Accounting for Innovation in Consumer Digital Services: Implications for economic growth and consumer welfare

David Byrne[*] and Carol Corrado[†]

November 10, 2017
(Preliminary Draft)

Abstract

This paper revisits the capitalization of consumer durables—specifically consumer digital goods—in national accounts with several goals in mind. First, the paper estimates whether accounting for the increase in stocks of household electronics during the ongoing digital transformation of the economy has an impact on real consumption and GDP. Second, the paper considers whether accounting for the intensity of consumer use of their digital gizmos changes the story. Third, we take steps to improve the capture of quality improvements in the digital capital services (purchased and imputed) consumed by households. All three moves are found to be needed to account for innovations in consumer digital services in the 21st century. Adjustments to GDP growth moderate its post-2005 slowdown by 1/4 percentage point per year, and the gain in consumer surplus is estimated to be very large—equivalent to 16 percent of the gain in disposable personal income between 2005 and 2015.

Keywords: Consumer Digital Services; Information and Communication Technology (ICT); Digital Transformation (DX); Consumer Durables; Consumer Surplus; Innovation, Productivity, Technology, and Price measurement

[*]Board of Governors of the Federal Reserve System, Washington, D.C.

[†]The Conference Board, New York, and Center for Business and Public Policy, McDonough School or Business, Georgetown University. Corresponding author: cac289@georgetown.edu

1 Introduction

This paper revisits the treatment of consumer durables—specifically consumer digital goods—with the goal of accounting for digital services consistently across business models used to deliver content and related services to consumers. In the business realm, the migration of information technology (IT) operations from in-house data centers to the cloud necessitates this type of analysis (Byrne and Corrado, 2017b; see also Byrne, Corrado, and Sichel, 2017a,b). In the consumer realm, the shifting blend of home-produced versus purchased gaming services illustrates the same point. Powerful smartphones and video game consoles with advanced processing technology deliver substantial IT services in many homes; at the same time, computer video apps and online games designed to connect users/players in different locations are run from datacenter servers. An accounting approach that provides useful comparisons over time and captures consumers' welfare gains needs to be robust to innovations in the ways consumer digital content and services are delivered in the 21st century.

Capitalization of consumer durables requires that the implicit services provided by consumers' ownership of assets be included in GDP and total income, a procedure implemented for household purchases of digital goods in this paper. Beyond implementing the standard approach to capitalizing consumer assets, this paper explores whether accounting for the increase in household time devoted to using stocks of digital devices in the home (a utilization effect) makes an empirically relevant impact on real consumption and real GDP. The paper also takes steps to improve the capture of quality improvements in digital capital goods purchased by households.

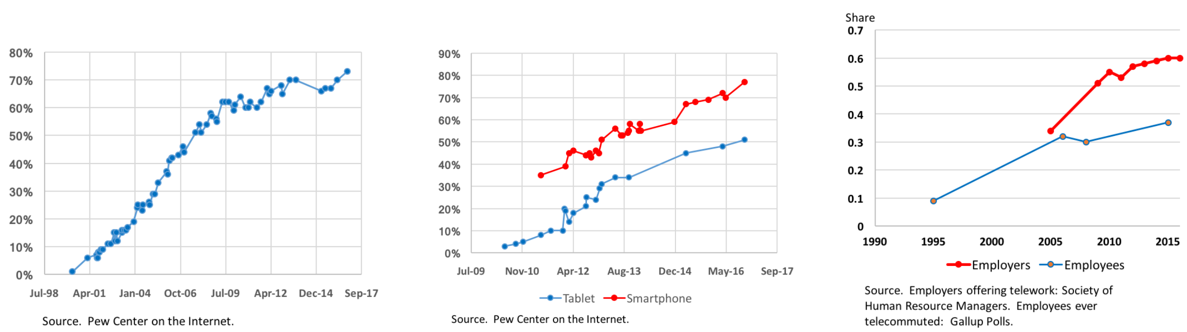
Household consumption of digital services reflects the intensity with which households use their own equipment and software to be sure, but it also reflects the intensity with which they use purchased digital services—internet access, cellular, and cable TV services, as well as cloud services (via gaming or other entertainment services, and computing or storage). Household IT capital utilization is thus inextricably tied to household's utilization of public broadband and cellular networks, a form of demand complementarity, if you will.[1] The analysis and measurement of household expenditures on digital access services is therefore addressed in this paper as well.

As suggested by the indicators shown in figure 1, the intensity with which households *use* their digital capital has increased sharply since 2000. Home broadband access, almost unknown in 2000,

[1]Thanks to Shane Greenstein for suggesting this interpretation.

is now used by three-quarters of American adults; the use of mobile devices providing internet access nearly anywhere at any time shot up just as broadband penetration gains began to slow; and an increasing number of adults, for good or ill, tax their home network with work activity. And, these indicators only begin to tell the story. The examples of rising *quality* delivered per unit of time spent connected are obvious: on-demand streaming of a seemingly endless library of video on nearly any device with a screen, high-quality video and still photography on your phone, seemingly intelligent navigation applications that thread us through traffic and entice us into the approaching coffee shop with coupons, etc. Although the standard approach in both national accounting (owner-occupied housing) and the productivity literature (when consumer durables are capitalized) is to ignore the utilization dimension, this paper finds that this convention leaves one of the most important aspects of the digital transformation of consumer activity out of the picture.

Figure 1: **Indicators of Consumer Digital Capital Use**



(a) Broadband Use (b) Mobile Device Use (c) Prevalence of Telework

The roadmap of this paper is as follows. First we set out a framework for thinking about (a) how capitalization of consumer digital goods impacts measured GDP and productivity, and (b) how household utilization of stocks fits into the picture, including their impact on payments for digital access services. Then we set out our empirical approach and present our results, which begin in 1985. We find that real consumer digital capital services grows more than 20 percent per year and contributes a tad less than 1/4 percentage points per year to real GDP growth (1985 to 2015). Our framework measuring real spending for network access services produces estimates that also growth about 20 percent per year. The implications of these estimates for productivity and consumer welfare are spelled out in the last section of the paper. They portray an economy in which the many innovations in the delivery of content to consumers that are captured in our estimates boost measured GDP growth in the United States by about .6 percentage points per year.

2 Framework and Approach

The framework used in this paper is adapted from (Byrne and Corrado, 2017b), who modified a model originally due to Oulton (2012) to include intermediate IT services to account for the growth and popularity of business use of the cloud platform. The macro equations of the Byrne-Corrado-Oulton model, reviewed below, are fundamentally unchanged when household production and use of digital capital are incorporated but parameters used to calibrate the model's solution are potentially affected substantially.

2.1 Model

Total final demand Y consists of investment (I) and consumption (C) produced in two sectors of the economy. The two producing sectors are: a general business sector excluding information and communication technology (ICT) producers (denoted by the subscript N), and an ICT sector (denoted by the subscript T) that consolidates business and household production of ICT goods and services. Thus we have

$$Y = C + I = Y_T + Y_N \ ; \quad Y_T = C_T + I_T \ ; \quad Y_N = C_N + I_N \ ; \tag{1}$$

and

$$PY = P_T Y_T + P_N Y_N \ ; \quad \overline{w}_T = \frac{P_T Y_T}{PY} \ . \tag{2}$$

where P is the price level, P_T and P_N are sector prices, and $\overline{w}_T$ represents the relative size of the ICT sector in total final demand in nominal terms.

The model assumes there is faster technical progress in the ICT sector. Denoting the rate of growth in the Hicksian shifter (A_i) in the sectoral production functions (not shown) as μ_i, this assumption is expressed as $\mu_T > \mu_N$. A major simplifying assumption is then employed to solve the model, namely, that the sectoral production functions exhibit constant returns and differ only by their A_i terms. This implies factor shares and input quantities are the same in both sectors.

Log differentiation of the model's factor payments equations (not shown) yields the result shown by Oulton (2012) that relative ICT price change equals (the negative of) relative ICT sector TFP growth.

