Productivity, Network Effects and Telecommunications Capital: Evidence from the US and Europe

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Abstract

Did the huge investment in telecommunications networks in the 1990s affect subsequent total factor productivity? Using data from 13 European countries and the US, 1995-2013, we document the substantial growth and then slowdown in "telecommunications" capital and ask if this is related to the growth and slowdown in TFP. We explore this by disaggregating ICT equipment investment into "IT" and "CT" equipment investment. We test for distinct effects from each using a simple framework where CT capital has network externalities and so potentially impacts TFP, with the marginal impact of CT capital growth being higher in countries spending more on renting CT capital. We find: a) evidence of a robust correlation between (lagged) growth in (rental share-weighted) CT capital services and TFP growth; b) the estimated externality from CT capital potentially explains around 30-40% of TFP growth in North European countries, 60% in Scandinavia and around 90% in the US; c) CT capital has a social return around five times its private return; and d) a slowdown in the accumulation of CT capital accounts for just over half of the post-2003 TFP slowdown in the US but only one-tenth of the TFP slowdown in the EU.

Keywords: spillovers, network effects, telecommunications, ICT, R&D, externalities, growth, TFP
JEL classification: O47, O38, O32

1 Introduction

The idea that communications networks might have positive externalities for users has motivated a number of studies of the link between telecoms investment and economic growth (e.g. using cross-country data, Röller and Waverman [2001] on telecommunications infrastructure and GDP growth; Koutroumpis [2009] and Gruber and Koutroumpis [2011] on broadband penetration and GDP growth).

This paper revisits these studies using a simple growth accounting model. We assume the economy invests in "telecommunications (CT) capital", comprising of (a) capital to access the network (e.g. phones and internet connections) and (b) network capital. Use of the network confers externalities on other users so the social value of communications capital potentially exceeds the private value. Since TFP growth is output growth less private return-weighted capital growth, growth in CT capital affects TFP growth (in proportion to spending on telecommunications services). We explore this by disaggregating ICT equipment investment into "IT" and "CT" equipment investment, calculating capital growth and rental payments and exploring the correlation with TFP growth using cross-country data.

The study therefore relates to previous literature in a number of different ways. First, we add to the cross-country literature above, but using an explicit model, new data and calculate social returns. In contrast to a number of other studies which estimate using data for aggregate ICT equipment [Stiroh, 2005], we disaggregate ICT equipment into IT hardware and CT equipment using newly available data on IT and CT investment.[1] Our model also implies a link between TFP growth and share-weighted CT capital growth (rather than unweighted CT capital growth), where the share reflects that economies that are more connected (i.e. rent a lot of CT equipment) are more likely to benefit from communications network externalities.

Second, there are numerous studies of the link between growth in GDP and ICT capital equipment: see for example Oliner and Sichel [2000]; Stiroh [2002] and Acharya [2016]. Most studies build from the key point that research into the contribution of ICT equipment needed accurate quality-adjusted investment deflators (see for example: Triplett [2004] on ICT equipment prices; Doms [2005], Corrado [2011] and Byrne and Corrado [2015] on CT equipment prices; and Schreyer and Colecchia [2002] on price harmonisation across countries). We are very much in the spirit of these contributions with the addition, following Oliner and Sichel [2000] and Schreyer and Colecchia [2002] in disaggregating ICT equipment and harmonising data across countries.[2]

Third, there has been much interest in the (global) labour productivity and TFP growth slowdown. Much of that occurred in the financial crisis, but as Fernald [2014] has noted, the slowdown started in the US in the early 2000s. Goodridge et al. [2016a] also document a productivity slowdown in the UK in the 2000's (prior to 2007) relative to the 1990s.[3] As we document, the building of communications networks peaked in the 2000s, so we are able to ask if at least some of the pre-crisis TFP slowdown was to be expected via the slowing in CT capital growth.[4]

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[1] National accounts data including disaggregated ICT equipment investment are available from OECD.Stat. We deflate each category of ICT investment (IT, CT, software) using OECD price indices for each country that are harmonised to US prices, as published by the Bureau of Economic Analysis (BEA). These price estimates update those in Schreyer and Colecchia [2002]. We thank Vincenzo Spiezia of the OECD for sharing these data. In this paper, references to ICT refer to IT hardware, CT equipment and software. References to ICT equipment refer to IT hardware equipment and CT equipment.

[2] We are not aware of another study that estimates ICT spillovers using share-weighted capital input.

[3] From Goodridge et al. [2016a]: in 1990-2007, UK TFP growth averaged 1.13% pa, compared to 0.94% pa in 2000-07.

[4] There are of course a host of micro studies on the effect of networks/broadband/the internet on e.g. educational outcomes [Faber et al., 2015] and productivity [De Stefano et al., 2014]. We aim here to estimate the social returns from communications networks. To do this on micro data would need data on all the other connections of everyone in the economy, suggesting that this particular question is amenable to macro data.

To preview our results: using data from thirteen European countries and the US, 1995-2013, a regression of TFP growth on lagged share-weighted CT equipment growth yields a statistically significant positive effect, robust to other controls, different data etc., consistent with network externalities. The effect "accounts for" around 30-40% of TFP growth in Northern Europe, around 60% in Scandinavia (where telecoms spending is higher) and just under 90% in the USA. The estimated social returns to investment in communications capital are approximately five times private returns. In terms of the slowdown that occurred prior to the crisis, a slowdown in the contribution of CT capital services explains approximately 10% of the TFP slowdown in Europe and 50% of the slowdown in the US.

The rest of this paper is set out as follows. Section 2 sets out our model in the context of the existing literature and section 3 sets out our data and method. Section 4 presents our results and section 5 discusses the economic significance of our results. Finally, section 6 concludes.

2 Model and existing literature

2.1 Model

Suppose that to get connectivity, businesses (a) buy capital to access the network (phones, computers etc.), and (b) rent network services. Consider then an economy with two sectors:

1. a consumption goods production sector (C) which buys "access capital", rents network services and produces consumption goods; and
2. a telecommunications network sector (NET), which provides network services.

We consider each sector in turn.

2.1.1 Consumption goods (C) industry

We assume gross output is described by:

$$G_i^C = F^G(X_i, Z_i, A^C) \tag{1}$$

which says that the gross output of firm i depends on inputs X (labour, capital and intermediates), a technology shifter A, and connectivity services, denoted Z.

We assume that the flow of connectivity services Z_i depends on three inputs. First, firms have to obtain access to the network: suppose they purchase (access) capital equipment to do this (a phone, internal switching gear, computer) denoted byK^{ACC}. Second, they have to rent network services, N (the network infrastructure connected to the access capital). Third, assume that the connectivity services of firm i depend on the connectivity of others (Z_{-i}): if there is congestion this might have a negative marginal effect, with Metcalfe's law it might rise (say with the square of connections). Thus we write Z as:

$$Z_i = F^Z(K_i^{ACC}, N_i^{NET}, Z_{-i}) \tag{2}$$

Let us write this technological relation in terms of log changes as (where lower case letter denote logs and dx is the change in lnX):

$$dz_i = \varepsilon^Z_{K^{ACC}} dk_i^{ACC} + \varepsilon^Z_{N^{NET}} dn_i^{NET} + \gamma dz_{-i} \tag{3}$$

and so in a symmetric equilibrium

$$dz = \frac{1}{(1-\gamma)}\varepsilon^{Z}_{K^{ACC}} dk^{ACC} + \frac{1}{(1-\gamma)}\varepsilon^{Z}_{N^{NET}} dn^{NET} \tag{4}$$

which shows that the flow of connectivity services to all those connected depends on the own-elasticity of access and network services (ε) scaled by the effect from the network externalities, $1/(1-\gamma)$. If there are congestion externalities then $\gamma < 0$, in which case the own-elasticities are scaled down $((1/(1-\gamma)<1)$. By contrast, if there are positive network externalities then $\gamma > 0$, in which case the own-elasticities are scaled up $((1/(1-\gamma)>1)$.

Rohlfs [1974] is generally credited with one of the first economic models of network effects. Rohlfs assumed that a consumer's utility depended both on the quantity consumed of their own communication services but also the quantity of services consumed by *others* on the network. Griffin [1982] was an early empirical estimate showing that intra-US state phone calls depended positively on the numbers connected within that state. What has become known in telecoms regulation as the Rohlfs-Griffin (RG) factor is the ratio between (marginal) willingness to pay for all of society and for one individual. Rohlfs assumed it to be between one and two: when RG=1, private individuals get no benefit from others (so private=social), when RG=2, private individuals get equal benefits if they subscribe and if others subscribe. In our notation this corresponds to $\gamma = 0$ and $\gamma = 1$.[5]

Suppose further that firms purchase access capital and network services competitively (there is competition in the phone market and regulation of networks say), in which case the own-elasticities are the share-weighted cost of such services. Thus log differentiating equation (1), substitution of (4) and replacing the elasticities by their shares, and forming a gross output weighted sum over all downstream firms gives, for the downstream C sector:

$$dg_i^C = \sigma_X^C dx^C + \frac{1}{(1-\gamma)}\sigma^{C}_{K^{ACC}} dk^{ACC} + \frac{1}{(1-\gamma)}\sigma^{C}_{N^{NET}} dn^{NET} + da_i^C \tag{5}$$

where σ are shares of downstream gross output. So (5) says that due to the positive network effects ($0 < \gamma < 1$), the effect on output of the components of communications services is greater than its payment share.

