The proposed merger of AT & T and T-mobile: Are there unexhausted scale economies in US mobile telephony?

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The proposed merger of AT&T and T-Mobile: Are there unexhausted scale economies in U.S. mobile telephony?[1]

By

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ABSTRACT

From the beginning, the debate on the likely results of the proposed acquisition of T-Mobile USA by AT&T focused more on the claims of the parties that "immense" merger efficiencies would overwhelm any apparent losses of competition than on the presence or absence of those losses, and the factors that might affect them, such as market definition. The companies based their "economic model" of the merger on estimates of efficiencies on AT&T's "engineering model", without addressing the credibility of the results of the latter in the context of the economics literature on the telecommunications sector. In this paper we first argue that the economics literature on economies of scale (especially) and economies of density in mobile telephony suggests caution in expecting such massive cost reductions from increasing the size of an already very large firm. We then present new econometric evidence from an international data base supporting the notion that most large mobile telephone service providers have reached the point of constant or even (rarely) declining returns to scale.

[1] Co-author Pittman worked as a staff economist in the DOJ investigation of the AT&T/T-Mobile merger proposal. However, this paper has been written using only public sources of information. The views expressed are not purported to reflect the views of the Department of Justice.

1. Introduction

AT&T's proposed $39 billion acquisition of T-Mobile USA (TMU) raised serious concerns for US policymakers, particularly at the Federal Communications Commission (FCC) and the Antitrust Division of the Justice Department (DOJ), which shared jurisdiction over the deal. Announced on March 20, 2011, the acquisition would have combined two of the four major national providers of mobile telephony services for both individuals and businesses, with the combined firm's post-acquisition share of revenues reportedly over 40 percent, Verizon a strong number two at just under 40 percent, and Sprint a distant number three at around 20 percent.[2]

As usual in a large and complex merger deal, there were questions about how exactly to define markets, in both the product and geographic dimensions. In the former category were the questions of both whether prepaid and postpaid services and whether individual and business ("enterprise") services might constitute separate markets; in the latter category it was noted that the four major national suppliers competed along some dimensions at both the local and national levels, and at the local levels both their shares and the identity of additional competitors varied to some degree. Both DOJ (in its Complaint, filed on August 31, 2011) and the staff of the FCC (in its Staff Analysis and Findings, filed on November 29, 2011) argued that the merger would be highly concentrating and anticompetitive regardless of the choices made on these more specific market definition questions.

An interesting and unusual aspect of the debate that ensued following the announcement of the merger, through the issuing of the DOJ complaint and the (negative) FCC staff report, until the companies abandoned the merger project on December 19, 2011, was that the merging firms did not seem to devote much effort to the presentation of evidence against the market definitions that implied these high levels of concentration. The companies' principal economic experts, Dennis Carlton, Allan Shampine, and Hal Sider (hereinafter CSS), in their Declaration filed at the FCC with the merger proposal, stated the basis of their support for the merger in very clear terms: "We conclude that the proposed transaction will promote competition by enabling the merged firm to achieve engineering-based network synergies that increase network capacity beyond the levels that AT&T and T-Mobile USA could achieve if the two companies continued to operate independently." (Declaration at ¶7) The Declaration proceeded to argue that the merged firm would continue to face competition from a variety of sources, as well as that the standard "unilateral effects" analysis expected to be engaged in by DOJ would be misleading for a variety of industry- and situation-specific reasons (Declaration at ¶9), but did not take strong

[2] FCC (2010); AAI (2011); Grunes and Stucke (2012). In its Complaint, DOJ emphasized not market shares but changes in the Herfindahl Hirschman Index (HHI): "Nationally, the proposed merger would result in an HHI of more than 3,100 for mobile wireless telecommunications services, an increase of nearly 700 points." DOJ Complaint, at ¶25.

issue with the basic market definition and concentration analysis that it deemed likely flow from the Horizontal Merger Guidelines of DOJ and the Federal Trade Commission.[3] In their Reply Declaration (June 9), CSS stated the point even more starkly: "These consumer benefits are independent of the scope of the product and geographic markets and, as a result, the precise definitions of the product and geographic markets are not central to the evaluation of the proposed transaction" (¶59).