Defining the relative ICT price as $p = P_T/P_N$, this result is expressed as a steady-state rate of change in relative prices $\dot{p}$ given by

(3) $$\dot{p} = \mu_N - \mu_T < 0 \ .$$

The model's steady-state solution for the contribution of ICT to the growth in GDP per hour $(O\dot{P}H)$ is then given by

(4) $$\text{Contribution of ICT sector to } O\dot{P}H = \underbrace{\frac{\overline{v}_{K_T} + \overline{\zeta}_T^N}{\overline{v}_L}(-\dot{p})}_{\text{Investment (use) and productivity (diffusion) effects}} + \underbrace{\overline{w}_T(-\dot{p})}_{\text{Production effect}} \ .$$

where $\overline{v}_{K^T}$ and $\overline{v}_L$ are the shares of ICT capital and labor in total income, respectively, and $\overline{\zeta}_T^N$ is ICT business services purchased by sector N relative to total income in the economy.[2] In the analysis that follows, the contribution of ICT to productivity via diffusion of its technologies to the non-ICT sector through purchases of ICT services is not discussed (but see Byrne and Corrado, 2017b). The analysis in this paper focusses on how the contribution of ICT to $O\dot{P}H$ via the investment and production effects changes when the asset boundary is extended to include consumer digital durable goods.

2.2 Asset boundary

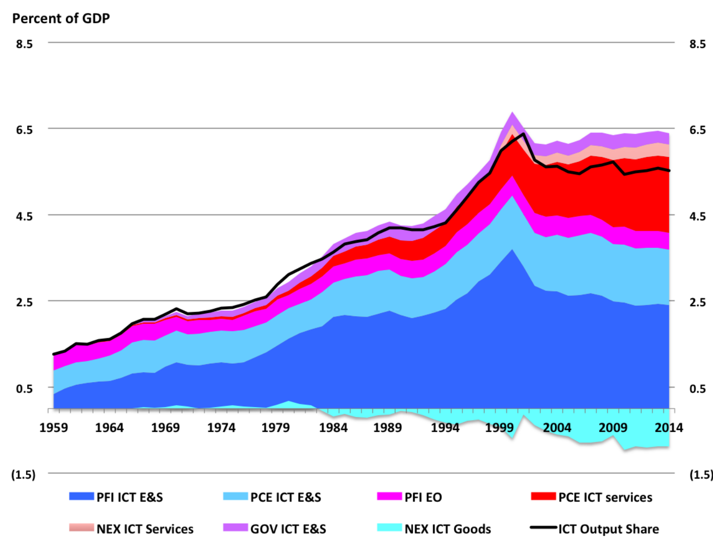
The extension of the asset boundary of GDP to include household spending on ICT equipment and software gives rise to two changes in national accounts. First, because household spending is a component of total *final* expenditures, when long-lived outlays previously counted as consumption are reclassified as capital spending, the expenditure reclassification, by itself, does not change GDP. But a second change creates a new final expenditure category—imputed services to the newly classified capital good—and this adds to GDP. As in capital services used by producers, the imputed service flow is a gross rental payment (Jorgenson, 1963), i.e., the service flow is a rental price multiplied by a volume measure of the newly capitalized net stocks.

[2] Equation (4) is derived in the online appendix (`http://www.csls.ca/ipm/33/Byrne_Corrado%20Appendix.pdf`) to Byrne and Corrado (2017b).

The foregoing implies the calibration of the parameters in equation (4) are affected by extending the GDP asset boundary to include household ICT stocks. First, the production effect is unequivocally larger because the additional services produced and consumed have been added to GDP, with the result that the ICT sector accounts for a larger share of final demand in the economy, $\overline{w}_T$. Second, the use or investment effect also becomes larger because the income imputed to the newly capitalized ICT stocks is added to total income and boosts the overall ICT capital income share, $\overline{v}_{KT}$. Last, because this paper also reconsiders existing price measures for consumer digital equipment investment and develops new price measures for consumption of digital services as part of the asset boundary expansion, estimates of $\dot{p}$ must be reevaluated in light of the new price measures.

ICT share of final demand ($\overline{w}_T$). The empirical importance of imputing services flows to consumer digital stocks is suggested by figure 2, which shows the (existing) relative size the digital sector of the U.S. economy in terms of what it supplies to final demand, 5.6 percent of GDP for the past ten years (2004 to 2014). Compare the relative size of the light versus dark blue shaded areas. Together they represent the share of total private ICT equipment and software spending (E&S) in private domestic final demand—a total that is more than 50 percent larger than the spending currently capitalized as private fixed investment in ICT (the dark blue section alone). Considering that capital services tends to approximate investment outlays (Jorgenson, 1966), the capitalization of consumer digital stocks would appear to be consequential for calibrating the potential contribution of ICT to $O\dot{P}H$.

Figure 2: **ICT Final Output Share**



Note: E&S is equipment and software. PFI = private fixed investment. PFI ICT E&S excludes software R&D. PCE components include audio, video, and cellular equipment and exclude landline telecommunications.

Source: Byrne and Corrado (2017b) based on data from BEA.

ICT share of capital income ($\overline{v}_{KT}$). Let K_i^j denote sector j's net stock of investment goods of type i ($i = T, N$), where recall sector T includes both households (H) and businesses (B) as producers of ICT services; the two subtypes of ICT producers will be distinguished when needed by these superscripts. Let total ICT capital income *prior* to recognizing household ICT stocks be given by $R_T^B(K_T^{T^B} + K_T^N)$, where R_T^B is the business sector's rental price for a unit of ICT capital.[3] Then in the boundary-extended version of the model,

$$\overline{v}_{K_T} = \frac{R_T^B(K_T^{T^B} + K_T^N) + R_T^H K_T^{T^H}}{PY} \tag{5}$$

where R_T^H is the household rental price for a unit of ICT capital, $K_T^{T^H}$, and $R_T^H K_T^{T^H}$ augments both factor income and final demand.

Should imputed services be use-adjusted? Let us be more precise and denote household ICT capital income as $\overline{R_T^H} K_T^{T^H}$, where a "bar" is placed over the household rental price to indicate it is based on an *ex ante* rate of return, and denote household ICT capital services consumption as $P^{S_T^{T^H}} S_T^{T^H}$ As conventionally represented, e.g., when imputing rents to consumer durables in productivity analysis, the imputed value of household ICT capital income and ICT capital services consumption are equal yielding

$$P^{S_T^{T^H}} S_T^{T^H} \equiv \overline{R_T^H} K_T^{T^H} = \underbrace{(\overline{\rho} + \delta_T^H)}_{Ex\ Ante\ Rental\ Rate} P^{I_T^{T^H}} K_T^{T^H} \tag{6}$$

where $\overline{\rho}$ is an *ex ante* real household discount rate, δ_T^H is a depreciation rate for household stocks of digital goods, and $P^{I_T^{T^H}}$ is a quality-adjusted investment (or asset) price index for those stocks. In this approach, the digital goods asset price deflator $P^{I_T^{T^H}}$ is also the price deflator for the consumption of digital capital services $P^{S_T^{T^H}}$ (e.g., see Jorgenson and Landefeld, 2006).

Private industry capital income is generally understood to include a utilization effect when the rate of return is calculated on an *ex post* basis following Jorgenson and Griliches (1967); see Hulten (2009) for a discussion. If we wish to account for household capital use rates in a conceptually parallel way, equation (6) would be viewed as a capacity flow, in which case imputed income and consumption

[3]The rental price of using ICT capital differs by producing sector in a two sector model, but differences across business sectors are not central to this paper and are ignored; see the Byrne and Corrado (2017b) online appendix for further details.

would be given by

$$P^{S_T^{T^H}} S_T^{T^H} \equiv R_T^H K_T^{T^H} = \underbrace{\lambda(\overline{\rho} + \delta_T^H)}_{\text{Ex Post Rental Rate}} P^{I_T^{T^H}} K_T^{T^H} \tag{7}$$

where λ is a factor of proportionality that reflects the use intensity of household digital stocks. The basic idea in equation (7) is that $\lambda\overline{\rho}$ better represents the actual (or *ex post*) net return households receive from each dollar spent on durable digital goods. This suggests that trends in use rates might affect actual asset prices, a topic examined later in this paper.[4]

It seems evident that if market prices or quantities of digital goods and services have been impacted by the dramatic increase in household digital asset use, i.e., that substitution across the production boundary used for GDP has taken place, estimates of real consumption and productivity growth may be misstated if the trends in household utilization suggested by figure 1 are ignored. But a literal use of (7) would not be compatible with a broader move to capitalize all consumer durable goods in national accounts based on (6). Are consumer nondigital stocks, e.g., lawnmowers, used 24/7?

3 Methods

The foregoing suggest a need to develop methods for capitalizing consumer digital goods that capture the changes in household production and consumption of digital services that are especially evident since the turn of the 21st century and do so in a national-accounts compatible way.

3.1 Real imputed digital services consumption

In terms of real growth, a use-adjusted approach to imputing services flows to consumer durables can be accomplished in two observationally equivalent ways.