2.1.2 Network (NET) industry

As above, the flow of connectivity services, Z, depends on the network, but also access and others connected. Now we consider network services, where we assume the network services industry produces network capital services from the network capital stock K^{NET}, inputs (such as labour) $X^{NET}$and technology A^{NET}:

$$N_i^{NET} = F^{NET}(X^{NET}, \mu_i K^{NET}, A^{NET}) \tag{6}$$

which is to say that the flow of network services to firm i depends on network capital times a factor μ, where μ most naturally captures utilisation of the network.[6] If we assume that the network services industry

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[5] In the voice phone market, RG=2 is generally viewed as an upper limit since most calls are in practice to a subscriber's particular contact set. When RG=2, a subscriber gets a full benefit from literally any other extra subscriber on the network regardless of their identity. In terms of our notation $RG = 1 + \gamma$: see below, we estimate $\gamma = 0.8$.

[6] The approach of multiplying the network capital by a utilisation factor contrasts with the Berndt-Fuss-Hulten [1986] approach, which is to specify the production function in terms of variable inputs (here X) and quasi-fixed inputs (here K). In that model, any utilisation effects are captured not by adjusting K by a μfactor, since by assumption the production function depends upon the stock of quasi-fixed inputs (see e.g. Berndt and Fuss [1986] equation (10) and the discussion immediately below). Instead, utilisation is captured by the appropriate rental price of those quasi-fixed inputs. This differs from the usual market

is regulated to competitive prices then it chooses X and K such that:

$$dn_i^{NET} = \sigma_X^{NET} dx^{NET} + \sigma_{K^{NET}}^{NET} (d\mu_i + dk^{NET}) + da^{NET} \tag{7}$$

where we have replaced the output elasticities by their factor shares with no mark-up, which is appropriate for an industry optimising in the face of regulated output prices.

2.1.3 Economy value added and TFP growth

To get to economy value added, we have to take some steps. For firms, rental paynents for network services are intermediate spending, whereas payments for access capital are expenditures on durable capital at the firm. Define nominal value added in the C sector implicitly as $P^G G^C = P^V V^C + P^{NET} N^{NET}$ (which says that gross output in the the downstream is the sum of value-added and intermediates). Construction of an appropriate price index for value-added means that $dg^C \equiv s_{VC}^{G^C} dv^C + s_N^{G^C} dn^{NET}$. Define economy-wide value added growth as $dv \equiv s_{VC}^V dv^C + s_N^V dv^N$ where $dv^N = dn^{NET}$ since there are no intermediates in the network providing sector by assumption. Substitution gives:

$$dv \quad = \sigma_X^V dx + \tfrac{1}{(1-\gamma)} \sigma_{K^{ACC}}^V dk^{ACC} + \tfrac{1}{(1-\gamma)} \sigma_{N^{NET}}^V (d\mu + dk^{NET}) + da \tag{8}$$

where da is the share-weighted sum of the sector technology terms ($da \equiv s_{VC}^{G^C} da^C + s_N^{G^C} da^{NET}$). Economy-wide TFP growth is measured by subtracting from output growth share-weighted input growth, where inputs include capital inputs weighted by their rental cost shares, giving:

$$dtfp^V \quad = \quad da + \frac{\gamma}{(1-\gamma)} \left(\sigma_{K^{ACC}}^V dk^{ACC} + \sigma_{K^{NET}}^V dk^{NET} \right) + \frac{1}{(1-\gamma)} \sigma_{K^{NET}}^V d\mu \tag{9}$$

Equation (9) suggests a number of points. First, the components of connectivity services affect TFP growth but only if there is an externality, γ: if $\gamma = 0$ then $dtfp^V = da$ i.e. TFP growth is simply the usual technology shifters. As above, if there are positive externalities from connections, $0 < \gamma < 1$, then TFP growth is faster than da with investment in access and network capital (if there is congestion on the network, $\gamma < 0$ and TFP growth is slowed with more network use (see e.g. Fernald [1999] for an application to road highways)).

Second, the network effect is multiplied by the share of spending on access capital and network capital. This is in contrast to many models of externalities in growth-accounting where TFP growth is assumed to be affected by growth in some capital variable, dk (growth of R&D capital for example), *not* its share-weighted growth. This is because the externalities in this model work via the purchase of communications services: that is, connectivity externalities only accrue to firms if they are connected, which costs them something. In the R&D literature, one might assume that spillovers occur even if firms are not spending anything and

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rental price since a quasi-fixed factor will be rented at a shadow input price reflecting quasi-rents, not the market input price (and as long as there is only one quasi-fixed factor, the ex post user cost method will correctly identify that shadow price). Corrado [2011] uses the gap between competitive and ex-post rentals to infer utilisation for the US. As Berndt and Fuss [1986] note in their footnote 10, one can always instead adjust the quantities of quasi-fixed factors using the competitive factor price. Since in most of countries in our dataset networks are typically regulated to competitive prices and then subsidised, we follow this approach here.

hence there would be no share weight in ((9)). [7]

Third, notice from ((9)) that TFP growth is also affected by changes in utilisation, $d\mu$, since the flow of capital services from a built-out network will depend upon how intensively the network is used. That intensity might be proxied by, for example, fractions of the population connected, or, fractions of the population using broadband, variables that are often used in studies. If this variable is capturing utilisation, then it is not strictly a network effect, although is likely correlated with dk^{ACC} and dk^{NET}. Notice that it is quite possible that μ is actually close to 1 and $d\mu \approx 0$ (on annual data); for example, mobile mast networks are typically built only when demand justifies them and hence utilisation on average is very high.

Fourth, notice that we have to be careful with our interpretation of the shares, σ. Firms and consumers are both sources of network externalities, and are both purchasers of access capital. In national accounts however, household purchases of durable goods are *not* counted as investment, and hence the measured share of access capital purchases only includes firm purchases of access capital equipment.

2.2 Existing literature

We now discuss the existing literature in the light of equation (9).

First, much of the work specific to the contribution of communications uses cross-country data following the method of Röller and Waverman [2001]. That paper argues that expansion of the telecommunications infrastructure generates excess returns to telecoms capital (which may be due to network effects, although they do not estimate network effects directly) and contributes to production in ways (e.g. reduced transaction costs, collaboration/co-operation benefits, process innovations etc.) which might raise TFP if not priced into an input's reward. They seek to address potential simultaneity bias and reverse causation by endogenising CT investment, and present evidence of a causal relationship between fixed line telephone penetration and economic growth. Koutroumpis [2009] and Gruber and Koutroumpis [2011] follow a similar method, finding a link between broadband penetration and GDP growth. Gruber and Koutroumpis [2011] find that, in high income countries, mobile telecommunications infrastructure contributes 0.2% pa to growth in GDP, compared to 0.11% pa in low income countries and Koutroumpis [2009] finds that a 1% increase in the broadband penetration rate raises growth in GDP by 0.025% pa, 2002-07.

Equation (9) suggests a link between TFP growth and various measures of telecoms presence, but the interpretation of that link varies. It is likely for example that (changes in) fixed/mobile/broadband penetration are correlated with dk^{ACC}, dk^{NET} and $d\mu$ but without knowing which effect is which the interpretation in terms of utilisation and/or network effects is not clear and one cannot read off a value for γ.

Second, there is of course a large literature on the relation between ICT equipment and productivity growth surveyed for example in Stiroh [2005] and Chen et al. [2016], who note a range of results. It might be that there are truly spillovers from ICT or that it is the CT capital within ICT generating the spillovers, but the range of results are due to the noisy measurement of this effect when using data on ICT. On CT directly, Acharya [2016] find a negative correlation between telecoms capital deepening and output growth and Stiroh [2002] finds that the late 1990s acceleration in US (manufacturing) TFP was negatively correlated with growth in CT capital, which is argued could reflect adjustment costs and/or mismeasurement.

Finally, we should of course note there are host of other candidates for spillovers, such as R&D and other

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[7] One might argue that benefits can accrue without being connected e.g. a non-connected firm expecting a delivery benefits from a connected set of trucks. However, such a benefit would show up in the price of delivery and thus not be a TFP benefit. It might also be that some network benefits are priced in, in the sense that regulators often allow some network externality to mobile phone prices at least, in which case the effect would not show up in TFP growth at all.

intangibles. They are excluded from the framework above, but could appear (as a dk effect) if, for example, R&D knowledge freely boosts productivity in non-R&D investing firms (see e.g Hall et al. [2009] for R&D and Corrado et al. [2013] for intangibles more generally).