In their FCC application and later in more detail at the agencies, the merging companies highlighted two categories of efficiencies that would result from the merger. The first category, apparently not quantified in a single summary figure, constituted cost savings that were a primary input into the companies' "engineering model," which in turn was a primary input into the CSS "economic model" of the impact of the merger. (Both models were in fact introduced subsequent to the filing of the merger application and the CSS Declaration.) These cost savings were summarized by the companies as follows:

> "[T]he transaction will enable the merged firm to create far greater capacity on the combined network than the two networks could achieve on their own by (i) creating a denser network with additional cell sites that increase aggregate capacity; (ii) increasing spectrum available to provide service by consolidating redundant GSM network control channels; (iii) increasing the efficiency of existing spectrum through 'channel pooling'; (iv) making greater use of underutilized networks; and (v) freeing up spectrum for more spectrally efficient services and thereby expanding the number of areas in which such services will be deployed. In so doing, the transaction will give the combined company much-needed flexibility to relieve capacity constraints by enabling it to optimize its use of spectrum on a market-by-market basis…." (Application, at p. 42)

The second category of efficiencies, estimated in the Application at $39 billion total, "with an annual run rate on the order of $3 billion from year three forward," included more efficient use of the cell towers owned by the two companies (including the sale of those no longer needed post-merger), as well as economies in combining retail operations, customer support, marketing, and procurement, the latter including "handsets as well as network equipment and infrastructure") (Application at pp. 51-52).

In this paper, we seek to place these very large merger efficiency claims in the context of the cost structure of mobile telephony and other network industries. Section 2 of the paper examines more closely the efficiencies claims made by the parties and their implications. Section 3 considers these claims in the context of the economic literature on economies of scale and

[3] Chang, Evan, and Schmalensee (2011) noted this as well: "AT&T's economists do not seem to be in significant disagreement with these product and geographic definitions" (i.e., those in the DOJ Complaint).

economies of density. We suggest there that the parties' claims of efficiencies, while certainly not outside the realm of possibility, are remarkably high for a company already as large and with as high a market share as AT&T.

We proceed to present a new set of econometric results on scale economies for 22 mobile carriers from seven countries (involving two North-American, three European and two East-Asian countries) over the time period 1998-2007, using a parametric stochastic frontier approach to identify the firms' economies of scale. Section 4 of the paper elaborates the methodology, including theoretical models and empirical applications. Section 5 describes the data, and Section 6 discusses the empirical results. Section 7 concludes with policy implications.

2. The Efficiencies Claimed by the Merging Firms

As noted above, the public record appears to contain no single dollar figure for the value of the efficiencies claimed by the companies in the "engineering model". However, the companies' Application at the FCC described them as "immense" (pp. 12 and 23), and the subsequent filing by the companies in "Opposition … to Petitions to Deny" (June 10, 2011) promised that the merger would create "*immense* new capacity that will provide *enormous* benefits to consumers" (at 1; emphasis supplied). We can make more precise inferences concerning the magnitude of these claims of efficiencies by combining information from various sources.

First, the FCC staff report summarizes the companies' redacted analysis as concluding that following the merger, "prices would fall between 3.8 and 9.4 percent" (Staff Analysis at ¶136). Second, a redacted letter from AT&T counsel to the FCC, accompanied by a redacted slide presentation titled "Competitive Effects of the AT&T – T-Mobile Transaction", notes that the economic model presented by CSS assumes linear demand in order to be on the conservative side regarding the pass-through of cost reductions to consumers. Since standard economic theory holds that firms facing linear demand pass through approximately fifty percent of cost changes,[4] this by itself would suggest that the parties are claiming cost reductions of between 7.6 and 18.8 percent.

But the same presentation implies that – as usual in merger simulation – the model would predict a post-merger price increase if there were no efficiencies: "Our analysis indicates that the cost and quality benefits are more than sufficient to counter *any upward pricing pressure...*" (slide 3, emphasis added). Similarly, AT&T economist Mark Israel noted in the FCC's "Workshop on the Economics of the Proposed AT&T – T-Mobile Merger" that "what really drives the results is the change in the AT&T marginal cost, and *whether that's large enough to overcome the competitive effects*" (transcript p. 251; emphasis supplied). Finally, in their Reply

[4] See, for example, Weyl and Fabinger (2011).

Declaration (June 9, 2011), CSS discuss the "Upward Pricing Pressure Analysis" calculated by Stephen Salop, Stanley Besen, Stephen Kletter, Serge Moresi, and John Woodbury and submitted on May 31 on behalf of Sprint's challenge to the merger. CSS report that, after making some but not all of their proposed corrections to the Sprint model, the model predicts upward pricing pressure "not very far from the threshold that is used at the Antitrust Division in determining whether GUPPI levels raise unilateral effects concerns" – by which a footnote explains that they mean 5 percent (¶87).

Thus the efficiencies claimed must reduce the price not from its current level but from its higher but-for level – adding a figure "not very far from" 5% into the mix, so perhaps 6-7%. Furthermore, the letter and the Application strongly emphasize that the efficiencies included in this pricing analysis should be considered an underestimate of the true efficiencies to be expected from the merger – that the efficiencies included in the "economic model" do not, for example, include the $39 billion of efficiencies included in the second category discussed above.

Thus we may confidently infer that the parties were claiming something at least in the range of 13.6 to 25.8 percent in cost reductions from the merger, and perhaps higher. (Recall that the merging parties characterize them as "immense".) We argue in the next section of the paper that this is a fairly remarkable claim for an already very large provider of mobile telephone services.