The first is to make a use adjustment is to estimate the new nominal imputed income as in equation (7), where the income adjustment generates a real output and productivity impact and $P^{I_T^H}$ remains the price index for imputed digital services consumption.[5] To see the real effects, let $\overline{\rho}$ and δ_t^H be held constant, and log differentiate (7). This reveals that the rate of change of real household digital capital

[4]Note that equation (7) also implies that higher use intensity is associated with higher depreciation, but this is ignored and not consequential to our final analysis.

[5]As we now focus on services produced exclusively in the T sector, the notation is simplified to indicate that the relevant distinction is whether the services are produced by households or businesses.

services with a use correction is given by $\dot{\lambda} + \dot{K_T^H}$, i.e., changes in the use intensity of household digital stocks augment real growth.

From the household perspective, however, the rate of change in the *effective* consumption price of services yielded by a unit of digital capital then is not $\dot{P^{I_T^H}}$, but rather $\dot{P^{I_T^H}} - \dot{\lambda}$. The second approach then makes a use-adjustment by retaining the standard method for calculating imputed nominal services, i.e., it uses equation (6) to determine $P^{S_T^H} S_T^H$, but it defines $\frac{P^{I_T^H}}{\lambda}$ as the consumption price index for the services $P^{S_T^H}$. The *actual* log price change for imputed consumer digital capital services is then given by

$$\dot{P^{S_T^H}} = \dot{P^{I_T^H}} - \dot{\lambda} \tag{8}$$

where S_T^H is defined as the volume of services *consumed* from ownership of digital stocks K_T^H, and a rising household use intensity boosts the rate of growth of real consumer digital capital services growth.

3.2 Complementarity with network access services

The generation of household digital services reflects not only households' use of digital devices, but also their take up of network access services. The typical delivery model for access services is a subscription model where households pay a monthly fee in return for continuous access to a range of services, e.g., broadband, smartphone, cable TV, subscription video-on-demand (or SVoD).

In terms of measurement, the demand complementarity between the use of devices and use of access services raises both possibilities and challenges. First, complementarity suggests we can exploit the degree to which access modes are utilized to obtain a measure of household use intensity. Note that while we generally have figures for hours of use by access mode, these are coarse indicators because they do not capture consumption intensity—just as automobile manufacturing plant hours don't capture the speed of the assembly lines running inside the plant (e.g., see Aizcorbe, 1992). Ideally, we want a measure of households' use of the potential performance of communication networks, where performance is a consistently-defined time series (e.g., as in Hilbert and López, 2011, who measured communication capacity in terms of optimally compressed megabytes per year).

Second, network access fees are a component of personal consumption expenditures in national accounts irrespective of use rates. If imputed services are adjusted for utilization, should network access services be measured on a consumption basis, too? And if that answer is yes, which it seems it should be, then the intensity of average network use is directly related to the quality component of access services consumed.

Third, an approach that defines $P^{S^H_T}$ as $\frac{P^{I^H_T}}{\lambda}$ does not disturb the conceptual basis for the measurement of the asset price of consumer digital capital, $P^{I^H_T}$. However, in reality, demand complementarity suggests that, taking the marginal productivity of the capital as given, if consumers viewed their ability or desire to utilize each unit of K^H_T as having increased (better broadband, greater access to content), they would be willing to pay either (a) a higher price for each unit of K^H_T capital and/or (b) a higher price for a digital access service plan per each unit of K^H_T capital owned. In a more complex model, limitations on household time and diminishing returns ultimately dampen these effects, but as shall be seen in the empirics to follow, these mechanisms appear to have been operating in recent years.[6]

3.3 Real digital access services

Consider now the decomposition of consumer outlays for subscriptions to digital access services into price and quantity components. From a producer perspective, ignoring differences by service type and service plan, and letting N be the number of plans (or users), these services are denoted as $P^{O^B_T}O^B_T$, where $\frac{O^B_T}{N}$ is the potential quantity of services offered per plan, and $\frac{P^{O^B_T}O^B_T}{N}$ is the average price of a plan. Taking into account the usual issues regarding peak load planning, etc., producers set this price based on their preferred rate of utilization in conjunction with the offered quantity.

From a consumer perspective, denote payments for subscription plans as $P^{C^B_T}C^B_T$ where $C^B_T = u^B O^B_T$, where u^B denotes the degree to which offered capacity is consumed. While this suggests that a higher u^B is associated with a lower effective average price per plan, consumers do not observe O^B_T because u^B is an outcome of their *ex post* consumption choice in relation to the expectation of producers. From the household view, they consume $\frac{C^B_T}{N}$ quantity of services per plan and pay the average price noted above for this consumption.[7]

Now define the quantity of access services consumed by households in terms of petabytes (PB) of Internet Protocol (IP) traffic, in which case $C^B_T = IP$, $O^B_T = IPC$, where IPC is providers' capacity

[6] The foregoing ignores network externalities and impacts they may have on households' view of the effective price.

[7] Although not directly relevant to the measurement story, note that if the actual quantity consumed exceeds producer expectations, producers will need to adjust capacity. But bringing new capacity online in this industry usually occurs with a lag—during which time access service prices may be higher than otherwise might be the case, depending of course on the degree of competition and the extent to which higher-than-preferred utilization of existing capacity pushes up operating costs.

and $u^B = \frac{IP}{IPC}$. This puts us in a position to define a measure for λ, the average use intensity of consumers digital capital,

$$\lambda = \frac{C_T^B}{N} = \frac{IP}{N} \tag{9}$$

and also a price index for purchased digital access services:

$$P^{C_T^B} = \frac{P^{O_T^B} O_T^B}{IP} \quad . \tag{10}$$

Note that the price index (10) implies that a higher average use intensity is associated with higher quality services.

This measure of λ reflects a chain of utilization margins, the most important of which is that, depending on the nature of the applications run by consumers, the number of unduplicated hours consumers devote to connectivity will not translate one-for-one to IP traffic. Other margins include that the number of users may differ from the number of plans and that this may change over time(e.g., when within a household, children become users); the number of devices may be greater than the number of users, and hours per device and per user may change over time.

The combined changes in these margins of use—the $\dot{\lambda}$ that enters equation (8), the definition of the price deflator for imputed capital services—may be measured as the difference between the price index for access services and the average price paid. To see this, starting from (9), we have the following:

$$\begin{aligned} \dot{\lambda} &= \dot{C}_T^B - \dot{N} \\ &= \dot{u}^B + \dot{O}_T^B - \dot{N} \\ &= I\dot{P} - IP\dot{C} + IP\dot{C} - \dot{N} \quad . \end{aligned} \tag{11}$$

After adding and subtracting $\dot{P^{O_T^B}} O_T^B$, we obtain

$$= (\frac{\dot{P^{O_T{}^B}} O_T^B}{IP}) - (\frac{\dot{P^{O_T^B}} O_T^B}{N}) \quad ,$$

which after substitution from (10) reduces to

$$= \dot{P^{C_T^B}} - (\frac{\dot{P^{O_T^B}} O_T^B}{N}) \quad .$$

3.4 Digital access service providers' utilization

Consider now how one might measure u^B, which can be used to help analyze price measures for consumer digital assets, capital services, and access services as defined above.

As previously indicated, private industry capital income is generally understood to include a utilization effect, and previous work has considered how to extract a measure of network capital utilization from productivity data for Internet service providers, or ISPs (Corrado, 2011; Corrado and Jäger, 2014; see also Corrado and van Ark, 2016). The basic idea in these works is that when an *ex ante* approach is used to determine an industry's return, a utilization factor can be calculated so as to exhaust observed capital income—provided, that is, the industry's aggregate net stock of capital is not particularly sensitive to composition differences in asset use, i.e., it acts more or less as a single capital good as in Hulten (1986, 2009). The above-cited works argue that this is largely the case for network services providers in the United States, and Corrado (2011) found substantial differences between their *ex post* calculated nominal rate of return and the market rates typically used in *ex ante* productivity analysis.

