{m^n + 1},$$

individual firm output and prices:

$$x_j^{n^*} = p_j^{n^*} = \frac{R^n + v^n\left(y^{n\,e^*}\right) + s_r^d}{m^n + 1},$$

and equal output for each network. We assume parameters such that $x_j^{n^*} \cdot p_j^{n^*} \geq F_j$ $\forall j$.

The marginal network consumer is $\tilde{r}^n$ for whom $\tilde{r}^n = \phi^{n^*} = p_j^{n^*} - v^n\left(y^{n\,e}\right) - s_{\tilde{r}}^d$. A greater $s_{\tilde{r}}^d$ moves $\tilde{r}^n$ to the left, implying more industry output, which we can understand as a faster growth rate. Thus the introduction of iAPs increases the demand for mobile broadband if it increases $s_{\tilde{r}}^d$ relative to the pre-iPhone situation.

In equilibrium, device producers i and k, $i \neq k$, each has positive sales only if:

$$p_i^d - v^d\left(\boldsymbol{y}_{D_i}^e\right) = p_k^d - v^d\left(\boldsymbol{y}_{D_k}^e\right) = \phi^d + s_r^n.$$

Every $r^d \geq \phi^d$ purchases a device such that $R^d - \phi^d = z^d$ is the number of device buyers, prices are:

$$p_i^d = R^d + v^d\left(\boldsymbol{y}_{D_i}^e\right) + s_r^n - z^d,$$

and each firm's profits are:

$$\pi_i \equiv \left(R^d + v^d\left(\boldsymbol{y}_{D_i}^e\right) + s_r^n - z^d\right) \cdot x_i^d - F_i \tag{3}$$

$\forall i$. Differentiating equation (3) with respect to individual output and rearranging terms, first-order conditions imply that the equilibrium sales levels $\forall i$ must satisfy:

$$x_i^{d^*} = R^d + v^d\left(\boldsymbol{y}_{D_i}^e\right) + \frac{1}{m^n + 1} - z^{d^*},$$

which gives total device sales:

$$z^{d^*} = \left\{m^d \cdot R^d + \sum_{i=1}^{m^d} v^d\left(\boldsymbol{y}_{D_i}^e\right) + \frac{m^d}{m^n + 1}\right\} / \left(m^d + 1\right),$$

where $m^d = m_A^d + m_G^d + m_L^d$, and individual sales and prices of:

$$x_i^{d^*} = p_i^{d^*} = \frac{R^d + \frac{1}{m^n+1} + \left(1 + \sum_{D_k \neq D_i} m_{D_k}^d\right) \cdot v^d\left(\boldsymbol{y}_{D_i}^{e\ *}\right) - \sum_{\forall D_k \neq D_i} m_{D_k}^d \cdot v^d\left(\boldsymbol{y}_{D_k}^{e\ *}\right)}{m^d + 1}.$$

We assume $x_i^{d^*} \cdot p_i^* \geq F_i \ \ \forall i$. The marginal device consumer is $\tilde{r}^d$ for whom $\tilde{r}^d = \phi^d = p_i^* - v^d\left(\boldsymbol{y}_{D_i}^{e\ *}\right) - s_{\tilde{r}}^n$.

C. Analysis

We are testing whether the introduction of iAPs increases $s_{\tilde{r}}^d$, thus moving $\tilde{r}^n$ to the left, implying more industry output. Let ${}^{\mathcal{B}}arg$ represent the value of arg before the introduction of iAPs and ${}^{\mathcal{A}}arg$ represent the value afterwards. Given that $s_r^d = r^d + v^d\left(\boldsymbol{y}_{D_i}^{e\ *}\right) - p_i^{d^*} \ \forall r^d$, the introduction of iAPs increases $s_{\tilde{r}}^d$ if:

$$v^d\left({}^{\mathcal{A}}\boldsymbol{y}_{D_i}^{e\ *}\right) - {}^{\mathcal{A}}p_i^{d^*} > v^d\left({}^{\mathcal{B}}\boldsymbol{y}_L^{e*}\right) - {}^{\mathcal{B}}p_i^{d^*}$$

which gives:

$$\frac{{}^{\mathcal{A}}m_{D_i}^d \cdot v^d\left({}^{\mathcal{A}}\boldsymbol{y}_{D_i}^{e\ *}\right) + \sum_{\forall D_k \neq D_i} {}^{\mathcal{A}}m_{D_k}^d \cdot v^d\left({}^{\mathcal{A}}\boldsymbol{y}_{D_k}^{e\ *}\right) - R^d - \frac{1}{m^n+1}}{{}^{\mathcal{A}}m^d + 1} > \frac{{}^{\mathcal{B}}m_L^d \cdot v^d\left({}^{\mathcal{B}}\boldsymbol{y}_L^{e*}\right) - R^d - \frac{1}{m^n+1}}{{}^{\mathcal{B}}m_L^d + 1} \quad (4)$$

Examination of (4) reveals that the introduction of iAPs can increase $s_{\tilde{r}}^d$ by increasing the number of device manufacturers, increasing the values of device network effects, or both. A sufficiently large increase in numbers of device manufacturers (conversely, in device network effects) can compensate for a decline in device network effects (conversely, in numbers of device manufacturers). Our empirical analysis is unable to separate the effects of changes in numbers of device makers and changes in device network effects, so our research should be viewed as testing for the aggregate effects.

IV. Data

We use ITU WTID (ITU 2019) data to address our question empirically, supplementing it with the World Bank's development database (World Bank 2019) and governance indicators (World Bank 2020). Table 1 summarizes the data and its sources. We include fixed broadband and telephone penetration as potential substitutes or complements to mobile broadband penetration. We also include average price of messages and price per minute of use to represent user costs of subscriptions, and demographic factors such as GDP per capita, percentage of urban population, and percentage of population aged 15 to 65 years following previously literature. We include population density as it might affect demand, costs of providing networking, or both.