First, however, let us note in passing that the FCC staff was quite sceptical of these efficiency claims – labelling them "seriously flawed", "implausible", and "extremely sensitive to adjustments" (Staff Analysis at ¶138) – though on the grounds of a close examination of the engineering model on which they were based rather than on the grounds examined in this paper. In particular, according to the Staff Analysis, the companies calculate merger efficiencies by projecting the costs of the two firms going forward independently, as demand increases and capacity levels are reached at the level of local markets, and then comparing those "but-for" costs with the costs of the combined firm under the same conditions. The staff objects first to the companies' extrapolation of their calculations for fifteen local markets to the totality of areas served by the two firms, as "the fifteen markets chosen by the Applicants do not seem to be particularly representative" (¶169).

More fundamentally, though, the staff believes that the methodology used to calculate costs in the but-for world "contains a serious flaw in the cell-splitting algorithm that appears to cause the model to greatly overestimate incremental costs, and the overestimate is much greater for the standalone firms than the merged firm" (¶147). In particular, the methodology modelled by which the companies would address growing tightness in capacity "is not rational and does not reflect how any wireless provider would operate or model its business…. As a result, the

Applicants significantly overstate the estimated cost savings of the proposed transaction (¶¶175-76).

Finally, let us note that at least one component of the second category of claimed efficiencies appears to confuse private benefits with public benefits. One of the sub-categories is labelled "cost savings … from combining the networks", and one element of this subcategory is described as follows: "savings from a reduction in interconnection and toll expenses as a result of switching [T-Mobile calls] to existing AT&T facilities where possible for transport."[5] There is no estimate reported of the value of these efficiencies, though the sub-category of which they are a part is estimated to provide efficiencies of $10 billion in net present value.[6]

The FCC staff report includes the "reduction in interconnection and toll expenses" as one of many elements of the efficiencies claims where it is difficult to determine what portion of the efficiencies should be counted as savings in fixed charges and what portion in variable charges, under the traditional thinking that savings in the latter are more likely to be passed along downstream in the form of lower prices than are savings in the former.[7]

It appears, however – it is impossible to be sure from the public record – that the FCC staff critique does not go far enough in this case. In fact the actual amount of interconnection and toll expenses that are paid by TMU to AT&T pre-merger and would be internal to the firm post-merger should count as a transfer, not a savings in resources. The only portion of this flow that constitutes a true efficiency comes from the fact that the internal transfer price for this service should be at marginal cost rather than something higher, in which case "double marginalization" is avoided and the merged firm would have the incentive to expand output accordingly. Both CSS and their fellow AT&T consultants Robert Willig, Jonathan Orszag, and Jay Ezrielev note that the merger eliminates pre-merger double marginalization in this area, but neither these nor other statements sponsored by the merging firms states that the resulting merger efficiencies are only those flowing from this particular incentive for output expansion, rather than the entire volume of cost savings from the internalization of these flows.[8]

3. The Literature on Scale Economies, Particularly in Network Industries

Early, seminal texts by Marshall (1920) and Viner (1931) discussed the importance of "net internal economies of large-scale production". Kahn (1971) and others applied this concept to the possibility that a single firm might be a "natural monopoly … [where there] is an inherent tendency to decreasing unit costs over the entire extent of the market." Some commentators

[5] Declaration of Rick L. Moore, at ¶34. Virtually the same language is in the parties' merger application to the FCC, at p. 52.
[6] Declaration of Rick L., Moore, at ¶34.
[7] FCC Staff report, at ¶228. Note that CSS (at ¶65-71) argue that this principle should not apply in this matter.
[8] CSS Reply Declaration at ¶143; Willig, Orszag, and Ezrielev Reply Declaration, at footnote 106.

have applied this concept to the AT&T/T-Mobile merger. For example, Goldfarb (2011), noted that

> The mobile wireless industry is characterized by economies of scale and scope. In a static market, it would be less costly and/or more efficient to build out and operate a single network instead of multiple networks with partially duplicative facilities; to give a single provider use of a large block of spectrum rather than giving a number of providers use of a subset of that block; and to design and mass produce a single suite of handsets rather than making handsets for smaller groups of customers using many different standards and network technologies.

This sounds reasonable, and yet it seems to suggest at least two follow-up questions. First, are we considering here local or national economies of scale? And second, do these economies exist for all relevant levels of demand – so that the firm may be a "natural monopoly" – or are they exhausted at some point, after which increases in output are accompanied by proportional or even greater than proportional increases in cost?

Regarding the first question, for decades now the economic literature on network industries has made the useful distinction between economies of overall system size and economies of density. Walters (2007) summarizes the difference succinctly in the railways context:

> A significant development in all of this research [in "rail cost analysis"] was refining the distinction between economies of scale and density. The latter is the behavior of costs as output expands over a given network, whereas economies of scale focuses on the behavior of costs if the network size increases as output expands.