3 Data and estimation of the model

3.1 Data

3.1.1 Inputs, outputs and TFP

Full detail on the construction of the dataset is provided in Goodridge et al. [2019]. For each capital asset a, statistical agencies supply nominal capital investment and a price index. Thus we build capital stocks of type a by a perpetual inventory model (PIM) so that for K_a we have:

$$K_{a,t} = \frac{P^{*}_{Ia} I_a}{P_{Ia}} + (1 - \delta^{Ka}) K_{a,t-1} \tag{10}$$

Where δ^{Ka} is an asset-specific depreciation rate and note that P^{*}_{Ia}, the true price of investment in asset a, may differ from the measured price of investment, P_{Ia}. Our asset types are: buildings, IT hardware equipment, CT equipment, other (non-ICT) plant & machinery, vehicles, software, R&D, and mineral exploration and artistic originals (investment in these latter two assets combined). Asset-specific rental costs are estimated by applying the user-cost relation between P_I and P_K:

$$P_{Ka} = P_{Ia}(\rho + \delta^{Ka} - (\Delta P_{Ia}/P_{Ia})) \tag{11}$$

Where ρ is an economy-wide net rate of return assumed equalised across all assets via competitive arbitrage.[8] User costs sum to economy-wide gross operating surplus and income shares for each asset sum to the total capital income share, which in turn is one minus the labour income share.

P_{Ka} are the price of capital services from asset type a. Capital services are translog aggregations over heterogeneous capital types a, where shares are of total capital payments for each asset type (w^{Ka}_{K}) are averaged over the current and previous period in order to form a superlative index.

$$\Delta lnK = \sum w^{Ka}_{K} \Delta lnK_{a,t} \tag{12}$$

where

$$w^{Ka}_{K} \equiv \frac{1}{2}\left(\left(\frac{P_{Ka}K_a}{P_K K}\right)_t + \left(\frac{P_{Ka}K_a}{P_K K}\right)_{t-1}\right) \tag{13}$$

For each factor input, s is a share of value added, estimated as an average over the two periods (we omit the usual overbar just to ease notation):[9]

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[8] Due to incomplete data across countries, we do not apply tax adjustment factors in the estimation of user costs.

[9] Estimation of labour services is perfectly analogous. Labour is in natural units, hours. P_{Lb} are the prices for labour services from labour type b. Labour services are translog aggregations over heterogeneous labour types b: $\Delta lnL = \sum w^{Lb}_{L} \Delta lnH_{b,t}$. Where $H_b$are the annual person-hours worked by type b workers and shares are of total labour payments for each type, averaged over the current and previous period: $w^{Lb}_{L} \equiv \frac{1}{2}\left((P_{Lb}L_b/P_L L)_t + (P_{Lb}L_b/P_L L)_{t-1}\right)$. Thus labour services are adjusted for composition of the workforce. Similarly, for labour shares of Q we define $s^{L}_{Q} \equiv \frac{1}{2}\left((P_{Lb}L_b/P_Q Q)_t + (P_{Lb}L_b/P_Q Q)_{t-1}\right)$

$$s^K \equiv \frac{1}{2}\left(\left(\frac{P_K K}{P_Q Q}\right)_t + \left(\frac{P_K K}{P_Q Q}\right)_{t-1}\right) \tag{14}$$

Finally, using data on factor inputs and payments, we decompose growth in value-added (Q) into contributions from labour, capital, and the residual, total factor productivity (TFP), estimated as:

$$\begin{aligned} \Delta lnTFP_{c,t} = {} & \Delta lnQ_{c,t} - \\ & s_{c,t}^{L}\Delta lnL_{c,t} - s_{c,t}^{K^{CT}}\Delta lnK^{CT}{}_{c,t} - s_{c,t}^{K^{IT}}\Delta lnK^{IT}{}_{c,t} - s_{c,t}^{K^{NON-ICT}}\Delta lnK_{c,t}^{NON-ICT} - \\ & s_{c,t}^{R^{Soft}}\Delta lnR^{soft}{}_{c,t} - s_{c,t}^{R^{R\&D}}\Delta lnR^{R\&D}{}_{c,t} - s_{c,t}^{R^{min}}\Delta lnR^{minart}{}_{c,t} \end{aligned} \tag{15}$$

where the subscript c is country, L are labour services (incorporating labour composition), $\mathrm{K}^{\mathrm{CT}}$are capital services from communications equipment, $\mathrm{K}^{\mathrm{IT}}$are capital services from IT hardware equipment and $\mathrm{K}^{\mathrm{NON\text{-}ICT}}$are capital services from other tangible, but non-ICT, equipment. R are capital services from measured National Accounts defined knowledge capital (software, R&D, mineral exploration and artistic originals).

3.1.2 Countries in data

Our dataset is a panel of fourteen countries including the US and thirteen European countries, 1995-2013. They are: Austria (AUT); Belgium (BEL); Denmark (DNK); Spain (ESP); Finland (FIN); France (FRA); Germany (DEU); Ireland (IRL); Italy (ITA); the Netherlands (NLD); Portugal (PRT); Sweden (SWE); and the United Kingdom (UK). [10]

3.1.3 Capital input

Capital services for each ICT asset (IT hardware, CT equipment and software) are constructed using OECD harmonised deflators, as described in Schreyer and Colecchia [2002]. These price indices are harmonised with those from the US which include *some* explicit quality adjustment.[11] The method to harmonise is to set the

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[10] The data were primarily built using country-level total economy data downloaded from OECD.Stat, which contains national accounts data submitted to the OECD by national statistical institutes (NSIs) of member countries. Where data were incomplete or missing, the data were supplemented with data from other sources, with some extrapolation or imputation where necessary. For further details, please see Appendix B. Countries included are determined by availability of data from OECD.Stat. The panel is not fully balanced. For some countries our TFP data begin later than 1995. TFP estimates begin in 1997 for SWE and 1999 for: BEL, DNK, IRL, PRT.

[11] The US BEA CT investment price index is a weighted aggregation of underlying indices, one of which is for "telephone switching equipment", which previously (largely prior to the period considered in this study) incorporated hedonic adjustments [Colecchia and Schreyer, 2002] based on research from the Federal Reserve and others [Byrne and Corrado, 2015]. However, this actually refers to the incorporation of research prices indices [Grimm, 1996, 1997] in the historic series through to approximately 1998 only. Quality-adjustment since then in the official US data is implicit and based on matched model estimation. For further information, please see discussion and references contained in Byrne and Corrado [2015]. Thus, over the period for which we estimate, the US and therefore harmonised indices for CT equipment are *not* constructed from hedonic components. For most countries, including the US, matched model techniques are used instead, which as noted rely on detailed data in the cross-section and the time-series if they are to adequately account for fast quality change. In the US, the Federal Reserve Board price data, on which the Bureau of Economic Analysis (BEA) index is based, consist of weighted estimates from narrow product classes and are collected every quarter. Data for EU countries which also rely on matched model techniques exhibit far slower price falls, possibly because the data are not sufficiently detailed to observe fast improvements in quality. Similarly, the more well-known BEA IT GFCF price index is a weighted aggregate, constructed from underlying indices for: computers and peripheral equipment; photocopy and related equipment; and office and accounting equipment. Within the underlying price index for computers and peripheral equipment, prices estimates for 'PCs and servers' are constructed using hedonics. Other components, and other sub-components of computers and peripherals, are *not* constructed using hedonics.

ratio of ICT to non-ICT prices in each country equal to the ratio in the US. Consider the CT price index. In terms of the log change, the log change in the CT price index for the chosen country is estimated as the log change in the US price index, less the log change in the US non-ICT price index, plus the log change in the non-ICT price index in the chosen country, as set out in (16).

$$\Delta lnPi_{c,t}^{CT} = \Delta lnPi_{US,t}^{CT} - \Delta lnPi_{US,t}^{NON-ICT} + \Delta lnPi_{c,t}^{NON-ICT} \tag{16}$$

Use of constant-quality prices means that we are less likely to underestimate the ICT contribution by better capturing real increases in the volume of ICT capital services. Thus we can be more confident that any evidence of an excess return is not a result of the underestimation of capital services in the underlying growth-accounting and we reduce the possibility of ascribing 'pecuniary' spillovers to pure spillovers. Capital services estimates for all other assets are estimated using national accounts deflators.[12]

3.1.4 Public R&D and intangible capital services

We also incorporate into our model data on public R&D, performed by the Government and Higher Education sectors as recorded in GERD and published by the OECD. Estimated private R&D capital services, also included, exclude public R&D. We therefore account for public R&D by simply including the ratio of public R&D to GDP ($P^{R\&D}R^{R\&D,PUB}/P_QQ$). The resulting coefficient is an estimate of the total social rate of return to public R&D. [13]

3.2 The transition to econometric work

Equation (9) sets out our model. In practice, our investment data do not break down CT capital into access and network equipment. Similarly, we have no separate estimates of price change and depreciation. Both access capital and network capital are therefore subsumed into K^{CT}. We do follow theory by incorporating

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Regarding software, the US GFCF price index is a weighted average of an hedonic index for pre-packaged software and a non-hedonic index for own-account software. Details on the use of hedonics in ICT investment deflation by the US and other countries can be found in Table 9 of Colecchia and Schreyer [2002]. For more information on the use of hedonic methods in US price statistics more generally, see Moulton [2001].

[12] On the primary subject of this paper, communications equipment, we note that measurement issues may exist in cases where different aspects of ICT are bundled in the same purchase. In the case of hardware, we note that the convention is that where software is bundled with hardware, and the values cannot be separated, then the investment transaction is recorded in hardware. We assume that the same applies to communications equipment, and that where software is bundled with CT and the values cannot be separated, then the transaction is recorded in CT equipment. Where CT is bundled with IT, we assume the transaction is recorded under IT hardware. However, we note the potential for practice to vary by country, with different countries potentially applying different methods and varying degrees of effort in unbundling various aspects of ICT investment.