[PLACE TABLE 1 ABOUT HERE]

The variable of interest is the penetration of mobile broadband subscriptions in each country, i.e. the "number of mobile broadband subscribers per 100." There is an issue associated with this variable. Prior to 2007, which is when Apple introduced the iPhone, all countries for which the ITU collected data reported a variable called "mobile broadband subscription," which the ITU defined as the "number of subscriptions to mobile cellular networks with access to data communications at broadband downstream speeds (greater than 256 kbits/s) -- potential not active." We call these potential subscribers. After 2010, all countries subsequently reported the variable "active mobile broadband subscription," which the ITU defines as "active mobile-broadband subscriptions: sum of mobile-broadband subscriptions and dedicated mobile-broadband subscriptions. Covers actual subscribers, not potential, even though the latter may have broadband enabled-handsets." We call these active subscribers. The newer defintion is a subset of the older definition. Between 2007 and 2010, about half of the OECD countries reported both potential and active subscriptions for at least one year. Table 2 shows the data for OECD countries from 2007 to 2009. Some non-OECD countries also reported data for both definitions for at least one year and Table 3 provides the corresponding data.

[PLACE TABLE 2 ABOUT HERE]

[PLACE TABLE 3 ABOUT HERE]

This change in definition presents a problem for our analysis. We need subscription data for years prior to the introduction of the iPhone to estimate the iAPs' impacts, but there are no data on active subscriptions prior to 2007. Using the reported potential subscriber penetration would introduce an error that would understate the effects of all post-2007 values of explanatory variables. We address this problem by exploiting the years in which some countries reported both actual and potential subscribers.

Conceptually, the number of active subscriptions is always a subset of the potential. So, in years where we do not have the new measure, we take advantage of the years with overlapping definitions to calculate an average ratio of active to potential penetration and multiply that ratio to the potential subscription values for prior years. For countries that did not report both active and potential for any years, we use the average active to potential ratio across countries[4] and multiply that value times that country's reported potential penetration. The resulting active mobile broadband penetration timeseries plots for OECD and non-OECD countries are

[4] The ratio is 0.215 for all countries with at least one overlapping definition, and nearly indistinguishable between OECD and non-OECD countries.

available in the Appendix Figures A1 and A2. If the active to potential mobile broadband penetration ratio is correlated with some other explanatory variables, our method will be invalid. However, we find this is not the case. Nevertheless, out results should still be taken with caution, because even though the ratio does not have any apparent correlation with variables in our sample, this does not mean it is truly uncorrelated with anything else in the error term.

Another important variable in our analysis is when the iPhone is introduced in a country. We use this variable as our measure of when iAPs became available. We constructed this variable by accessing archived data on various mobile carrier sites and news sites. We consider only the official iPhone introduction by at least one mobile carrier within each country, and count the iPhone as introduced in that market in that year only if the official introduction occurred in the first half of the year. Overall, one country received an official iPhone introduction in 2007, 29 countries received it in 2008, 20 in 2009, 6 in 2010 and one in 2011. We do not have data on when Android phones became available on a country basis. This affects only our 2011 observation because the first successful Android phone, the Motorola Droid, was not introduced until late 2009 and so we would have counted its introduction into a country as happening no earlier than 2010.

V. Estimation and Results

A. Model and Results

It is more plausible to think of iAPs as not instantaneously increasing mobile broadband adoption but rather increasing the speed of adoption year over year. Given the method mentioned in the previous subsection to deal with the inconsistent dependent variable, and following literature, the empirical model we test is:

$$y_{it} = \delta z_{it} + \gamma z_{it} \times t + Tq + \boldsymbol{X}_{it}\boldsymbol{\beta} + u_i + \epsilon_{it} \tag{5}$$

where y_{it} denotes the active mobile broadband penetration per country per year from 2003 through 2017, and z_{it} is a dummy variable equal to one if the iPhone is introduced in the first half of that year in the country and zero otherwise. $\boldsymbol{X}_{it}$ are covariates, including penetration rates of fixed broadband, telephones, and computers, prices of talk and text, GDP per capita, percentage urban population, population density, percentage of population aged 15 – 65 years, and institutional controls regulatory quality and rule of law. u_i denotes country fixed effects. To capture the time trend in active penetration as well as its curvature, we include the linear and square values of year in the regression as vector $\boldsymbol{T}$, beginning with 2003 as year one. We also include the cross term between iPhone introduction in each country and the linear time trend, $z_{it} \times t$, to examine if iPhone introduction indeed changed the speed of mobile broadband adoption, using existing variation in the timing of the iPhone release to each country.

[PLACE TABLE 4 ABOUT HERE]

Table 4 shows our results. Driscoll-Kraay standard errors are reported for robustness to potential country specific heteroskedasticity, cross-correlation, and error-autocorrelation.[5] The coefficient on t is the yearly increase in mobile broadband penetration for countries that did not yet receive the iPhone. On average a year adds around 4.5 percentage points in mobile broadband subscriptions per 100 residents, for countries without the iPhone.

The effect of the iPhone is revealed by examining the coefficients of three variables: $iPhone(z_{it})$, t, and $z_{it} \times t$. We find $z_{it} \times t$ statistically significant and

[5] Error structure is assumed to be heteroskedastic, autocorrelated up to two lags, and possibly correlated between panels.

positive in each of our models, indicating that the effect of the iPhone was to accelerate growth in mobile broadband subscriptions over time. To illustrate using our pooled model, penetration increased annually at an additional 6 subscriptions per 100 residents over and above the non-iPhone growth of approximately 4.5 subscriptions per 100 persons. In other words, nearly 60% of the rising trend in mobile broadband penetration rate can be explained by the iPhone's introduction. Said differently, the iPhone increased the growth rate of mobile broadband over 130%.

Figure 1 illustrates this average effect of the introduction of the iPhone. It plots the predicted active mobile broadband penetration for regressions in Table 4 Column 1, for 2003 through 2017, with grey dots representing actual country-level mobile broadband penetration. The red line is the predicted active mobile broadband penetration for countries if they had never received the iPhone. The blue line is the prediction assuming they had received the iPhone.

[PLACE FIGURE 1 ABOUT HERE]

Compared to countries that have not received the iPhone, countries where iPhones are introduced on average have significantly higher mobile broadband adoption rates. Examining OECD and non-OECD countries separately, the iPhone introduction had a greater impact on developing countries than developed countries. The introduction increased the growth rate of mobile broadband roughly 25% in OECD countries.[6] Based on model 5 in Table 4, in non-OECD countries the iPhone accounts for all the 7.7 per 100 residents per year rise in mobile broadband subscription because the time variable t is statistically insignificant.