Let us then define the network services providing industry's *ex post* gross return as

$$\Phi^{ISP} = (r^{ISP} + \delta^{ISP} - \pi^{ISP}) \tag{12}$$

where r^{ISP} is a nominal net return determined residually in the usual way, given depreciation δ^{ISP} and revaluation of the industry's capital stock π^{ISP}. Now define the industry's *ex ante* gross return as

$$\overline{\Phi}^{ISP} = (\overline{r} + \delta^{ISP} - \pi^{ISP}) \tag{13}$$

where $\overline{r}$ is an *ex ante* nominal rate of interest. Let u^{ISP} be the industry's capital utilization rate. As shown in the appendix, this utilization rate is given by

$$u^B = \frac{\Phi^{ISP}}{\overline{\Phi}^{ISP}} \tag{14}$$

which suggests the relationship between the *ex post* and *ex ante* rate of return, i.e., r versus $\overline{r}$, for an industry or sector is an indicator of its capital utilization. In models that introduce imperfect competition in an otherwise standard neoclassical growth framework (e.g., Rotemberg and Woodford, 1995), utilization is absorbed in a more general inefficiency wedge capturing, among other things, the ability of firms to maintain a price markup.

4 Data Sources and Empirical Scope

The data sources and empirical scope of the estimates we develop in this paper—consumer digital asset stocks, digital asset prices, household use intensity of digital networks, network provider capital utilization, and services prices for imputed digital capital services and digital access services—are set out below.

4.1 Current Cost Net Stocks

Table 1, column (1), lists the 14 product classes of consumer durable goods whose spending is capitalized in our analysis. They range from TVs, to computers and software, to cell phones. In terms of service lives, the products are grouped into two categories, those with a 9 year service life (A) and those with a 5 year service life (B). These groupings are indicated in column (2) of the table, and are a (slight) simplification of the service life categories used by BEA in their fixed asset accounts, with the result that our estimates of nominal net stocks (i.e., stocks at current cost) differ only slightly from those issued by BEA in its fixed asset accounts.

To compute our current cost net stocks we follow BEA and use a Hulten-Wykoff declining-balance rate of 1.65 for all categories (including computers, unlike BEA), implying geometric depreciation rates for groups A and B of .1833 and .3300, respectively.[8] We first calculate an end-of-year (EOY) net stock of capital for each product class j in table 1 using the perpetual inventory method with geometric depreciation:

$$K^H_{j,EOY} = I^H_{j,t}(1 - \frac{\delta^H_j}{2}) + (1 - \delta^H_j)K^H_{j,EOY-1} \tag{15}$$

where $I^H_{j,t}$ is annual average real investment for the year t, calculated by deflating nominal spending on each product class using price indexes $P^H_{j,t}$ based on the sources listed in column (3) of table 1, discussed and presented below. Following BEA, we then calculate a mid-period net stock $K^H_{j,t}$ by averaging adjacent EOY net stocks, which we multiply by its corresponding (annual average) price

[8] Documentation of depreciation in BEA's fixed asset accounts may be found *here*.

Table 1: **PCE durable digital goods**

	Product class	Depreciation	Network access	Source for Asset Price Index
	(1)	(2)[a]	(3)	(4)
1.	Televisions	A	Y	Byrne-Corrado (2017a,b)
2.	Cameras	B	N	Japanese CPI, cameras
3.	Photographic equip. ex. cameras	A	N	PCE price index
4.	Video equipment	A	N	Japanese CPI, video equipment[b]
5.	Audio equipment	A	N	PCE price index
6.	Recording media	A	N	PCE price index
7.	Computers	B	Y	Byrne-Corrado (2017a,b)[c]
8.	Data storage equip.	B	Y	Byrne (2015)
9.	Monitors	B	Y	Same as TVs (line 1)
10.	Computer peripherals	B	Y	BEA investment price index
11.	Misc. office equip	B	N	PCE price index
12.	Software and accessories	B	Y	PPI, game software, bias-adjusted[d]
13.	Telephone equip. ex. cellular	A	N	Byrne-Corrado (2015a,b)
14.	Cell phones	B	Y	Byrne-Corrado (2015a,b)

NOTES: a. A = 9 year service life, B = 5 year service life.
b. The Japanese CPI for video equipment begins in 1990; the Japanese CPI for cameras is used for prior years.
c. Reweighted for consumers.
d. Bias adjustment based on a game software index from Copeland (2013) and the software investment price index from Byrne and Corrado (2017a), equally weighted.

SOURCES: For spending (column 1), BEA's annual PCE bridge tables, for which data are available from 1998 on; data for prior years are as follows: Byrne and Corrado (2015a,b) for the cell phone/other telephone equipment split, NIPA 2.4.5U for total; authors' estimates for computer and peripheral equipment and photographic equipment detail, NIPA table 2.4.5U for total and other 9 categories.

index. Summing over product classes ($j = 1, 14$):

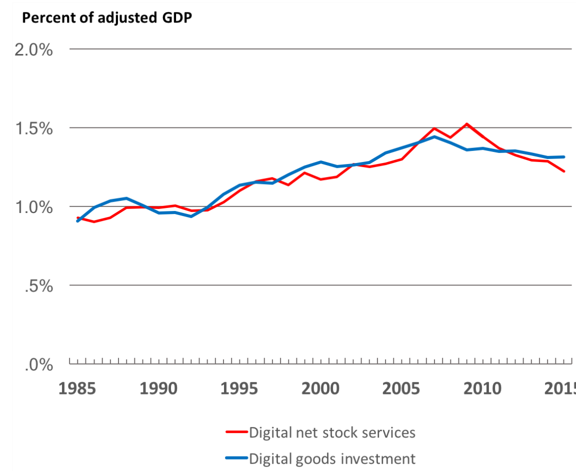
$$P^{I_T^H} K_T^H = \sum_j P_j^{I_T^H} K_j^H \tag{16}$$

yields the value of consumer digital capital referred to in equation (6), the equation that is used in our analysis.

When we consider the demand complementary of digital access services with the stocks of devices shown in table 1, we concentrate only on the equipment used for Internet or cellular network access. Column (3) of the table is an indicator of whether the product class is included in a sub-aggregate for digital access equipment that is created for this purpose.

4.2 Nominal Imputed Services

Figure 3: **Consumer Digital Investment and Capital Services, 1985 to 2015**



Note. Consumer durable digital goods are listed in table 1.

We calculate a gross rental rate using the depreciation rates described above and an *ex ante* net return measured using the 10-year constant maturity government bond rate and actual price change for the relevant asset type. Summing over asset types yields an estimate of consumer digital services. This series, which is in nominal terms, is shown in figure 3, where it has been plotted relative to GDP adjusted to include it. Relative to this metric, imputed services have averaged 1.3 percent of GDP for the last 20 years. Imputed services rose beginning in the early 1990s and reached a peak in 2009, after which they fell back to their relative level in 2005. The ratio of consumer digital investment to GDP has been more stable of late, averaging 1.34 percent of adjusted GDP since 2010.[9]

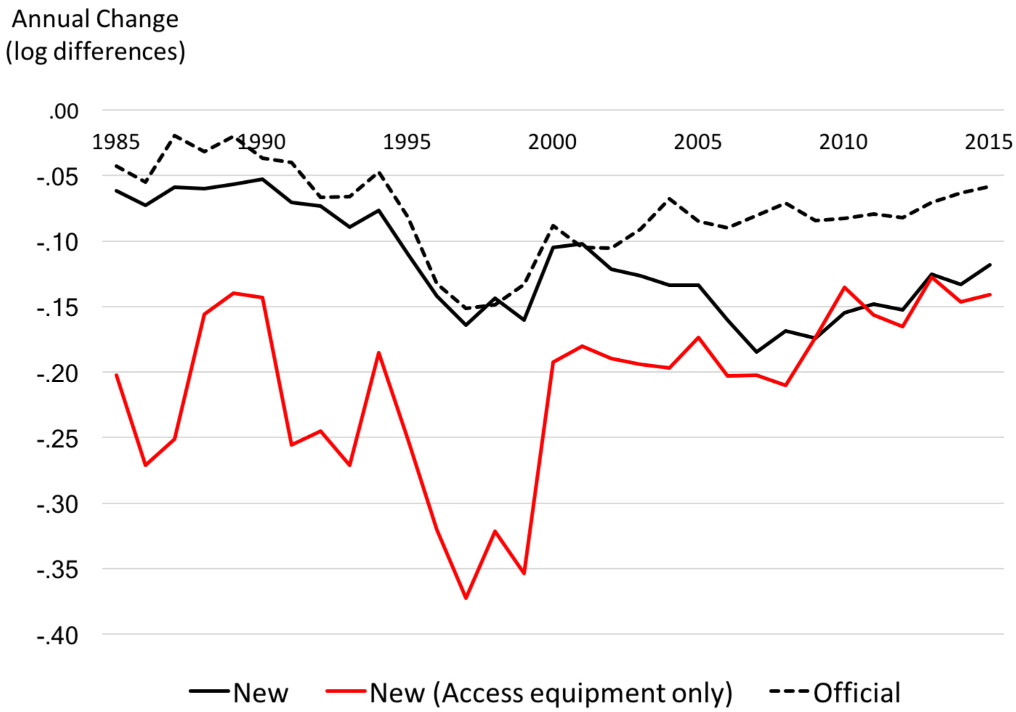
4.3 Asset price indexes

Table 1, column (4), shows the sources for the components of the price index we construct for the PCE ICT investment goods shown in column (1). As may be seen, deflators for more than half of the product classes shown in table 1 are taken or adapted from our own prior work (Byrne and Corrado, 2015a,b; Byrne, 2015; Byrne and Corrado, 2017a,b). In new moves, we incorporate two quality-adjusted price indexes from the Japanese consumer price index and exploit work by Copeland (2013) on consumer game software, in combination with results from the BLS PPI.