[13] The reason we exclude public R&D from our measure of (private) R&D capital services is that it is typically assumed that, due to its more basic nature, public R&D either does not depreciate or at least depreciates more slowly than privately performed R&D. Thus R&D capital services would be incorrectly measured if the same geometric depreciation rate (20%) were applied to both private and public R&D. This helps in the interpretation of our coefficients. Our estimated econometric coefficient on private R&D is an excess elasticity over and above the contribution uncovered from growth-accounting. Public R&D was not accounted for in the estimation of TFP so the coefficient is an estimate of the gross social rate of return to public R&D. We note that conceptually this procedure is consistent with national accounting data and methods. According to national accounting convention, the cost of public (i.e. government and other non-market) capital consists of only capital consumed (i.e. depreciation) and does not incorporate a rate of return (i.e. profit rate) since it is assumed that public assets generate no net operating surplus (see for example Jorgenson and Schreyer [2012]). However, in our estimation of the user costs of capital (for (private) R&D and all other assets), we do incorporate the net rate of return to capital, as shown in equation (11). Thus our modified treatment of R&D is consistent with national accounting practice, although we lack the data to apply any adjustment to other assets included in our growth decomposition. Although not reported, in robustness checks we have re-estimated our coefficients using measures of (total) R&D capital services and TFP calculated with public R&D included, and the conclusions are the same.

the share, s_K^{CT}, but note that the measured share excludes household spending.

We experiment with different specifications, but using country-year panel data, the basic equation we estimate is:

$$\Delta_M lnTFP_{c,t} = \alpha + \beta\,(s_K^{CT}\,\Delta_M lnK^{CT})_{c,t-k} + \theta\,\Delta_M lnX_{c,t-k} + \rho\left(\frac{P^{R\&D} R^{R\&D,PUB}_{c,t-k}}{P^Q Q_{c,t-k}}\right)_M + \lambda_c + \lambda_t + u_{c,t} \quad (17)$$

Where Δ_{M} refers to the length of the difference taken and λ terms control for time[14] and country fixed effects. X are capital services from private R&D and IT hardware. Note that since CT, IT and (private) R&D were already accounted for in the estimation of TFP, any estimated effect is over and above the private return estimated in a growth decomposition and in particular $\widehat{\beta} = \gamma/(1-\gamma)$ so that we should be able to recover estimates of the network externalities effect, γ.

Regarding practical implementation, the following points are worth noting.

First, as we are seeking evidence of externalities derived after that capital has been utilised in production, we assume a lag structure as indicated by the subscripts (t-k). Thus, as per Reed [2015], we are not assuming a contemporaneous effect and using a lagged variable to instrument. Rather, we assert that spillovers take some time to diffuse and we therefore assume a lagged effect thus sidestepping problems outlined in Reed [2015]. Since we have little a priori evidence on the correct lag structure we experiment with different values although we note that Basu et al. [2003] suggest long lags of around five (to fifteen) years in the context of total ICT equipment. In their work with microdata, Brynjolfsson and Hitt [2003] suggest lags of five to seven years. Contemporaneous correlations between TFP growth and changes in capital input could be due to unmeasured utilisation, or reverse causation and impose instant spillover transmission which seems unlikely. We therefore use lagged independent variables.

Second, given the findings on spillovers from R&D, to reduce omitted variable bias, we also include both private and public R&D. Third, we experiment with capital services from IT hardware equipment on the grounds that: a) there may be separately identifiable network effects and externalities that derive from the use of IT; or alternatively b) that the unbundling of ICT investment as undertaken by national statistical agencies means that, in practice, some part of CT investment remains measured within IT equipment.[15]

Fourth, some research conjectures that ICT capital generates externalities, but other work suggests investment in ICT requires complementary investments in intangible (or knowledge) capital in order to reap productivity advantages. Some intangibles are included in the national accounts production boundary but some are outside. [16]

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[14] We include time dummies to control for cyclical effects. It might be argued that due to the potential presence of autocorrelation in TFP, we could include a lagged value for TFP growth in the specification, although while there may be autocorrelation in the level of TFP it is less clear that there will be in the change. However, in our robustness checks we have included a lagged (t-1) term for the change in TFP and it makes little difference to the interpretation of our results. To preview our results, in our baseline estimates we estimate a coefficient for share-weighted CT capital of approximately 4.1. Including a lagged estimate of TFP growth reduces that coefficient to approximately 3.5 and the statistical significance of the estimate is increased. The coefficient for private R&D capital services is however rendered statistically insignificant once the lagged term for TFP is incorporated as an independent variable.

[15] The extent to which this is the case likely varies across countries, but from our discussions with the UK Office for National Statistics we know that they are reviewing their data and methods for the disaggregation of investment in plant and machinery including ICT equipment.

[16] In some robustness checks (not reported) we also included additional measures of non-R&D intangible capital services (outside the national accounts production boundary): they did not affect the magnitude or significance of the CT term, nor were they statistically significant. We also included growth in capital services from computerised information (software and databases) as measured in the national accounts in case that asset also generates some form of excess return or network effect but found

Finally, it might be argued that, since our growth-accounting estimates assume competitive markets and constant returns to scale, the presence of mark-ups and increasing returns may mean that any uncovered excess return reflects mark-ups. We note that the size of the effect we estimate would mean that those mark-ups would be necessarily very large. Additionally, we note that Basu et al. [2006]estimate close to constant returns to scale for US industries: 1.07 for durable manufacturing, 0.89 for nondurable manufacturing and 1.10 for non-manufacturing.

4 Correlations and regression results

4.1 Raw correlations

We first display some charts for the correlations we are seeking to estimate.

Figure 1 presents data on smoothed growth in TFP (blue connected line, left-hand y-axis) and telecoms capital services[17] (red connected line, right-hand axis) for the aggregate of the fourteen countries in our dataset, each constructed using country-share-weighted averages. We note the dramatic growth and acceleration of telecoms capital services in the 1990s, particularly the late 1990s. We interpret this period as one of network build-out, with much investment in creating network infrastructure by the telecommunications industry itself. TFP growth also accelerated in the 1990s before starting to decelerate in the early 2000s, by which point, growth in telecoms capital services had also slowed.

In our estimation we work at the country-level. To study the correlations, Figure 2 plots growth in our explanatory variables against growth in TFP, all in deviations from the time mean. In producing these charts we experimented with different lags, which we introduce because it seems likely that the diffusion of spillovers takes some time, although we might expect benefits from participation in a telecoms network effects to materialise quicker than say, those from a new scientific discovery.

The first chart, top left, plots income share-weighted (i.e. the contribution of) CT capital services lagged twice (t-2) versus TFP growth. We find a correlation using zero (t), one (t-1), two (t-2) or three (t-3) lags, but the correlation appears stronger with one or two lags. All data points are in deviations from the time mean, therefore showing that following periods of above average share-weighted growth in CT capital services, TFP growth was higher than average in subsequent periods.

In the second chart, top right, we present a similar chart suggesting a positive correlation but this time using capital services from IT hardware (t-2). Similar charts using different lag structures also showed a correlation when using three (t-3) or four (t-4) lags. In the case of IT hardware, evidence from the literature is also suggestive of any spillovers operating with a longer lag. The correlation appears somewhat driven by data points for Finland.

In the third chart, bottom left, we present the correlation with private R&D capital services. In the case of private R&D, the correlation appears strongest when working with either four or five lags. Here we present the fifth lag. In the top right quadrant of the chart we again observe data points for Finland, as well as Ireland and Portugal.

Finally, in the fourth chart, bottom right, we present the correlation between growth in TFP and the flow of public R&D in GDP, lagged one period, again suggesting a positive correlation.

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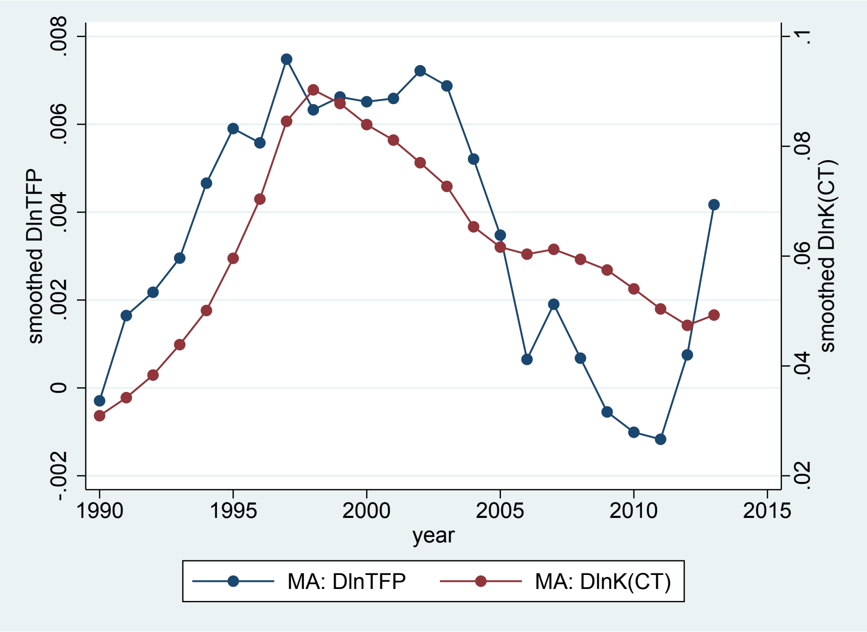
it to be statistically insignificant.