[6] Mobile broadband penetration increased 14.4 per 100 per year on average for OECD countries without the iPhone and an additional 3.7 per 100 per year for OECD countries that had the iPhone.

Our results support the conclusion that introduction of iAPs increased the sales of mobile broadband subscriptions, but do not tell us the exact mechanism. That the effect arrives through the growth rate is consistent with the conclusion that network effects in and across devices contributed to the growth, consistent with an increase in the $v^d\left({}^{\mathcal{A}}\boldsymbol{y}_{D_i}^{e}{}^*\right)$ and $v^d\left({}^{\mathcal{A}}\boldsymbol{y}_{D_k}^{e}{}^*\right)$ terms in the numerator on the left-hand side of equation (4). However, evidence in Section II points to an increase in the number of suppliers of smartphones, which is consistent with equation (4).

The non-OECD results deserves further exploration. It seems incorrect to conclude that mobile broadband would not have grown in non-OECD absent the introduction of iAPs. Recall, however, our conclusion in Section III that the iAPs could affect both the demand for mobile broadband and the supply of mobile broadband devices. Pew Research Center (2018) found that developing countries continued to lag developed countries in terms of internet use and smartphone ownership in 2018, the use of social media was nearly the same, implying that the network effects found in apps and made possible by iAPs may have a greater positive impact on demand in developing countries than in developed countries. And there are many reports of apps being created specifically for developing countries, such as those that enable entrepreneurs to better market their products. On the supply side, some device manufacturers have developed inexpensive phones specifically for the developing country market. It seems reasonable that the availability of the Android operating system lowers the costs of developing such phones.

Fixed broadband penetration is overall negatively associated with mobile broadband penetration for OECD countries, implying a substitution effect. The opposite is true for non-OECD countries, implying a complementary relationship between fixed and mobile broadband. These opposite results could reflect differences in fixed-line infrastructure between developed and developing countries. Where fixed line is more available, which is the case for developed countries, customers might choose between fixed broadband and mobile broadband. But where fixed broadband is largely unavailable, many customers do not have the fixed broadband option and so the network effects between fixed and mobile dominate the results.

Higher per capita GDP increases mobile broadband sales in our pooled and OECD models, but not in our non-OECD models. This could indicate that the iAPs and mobile broadband are serving a more fundamental need in these developing countries that is important regardless of income level. This is consistent with reports that iAPs are used by small entrepreneurs, healthcare providers, and the like, indicating that such devices are important for people of all income levels. But it could also result from developing countries having more vibrant secondary markets for used iAPs than do developed countries, which would lower consumer costs. Both are consistent with the $z_{it} \times t$ coefficients for the non-OECD countries demonstrating an effect that is approximately three times greater than in OECD countries.

Quality government institutions mattered in both developed and developing countries, but in different ways. Regulatory quality mattered most in developed countries, perhaps indicating that the populations hold a relatively high trust in government, but quality of regulatory institutions was more variable. General rule of law was more important in developing countries. Rule of law is more variable in developing countries than across developed countries, which may contribute to this result. It may also be true that rule of law is a precondition for quality regulatory institutions and that this is driving our results.

In short, the iPhone introduction in each country is certainly associated with a higher speed of adoption of mobile broadband for a country in subsequent years. Per our analysis in Section III, there are at least two possible reasons for this impact. One is that customers valued the additional features and device-related network effects of the iAPs over those of the legacy devices. Anecdotally this appears feasible since the Android phones quickly imitated the iPhone. Another possibility is that the iAP phones changed the economics of production such that there could be more manufacturers. This also appears feasible: as we discussed in Section II, it appears that there are more device manufacturers now than prior to 2007. But it could also be that the availability of the Android operating system lowered the cost of entry.

B. Robustness

Before and After 2007 — We test robustness of our results by running separate regressions for before 2007 and after (and including) 2007. Table 5 shows the results for our pooled data, taking the cut in 2007 since that was the year the iPhone was first introduced. Since 2007 was also the year for which ITU WTID first started changing the method of its data collection from “potential" to “active", it is worthwhile to check for differences between these two subsamples.

The growing trend of mobile broadband adoptions is almost zero for the sample from 2003 to 2007, and around 10 per hundred residents per annual after 2007 with the iPhone included. Besides the trend variables, all other control variables have similar signs and magnitude. Importantly, we are still able to pick up an iPhone effect in how it brought about a faster rate of growth of mobile broadband adoption to countries even just looking at the 2007 and forward subsample.

[PLACE TABLE 5 ABOUT HERE]

Region Specific Error Adjustment — As mentioned before, important in our analysis is how we dealt with the ITU’s change in the definition of the dependent variable. Using the over-lap of some countries reporting data for both definitions we were able to create a ratio and apply it to the potential penetration measures. As an additional robustness check, we grouped countries into six regions and found the average ratio of active to potential for available observation between 2007 and 2010 within each region. For each country that does not have those overlapping observations, we then apply the region-specific mean ratio[7] to observations of that country from 2003 to whenever it started reporting active mobile broadband subscriptions. Regression with this dependent variable is recorded in Table 6. Results are comparable to our baseline results in columns 1 to 2 of Table 4. We find that our results are robust to the region-specific error adjustment.

[PLACE TABLE 6 ABOUT HERE]

Arellano-Bond Estimates — Mobile platforms admit network effects. This provides rationale for including lagged dependent variables in the regressors because buyers probably base their expectations in part on their past experiences. Using this, the regression specification, with one year lagged dependent variable, takes the form:

$$y_{it} = \rho y_{it-1} + \delta z_{it} + \gamma z_{it} \times t + Tq + \boldsymbol{X}_{it}\boldsymbol{\beta} + u_i + \epsilon_{it} \qquad (6)$$

Table 7 presents the results for the estimates using the Arellano-Bond estimator. The previous year active penetration is a significant predictor of concurrent active penetration, suggesting that indeed the recent past affects expectations. Here, in the pooled sample, receiving the iPhone is still associated with a significant increase in the speed of adoption. While we no longer find any statistically significant effects of iAPs in OECD countries, for non-OECD countries the interaction term of iPhone

[7] The mean active to potential mobile broadband penetration ratio for each region are Africa, 0.342, Asia & Pacific, 0.299, Europe, 0.438, Middle East, 0.058, North America, 0.504, South/Latin America, 0.124.

and the time trend remains significant and of about the same magnitude. It could be that previous year mobile broadband explains iAP uptake in OECD countries so that the effect of the introduction of the iPhone was muted. It could also be that network effects of mobile broadband explain the faster speed of adoption of mobile broadband in some OECD countries, which coincided with earlier iPhone introduction in those markets. However, even accounting for network effects in non-OECD countries, a significant amount of growth is still attributed to the iPhone introduction, suggesting that the device itself had some impact on increasing the value of consumption of mobile broadband, and therefore the rise in the speed of its adoption for these non-OECD countries.