The results for the new PCE ICT investment goods price index are shown by the solid black line in figure 4 and on line 1 of the table below (table 2, along with a corresponding aggregate based on the relevant PCE durable goods price deflators currently used by BEA (the short-dashed line). As may be seen, the two series are not all that different through about 2001, after which their dynamics

[9]The softening of investment in the last 5 years relative to the prior 5 years primarily reflects a sharp slowing in consumer outlays on computer software; consumer outlays for software grew 9.6 percent per year from 2005 to 2010 but dropped back to 3.0 percent per year from 2010 to 2015.

Figure 4: **New Estimates of Price Change for PCE Digital Assets**



SOURCES: Official, authors' elaboration of data from NIPA tables 2.4.4U and 2.4.5U; New, table 1.

are different. The new consumer investment price index indicates that consumer digital goods prices dropped 14 percent per year, on average, from 2005 to 2015, 6-3/4 percentage points faster than implied by the official data.

What is especially interesting about these new measures of price change is that, based on the discussion about the impact of rising use rates on asset prices, figure 4 shows a slowing in the rates of decline in our subcategory of asset prices for digital access equipment beginning in 2000. This is not mis-measurement (we hope), but rather (we conjecture) the impact of rising real demand for the *consumption* of services from consumer-owned digital stocks.

Table 2: **Rates of Change for PCE Digital Asset Prices (annual average rate)**

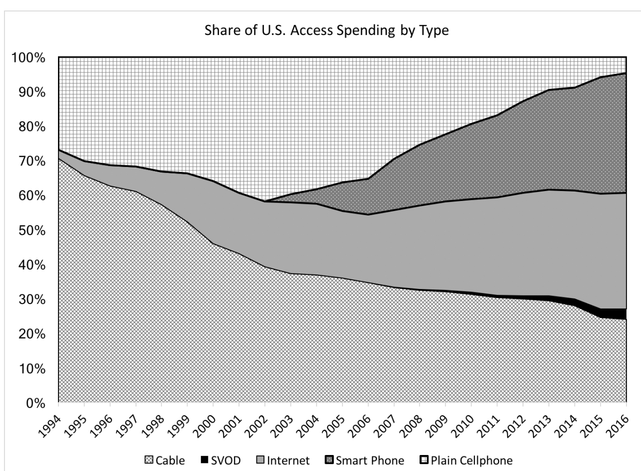
	1985 to 2015	1985 to 1995	1995 to 2005	2005 to 2015	2005 to 2010	2010 to 2015
	(1)	(2)	(3)	(4)	(5)	(6)
1. PCE digital asset price	-11.2	-7.0	-12.5	-14.1	-15.5	-12.7
1a. Access equipment only	-19.0	-19.5	-22.1	-15.3	-16.9	-13.7
Memos:						
2. Official	-7.5	-4.6	-10.5	-7.4	-7.9	-6.8
3. Line 1 less line 2	-3.7	-2.4	-2.0	-6.8	-7.7	-5.8
4. Real asset price	-13.1	-9.5	-14.2	-15.6	-17.1	-14.1

NOTE: For sources used to construct line 1, see figure 4. Line 4 is Line 1 relative to the GDP deflator.

4.4 Digital services price index

Column (1) of table 3, lines 1 to 4, list the types of digital access services included in BEA's detailed PCE tables. These BEA tables also show data for landline telephone services and video media rental services, which are not included in our analysis. The latter is not included because it does not appear to include subscription video on demand services (SVoD), e.g. payments for Hulu, Netflix, and Amazon video services. To include these services in our analysis, consumer payments are estimated from company financial reports.[10] The resulting shares are shown in figure 5.

Figure 5: **Spending Shares for Types of Consumer Digital Access Services**



SOURCES: Official, authors' elaboration of data from NIPA table 2.4.5U and table 3 of this paper.

[10] Users are from company financial reports and eMarketer; consumer SVoD traffic is estimated from total SVoD traffic from Cisco based IP traffic shares by service from Sandvine Global Internet Phenomena Report, 2016 and earlier years.

Table 3: **PCE digital access services**

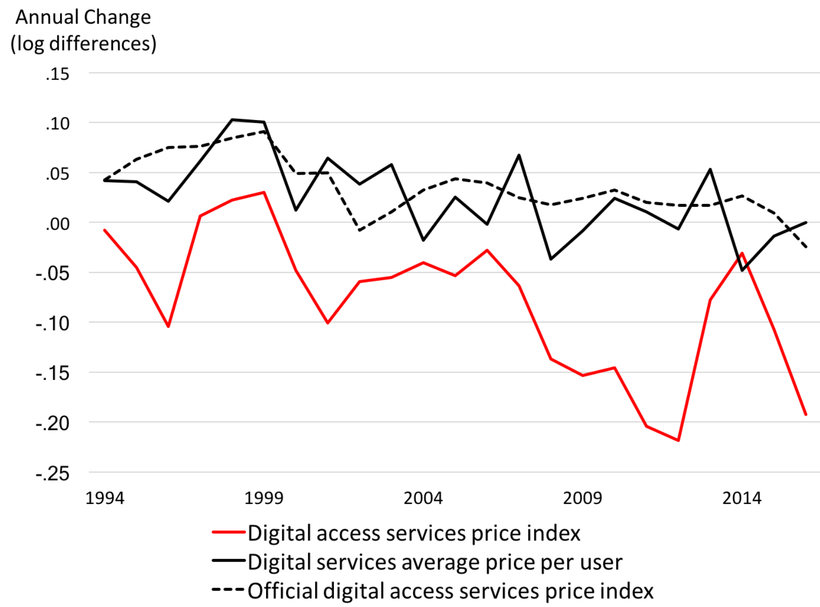
		Sources:		
	Type of service	Payments	Users	Volume
	(1)	(2)	(3)	(4)
1.	Internet access	Line 283	ITU	Cisco
2.	Cellular (conventional) telephone	Line 279, Nielsen	ITU, Nielsen	n.a.
3.	Smartphone	Line 279, Nielsen	ITU, Nielsen	Cisco
4.	Cable and satellite TV and radio	Line 215	all households	Nielsen
5.	SVoD	Company reports	Company reports[a]	Cisco[a]

NOTES: a. Supplemented with industry sources; see footnote 10 for elaboration.
SVoD is subscription video on demand. Line numbers refer to NIPA table 2.4.5U. Line 279 split between conventional cellular and smartphone based on Nielsen reports of adoption and revenue data developed in Byrne and Corrado (2015a). ITU is International Telecommunication Union.
In column (4), Cisco is Cisco Virtual Networking Index of North American consumer IP traffic, consumer mobile IP traffic, and total SVoD traffic, various years. Nielsen refers to reports of hours of television, including replay of recordings.

The remaining columns of the table show for number of users (need to compute an average price) and our indicator of services volume. Recall, the basic idea behind our estimates of use intensity is to view access payments per user as the price paid for access to the service plan capacity, potentially on a continuous basis throughout the year. The actual volume, i.e., the use of the capacity is based sources shown in column (4), and access payment per volume of service is the price corresponding to actual digital network use. Measures of data traffic are used to represent volumes for internet, smartphone services and SVoD; hours are used as a volume measure for cable television services. For conventional cellular telephone service, use intensity is treated as unchanged over time. In effect, the accessibility component of this service—the fact that a user is always reachable—is viewed as predominant.