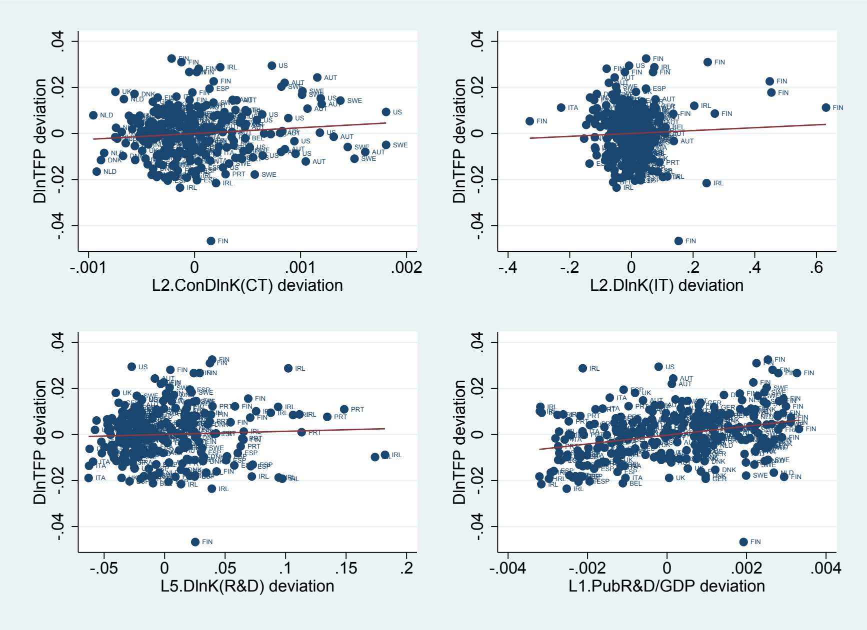
[17] Each are smoothed as a uniformly weighted moving average constructed from the current term, three lead terms and three lagged terms.

Figure 1: $\Delta \mathrm{lnTFP}_{\mathrm{c,t}}$ vs $\Delta \mathrm{lnK}_{\mathrm{c,t}}{}^{\mathrm{CT}}$, moving averages, 14-country aggregate (US & EU-13)



Note to figure: Series' are a moving average using 3 lagged values, 3 lead values, and the current period, all equally weighted, for annual TFP growth for the aggregate of the fourteen countries in our dataset (left-hand axis) and annual growth in CT capital services for the same aggregate (right-hand axis).

Figure 2: $\Delta \mathrm{lnTFP}_{\mathrm{c,t}}$ vs $\Delta \mathrm{lnX}_{\mathrm{c,t\text{-}k}}$, all in deviations from time mean



Note to figure: Each data point is a country-time value. Estimates for growth in TFP and capital services all in deviations from the time mean. Top left is the contribution of CT capital services, t-2. Top right is IT capital services, t-2. Bottom left is(private) R&D capital services, t-5. Bottom right is the public R&D:GDP ratio, t-1. Growth rates calculated as changes in the natural log.

4.2 Results

Table 1 presents results, using country-year panel data for fourteen countries, 1995 to 2013. We show random effects, with fixed effects below for robustness (the main difference is that, when using random effects, we find a more consistent correlation between TFP growth and the flow of public R&D).[18] All explanatory variables are lagged on the assumption that spillovers will not be instant. [19] All regressions include year dummies and a constant (not reported).

In column 1 our explanatory variables include lagged terms for the contribution of CT capital services $(s_K^{CT}\Delta lnK^{CT})_{c,t-2}$, growth in private R&D capital services $(\Delta lnK^{R\&D}_{c,t-5})$ and the public R&D/GDP ratio $(\frac{P^N N^{PUB}}{P^Q Q})_{c,t-1}$. The $(s_K^{CT}\Delta lnK^{CT})_{c,t-2}$ term is statistically significant at the 5% level, implying an (excess) effect on output growth, over and above its direct contribution (social returns are approximately 5 times private, see below).[20] Private R&D capital services, lagged five periods, are also weakly statistically significant, with a coefficient implying an excess elasticity of 4%. The coefficient on public R&D is strongly significant and can be read directly as a gross social rate of return, surely over-estimated at 241% (this number is much less with fixed effects).

In column 2 we add the contribution of IT hardware, in the light of the findings around ICT: that is, we effectively break out the contributions of ICT equipment into IT and CT. The IT contribution is negative and statistically insignificant. In column 3 we enter ΔlnK^{IT}, rather than its contribution in column 2: again, this is insignificant. In column 4 we enter the contribution of ICT equipment and it is statistically insignificant. For completeness, column 5 enters ΔlnK^{CT} and ΔlnK^{IT}. Although theory suggests it should instead be in contribution terms, the raw CT capital growth term is statistically significant.[21]

4.3 Robustness checks

In Table 2 we present a series of robustness checks.

In column 1 we add utilisation. We experimented with a large number of terms such as numbers connected (for each tecnholgy and across all technologies), population with fixed and mobile lines, population with broadband and others: none altered the statistical significance of the $s_K^{CT}\Delta lnK_{t-2}^{CT}$ term (here in column 1 we use the change in the log of total connections (fixed telephone plus fixed internet plus mobile) per population). Column 2 shows the $s_K^{CT}\Delta lnK_{t-2}^{CT}$ coefficient when entering country fixed effects: it raises the

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[18] Variation in the public R&D/GDP ratio is almost entirely variation between countries so using country dummies removes most of the variation in those data: the other variables show variation in both the time-series and the cross-section. On our preferred specification the Breusch/Pagan LM rejected OLS and the Hausman test suggested random effects were acceptable against fixed effects. The results of the Hausman test were a chi2 statistic of 3.90 with p-value of 0.5636 meaning we cannot reject the null hypothesis of random effects.

[19] Although not presented here, we ran a series of regressions to determine which lag structure was most effective. Statistical significance tended to be stronger with a two year lag for CT a four or five year lag for private R&D. For public R&D, due to the lack of time-series variation within countries, we found that our results were largely invariant to the number of lags taken.

[20] We lag our independent variables since we consider instant spillover diffusion to be unrealistic. For completeness, we also tried instrumenting the (weighted) contribution of CT input. Estimating using contemporaneous share-weighted CT input in an RE framework, we estimate a coefficient of 1.17 with a t-statistic of 0.54. Instrumenting using changes in termination charges, we estimate a coefficient of 24.6 with a t-statistic of 1.69.

[21] We note that we do estimate positive and sometimes significant coefficients for (non-share-weighed) IT and ICT equipment capital services, when using additional lags (e.g. 4 lags for IT). When including (unweighted) IT or ICT capital services, the CT result is unaffected. Coefficients on share-weighted IT capital services are statistically insignificant. Including share-weighted ICT equipment does reduce the significance of the CT coefficient, but this is to be expected since CT is wrapped up within ICT equipment. Since we are trying to determine whether the ICT equipment correlation is driven by CT or IT, it seems appropriate to test that with the same number of lags on each.

Table 1: Econometric results: random effects (dependent variable: $\Delta lnTFP_{c,t}$)

	(1)	(2)	(3)	(4)	(5)
VARIABLES					
$(s_K^{CT}\Delta lnK^{CT})_{c,t-2}$	4.08**	4.18**	4.05**		
	(2.18)	(2.13)	(2.13)		
$(\Delta lnK^{CT})_{c,t-2}$					0.058***
					(3.55)
$(s_K^{IT}\Delta lnK^{IT})_{c,t-2}$		-0.17			
		(-0.20)			
$(\Delta lnK^{IT})_{c,t-2}$			0.0029		-0.0080
			(0.36)		(-0.92)
$(s_K^{ICT}\Delta lnK^{ICT})_{c,t-2}$				0.68	
				(0.89)	
$(\Delta lnK^{R\&D})_{c,t-5}$	0.039*	0.041*	0.041**	0.044**	0.036*
	(1.93)	(1.95)	(1.97)	(2.01)	(1.70)
$(P^{R\&D}R^{R\&D,PUB}/P^QQ)_{c,t-1}$	2.41***	2.40***	2.43***	2.43***	2.16***
	(4.48)	(4.21)	(4.40)	(4.04)	(3.71)
Observations	231	231	231	231	231
Number of countries	14	14	14	14	14

Notes to table: All regressions estimated using random effects and include year dummies and a constant (not reported). t-statistics in parentheses. In all specifications the dependent variable is growth in TFP. Column 1 includes the contribution of CT capital services. Column 2 is as column 1 but with the added contribution of IT equipment capital services. Column 3 also incorporates IT but this time as (unweighted) IT capital services, rather than the contribution. Column 4 replaces CT and IT with the contribution of capital services from (aggregate) ICT ***equipment***. Column 5 includes separate IT and CT equipment capital services, not share-weighted. All regressions estimated on same sample.