[PLACE TABLE 7 ABOUT HERE]

VI. Conclusion

We started with the observation that since 2007, the year Apple unveiled the iPhone, there has been somewhat of a mobile digital revolution, where “legacy phones” of the previous generation were quickly replaced by full-featured smartphones, capable of a variety of functions including email, web-browsing, social media, and mobile gaming. In the meantime, demand for mobile data has expanded dramatically as all these activities require users to be constantly plugged into the internet. We then developed a stylized model in which the superior features, network effects, and production economies enabled by the iAPs indeed can produce a dramatic rise in mobile broadband adoption.

We then turned to the empirical analysis and observed that for countries that received the iPhone, their mobile broadband adoptions rate indeed rose, by 6 subscribers per 100 per year compared to other countries that did not receive the iPhone. Breaking the pooled sample into OECD versus non-OECD countries, we find that the iPhone introduction is correlated with an about 3.7 per 100 per annual rise in mobile broadband subscriptions for OECD countries and a about 7.7 per 100 per annual rise in mobile broadband subscription for non-OECD countries.

One important shortcoming in our paper is the lack of a statement of causality. Although there is overwhelming evidence pointing towards causation, for example, countries that received the iPhone tend to have faster rate of growth of active mobile broadband penetration, this may be due to confounding. For example, Apple's strategic planning might have targeted markets that were already on the verge of a mobile telecommunications revolution. However, as we argue in the paper, the importance of the iPhone in shifting people's habits and driving the significant increase in mobile broadband data consumption, from a theoretical perspective and from evidence in data, should not be dismissed.

Another concern we address in the paper is the change in definition and collection associated with the key dependent variable, mobile broadband penetration. In the paper we presented a plausible solution to mitigate the inconsistent data by exploiting the years for which there are overlapping of the previous "potential mobile broadband penetration" and the latter "active mobile broadband penetration". More sophisticated models, such as a composed error model, is left for future research.

Our work opens avenues for further research. In addition to further work on causality, there is a need to quantify impacts of this technology change. Today some policy makers and antitrust experts are attacking Apple and Google for how they manage apps on their phones. If these companies' practices were central to how the iAP devices prompted the growth of mobile broadband, the attacks might be damaging, especially to poor countries. And if there is a positive correlation between effects on poor countries and effects on the poor in richer countries, altering the effectiveness of the iAPs' platform management should be done with great caution.

Tables and Graphs

Table 1. Summary Statistics

Variable	Mean	Std. Dev.	Source
Active Mobile BB Penetration per 100 population	47.33933	40.14445	ITU WTID
Fixed Broad Penetration per 100 population	23.54648	11.00939	ITU WTID
Telephone Penetration per 100 population	41.61935	13.89479	ITU WTID
Computer Penetration per 100 population	70.63565	18.16392	ITU WTID
Average message price (USD per message)	.1241852	.0644901	ITU WTID
Average price per minute (USD per minute)	.2825527	.2126663	ITU WTID
GDP per capita (thousands USD)	37.46785	21.87139	World Bank
Proportion of urban population (percent)	77.19716	11.369221	World Bank
Population density (persons per square km)	140.7268	134.702	World Bank
Proportion of population 15-65 (percent)	66.81017	2.4195845	World Bank
Regulatory Quality Index	0.794139	0.8567194	World Bank
Rule of Law Index	0.683468	1.0242710	World Bank

Table 2. Active and Potential Subscribers for OECD Countries, 2007-2009

	2007		2008		2009	
Country	**Active**	**Potential**	**Active**	**Potential**	**Active**	**Potential**
Australia	56.18	21.87	80.56	40.57	96.64	57.67
Austria	7.3	29.67	11.63	42.71	29.34	53.68
Belgium		5.38	3.42	6.98	5.66	8.43
Canada		1.48		4.56		
Chile		0.83		2.43	3.56	
Czech Republic		6.49		13.08	19.44	
Denmark	6.09	12.25	19.19	22.6	29.6	36.49
Estonia		3.32		14.91		18.65
Finland		115.08	9.02	128.76	71.28	144.59
France	9.51	13.84	18.35	23.58	28.24	28.58
Germany	11.31	15.06	16.76	21.76	23.47	31.64
Greece		22.49		25.72	12.01	35.15
Hungary	1.9	7.87	3.66	15.51	6.17	22.89
Iceland			15.71	2.66	30.62	6.12
Israel		24.88		32.42	49.46	39.69
Italy		25.98		34.43		62.53
Japan		41.39	13.59	48.81	17.24	52.76
South Korea		69.51		78.27	77.94	85.77
Luxembourg		49.19	71.79	71.64	86.38	83.59
Mexico		42.41		82.6		84.02
Netherlands		0.53	0.04	1.75	0.06	5.06
New Zealand		12.57		15.11		21.5
Norway		27.92		45.24		64.24
Poland		13.26	57.89	20.93	68.56	
Portugal		7.84		16.94	42.54	26.02
Slovakia		28.89		40.46	20.35	55.89
Slovenia	3.56	11.02	10.51	30.67	15.39	41.38
Spain		11.57		26.28		28.58
Sweden		22.77		38.92	9.89	51.38
Switzerland		110.46	65.25	118.33	69.89	125.87
Turkey		19.26		28.3	24.94	37
United Kingdom					3.45	9.44
United States		20.55		33.86	36.35	37.96