Similarly, Caves, Christensen, and Tretheway (1984) make the distinction in their analysis of airline costs:

> "We define returns to density as the proportional increase in output made possible by a proportional increase in all inputs, with points served, average stage length, average load factor, and input prices held fixed…. We define returns to scale as the proportional increase in output *and points served* made possible by a proportional increase in all inputs, with average stage length, average load factor, and input prices held fixed." (emphasis in original)

It seems useful, indeed important, to make this distinction in the present case of the market for mobile telephony. A significant portion of the economies claimed by AT&T for the merger seem to be some variant on economies of density, involving as they do the more efficient utilization of (especially) spectrum and cell towers in particular metropolitan areas. However, other claimed economies are firm-wide in scope and independent of the density of local areas, including those associated with marketing, customer service, procurement, and overall company administration.

All of this raises the crucial question: How reasonable is it to assume that under current (i.e. without the merger) conditions, AT&T and T-Mobile enjoy substantial unexhausted economies of density and size of national operations? Recall that the fragmentary estimates made public suggest claims of at least 10-15 percent reductions in cost, and perhaps 25 percent or more. Absent an econometric examination of mobile telephony for the US as a whole as well as for individual metropolitan areas, what can we infer from the existing literature?

The literature on at least one other network industry is not particularly supportive. In the freight railways sector, the literature suggests that in Western Europe, the railways have reached efficient scale in terms of system size but have not exhausted all available economies of density.[9] In the much larger and more intensely operated US freight railroads, however, the most recent study suggests that the largest companies have reached or are reaching minimum efficient scale in both system size and density (Christensen Associates, 2008).

What about mobile telephony? Here we are hampered by both the very dynamic nature of the industry – so that even fairly recent data may not well reflect economies going forward – as well as the paucity of publicly available data, especially regarding economies of density. One of the most knowledgeable of U.S. analysts, Ingo Vogelsang (2010), in a survey article laments the lack of convincing studies but seems to lean toward believing in constant returns to scale, even with regard to economies of density:

> "The case for constant returns comes from the observation that a doubling of traffic leads to cell splitting and increases the number of cells required even in the same area, roughly doubling costs."

Writing eight years earlier, Cave, Majumdar, and Vogelsang (2002) seem to agree:

> "If the econometric models were to be relied on, there would be a strong case for pursuing infrastructure competition throughout the network. If the engineering models were to be relied on, infrastructure competition in local areas would make sense only in very dense networks, where economies of density are exhausted…. [C]onceptually, there could exist two important ranges of natural monopoly.
>
> In the first stage, the natural monopoly property can be weak. In this range, economies of scale and scope are almost exhausted and sunk costs tend to be small. In this situation, competition is likely to be beneficial, because it leads to pressure on costs, prices and innovation. Competition is also likely to occur here, because in most telecommunications markets demand is moderately to strongly inelastic. Thus, we can

[9] See the discussion in Pittman (2007), discussing, among others, the results of Savignat and Nash (1999).

expect duplicate network investments, associated with some cost inefficiency and excess capacity, but possibly lower prices than under regulated monopoly. This is the case of long-distance services, mobile telephony and local business services in downtown areas of industrialized countries" (pp. 30-10).

In fact the parties' own engineering experts concede at least the possibility of the effective exhaustion of economies of density in one area; they note that "the percentage gains from channel pooling diminish as the size of the pool increases".[10] And all of this would be consistent with the findings of Gabel and Kennet (1991) that for the local fixed wire network, economies of density are exhausted in densely populated urban areas.[11]

Most of the existing empirical literature features observations at the firm level, with output measured as number of subscribers or, less frequently, revenues or airtime minutes. These studies tend to find constant returns to scale or even decreasing returns to scale for the largest operators – i.e., generally U-shaped cost curves. These papers include McKenzie and Small (1997), examining five US firms; Gagnepain and Pereira (2007), three Portuguese firms; Vendruscolo and Alves (2009), 38 Brazilian firms (the number declining over time); and Nam, Kwon, Kim, and Lee (2009), three Korean firms. The only paper we have found directly related to economies of density in local mobile telephone markets is Foreman and Beauvais (1999), which uses internal, local market level data for GTE, at the time a supplier in primarily rural areas with coverage of a few urban areas in California and Florida, and finds economies of scale with respect to the number of subscribers, controlling for airtime minutes per cell site. Even this paper finds economies for mobile telephony "below those that have been estimated for wireline technology."