Table 2: Robustness checks

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Utilisation	Fixed eff	Excl FIN,SWE	Sample to 2007	Long diffs
$(s_K^{CT}\Delta lnK^{CT})_{c,t-2}$	4.12**	5.63*	3.99**	3.72*	2.09
	(1.99)	(1.95)	(1.96)	(1.66)	(1.42)
$s_K^{CT}\Delta ln(N/P)_{c,t}$	-0.12				
	(-0.14)				
$(\Delta lnK^{R\&D})_{c,t-5}$	0.043	0.090***	0.048**	0.023	0.036**
	(1.26)	(2.66)	(2.21)	(0.88)	(2.00)
$(P^{R\&D}R^{R\&D,PUB}/P^{Q}Q)_{c,t-1}$	2.08***	1.74	2.71***	3.20***	2.01***
	(2.95)	(1.13)	(3.76)	(3.99)	(4.07)
Observations	201	231	199	147	231
R-squared		0.563			
Number of countries	11	14	12	14	14

Notes to table: All regressions include year dummies and a constant (not reported). t-statistics in parentheses. In all specifications the dependent variable is growth in TFP. Column 1 incorporates a term for utilisation, estimated as (share-weighted) Dln(N/P) (where N is number of (telephone/mobile/broadband) connections and P is population). Column 2 includes country fixed effects. Column 3 excludes observations for Finland and Sweden. Column 4 is estimated using an endpoint prior to the crisis (2007). Column 5 uses four-year differences.

estimated CT coefficient to 5.6, but it is less precisely estimated than with random effects. The estimated elasticity for private R&D is also raised to 9% and is strongly significant; public R&D is no longer statistically significant (recall there is little variation in the time-series). Column 3 shows the CT effect is robust to excluding observations for Finland and Sweden, each of whom have strong CT capital services growth and TFP growth (see Figure 2). Column 4 restricts the sample up to 2007 and column 5 incorporates long (four year) differences: statistical significance is somewhat reduced.[22]

5 Economic Significance

We interpret the economic significance of our estimates in two ways. First, recall from (8) that the total elasticity of $K^{CT}$is $1/(1-\gamma)$ times the private elasticity. From table 1, column 1 we have $\widehat{\beta}=\gamma^{Z}/(1-\gamma^{Z})=$ 4.08 which implies $1/(1-\gamma)$=5, that is, the social returns to telecoms capital are five times the private returns (on the assumption that the ratio of social elasticities to private is the ratio of social to private returns, see Fernald [1999] for a similar logic for roads). The only similar estimates for telecommunications networks that we are aware of are those set out in note 5, namely of the Rohlfs-Griffin factor. These are usually cast as a ratio of social to private willingness to pay and hence are a ratio of prices not, as here, a ratio of returns to capital. Our findings suggest γ=0.8, which would give a Rohlfs-Griffin factor of 1.8, although we obtain it from the business productivity side not the consumer demand side. That said, regulators typically assume RG factors of around 1.3-1.7, so we are quite in line with this.

Second, we ask: what fraction of $\Delta lnTFP$ we can account for? We do this in Table 3 which is set out as follows. There are two panels. In the top panel: column 1 presents a set of country-group aggregates constructed to aid comparison (see Appendix for results for each country); column 2 is mean $\Delta lnTFP$ (1995-2013);[23] column 3 is the mean contribution of CT capital services; and column 4 is the mean contribution of CT spillovers i.e. $\gamma/(1-\gamma)$ times column 3. Column 5 shows the percentage of TFP growth accounted for by CT spillovers (i.e. column 4 over column 2).

The bottom rows of the top panel summarise Table 3. Excluding the Southern European countries, who have negative average $\Delta lnTFP$, average $\Delta lnTFP$ was 0.52%, with CT spillovers accounting for 29% of this. Looking at the upper panel, this varies between 63% in the Scandinavian countries and 33% in large Northern European countries. We account for 88% of TFP growth in the US, where growth in CT capital accumulation was much stronger.

In the bottom panel of Table 3 we attempt to explain the TFP slowdown prior to the crisis. We therefore break the data into two periods: 1995-2003 and 2004-2013. Column 2 presents the slowdown in TFP growth between the two periods and column 3 the slowdown in the contribution of CT capital services (note, the CT contribution sped up very marginally in Scandinavia so was the same with rounded numbers). In column 4 we use our econometric estimate ($\hat{\beta}$) to predict the TFP slowdown due to the slowdown in CT capital input (estimated as $\hat{\beta}$ times column 3). Finally in column 5 we estimate the percentage of the slowdown accounted for by the estimate in column 4 (column 4 over column 2).

We find that the US slowdown in the CT contribution was substantial and we account for around half (54%) of the slowdown in US TFP growth. We are unable to perform the calculation for Scandinavia as

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[22] We also entered growth in non-R&D intangible assets (outside the national accounts production boundary): they did not affect the magnitude or significance of the CT term, but since these are not capitalised into output their interpretation is not clear.

[23] For some countries, our data on growth in TFP begin later: BEL (1999); DNK (1996); IRL (1999); PRT (1999); SWE (1997). Mean TFP is therefore estimated over the years 1995 to 2013 for which data are available.

Table 3: Economic significance: contribution of CT capital services, 1995-2013; and accounting for slowdown

Country group (1995-2013)	$\Delta lnTFP$	$s_K^{CT} \Delta lnK^{CT}$	Spillover $=\hat{\beta}\ (s_K^{CT} \Delta lnK^{CT})$	% of $\Delta lnTFP$
Scand	0.78%	0.12%	0.49%	63%
N Europe (small)	0.50%	0.05%	0.20%	40%
N Europe (large)	0.51%	0.04%	0.17%	33%
S Europe	-0.23%	0.03%	0.12%	
US	0.56%	0.12%	0.49%	88%
EU-13	0.32%	0.04%	0.16%	49%
EU-10 (excl. ESP, ITA, PRT)	0.52%	0.04%	0.15%	29%
	$\Delta(\Delta lnTFP)$	$\Delta(s_K^{CT} \Delta lnK^{CT})$	$\hat{\beta}\Delta(s_K^{CT} \Delta lnK^{CT})$	% of $\Delta(\Delta lnTFP)$
Scand	-1.19%	0.000%	0.00%	
N Europe (small)	-0.63%	-0.002%	-0.01%	1%
N Europe (large)	-0.60%	-0.010%	-0.04%	7%
S Europe	-0.21%	-0.004%	-0.02%	7%
US	-0.58%	-0.076%	-0.31%	54%
EU-13	-0.52%	-0.012%	-0.05%	9%
EU-10 (excl. ESP, ITA, PRT)	-0.62%	-0.014%	-0.06%	9%

Notes to table: Top panel: Data are estimates for the years 1995-2013. Column 1 presents country aggregations. Column 2 presents mean TFP growth (estimated as the change in the natural log) over the years 1995 to 2013 for which data are available (for some countries our TFP data begin later). Column 3 presents estimates of the mean contribution of CT capital services over the same years for which data are available. Column 4 is the estimated contribution of CT network externalities to growth. Column 5 is the percentage of TFP explained by the CT spillover estimate, estimated as column 4 over column 2. Country groups are estimated as weighted averages constructed as: 1) North Europe (large), consisting of FRA, DEU, UK; 2) North Europe (small), AUT, BEL, IRL, NLD; 3) Scandinavia, DNK, FIN, SWE; 4) Southern Europe, ESP, ITA, PRT. Bottom panel: Column 1 presents country aggregations. Column 2 presents the change in mean TFP growth between the first (1995-2003) and second (2004-13) period. A negative number represents a slowdown. Column 3 presents the change in the mean contribution of CT capital services over the same years. Column 4 is the predicted slowdown in TFP growth due to the CT slowdown observed in column 3. Column 5 presents the estimated percentage of the slowdown in TFP growth explain by the CT slowdown, estimated as column 4 over column 2.

there the CT contribution accelerated slightly. The CT slowdown was much less in Europe than the US and we find it “explains” 1% of the TFP slowdown in smaller North European countries and 7% in larger North European as well as South European countries. In terms of the EU-13 aggregate, the CT slowdown only explains 9% of the TFP slowdown in Europe.

6 Conclusions

In this paper we seek to estimate whether there is an indirect effect from growth in CT capital input on total factor productivity growth via network effects, or spillovers. Using an international growth-accounting dataset for the US and thirteen European countries, we look for evidence consistent with spillovers derived from the accumulation and deployment of CT equipment. Within that, our model also incorporates potential spillovers from IT hardware (as either distinct or as a result of mismeasurement) and activity in R&D, both private R&D conducted by firms and also public R&D. Our findings are as follows.

First, we find evidence of a statistically significant correlation between lagged growth in the contribution of CT capital services and TFP growth, which is consistent with the presence of network effects or spillovers. Our results are also economically significant. Using our estimated output elasticity for CT equipment, we estimate that CT spillovers potentially explain: around a third of TFP growth in North European economies; two-thirds in Scandinavian economies; and around nine-tenths in the US.

Second, we estimate that the total social rate of return to CT capital is around five times its private rate of return. The finding that social returns to CT investment are indeed greater than private returns suggests a prima facie case for public subsidy for telecommunications infrastructure and access capital.

Finally, we use our estimates to shed some light on the productivity slowdown that occurred prior to the crisis. Our estimates suggest that a slowdown in CT capital accumulation ’explains’ only 9% of the TFP slowdown in the EU and 54% in the US.

Given the ongoing interest in the slowdown of productivity in developed countries, we see scope for further work with improved data on possible spillovers as the character of communications equipment changes e.g. increasingly to mobile and the Cloud and whether this might portent a productivity speedup.