Table 3. MBP Old vs. New Definition Non-OECD

Country	2007		2008		2009	
	Active	Potential	Active	Potential	Active	Potential
Angola		0.16		0.77	0.53	2.76
Argentina		0.39		1.87		5.78
Bahrain	0.51	10.07	1.48	25.18	1.59	57.4
Brazil		1.1	1.81	1.81	4.47	4.47
China			0		0.91	0.92
Columbia			0.35		2.05	
Ecuador		0.17		0.26		1.56
Guatemala		0.35		0.66	2.03	2.08
Hong Kong		31.64		42.83	34.20	63.05
Indonesia		1.47		3.5	0.70	6.41
Kazakhstan						
Mauritius	3.17	3.08	8.46	4.01	14.39	8.02
Moldova		2.21	0.85	0.1	1.95	2.21
Nicaragua			0.12	0.41	0.37	1.15
Peru				0.41	0.29	2.34
Romania	3.76	7.93	4.99	21.53	7.07	26.32
Russia		0.03		0.6		32.87
South Africa		2.61		4.98		10.52
Taiwan	5.35	28.51	9.43	46.82	14.98	61.53
Thailand				0.52	0	2.02
UAE		17.43		40.28		55.34
Uruguay		0.27		1.4	3.28	3.24
Venezuela	0	5.11		8.48		12.22

Table 4. Primary Regression Results

	Pooled		OECD		Non-OECD	
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
iPhone	-41.28***	-45.20***	-26.06***	-30.96***	-58.61***	-59.00***
	(4.689)	(5.363)	(7.406)	(8.010)	(16.57)	(15.79)
iPhone × t	6.067***	6.633***	3.721**	4.491**	7.670***	7.873***
	(0.887)	(0.865)	(1.453)	(1.616)	(2.090)	(2.018)
t	4.468***	1.847	14.40***	11.31***	-2.021	-3.056**
	(1.281)	(1.415)	(1.729)	(2.363)	(1.546)	(1.111)
t^2	-0.131***	-0.0736	-0.381***	-0.323***	0.0247	0.0413
	(0.0306)	(0.0513)	(0.0586)	(0.0682)	(0.193)	(0.171)
Fixed Broadband Pen.	0.347	0.541	-1.692***	-1.376***	2.746**	2.678**
	(0.296)	(0.341)	(0.376)	(0.395)	(1.019)	(1.068)
Telephone Penetration	-0.533*	-0.735*	-0.456**	-0.682***	1.629*	1.712*
	(0.264)	(0.381)	(0.166)	(0.228)	(0.786)	(0.887)
Computer Penetration	0.00742	0.202	-0.0871	0.179	0.0519	0.0526
	(0.143)	(0.128)	(0.256)	(0.199)	(0.176)	(0.211)
Messaging Price		-14.81		-14.42		-2.241
		(25.28)		(25.66)		(44.97)
Minute Price		-8.645		-2.241		-20.27
		(6.737)		(6.132)		(16.24)
GDP per capita	0.473***	0.567***	0.475**	0.539***	-1.196	-1.248
	(0.118)	(0.115)	(0.164)	(0.151)	(1.171)	(1.246)
Proportion Urban	0.135	0.252	-0.100	-0.507	2.427**	2.942**
	(0.539)	(0.439)	(0.814)	(0.764)	(0.905)	(1.035)
Population Density	0.0999***	0.101***	-0.240*	-0.149	0.139***	0.146***
	(0.0164)	(0.0170)	(0.116)	(0.0916)	(0.0304)	(0.0357)
Proportion aged 15-65	-3.555***	-2.747**	-3.041***	-3.000***	-3.071	-2.524
	(0.857)	(1.017)	(0.766)	(0.616)	(2.085)	(2.293)
Regulatory Quality	9.826***	8.551**	11.65***	12.24**	-10.79	-2.561
	(2.934)	(3.244)	(3.510)	(5.377)	(7.858)	(10.02)
Rule of Law	14.14**	13.09**	1.164	-2.819	35.38***	34.98***
	(6.537)	(5.410)	(7.792)	(7.652)	(10.18)	(10.88)
Constant	174.6*	120.9	226.8**	246.3**	-44.51	-116.6
	(92.90)	(94.93)	(96.54)	(85.04)	(150.3)	(162.2)
Observations	716	643	461	406	255	237
Number of groups	56	56	34	34	22	22

Driscoll-Kraay standard errors in Parentheses.

Table 5. Time Trend Regressions Before 2007 and After 2007

	Before 2007		After 2007	
VARIABLES	(1)	(2)	(3)	(4)
iPhone	*_*	*_*	-29.22***	-46.85***
			(3.710)	(14.41)
iPhone × t	*_*	*_*	3.397***	5.938**
			(0.667)	(2.163)
t	-1.024	0.104	6.690***	3.121
	(2.242)	(0.224)	(0.901)	(2.536)
t^2	0.456	0.287***	-0.137***	-0.118***
	(0.280)	(0.0339)	(0.0369)	(0.0367)
Fixed Broadband Penetration	0.0772	0.114	0.685	0.973
	(0.222)	(0.0492)	(0.570)	(0.591)
Telephone Penetration	-0.386***	0.397***	-0.233	-0.0429
	(0.0526)	(0.0329)	(0.335)	(0.356)
Computer Penetration	-0.311**	-0.143**	0.271**	0.309**
	(0.0811)	(0.0429)	(0.0873)	(0.110)
Messaging Price		-1.800		-45.69**
		(1.887)		(17.84)
Minute Price		-0.354		-5.160
		(0.454)		(3.702)
GDP per capita	0.205	0.266*	0.313***	0.334***
	(0.162)	(0.0893)	(0.0777)	(0.0708)
Proportion Urban	5.859**	-1.151***	0.0947	0.692**
	(1.010)	(0.0299)	(0.327)	(0.268)
Population Density	0.0719*	0.0214	0.149***	0.160***
	(0.0246)	(0.0113)	(0.0161)	(0.0189)
Proportion aged 15-60	-2.512***	-1.025***	-3.666***	-2.990***
	(0.400)	(0.126)	(0.955)	(0.932)
Regulatory Quality	-0.0605	-2.370*	12.24**	10.04**
	(4.239)	(0.880)	(4.363)	(4.451)
Rule of Law	-3.608*	-7.129***	7.810	8.867
	(1.151)	(0.883)	(6.691)	(5.495)
Constant	-266.1*	138.4***	139.8	63.43
	(102.6)	(8.749)	(90.55)	(67.22)
Observations	118	91	598	552
Number of groups	43	39	56	56

Driscoll-Kraay standard errors in parathesis.