In (unsatisfying) summary, the literature suggests that it is unlikely that a firm as large as AT&T – and perhaps T-Mobile as well – is operating at a point on its overall enterprise cost curve of substantial unexhausted economies of scale. With regard to economies of density at the metropolitan level, the little evidence available is more supportive of the presence of at least some unexhausted economies of density in some locations, though not in the most dense urban areas. But even in that case we may justifiably ask whether if one believes the evidence of "immense" economies presented by the merging companies, one should take the next step and consider whether mobile telephony in U.S. cities is a "natural monopoly", with declining costs throughout the relevant regions of demand?

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[10] However, they proceed to suggest that "the vast majority" of locations served by the merging firms still "have characteristics that will permit large gains." Jeffrey Reed and Nishith Tripathi, "AT&T/T-Mobile: Further Analysis of Capacity, Spectrum Efficiency and Service Quality Gains from Network Integration", at p. 7.

[11] The authors find that those areas with unexhausted economies of density (though they do not use this term) are "slightly higher than the high end of the density found in districts dominated by single family homes" (Gabel and Kennet [1991, at 77]).

In fact one party challenging the merger at the FCC, the Ad Hoc Telecommunications Users Committee, makes this precise point, both on its own and in an attached Declaration by economist Lee Selwyn. They two begin by noting at least an implicit tension between the merging parties' contention that only this merger can ease the capacity constraints faced by each firm separately, and the merging parties' simultaneous contention that the merger could not be anticompetitive because much smaller firms like MetroPCS and Cellular South would easily expand in order to discipline any post-merger price increase. They then go on to make the argument that if firms as large as AT&T and T-Mobile can achieve "immense" cost reductions through merging their operations, presumably AT&T, T-Mobile, and Verizon would achieve even greater economies by merging. In other words, if the efficiencies claimed by the parties are correct, then unless (for example) economies of density in the industry are coincidentally exhausted at the point of around 40 percent of current capacity – and the parties make no such claim, much less provide evidence for it – then mobile telephony may well be a sector characterized by natural monopoly, and the FCC should rely on regulation rather than competition going forward.

The FCC staff analysis does not appear to address this point. CSS, in their Reply Declaration, simply state that in that case every merger case in which the parties claim economies of scale or scope must be a natural monopoly – hardly a serious response. Certainly overall it seems that the economic analysis that uses the engineering model and its associated efficiencies claims in support of a precompetitive outcome to this merger is implicitly assuming a very specific, and arguably unlikely, state of the world regarding the existence of unexhausted economies of firm size and metropolitan area density in the provision of mobile telephony, with no econometric support.

In the next section we describe our own analysis of economies of scale in mobile telephony at the firm level, using the most recent data available.

4. Methodology

In this section, we describe briefly the measure, in the literature, used for economies of scale. We then focus on the frontier model used in this present study for the evaluation of firm scale efficiency as our preferred measure of scale economies.[12]

The most convenient measure for economies of scale in the literature is the return to scale (*RTS*),[13] which is, by geometrical point of view, defined as measuring how accurately the distance in input space reflects the distance in output space.[14] In our case with multiple inputs,

[12] Appendix A presents non-parametric DEA approach for a robustness check to our conclusion.
[13] See for example Baumol (1976).
[14] For detailed description see Chambers (1988). In other words, *RTS* is the ratio of the proportionate change in the output to a

we require to look at *ray average productivity* increases (decreases) with an increase in the overall inputs scale when *RTS* exceeds (falls short of) unity.[15]

The other measure documented in the recent literature is named scale efficiency (*SE*), which measures the *ray average productivity* at the observed inputs scale on the production frontier relative to the maximum *ray average productivity* attainable at a vector of inputs bundle (x) characterized by constant return to scale (CRS). The *SE* is equal to one, indicates the firm at the *most productive scale size* as defined by Banker et al. (1984). That is also the only point where the CRS prevails, and *SE* is equal to the overall *RTS*. Elsewhere *SE* is below unity regardless of whether scale (inputs) elasticity is greater than or less than one (Ray, 1998). Given the multiple inputs application in this study, we prefer the later measure of scale economies, using *SE*, which can be estimated using stochastic frontier approach.

Given a panel dataset we have, this study considers a *true* fixed effects stochastic production frontier model specified for panel data as proposed by Greene (2004, 2005):[16]

$$y_{it} = \alpha_i + \beta' x_{it} + v_{it} - u_{it},\ i = 1, 2, ..., N;\ t = 1, 2, ..., T\ , \tag{1}$$

where y_{it} is the (logarithm) output of the *i*-th firm in the *t*-th year; x_{it} is a vector of (logarithm) inputs of the *i*-th firm in the *t*-th year; β is a vector of unknown parameters to be estimated; α_i is the firms' individual specific effects capturing all time invariant effects including unobserved heterogeneity, v_{it} is the random error term which is assumed to be i.i.d. (independent and identically distributed) with $N(0, \sigma_v^2)$ distribution and independent of u_{it} – the inefficiency term that vary freely through time with $N(\mu_{it}, \sigma_u^2)$ distribution.