The results of aggregating the individual price deflators to an overall digital access services price index are shown in figure 6 and table 5. There are two very interesting properties of the indexes shown in this figure and table. First, the new price appears to be capturing quality change as shares shift toward smartphones. Second, the trend in changes in the official index is not much different from changes in the average price per user. The access service price developed for this paper falls substantially faster, especially after 2005 (see line 4 of the table)

Figure 6: **Price Change for Consumer Digital Access Services**



SOURCES: Official, authors' elaboration of data from NIPA tables 2.4.4U and 2.4.5U; New digital access services price index, table 3 of this paper.

Table 4: **Rates of Price Change for PCE Digital Services (annual average rate)**

	1985 to 2015	1985 to 1995	1995 to 2005	2005 to 2015	2005 to 2010	2010 to 2015
	(1)	(2)	(3)	(4)	(5)	(6)
1. Digital access services price index (new)			-3.9	-11.0	-10.0	-12.0
2. Digital access services average price per user			4.9	0.8	0.9	0.7
Memos:						
3. Official price index	-.1[a]	-.4[a]	.1	-.1	.1	-.4
4. Line 1 less Line 3			-4.0	-10.9	-10.1	-11.6

NOTE: a. Series begins in 1986. For sources for line 1, see table 3. Line 2 is authors' elaboration of data from industry sources and BEA. Line 3 is authors' aggregation of data from NIPA tables 2.4.4U and 2.4.5U.

4.5 Household use intensity (λ)

To construct an aggregate measure of utilization, we construct $\dot{\lambda}$ using the approach described in section 3.3. As shown there, $\dot{\lambda}$ is implied by the difference between the rate of change of a use-adjusted (or quality-adjusted) price index for digital access services and the average price. As previously indicated, a digital access price index and an average price is calculated for each category shown in table 3. The five components (internet, cable, SVoD, smartphone, and conventional cellular service) of each index are aggregated using spending weights, and the difference in the rates of change of the two aggregate indexes-is our estimate of the change in use intensity $\dot{\lambda}$.

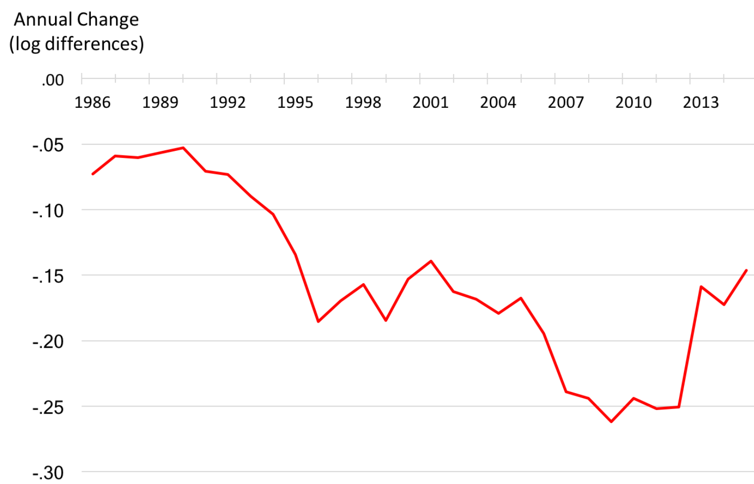
Expressed as a contribution to price change for digital access equipment capital services, we have

$$-\dot{\lambda} = \underbrace{\sum_{j=1}^{5} \overline{w_j} \Delta ln \frac{P_{T_j}^{O^B} O_{T_j}^{B}}{N_j}}_{Per\ User\ Price\ Change} - \underbrace{\sum_{j=1}^{5} \overline{w_j} \Delta ln \frac{P_{T_j}^{O^B} O_{T_j}^{B}}{Vol_j}}_{Volume\ Price\ Change} \tag{17}$$

where $\overline{w_j}$ is the share of payments for digital access service type j in total digital access service payments (shown in figure 5), and Vol_j is IP traffic for 3 of the 5 components.

The results of calculating equation (17) and folding this into services price indexes are shown in figure 7 and table 5. As may be seen, we find that the contribution of increasing household connectivity and intensity of network use to declines in the price index for digital access equipment capital services, i.e., $-\dot{\lambda}$, notable, averaging about 6 (log) percentage points since 2005. All told, the price index for imputed capital services falls nearly 20 percent per year since 2005 (table 5, line 1, column 4), reflecting the combination of increases in household use (whose effects are subtracted) and falling quality-adjusted asset prices.

Figure 7: **Price Change for Consumer Digital Capital Services**



SOURCE: This paper.

Table 5: **Rates of Price Change for Consumer Digital Capital Services (annual average rate)**

		1985 to 2015	1985 to 1995	1995 to 2005	2005 to 2015	2005 to 2010	2010 to 2015
		(1)	(2)	(3)	(4)	(5)	(6)
1.	Capital services	-14.2	-7.4	-15.3	-19.5	-21.1	-17.8
MEMOS:							
2.	$-\dot{\lambda}$			-0.09	-0.14	-0.15	-0.13
2a.	Contribution of $-\dot{\lambda}$ to line 1[a]			-0.03	-0.06	-0.07	-0.06

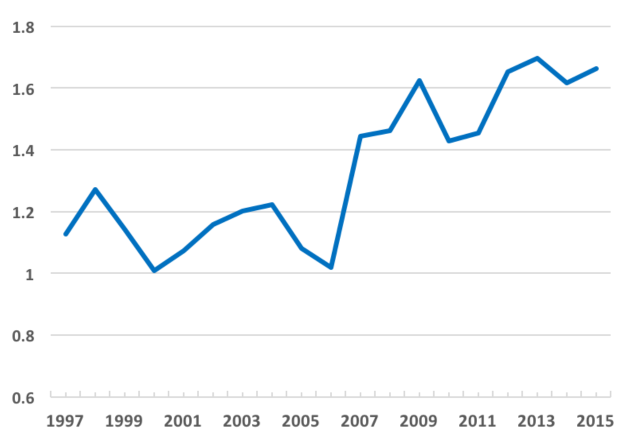
NOTES: Lines 2 and 3 are log differences. a. Contribution reflects both $\dot{\lambda}$ and the weight of digital access equipment in total consumer digital capital spending.
SOURCE: This paper.

4.6 Network Utilization

Figure 8 shows the implied network utilization calculating according to equation (14) where $\overline{r}$ is set to Moody's AAA corporate bond rate and r is calculated from productivity data for the industries listed in the figure's footnote. As may be seen, although this measure of u^B bounces about year by year, it generally rises sharply after the early 2000s.

Figure 8 is interesting for several reasons. First, as a cautionary note, the measure shown in this figure pertains to the entire ISP industry, i.e., including commercial and enterprise customers, and therefore does not reflect the interaction between consumer demand and supply alone. But that said, the figure is consistent with the upward trend in household indicators shown previously on figure 1. Second, figure 8 reflects the fact that the *ex post* gross rate of return in the network services industry and, by extension, its net nominal rate of return, is usually notably greater than market rates. And while the rise in ISP relative profitability suggests a strengthening of ISP pricing power for network and video access services, especially between 2005 and 2013, on a per user basis, concomitant changes in average prices *decelerated* relative to earlier experience (see again table 5, line 2). This suggests the rise in industry utilization reflected a demand shock and that ISP productivity growth during this period may not be indicative of longer-term underlying trends.

Figure 8: **Implied Network Utilization**



NOTE: Ratio of ex post and ex ante gross return for the combined Motion Picture, Sound Recording, Telecommunications, and Broadcasting industries (NAICS 512,515,517). Moody's AAA corporate bond rate is used in the ex ante formulation.

SOURCE: Authors calculations using industry-level data from BEA.

5 Results and Implications

We present and describe the new consumer digital goods and services measures and analyze their implications for productivity growth and consumer surplus.

5.1 Results

Our results for households' nominal and real digital goods investment, nominal and real digital services consumption, and their impacts on GDP are summarized in table 6.