Table 6. Robustness to Region Specific Active MBP Correction

VARIABLES	(1) ActiveMBP_Region	(2) ActiveMBP_Region
iPhone	-39.36***	-43.14***
	(4.762)	(5.505)
iPhone × t	5.829***	6.378***
	(0.872)	(0.852)
t	4.235***	1.610
	(1.215)	(1.336)
t^2	-0.112***	-0.0536
	(0.0301)	(0.0497)
Fixed Broadband Penetration	0.364	0.559
	(0.293)	(0.341)
Telephone Penetration	-0.519*	-0.718*
	(0.263)	(0.379)
Computer Penetration	0.00854	0.202
	(0.144)	(0.130)
Messaging Price		-11.50
		(23.58)
Minute Price		-9.359
		(6.542)
GDP per capita	0.492***	0.581***
	(0.103)	(0.106)
Proportion Urban	0.113	0.222
	(0.541)	(0.434)
Population Density	0.100***	0.101***
	(0.0163)	(0.0169)
Proportion aged 15-60	-3.609***	-2.791**
	(0.867)	(1.024)
Regulatory Quality	9.704***	8.630**
	(2.832)	(3.097)
Rule of Law	14.73**	13.43**
	(6.455)	(5.360)
Constant	178.7*	125.0
	(93.59)	(95.32)
Observations	716	643
Number of groups	56	56

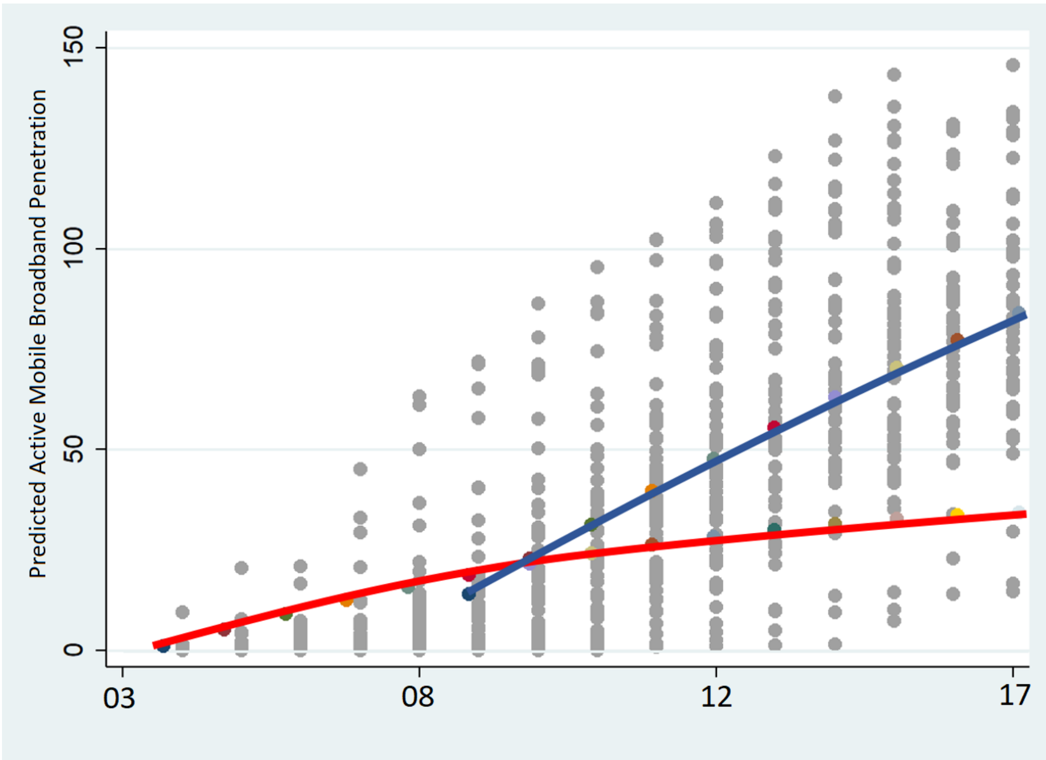
Driscoll-Kraay standard errors in parathesis.

Table 7. Arellano-Bond Panel Regression

	Pooled		OECD		Non-OECD	
	(1)	(2)	(3)	(4)	(5)	(6)
L.Active MB Pen.	0.689***	0.611***	0.576***	0.473***	0.797***	0.742***
	(0.0606)	(0.0734)	(0.0684)	(0.0771)	(0.0590)	(0.0659)
iPhone	-16.84***	-35.20***	-2.269	-19.16	-41.59***	-57.37***
	(6.456)	(11.91)	(7.300)	(13.94)	(15.59)	(22.02)
iPhone × t	2.330**	5.077***	-0.422	2.265	6.080***	8.498**
	(1.052)	(1.813)	(1.260)	(2.051)	(2.256)	(3.322)
t	1.820	-0.351	9.300***	8.043***	-3.613	-5.209
	(1.354)	(2.016)	(1.950)	(2.686)	(2.754)	(3.778)
t^2	-0.103*	-0.103*	-0.229***	-0.244***	-0.103	-0.129
	(0.0573)	(0.0610)	(0.0650)	(0.0670)	(0.148)	(0.156)
Fixed Broadband Pen.	0.758***	0.725**	-0.628	-1.304***	1.735***	1.832***
	(0.275)	(0.332)	(0.390)	(0.495)	(0.351)	(0.418)
Telephone Penetration	0.250*	0.298*	0.126	0.230	2.521***	3.030***
	(0.140)	(0.165)	(0.135)	(0.156)	(0.526)	(0.620)
Computer Penetration	0.144	0.242**	0.208	0.482***	0.0206	0.0326
	(0.103)	(0.121)	(0.143)	(0.180)	(0.160)	(0.179)
SMS Price		-11.83		-14.90		-56.23
		(13.95)		(13.17)		(41.38)
Minute Price		2.659		-1.095		10.68
		(3.996)		(4.116)		(11.27)
GDP per cap	0.0390	0.0589	-0.0316	-0.0302	-0.598	-0.834
	(0.112)	(0.125)	(0.105)	(0.114)	(0.490)	(0.544)
Urban Prop.	0.144	0.260	-1.678**	-2.393**	3.759***	4.868***
	(0.595)	(0.911)	(0.717)	(1.182)	(1.050)	(1.457)
Pop. Density	0.00385	0.0306	-0.0377	0.0486	0.0552***	0.0704***
	(0.0153)	(0.0239)	(0.124)	(0.169)	(0.0181)	(0.0269)
Prop. aged 15-65	-1.121	-1.158	-2.247**	-3.648***	-0.208	-1.001
	(0.740)	(0.929)	(0.929)	(1.148)	(1.262)	(1.700)
Regulatory Quality	-2.347	-2.065	-2.767	-4.369	9.677	11.17
	(4.664)	(5.089)	(5.241)	(5.667)	(7.844)	(8.649)
Rule of Law	1.443	3.618	-9.142	-10.15	11.80	11.67
	(5.777)	(6.215)	(7.024)	(7.331)	(9.100)	(10.16)
Constant	36.37	28.15	267.2***	410.7***	-296.4***	-327.4**
	(64.03)	(84.71)	(85.62)	(113.7)	(91.53)	(131.0)
Observations	598	508	389	319	209	189
Number of country	56	56	34	34	22	22