We firstly conduct three likelihood ratio (LR) specification tests to identify the most favourable functional form for our parametric SFA model (see Table 1 for the test results). The first model specification test is for the Cobb-Douglas functional form versus the Translog functional form.[17] The second test is related to time effects that indicate the existence of

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small proportionate change in the input quantity in the single input case or to a small equi-proportionate change in all inputs in the multiple inputs case. Specifically, three possible characteristics of production technology can be defined as follows: for a *RTS* exceeds unity, $\varepsilon(x) \succ 1$, the distance in input space under-estimates the distance in output space, and the production technology exhibits increasing returns to scale; for an $\varepsilon(x) = 1$, the production technology is embodied by constant returns to scale, and the isoquant is evenly spaced; and finally for an $\varepsilon(x) \prec 1$, the distance in input space over-estimates the distance in output space, and the production technology shows decreasing returns to scale (and of course, such returns to scale properties hold, in general, only locally).

[15] See Ray (1998). In the single-input, single-output case, average productivity increases with the input quantity when the technology exhibits increasing returns. In the multiple inputs case, the average productivity is not defined in the usual sense, and ray average productivity is introduced instead of.

[16] This model has several distinct advantages: (1) allowing technical *in*efficiency effects to vary freely through time; (2) dispensing with the undesirable assumption that the firm inefficiency and heterogeneity are uncorrelated with the input variables; (3) controlling the effect of unobservable & time invariant heterogeneity on measuring *in*efficiency. See Greene (2004ab; 2005) for a comprehensive discussion and comparison of different stochastic frontier models.

[17] H_0: Cobb-Douglas specification is preferred ($\beta_{kj} = \beta_{k\tau} = \beta_{\tau\tau} = 0$, $k, j = 1, 2, 3$). According to model estimation results, LR = $2(Logl_u\text{-}Logl_r) = 2(-19.13693-(-32.11519)) = 25.96 > \chi^2(10) = 18.31$. Hence, we reject H_0 in favour of more flexible translog model specification.

significant technical change.[18] The last test is to identify the distribution of the inefficiency error term.[19] According to our LR test results, the preferred empirical frontier model for our study is a translog stochastic production function with the inclusion of time effects, and normal-truncated normal distribution in the inefficiency errors. The SFA model is specified as:

$$\begin{aligned}\ln y_{it} &= \alpha_i + \sum_{k=1}^{3}\beta_k \ln x_{kit} + \beta_\tau T + \frac{1}{2}\left\{\sum_{k=1}^{3}\sum_{j=1}^{3}\beta_{kj}\ln x_{kit}\ln x_{jit} + \beta_{\tau\tau}T^2\right\}, \\ &+ \sum_{k=1}^{3}\beta_{k\tau}\ln x_{kit}T + v_{it} - u_{it},\ \left(i = 1, 2, ..., N;\ t = 1, 2, ..., T\right)\end{aligned} \tag{2}$$

The more expanded form can be written as:

$$\begin{aligned}\ln Output_{it} &= \alpha_i + \beta_1 \ln L_{it} + \beta_2 \ln M_{it} + \beta_3 \ln K_{it} + \beta_4 T \\ &+ \frac{1}{2}\beta_{11}(\ln L_{it})^2 + \frac{1}{2}\beta_{22}(\ln M_{it})^2 + \frac{1}{2}\beta_{33}(\ln K_{it})^2 + \frac{1}{2}\beta_{44}T^2 \\ &+ \beta_{12}\ln L_{it}\ln M_{it} + \beta_{13}\ln L_{it}\ln K_{it} + \beta_{23}\ln M_{it}\ln K_{it} \\ &+ \beta_{14}\ln L_{it}T + \beta_{24}\ln M_{it}T + \beta_{34}\ln K_{it}T + v_{it} - u_{it},\ \left(i = 1, 2, ..., N;\ t = 1, 2, ..., T\right)\end{aligned}, \tag{3}$$

where the one output and three inputs of the *i*-th firm in the *t*-th year are all measured in quantities and in logarithm form (L_{it}, M_{it} and K_{it} denote the quantities of the labour input, material input and capital input of the *i*-th firm in the *t*-th year, respectively). The time trend variable, *T*, is included to capture the technical change which may affect the location of production frontier.