Table 6: **Investment in Consumer Digital Goods and Consumption of Digital Services (annual percent change)**

		1985 to 2015	1985 to 1995	1995 to 2005	2005 to 2015	2005 to 2010	2010 to 2015
		(1)	(2)	(3)	(4)	(5)	(6)
Investment:							
1.	Nominal	6.2	8.3	7.6	2.8	2.7	2.9
1a.	Access equipment	13.2	25.1	11.1	4.3	5.5	3.2
2.	Real	19.6	16.4	22.9	19.7	21.9	17.8
2a.	Access equipment	39.8	55.4	42.6	23.2	26.9	19.6
Capital services:							
3.	Nominal	5.9	7.8	7.6	2.3	4.5	0.1
3a.	Access equipment	7.9	11.1	9.3	3.5	5.7	1.3
4.	Real	23.4[a]	16.5[a]	27.1	27.0	32.4	21.7
4a.	Access equipment	44.7[a]	40.6[a]	53.9	40.0	47.2	33.1
Access services:							
5.	Nominal	12.4	14.7	15.2	7.6	8.8	6.5
6.	Real	16.5[a]	9.3[a]	19.9	20.5	20.9	20.2
Contrib. to $\dot{GDP}$:[b,c]							
8.	Consumer digital services	.39	.15	.40	.61	.67	.55
8a.	Net of existing	.32	.13	.31	.52	.57	.47
9.	Capital services	.23	.12	.25	.32	.41	.24
10.	Access services	.16	.03	.15	.28	.26	.31
10a.	Net of existing	.09	.00	.06	.20	.16	.23

NOTES: a. The deflator used to obtain real capital services on lines 4 and 4a is preliminary in that it is not use-adjusted prior to 1994. Similarly, the deflator used to obtain real access services on line 6 is based on a volume measure of digital network use beginning only in 1994 and uses the BEA deflator in earlier years.
b. Percentage points. c. GDP contributions are calculated assuming PCE digital goods are imported and that total real GDP is unaffected by the differences between the PCE ICT investment price index developed in this paper and official prices used in the construction of GDP.

Table 6 has several key takeaways. First, as shown on line 4, column (1), real services yielded by consumer stocks of digital goods grow robustly, averaging 23.4 percent per year for the period shown. From 2005 to 2010, column (5), real growth was especially robust, but tapered off thereafter.

This tapering is partly a compositional effect, reflecting a relative slowing in the growth of consumer software stocks, whose weight in aggregate real services is higher than it is in aggregate real investment. Note also that even though the growth rate of consumer outlays for digital equipment and software has been historically weak in nominal terms since 2005 (line 1, column 4), this is not indicative of weakness in underlying (i.e., real) consumer investment demand. A second takeaway from table 6 is that our new results for real access services (line 6) show very strong, and consistent, underlying real growth (averaging 20.5 percent per year) from 2005 to 2015, a result presaged by the steady expansion of the IP traffic figures used as volume indicators for these services.

Finally, as shown on line 8, this paper's approach to accounting for innovation in consumer digital services has notable consequences for GDP growth: From 2005 to 2015 as a whole, annual GDP growth would be 1/2 percentage points higher per year if the methods set out in the paper were incorporated in national accounts (the circled item in line 8a). This result in the sum of two terms: first, the contribution of real digital capital services, which is an addition to GDP that averages 1/4 percentage points per year (line 9) and the net contribution of the new volume measures used for digital access payments (line 10a).

5.2 Productivity and Consumer Surplus

The contribution to GDP growth of our estimates for consumer digital services is also their impact on total economy OPH growth in the two-sector model of section 2. (This is both because capital services are included in GDP and that measurement allows for multiple relative prices and multiple production possibilities).

Before we discuss productivity, let us review consumer surplus as it, too, is related. The idea here is that we have quality-adjusted price change so that, to the extent possible, the increase in consumer welfare from innovations in content delivery is included in our estimates. Supplemental estimates of "free goods" are, theoretically, not needed as long as our quality-adjusted (and use-adjusted) price indexes reflect Hicksian-like reservation prices for the services in question. We cannot, of course, quantify Harberger-type triangles for individual innovations (e.g., Facebook, HDTV, or Netflix services) because the analysis of this paper is not that detailed. But the two new series developed for consumer digital services can be used to compute the consumer surplus that arises from "continuing commodities" where the expectation is that quality-adjusted price indexes will capture what is going on. Following Diewert and Fox (2017), we calculate the consumer surplus from continuing commodities as

$$.5\big(\Delta P^{S_T^H}\Delta S_T^H\big) + .5\big(\Delta P^{C_T^B}\Delta C_T^B\big) \quad . \tag{18}$$

We do this for two periods, 1995 to 2005, and 2005 to 2015, and examine the change. The results are presented in table 7.

Table 7: **Consumer Surplus from Innovations in Digital Content Delivery, billions of dollars**

	1995 to 2005	2005 to 2015	Acceleration (2) - (1)
	(1)	(2)	(3)
1. Consumer surplus	381.7	1,074.8	693.1
2. Capital services	349.7	784.9	435.2
3. Access services	31.9	289.9	257.9
Fraction of ΔDPI:			
4. Consumer surplus	.10	.27	.16
5. Capital services	.09	.20	.10
6. Access services	.01	.07	.06

NOTE: DPI is disposable personal income, adjusted to include imputed digital capital income. The fractions in column 3 are calculated relative to the 2005 to 2015 change in DPI.

As may be seen, the increase in consumer welfare due to innovations in digital content delivery during the first 10 years of this century (compared with the last 10 of the previous one) is estimated to be nearly $700 billion (line 1, column 3). This acceleration is equal to 16 percent of the ten-year change in disposable personal income (line 4, column 3). The gain in capital services ("free goods") accounts for more than 60 percent of the increase.

Consider now the implications of line 8a of table 6 for productivity growth. Adopting the results presented in this paper would shave about 1/4 percentage points from the slowdown in total economy multi-factor productivity (MFP) growth in the United States. While small relative to the existing 1.4 percentage points MFP growth slowdown according to BLS estimates for the total economy, the revision is consequential nonetheless. Equally consequential is the prospective contribution of this paper's estimates of consumer digital services to the underlying trend in total economy output per hour growth in the United States. This prospective contribution is summarized in table 8.

Table 8 evaluates equation (4) in light of the estimates reported in this paper; as may be seen there are two broad channels at work, an investment effect and a production effect. The investment effect is relatively easy to evaluate because the ratio of household capital income to GDP is fairly constant (see again figure 3) at 1.3 percent of total domestic income. The rate of change in real PCE ICT assets is used to inform the estimate of the relative productivity differential for this effect, and it also has been fairly steady over time; the long-term average shown in table 2, line 4, column (1), is used. The production effect is a bit trickier because the ratio of digital access payments to nominal GDP has risen steadily over time; we use its average for the last two years (1.7 percent of GDP), a conservative assumption, that when added to the steady average for capital services (1.3 percent of GDP) yields the 3 percent shown in the table on line 3 (a). The estimate of the productivity differential is based on a weighted average of the trend in capital services assuming $\dot{\lambda} = 0$, which is the real ICT asset price change, and the trend in real access services price change, which is estimated to be -9 percent per year.

When the above-described effects are evaluated, we obtain the table's top line estimate that measuring the impact of innovations in consumer content delivery as we have done in this paper implies that the combined impact of growth in real digital capital services and real digital access services will contribute .57 percentage points per year to the growth in labor productivity. Although this is similar to the post-2005 actual effects shown on line 8 of table 6, the actual effects are boosted by the disequilibrium effects of climbing use rates (i.e., $\dot{\lambda} \neq 0$ over history) and the prospective effects are boosted by inserting recent values for the final demand share for access services spending (which climbed over history).

Table 8: **Consumption of Digital Services and Productivity Growth (percentage points, annual rate)**

		Estimated Trend
1.	**Contribution to total economy $\dot{\mathrm{OPH}}$**	.57
of which:		
2.	ICT investment effect	.25
(a)	Weight (ratio): $\frac{\overline{v}_{K_T^H}}{\overline{v}_L}$	.02
(b)	Productivity differential: $-\dot{p}$	13.1
3.	ICT production effect	.32
(a)	Weight (ratio): $\overline{w}_{T^H}$	.03
(b)	Productivity differential: $-\dot{p}$	10.8

Notes—OPH is output per hour. Contributions are for household sector only, based on equation (4). Line 2 (a) is ratio to labour share of total gross domestic income including the imputation for households' capital income from its digital stocks, and line 3 (a) is ratio to gross domestic income with the same adjustment. Line 2 (b) is an estimate of the productivity differential based on PCE ICT assets (i.e., assuming $\dot{\lambda} = 0$ and line 3 (b) is an estimate based on PCE ICT final goods and services.
Source—Calculations use estimates reported in prior tables and figures in this paper.