Results for Arellano-Bond Estimator with one lagged dependent variable.

Figure 1: Predicted Mobile Broadband Penetration with and without the iPhone, 2004 - 2017



Grey dots represent actual country-level mobile broadband penetration, the red line is the predicted active mobile broadband penetration for countries assuming they never received the iPhone, and the blue line is the predicted active mobile broadband penetration for countries that received the iPhone, 2004 – 2017. Sources: Authors calculations and the ITU (2019).

References

Berndt, E. R., E. R. Dulberger, and N. J. Rappaport. (2000) "Price and Quality of Desktop and Mobile Personal Computers: A Quarter Century of History." NBER Working Paper, http://www.nber.org/~confer/2000/si2000/berndt.pdf.

Birke, Daniel. (2009) "The Economics of Networks: A Survey of the Empirical Literature." Journal of Economic Surveys, 23(4): 762–793.

Blalock, Garrick, Vrinda Kadiyali and Daniel H. Simon. (2007) "The Impact of Post-9/11 Airport Security Measures on the Demand for Air Travel," The Journal of Law & Economics, 50(4): 731-755.

Boik, Andre, Shane M. Greenstein, and Jeffrey Prince. (2017) "The Empirical Economics of Online Attention." Kelley School of Business Research Paper No. 16-57, Indiana University.

Brown, J. and Lee, S. (2010) *Examining Broadband Adoption Factors: An Empirical Analysis Between Countries*, Journal of Policy, Regulation and Strategy for Telecommunication, Information and Media, 10(1), 25-39.

Campbell-Kelly, Martin, and Daniel D. Garcia-Swartz. (2015) "From Mainframes to Smartphones: A History of the International Computer Industry." Cambridge, Massachusetts; London, England: Harvard University Press.

Campbell-Kelly, Martin, Daniel Garcia-Swartz, Richard Lam, and Yilei Yang. (2015) "Economic and business perspectives on smartphones as multi-sided platforms," Telecommunications Policy 39: 717-734.

Economides, Nicholas, and Steven C. Salop. (1992) "Competition and Integration Among Complements, and Network Market Structure." The Journal of Industrial Economics 40(1): 105-123.

Fan, Ying, and Chenyu Yang. (20200 "Competition, Product Proliferation, and Welfare: A Study of the US Smartphone Market." American Economic Journal: Microeconomics, 12 (2): 99-134.

Frattasi, Simone, Hooshang Fathi, Antje Gimmler, Frank H. P. Fitzek, and Devi Rangistty. (2006) "Designing socially robust 4G wireless services," IEEE Technology and Society Magazine, 25(2):51 – 64.

Garcia-Swartz, Daniel D., and Florencia Garcia-Vicente. (2015) "Network effects on the iPhone platform: An empirical examination." Telecommunications Policy, 39(10): 877-895.

Govil, Jivesh, and Jivika Govil. "4G: Functionalities Development and an Analysis of Mobile Wireless Grid," 2008 First International Conference on Emerging Trends in Engineering and Technology, Nagpur, India, 2008, pp. 270-275,

Griva, Krina and Nikolaos Vettas. (2011) "Price competition in a differentiated products duopoly under network effects," Information Economics and Policy 23(1): 85-97.

Hommen, L., and E. Mannenin. (2003) "The Global System for Mobile Telecommunications (GSM): Second Generation," in C. Edquist (ed.) The Internet and Mobile Telecommunications System of Innovation: Determinants in Equipment, Access, and Content, Edward Elgar Publishing, Cheltenham, 71-128.

Hui, Suk Yu; Kai Hau Yeung. (2003) "Challenges in the Migration to 4G Mobile Systems," IEEE Communications Magazine 41(12): 54-59.

International Telecommunication Union Data and Statistics (IDS). 2019. ITU World Telecommunications/ICT Indicators Database 2019 Version 1.1.1.

ITRS. 2002 (updated). International Technology Roadmap for Semiconductors: 2002 Update. https://ece.northeastern.edu/edsnu/mcgruer/class/eceu606/2002Update.pdf (accessed February 6, 2021).

Katz, M. and Shapiro, C. (1986) *Technology Adoption in the Presence of Network Externalities*. Journal of Political Economy, 94(4), pp. 822-841.

Kaufmann, Daniel, Aart Kraay, and Massimo Mastruzzi. 2010. The Worldwide Governance Indicators: Methodology and Analytical Issues. The World Bank Policy Research Working Paper 5430 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1682130

Lee, C., Chan-Olmsted, S., and Kim, T. (2009), *The Deployment of Third-Generation Mobile Services: A Multinational Analysis of Contributing Factors*, Unpublished Manuscript.

Lee, S., Marcus, M. and Lee, S. (2011) "An Empirical Analysis of Fixed and Mobile Broadband Diffusion," Informational Economics and Policy 23(3-4): 227-233.

MacCrory, F. and Shivendu, S. (2014) "The Smartphone as a Multiplayer Two-sided Platform." Unpublished Manuscript.

Pachis, A. and Yannelis, D. (2018) Determinants of Mobile Broadband Penetration: An Empirical International Study, Unpublished Manuscript.