-- Please insert Table 1 about here --

To calculate firm *SE* scores, we exploit the output-oriented measure of scale efficiency developed by Ray (1998) from an empirically estimated single output and multiple inputs translog production function.[20] The output-oriented *SE* for the *i*-th firm in the *t*-th year can be calculated using

$$SE_{it}\left(x_{it}\right) = \exp\left\{\frac{\left(1-\varepsilon_{it}\left(x_{it}\right)\right)^2}{2\beta}\right\}, \tag{4}$$

[18] H_0: No time effects in the model, i.e. no technological change ($\beta_\tau = \beta_{k\tau} = \beta_{\tau\tau} = 0$, $k = 1, 2, 3$). According to model estimation results, LR = 2($Logl_u$-$Logl_r$) = 2(-19.13693-(-28.35059) = 18.43 > $\chi^2(5)$ = 11.07. Hence, we reject H_0, and find evidence of the existence of significant technological change.

[19] H_0: $u_i \sim N(\mu_i, \sigma_u^2),\ \mu_i = 0.$ i.e. normal-half normal distribution. According to model estimation results, LR = 2($Logl_u$-$Logl_r$) = 2(43.483-25.634) = 35.69 > $\chi^2(1)$ = 3.84. Hence, we reject H_0, and in favor of the normal-truncated normal distribution model.

[20] The input-oriented measure of *scale efficiency* is identical to the output-oriented measure, in the absence of technical inefficiency, i.e. u_{it} = 0. In the more general case involving technical inefficiency, the input-oriented *scale efficiency* is then calculated using $SE_{it}(x_{it}) = \exp\left\{\frac{\left(1-\sqrt{\varepsilon_{it}\left(x_{it}\right)^2 - 2\beta u_{it}}\right)^2}{2\beta}\right\}$, where u_{it} is the estimated technical inefficiency of the *i*-th firm in the *t*-th year using the 'true' fixed effects procedure; and all the other terms are the same as those defined in the output-oriented measure, Equation (4).

where $\varepsilon_{it}(x_{it})$ is the overall *RTS* of the *i*-th firm in the *t*-th year, estimated using equation (5) described below; $\beta = \sum_{k=1}^{3}\sum_{j=1}^{3}\beta_{kj}$, assumed to be negative to ensure $SE_{it}(x_{it}) \leq 1$. The SE_{it} scores are between zero and one, where a value equals one indicating the firm at the *most productive scale size*. Below we demonstrate the calculation of the *RTS* from the specified translog production function.

Given the preferred translog production function, which is non-homothetic and imposes no restrictions on production technology, the elasticity of the output with respect to the inputs is a function of the inputs and time trend variable.[21] That is for any given inputs level, the *RTS* is $\varepsilon_{it}(x_{it}) = \sum_{k=1}^{3}\frac{\partial \ln y_{it}}{\partial \ln x_{kit}}$, where y_{it} is the output and x_{kit} is a vector of three inputs. Thus, the *RTS* for the *i*-th firm in the *t*-th year can be calculated directly from the empirically estimated parameters in the production function (4) using

$$\varepsilon_{it}(x_{it}) = \sum_{k=1}^{3}\left(\beta_k + \sum_{j=1}^{3}\beta_{kj}\ln x_{jit} + \beta_{k\tau}T\right). \tag{5}$$

Detailed data information on mobile carriers' operation output and inputs are described in the next section.

5. Data

The output and inputs data used for calculating firms' scale efficiencies are extracted from mobile carriers' annual reports. An unbalanced panel dataset is in turn compiled for twenty-two mobile network providers, over 1998-2007, from seven countries selected to represent different regions and major economic powers, including the USA, Canada, the UK, France, Germany, China and Korea.[22] Table 2 lists the names of these mobile carriers, their served market regions, and the time periods observed.[23]

-- Please insert Table 2 about here --

- *Output measures*

[21] For a homothetic production function, the marginal rate of technical substitution is homogeneous of degree zero in inputs, which requires $\sum_j\beta_{kj} = 0$, yielding a Kmenta approximation of the CES function. The production function is homogeneous of degree φ if $\sum_k\beta_k = \varphi$, $\sum_j\beta_{kj} = 0$, and $\sum_k\beta_{k\tau} = 0$. Linear homogeneity obtains if φ = 1, i.e. constant returns to scale.

[22] Seven representative countries (i.e. six from the OECD members plus China) are selected to conduct this firm-level efficiency and productivity study, involving two North-American countries, three European countries and two East-Asian countries (the Japanese mobile carriers are not included primarily due to severe lack of data information on the inputs). The twenty-two mobile network providers cover the main mobile network operators in each selected country, based on their market share. Most selected network providers are ranked as the top twenty mobile operators by the International Telecommunications Union (ITU).

[23] The output and inputs are recorded as what happened in the individual specific operating market of each firm. For example, we record the inputs used by Vodafone in the UK mobile market for producing the output in the UK mobile market only as the inputs and output for Vodafone UK; and record the inputs used by Vodafone in the German mobile market for producing the output in the German mobile market only as the inputs and output for Vodafone Germany; and so forth. In addition, all output and inputs information used in this current study is for the mobile phone service segment only.