References

Ram C. Acharya. ICT use and total factor productivity growth: intangible capital or productive externalities? *Oxford Economic Papers*, 68(1):16–39, jan 2016. ISSN 0030-7653. doi: 10.1093/oep/gpv058. URL `https://academic.oup.com/oep/article-lookup/doi/10.1093/oep/gpv058`.

Susanto Basu, John G Fernald, Nicholas Oulton, and Sylaja Srinivasan. The Case of the Missing Productivity Growth: Or, Does Information Technology Explain why Productivity Accelerated in the United States but not the United Kingdom? 2003. URL `http://www.nber.org/papers/w10010`.

Susanto Basu, John G Fernald, and Miles S Kimball. Are Technology Improvements Contractionary? *American Economic Review*, 96(5):1418–1448, dec 2006.

Ernst R. Berndt and Melvyn A. Fuss. Productivity measurement with adjustments for variations in capacity utilization and other forms of temporary equilibrium. *Journal of Econometrics*, 33(1):7–29, oct 1986. ISSN 03044076. doi: 10.1016/0304-4076(86)90025-4. URL `http://www.sciencedirect.com/science/article/pii/0304407686900254`.

Erik Brynjolfsson and Lorin M. Hitt. Computing Productivity: Firm-Level Evidence. *Review of Economics and Statistics*, 85(4):793–808, nov 2003. ISSN 0034-6535. doi: 10.1162/003465303772815736. URL `http://www.mitpressjournals.org/doi/abs/10.1162/003465303772815736`.

David M Byrne and Carol A Corrado. Prices for Communications Equipment: Rewriting the Record. 2015. URL `http://dx.doi.org/10.17016/FEDS.2015.069.`

Wen Chen, Thomas Niebel, and Marianne Saam. Are intangibles more productive in ICT-intensive industries? Evidence from EU countries. 2016. doi: 10.1016/j.telpol.2015.09.010.

Alessandra Colecchia and Paul Schreyer. ICT Investment and Economic Growth in the 1990s: Is the United States a Unique Case? *Review of Economic Dynamics*, 5(2):408–442, apr 2002. ISSN 10942025. doi: 10.1006/redy.2002.0170. URL `http://www.sciencedirect.com/science/article/pii/S1094202502901705`.

C Corrado, J Haskel, C Jona-Lasinio, and M Iommi. Intangible Capital and Growth Strategies for Advanced Economies: Measurement Methods and Comparative Results. *Working Paper, June, available at http://www.intan-invest.net/*, 2012. URL `http://www.intan-invest.net/`.

Carol Corrado. Communication Capital, Metcalfe's Law, and US Productivity Growth. *The Conference Board, Economics Program Working Paper Series, EPWP1101*, 2011.

Carol Corrado, Jonathan Haskel, Cecilia Jona-lasinio, and By Carol Corrado. Knowledge spillovers, ICT and productivity growth. *Working Papers*, (April 2013):1–40, jul 2013. URL `http://ideas.repec.org/p/imp/wpaper/14624.htmlhttp://papers.ssrn.com/sol3/papers.cfm?abstract{%}7B{_}{%}7Did=2114913`.

Timothy De Stefano, Richard Kneller, and Jonathan Timmis. The (Fuzzy) Digital Divide: The Effect of Broadband Internet Use on UK Firm Performance. Technical report, 2014. URL `http://beta.nottingham.ac.uk/economics/documents/discussion-papers/14-06.pdf`.

Mark Doms. Communications Equipment: What Has Happened to Prices? In *Measuring capital in the new economy*, pages 323–362. University of Chicago Press, 2005.

Benjamin Faber, Rosa Sanchis-Guarner, and Felix Weinhardt. ICT and Education: Evidence from Student Home Addresses. Technical report, 2015. URL `http://eprints.lse.ac.uk/65020/1/{_}{_}lse.ac.uk{_}storage{_}LIBRARY{_}Secondary{_}libfile{_}shared{_}repository{_}Content{_}SERCdiscussionpapers{_` `pdf`.

John Fernald. Productivity and Potential Output Before, During, and After the Great Recession. In *NBER Chapters*. National Bureau of Economic Research, Inc, 2014. URL `http://ideas.repec.org/h/nbr/nberch/13407.html`.

John G Fernald. Roads to Prosperity? Assessing the Link between Public Capital and Productivity. *The American Economic Review*, 89(3):pp. 619–638, 1999. ISSN 00028282. URL `http://www.jstor.org/stable/117036`.

P Goodridge, J Haskel, and G Wallis. The "C" in ICT: Communications Capital, Spillovers and UK Growth. *Imperial College Discussion Paper*, 2013.

P. Goodridge, J. Haskel, and G. Wallis. Accounting for the UK Productivity Puzzle: A Decomposition and Predictions. *Economica*, 2016a. ISSN 14680335. doi: 10.1111/ecca.12219.

Peter Goodridge, Jonathan Haskel, and Harald Edquist. The economic contribution of the "C" in ICT: evidence from OECD countries. 2016b.

Peter Goodridge, Jonathan Haskel, and Harald Edquist. The economic contribution of the âCâ in ICT: Evidence from OECD countries. *Journal of Comparative Economics*, jul 2019. ISSN 0147-5967. doi: 10.1016/J.JCE.2019.07.001. URL `https://www.sciencedirect.com/science/article/pii/S0147596719300629`.

James M. Griffin. The Welfare Implications of Externalities and Price Elasticities for Telecommunications. *The Review of Economics and Statistics*, 64(1):59–66, 1982. URL `https://www.jstor.org/stable/pdf/1937943.pdf`.

Bruce T Grimm. A Quality-Adjusted Price Index for Digital Telephone Switches. 1996.

Bruce T Grimm. Quality-Adjusted Price Indexes for Digital Telephone Switches. 1997.

Harald Gruber and Pantelis Koutroumpis. Mobile telecommunications and the impact on economic development. *Economic Policy*, 26(67):387–426, 2011.

B H Hall, J Mairesse, and P Mohnen. Measuring the Returns to R&D. Technical report, 2009.

Dale W Jorgenson and Paul Schreyer. Industry-level Productivity Measurement and the 2008 System of National Accounts. *Review of Income and Wealth*, 68:1–27, 2012.

Pantelis Koutroumpis. The economic impact of broadband on growth: A simultaneous approach. *Telecommunications Policy*, 33:471–485, 2009. doi: 10.1016/j.telpol.2009.07.004.

Brent R Moulton. The Expanding Role of Hedonic Methods in the Official Statistics of the United States. 2001.

OECD, editor. *OECD Science, Technology and Industry Scoreboard 2015.* OECD Science, Technology and Industry Scoreboard. OECD Publishing, oct 2015. ISBN 9789264239777. doi: 10.1787/sti_scoreboard-2015-en. URL `http://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-industry-scoreboard-2015{_}sti{_}scoreboard-2015-en`.

Stephen D Oliner and Daniel E Sichel. The Resurgence of Growth in the Late 1990s: Is Information Technology the Story? The Analytical Framework and Data. *Journal of Economic Perspectivesâ Volume*, 14(4):3–22, 2000.

Mary O'Mahony and Marcel P Timmer. Output, input and productivity measures at the industry level: The eu klems database*. *The Economic Journal*, 119(538):F374–F403, 2009.

William Robert Reed. On the Practice of Lagging Variables to Avoid Simultaneity. *Oxford Bulletin of Economics and Statistics*, 77(6):897–905, dec 2015. ISSN 03059049. doi: 10.1111/obes.12088. URL `http://doi.wiley.com/10.1111/obes.12088`.

Jeffrey Rohlfs. A Theory of Interdependent Demand for a Communications Service. *The Bell Journal of Economics and Management Science*, 5(1):16–37, 1974. URL `https://www.jstor.org/stable/pdf/3003090.pdf`.

Lars-Hendrik Röller and Leonard Waverman. Telecommunications Infrastructure and Economic Development: A Simultaneous Approach. *American Economic Review*, 91(4):909–923, sep 2001. ISSN 0002-8282. doi: 10.1257/aer.91.4.909. URL `http://pubs.aeaweb.org/doi/10.1257/aer.91.4.909`.

Paul Schreyer and Alessandra Colecchia. The contribution of information and communication technologies to economic growth in nine OECD countries. *OECD Economic Studies*, 2002(1):153–171, aug 2002. ISSN 0255-0822. doi: 10.1787/eco_studies-v2002-art5-en. URL `http://www.oecd-ilibrary.org/economics/the-contribution-of-information-and-communication-technologies-to-economic-growth-in-nine-oecd-count`

Kevin J Stiroh. Are ICT spillovers driving the new economy? *Review of Income and Wealth*, 48(1):33–57, 2002.

Kevin J Stiroh. Reassessing the Impact of {{}IT{}} in the Production Function: {{}A{}} Meta-Analysis and Sensitivity Tests. *Annals of Economics and Statistics*, (79/80):529–561, 2005.

J.E Triplett. HANDBOOK ON HEDONIC INDEXES AND QUALITY ADJUSTMENTS IN PRICE INDEXES: SPECIAL APPLICATION TO INFORMATION TECHNOLOGY PRODUCTS. 2004.

ONLINE APPENDIX

A Fixed effects

As noted in the main text, we estimate using random effects.In the table below, we repeat our main results, but this time all estimated using country fixed effects.