6 Conclusion

The household has been an important locus of the ongoing ICT revolution and arguably the most visible locus in recent years. Entertainment, communication, and indeed work from home have been supercharged by advances in hardware, software, and communication. Hardware innovation has proceeded at a blistering pace as the major household platforms—smartphones, tablets, televisions, and gaming consoles—have become extraordinarily powerful and cheap and as datacenter innovation (i.e. the cloud) has charged ahead in the background, fueled by ongoing improvements in underlying components. Communication speeds—both wireline and wireless—have been essential as well; for example, nearly one-third of all IP traffic was accounted for by Netflix alone in 2016. All this highly visible innovation has raised the question of whether existing national accounts are missing consequential growth in output and income associated with home use of ICT platforms.

The changing production border for digital content delivery illustrates the need for a framework that embraces an expanded asset and production boundary. Accordingly, this paper looked at the digital transformation of consumer content delivery through the lens of capitalization of certain consumer durable goods in national accounts and offered methods for accounting for the increasing use households make of their digital devices. In this approach, services are imputed to investments in long-lived purchases of digital goods, as is done now for owner-occupied housing. Like the selective treatment of housing in national accounts, the notion is to avoid imparting a bias to GDP—in this case not because the size of the services is large (as in housing) but rather because the relatively faster productivity growth of the ICT (or digital) sector provides an extra kick to overall growth. Our effort to quantify this manifestation of the ongoing ICT revolution suggests the effect of expanding the asset boundary to include consumer digital goods is empirically very relevant. Consumer welfare is enhanced by nearly $700 billion from 2005 to 2015 (16 percent of the increase in DPI) relative to 1995 to 2005 according to our estimates, and real consumer digital services are estimated to potentially contribute 1/2 percentage point per year to long-term productivity growth.

References

Aizcorbe, A. M. (1992). Procyclical labour productivity, increasing returns to labour and labour hoarding in car assembly plant employment. *The Economic Journal 102*(413), 860–873.

Byrne, D., C. Corrado, and D. Sichel (2017a). Own-account IT equipment investment. FEDS Notes (October 2), Federal Reserve Board, Washington, D.C.

Byrne, D., C. Corrado, and D. Sichel (2017b). The rise of cloud computing: Minding your P's and Q's (and K's) Paper presented at the NBER/CRIW conference, *Measuring and Accounting for Innovation in the 21st Century*, held in Washington, D.C., March 10-11, 2017.

Byrne, D. M. (2015). Prices for data storage equipment and the state of IT innovation. FEDS Notes (July 15), Federal Reserve Board, Washington, D.C.

Byrne, D. M. and C. A. Corrado (2015a). Prices for communications equipment: Rewriting the record. Finance and Economics Discussion Series 2015-069 (September), Board of Governors of the Federal Reserve System, Washington, D.C.

Byrne, D. M. and C. A. Corrado (2015b). Recent trends in communications equipment prices. FEDS Notes (September 29), Federal Reserve Board, Washington, D.C.

Byrne, D. M. and C. A. Corrado (2017a). ICT asset prices: Marshalling evidence into new measures. Finance and Economics Discussion Series 2017-016 (February), Board of Governors of the Federal Reserve System, Washington.

Byrne, D. M. and C. A. Corrado (2017b). ICT Services and their Prices: What do they tell us about Productivity and Technology? *International Productivity Monitor* (29, forthcoming).

Copeland, A. (2013). Seasonality, consumer heterogeneity and price indexes: the case of prepackaged software. *Journal of Productivity Analysis 39*, 47–59.

Corrado, C. (2011). Communication capital, Metcalfe's law, and U.S. productivity growth. Economics Program Working Paper 11-01, The Conference Board, Inc., New York. Available at `http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2117784`.

Corrado, C. and K. Jäger (2014). Communication networks, ICT, and productivity growth in Europe. Economics Program Working Paper 14-04, The Conference Board, Inc., New York.

Corrado, C. A. and B. van Ark (2016). The Internet and productivity. In J. M. Bauer and M. Latzer (Eds.), *Handbook on the Economics of the Internet*, pp. 120–145. Northamption, Mass.: Edward Elgar Publishing, Inc.

Diewert, W. E. and K. J. Fox (2017). The digital economy, GDP and consumer welfare. Technical report, Paper presented at the CRIW Workshop at the NBER Summer Institute (July 17-18).

Gordon, R. J. (1990). *The Measurement of Durable Goods Prices.* Chicago: University of Chicago Press.

Hilbert, M. and P. López (2011). The world's technological capacity to store, communicate, and compute information. *Science 332*(6025), 60–65.

Hulten, C. (1986). Productivity change, capacity utilization, and the sources of efficiency growth. *Journal of Econometrics 33*, 31–50.

Hulten, C. (2009). Growth accounting. Working paper, NBER Working Paper 15341 (September).

Hulten, C. R. and F. C. Wykoff (1981a). The estimation of economic depreciation using vintage asset prices. *Journal of Econometrics 15*, 367–396.

Hulten, C. R. and F. C. Wykoff (1981b). The measurement of economic depreciation. In C. R. Hulten (Ed.), *Depreciation, Inflation & the Taxation of Income from Capital*, pp. 81–125. The Urban Institute.

Jorgenson, D. W. (1963). Capital theory and investment behavior. *American Economic Review 53*(2), 247–259.

Jorgenson, D. W. (1966). The embodiment hypothesis. *Journal of Political Economy 74*(1), 1–17.

Jorgenson, D. W. and Z. Griliches (1967). The explanation of productivity change. *The Review of Economic Studies 34*(3), 249–283.

Jorgenson, D. W. and J. S. Landefeld (2006). Blueprint for expanded and integrated U.S. accounts: Review, assessment, and next steps. In D. W. Jorgenson, J. S. Landefeld, and W. D. Nordhaus (Eds.), *A New Architecture for the U.S. National Accounts*, Volume 66 of *NBER Studies in Income and Wealth*, pp. 13–112. Chicago: University of Chicago Press. Available at http://www.nber.org/chapters/c0133.pdf.

Oulton, N. (2012). Long term implications of the ICT revolution: Applying the lessons of growth accounting and growth theory. *Economic Modelling 29*(5), 1722–1736.

Rotemberg, J. J. and M. Woodford (1995). Dynamic general equilibrium models with imperfectly competitive product markets. In T. F. Cooley (Ed.), *Frontiers of Business Cycle Research*, pp. 243–293. Princeton University Press.

Appendix

This appendix provides a derivation of equation (14) in the main text, i.e., we set out how to extract a measure of network capital utilization from productivity data.

What follows is based on the framework set out for analyzing communication networks and network externalities in Corrado (2011), in which it is assumed there no markups due to imperfect competition or other inefficiency wedges; see also Corrado and Jäger (2014) and Corrado and van Ark (2016).

In sources-of-growth accounting, the contribution of private capital is expressed in terms of the services it provides. Let the value of the relevant private stocks be denoted as $P^I K$ where the price of each unit of capital P^I is the investment price and the real stock K is a quantity obtained via the standard perpetual inventory model. In our application, the value $P^I K$ represents the replacement value of network service provider capital in terms of its capacity to deliver digital services (i.e., including in this application, the value of the "originals" for the content the provider can diseminate). The value $P^K K$ represents the service flow provided by that capital.

The price P^K is an unobserved rental equivalence price, but which is related to the investment price by the user cost formula, $P^K = P^I(r + \delta - \pi)T$, where r is an after-tax *ex post* rate of return, δ the depreciation rate used in the perpetual inventory calculation, π is capital gains, and T is the Hall-Jorgenson tax term. The rental equivalence price is simplified by defining the gross return $\Phi = (r + \delta - \pi)T$, so that when capital services $P^K K$ are equated with observed capital income via the residual calculation of an *ex post* after-tax rate of return r, we have

$$\text{(A1)} \qquad \textbf{observed capital income} = P^I K * \Phi$$

When capital services are computed on the basis of an *ex ante* financial rate of return $\overline{r}$, the value for capital income of network providers must be expressed differently. Defining the *ex ante* gross return $\overline{\Phi} = (\overline{r} + \delta - \pi)T$ accordingly, network provider capital income is expressed as

$$\text{(A2)} \qquad \textbf{observed capital income} = P^I K u^{ISP} * \overline{\Phi}$$

where u^{ISP} is network capital utilization and, via Berndt-Fuss (1986), capital utilization u^{ISP} (rather than r) exhausts capital income.

Equating expressions (A1) and (A2)

$$P^I K * \Phi = P^I K u^{ISP} * \overline{\Phi}$$

and solving for u^{ISP} yields

$$\text{(A3)} \qquad u^{ISP} = \frac{\Phi}{\overline{\Phi}}$$

which suggests the relationship between the *ex post* and *ex ante* rate of return for an industry or sector is an indicator of its capital utilization.