Padgett, J.E., C.G. Gunther, and T. Hattori. (1995) "Overview of wireless personal communications," IEEE Communications Magazine 33(1): 28-41.

Pashigian, B. Peter, and Eric D. Gould. (1998) "Internalizing Externalities: the Pricing of Space in Shopping Malls," The Journal of Law and Economics 41(1): 115-142.

Pew Research Center. (2018) "Social Media Use Continues to Rise in Developing Countries but Plateaus Across Developed Ones," Pew Research Center: Washington, DC.

Rochet, J. and Tirole, J. (2003) *Platform Competition in Two-sided* Markets". Journal of the European Economics Association Vol. 1, pp. 990-1029.

Rochet, J. and Tirole, J. (2006) *Two-sided Markets: A Progress Report"*. RAND Journal of Economics 37(3), pp. 645-667.

Rohlfs, Jeffrey. (1974) "A Theory of Interdependent Demand for a Communications Service." Bell Journal of Economics. 5(1): 16-37.

Rysman, M. "The Economics of Two-sided Markets." Journal of Economic Perspectives. 23(3), pp. 125-143

Sagbansua, L., Sahin, O., and Col, M. (2015) Determinants of Mobile Penetration to Forecast New Broadband Adoption: OECD Case, Alphanumeric Journal 3(2).

Shankar, Venkatesh, and Barry L. Bayus. (2003) "Network effects and competition: an empirical analysis of the home video game industry." Strategic Management Journal 24: 375–384.

Shinohara, S., Akematsu, Y., and Tsuji, M. (2015) Panel Data Analysis of the Factors of Mobile Broadband Adoption in Selected Countries: Focusing on Smartphones, Proceedings of Pacific Telecommunications Council, Hawaii, U.S.

Shinohara, Sobee. (2017) *An Empirical Analysis of Mobile Broadband Adoption*, IEEE International Symposium on Technology in Society Proceedings.

Shy, Oz. (2011) "A Short Survey of Network Economics." Review of Industrial Organization 38: 119-149.

Singularity.com. (2020) "Microprocessor Speed Clock," http://www.singularity.com/charts/page61.html (accessed October 20, 2020)

Statista. 2020. "Number of active mobile broadband subscriptions worldwide from 2007 to 2019," https://www.statista.com/statistics/273016/number-of-mobile-broadband-subscriptions-worldwide-since-2007/ (accessed October 20, 2020).

Statista. 2021. "Vendors' market share of mobile phone unit sales to end users worldwide from 1997 to 2014." https://www.statista.com/statistics/271574/global-market-share-held-by-mobile-phone-manufacturers-since-2009/ (accessed February 8, 2021).

The Wall Street Journal. 2017. “The iPhone Decade in 12 Charts,” The Wall Street Journal, June 29, 2017 https://www.wsj.com/graphics/iphone-10-years/ (accessed October 20, 2020).

Thomas, Owen. (2007) “Apple: Hello, iPhone,” CNN Money, https://money.cnn.com/2007/01/09/technology/apple_jobs/ (accessed March 5, 2021).

Vogelstein, Fred. (2008) “The Untold Story: How the iPhone Blew Up the Wireless Industry.” Wired. https://www.wired.com/2008/01/ff-iphone/ (accessed March 5, 2021).

Vogelstein, Fred. (2013) “The Day Google Had to 'Start Over' on Android,” The Atlantic. https://www.theatlantic.com/technology/archive/2013/12/the-day-google-had-to-start-over-on-android/282479/ (accessed March 5, 2021).

World 2020 Stats. (undated) Internet Growth Statistics. Internet World Stats (undated) https://www.internetworldstats.com/emarketing.htm (accessed October 20, 2020).

World Bank. (2019) World Development Indicators. Retrieved from https://data.worldbank.org/indicator. (accessed Feb. 2020).

World Bank. (2020) “World Governance Indicators.” http://info.worldbank.org/governance/wgi/ (accessed 2019, 2020).

Yang, Chenyu. (2020) "Vertical structure and innovation: A study of the SoC and smartphone industries." RAND Journal of Economics, 51 (3): 739-785.

Zaber, Moinul, and Marvin Sirbu. (2012) “Impact of spectrum management policy on the penetration of 3G technology.” Telecommunications Policy 36(9): 762-782.

Appendix

Figure A1: Active Mobile BB Penetration Time-series: OECD

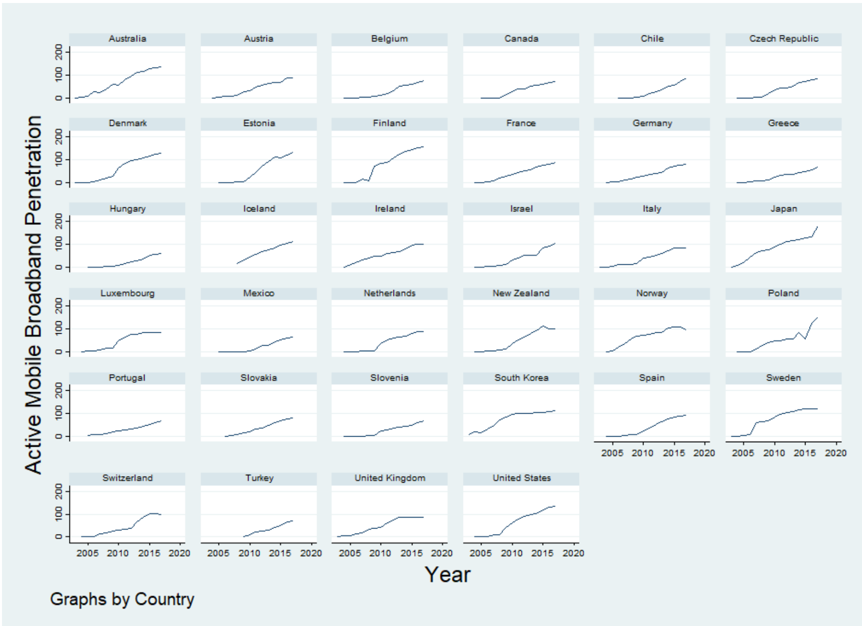


Figure A2: Active Mobile BB Penetration Time-series: non-OECD