B Data Appendix

Briefly, missing data on GFCF in intellectual property products (IPPs, i.e. software, R&D, artistic originals and mineral exploration) were filled in making use of the IPP total and calculating GFCF in other assets as a residual, including if necessary, using the share of GFCF in a particular asset in previous years and the IPP total to impute estimates for missing years. Where data for mineral exploration and artistic originals remained missing, these were replaced using values for the same series from either Intan-Invest [Corrado et al., 2012] or EUKLEMS [O'Mahony and Timmer, 2009]. Note, data from Intan-Invest are for the market sector, so we necessarily assume that the market sector makes all investments in these two assets, as opposed to any government investment.

In the OECD.Stat data, ICT equipment is defined as the aggregate of IT hardware and CT equipment and so does not include software. Where data on GFCF in IT or CT were missing, data were either estimated as a residual using total GFCF in ICT equipment, or imputed using the estimate of total GFCF in ICT equipment and a moving average of the component share for either IT or CT. Where ICT (or IT/CT) equipment remained missing, we used the ratio implied in the EUKLEMS data to extrapolate and/or impute. In the case of Germany, a split into IT and CT equipment is unavailable in the official data. Therefore, for this country, pre-2007 GFCF in IT and CT equipment is taken from EUKLEMS. Post-2007 data were imputed using ICT GFCF as a share of GDP in 2013, taken from the OECD Science, Technology and Industry Scoreboard 2015 [OECD, 2015], changes in gross value-added, and the share of CT GFCF in ICT equipment. Similarly for other assets/countries, for years where GFCF data were missing, data were imputed using the profile of the same respective series in EUKLEMS. Where data on GFCF in R&D were missing, data were extrapolated or imputed using cross-country data on Gross Expenditure on R&D (GERD), downloaded from the OECD. Imputed data make use of the ratio between R&D GFCF and GERD in countries where both series are available. We exclude GFCF in dwellings which are not capital in the context of productivity analysis.[24]

UK data on nominal GFCF in CT equipment were taken from OECD.Stat, in turn from the UK national accounts. We note that the estimate for investment in CT equipment in the UK is, by some distance, the smallest of all large, advanced European economies, and is considerably lower than in a number of much smaller economies. Official estimates for the UK are also in stark contrast to estimates from our previous work [Goodridge et al., 2013] (hereafter, GHW) and those in EUKLEMS (both estimated using previous vintages of the Input-Output Supply and Use tables (SUTs)). A comparison of official UK estimates with those in GHW and EUKLEMS is presented in Goodridge et al. [2016b]. They show that the latest revised UK data do not incorporate the dramatic run-up of investment in the late 1990s as observed in GHW,

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[24] Strictly, for consistency, we should therefore also exclude the output of the real estate sector from GVA, since this is largely made up of the actual and imputed rents (for owner-occupiers) of dwellings. However data on the output of the real estate sector were not available for all countries. We therefore use total economy GVA including actual and imputed rents for each country, but note this issue in our data and estimation.

Table 4: Econometric results: fixed effects

	(1)	(2)	(3)	(4)	(5)
VARIABLES					
$(s_K^{CT}\Delta lnK^{CT})_{c,t-2}$	5.63*	5.70*	5.49*		
	(1.95)	(1.93)	(1.90)		
$(\Delta lnK^{CT})_{c,t-2}$					0.074***
					(4.00)
$(s_K^{IT}\Delta lnK^{IT})_{c,t-2}$		-0.13			
		(-0.12)			
$(\Delta lnK^{IT})_{c,t-2}$			0.0077		-0.0028
			(0.86)		(-0.31)
$(s_K^{ICT}\Delta lnK^{ICT})_{c,t-2}$				0.77	
				(0.83)	
$(\Delta lnK^{R\&D})_{c,t-5}$	0.090***	0.089***	0.099***	0.084**	0.11***
	(2.66)	(2.61)	(2.79)	(2.45)	(3.08)
$(P^{R\&D}R^{R\&D,PUB}/P^{Q}Q)_{c,t-1}$	1.74	1.70	1.99	1.86	2.18
	(1.13)	(1.08)	(1.27)	(1.18)	(1.44)
Observations	231	231	231	231	231
R-squared	0.563	0.563	0.565	0.556	0.591
Number of ctrycode	14	14	14	14	14

Notes to table: All regressions estimated using fixed effects and include year dummies and a constant (not reported). t-statistics in parentheses. In all specifications the dependent variable is growth in TFP. Column 1 includes the contribution of CT capital services. Column 2 is as column 1 but with the added contribution of IT equipment capital services. Column 3 also incorporates IT but this time as (unweighted) IT capital services, rather than the contribution. Column 4 replaces CT and IT with the contribution of capital services from (aggregate) ICT *equipment*. Column 5 includes separate IT and CT equipment capital services, not share-weighted. All regressions estimated on same sample.

interpreted there as the creation of network infrastructure, and also EUKLEMS. In comparison the official series is flat, with a clear level difference of at least £2bn for most of the period reported. In 2001, the peak of UK telecoms investment, the difference between GHW and the latest official estimates is as much as £5.6bn. The difference between EUKLEMS and official estimates is even greater. We therefore use estimates from GHW as an alternative series for UK investment in CT equipment, with estimates extrapolated forward (from 2009) using growth rates taken from the official series.

The GFCF price index for each asset, and the value-added price index, were derived implicitly using constant and current price data, and the price index re-referenced to 2005=1. Nominal GFCF and the corresponding price index were then extrapolated using data from EUKLEMS where available, and the constant price series re-estimated using the re-referenced price index. Where national price indices for either software, or mineral exploration and copyrights, were missing or unavailable, we either applied the aggregate price index for IPPs, or extended the asset price index using the aggregate price index for IPPs for that country. To deflate GFCF in R&D, we used each country's gross value-added price index. Where data for the US were missing, GFCF price indices were downloaded directly from the BEA. For Sweden, GFCF price indices were extended using data downloaded from Statistics Sweden.

For capital stock initial values, where we had estimates from EUKLEMS, the initial value (re-based to 2005 prices) from EUKLEMS was used. Where we had no information from EUKLEMS (e.g. as for R&D), the initial value was estimated using the standard steady-state formula, $K_t = I_t/(g + \delta)$, where g is mean growth in real investment and δ is the asset-specific depreciation rate. Growth in capital services by country is thus estimated as share-weighted growth in capital services from different assets, as in equation (12), where the shares are asset user costs as a share of total economy gross operating surplus as in equation (13), and ρ is estimated ex-post such that user costs exhaust total gross operating surplus.

Regarding labour, the share of labour payments in GVA is taken directly from the Total Economy Database (TED) produced by The Conference Board, the reason being that OECD (NSI) data on Compensation of Employees do not include any element of the mixed income earned by the self-employed. The TED data on labour shares do however include an estimate of the labour remuneration (from within mixed income) earned by the self-employed, as does EUKLEMS, which we use to backcast the TED labour share. For consistency, and to incorporate data on growth in labour services and therefore labour composition, all labour input data are taken from TED, with growth in annual person-hours worked benchmarked in levels to OECD (NSI) data in 2013. If labour types are paid (in proportion to) their marginal products then the index of labour services (times the labour share) captures entirely the per hour contribution of skill changes and hence does not affect TFP (since TFP is calculated by subtracting off this from output growth). The capital per hour terms are analogous: growth in different capital types per hour, weighted by their rental shares, giving composition-adjusted growth in total capital services per hour. Finally, Data on GVA are nominal and real at basic prices, backcast using EUKLEMS where available. When we switch between alternative deflators for ICT assets, we make a corresponding adjustment to the value-added price index, so that real gross value-added incorporates the change to real GFCF.

C Country detail on contribution of spillovers

This table sets out the contribution of spillovers by country.

Table 5: Economic significance: contribution of CT capital services, 1995-2013, by country

Country	$\Delta lnTFP$	$s_K^{CT} \Delta lnK^{CT}$	Spillover $=\hat{\beta}\ (s_K^{CT} \Delta lnK^{CT})$	% of $\Delta lnTFP$
AUT	0.93%	0.10%	0.39%	42%
BEL	0.00%	0.06%	0.23%	
DNK	0.34%	0.01%	0.05%	14%
ESP	-0.55%	0.04%	0.18%	
FIN	1.05%	0.05%	0.20%	19%
FRA	0.52%	0.04%	0.16%	31%
GER	0.59%	0.03%	0.14%	23%
IRL	0.38%	0.07%	0.28%	74%
ITA	-0.10%	0.04%	0.18%	
NLD	0.48%	0.01%	0.04%	8%
PRT	0.53%	0.07%	0.27%	52%
SWE	0.66%	0.14%	0.56%	86%
UK	0.38%	0.02%	0.06%	17%
US	0.56%	0.12%	0.49%	88%

Notes to table: Data are estimates for the years 1995-2013. Column 1 presents countries included. Column 2 presents mean TFP growth (estimated as the change in the natural log) over the years 1995 to 2013 for which data are available (for some countries our TFP data begin later than 1995). Column 3 presents estimates of the mean contribution of CT capital services over the same years for which data are available. Column 4 is the estimated contribution of CT network externalities to growth. Column 5 is the percentage of TFP explained by the CT spillover estimate, estimated as column 4 over column 2.