Output value is measured by total operating revenue from the mobile service segment. It typically consists of network service revenue (i.e. voice services, messaging and other data services) and sales of terminal equipment, but excludes interest income, disposals, capital gains/losses and dividends.[24]

Output price is used to deflate the value of output into a quantity measure that is consistent across carriers. Output price is based on the national average mobile price index, calculated for each sample country and collected from ITU.

Output quantity is measured by total operating revenue deflated by the average mobile price index in each country in US$s at 2000 prices.

- *Input measures*

(i) Labour quantity is the number of employees working in the mobile service segment.

(ii) Material cost is measured by non-personnel operating expenses in the mobile service segment. It consists primarily of consumption of goods and merchandise, services obtained from outside suppliers, materials, cost of acquisition and maintenance of customer services, and administration.

Material price is used to deflate material cost into quantity measure that is consistent across carriers. Material price is proxied by a producer price index (PPI) for a manufacturing products basket (2000 = 100). The PPI data are available for all sample countries in this study at the OECD online statistical database.

Material quantity is PPI deflated non-personnel operating expenses.

(iii) Capital cost is measured by the total depreciation and amortization of property, plant and equipment in the mobile service segment in each year.

Capital price is proxied by the weighted average cost of borrowings reported in carrier annual reports.[25]

Capital quantity is calculated by dividing capital cost by capital price.

-- Please insert Table 3 about here --

[24] The information on the sales of terminal equipments were only separately reported by a very few carriers in our sample. We cannot separate this value from the total operating revenue at a consistent basis across all firms. However, based on those information reported, the equipment sales only count very small proportion of the total revenue.

[25] There is a debate in measuring the price (cost) of capital. In the existing literature of telecoms efficiency and productivity study, various measures have been used, with two in particular. The first one is related to the rate of depreciation. The second one uses PPI as a deflator of capital expense. Since we have used PPI as a proxy of material price to deflate money value of material expenses into the quantity measure of material input, the second PPI proxy is thus not preferred if a better proxy is available. As for the first one, depreciation rate, is little suitable for measuring the capital price in the mobile network industry, since the depreciation rate for mobile network carriers is very high, and in many cases even exceeds 100%. Therefore, the results are highly likely to be distorted when using depreciation rate related measure of capital price in our frontier estimation.

Despite that to the authors' knowledge, the method of weighted average cost of capital (WACC) is a common practice used in accounting and finance to approach cost of capital (see e.g., Bruner et al. 1998; Truong et al. 2008); this approach cannot be applied in this study as a result of lack of financial and stock market information for most of sample mobile carriers. Accordingly, the closest measure – weighted average cost of borrowings (WACB) – is used as the proxy of capital price.

Table 3 summarizes the statistics of the output and inputs (labour, material and capital) over 1998-2007 (i.e. calculated means across 22 mobile carriers by year). The first four columns present the money values in US$s, and followed by the converted quantities in the same order. We use the quantity measures of the output and inputs in our SFA model estimating scale efficiencies for those twenty-two mobile carriers over their observation years.

6. Results

In this section, we present the results of our SFA estimation regarding scale economies for the sample mobile network companies.

-- Please insert Tables 4 and 5 about here --

Table 4 presents the *SE* and *RTS* scores for each firm across their observation years.[26] The results suggest that on average, most mobile network operators in our sample (16 out of 22) operate in the region of constant returns to scale, with their average *SE* scores insignificantly different from one.[27] The *RTS* estimates indicate that on average, almost all observed firms operate in either constant (i.e., the mean average *RTS* cross-year are equal to or very close to 1) or mildly increasing returns to scale. For example, KTF, LG Telecom, Orange France and Rogers show an average *RTS* at 1.12, 1.14, 1.06 and 1.02, respectively.

In Graph 1, the firms are presented in an ascending order of firm sizes measured by their 2007 total revenue in the mobile service segment and showing their estimated SE and RTS scores. Note that AT&T and T-Mobile USA both are among the firms that appear to be operating in the range of constant returns.[28] There are three firms – China Mobile, China Unicom and Verizon Wireless – operating in the range where we estimate decreasing returns to scale, with an average *RTS* significantly less than one (in fact below 0.9).[29]

Graph 1: Average SE and RTS across firms

[26] DEA estimated *SE* sores for each mobile carriers over their observation years are reported in the 1st column of Table 4 for reference. See Appendix B for the decomposed inputs elasticities in detail.
[27] In contrast, the DEA results reported in Appendix A: Graph 2, suggest that there are relatively fewer firms (10 out of 22) at the *MPSS*. However, we concern the results with accumulated statistical errors given the inability of statistical underpinning of DEA.
[28] Due to the lack of detailed information on each individual input measure, we cannot include AT&T in our frontier analysis. The AT&T's *RTS* and *SE* scores are fitted using the information on the aggregated total costs and total revenues from the company's annual financial reports over 2002-2007. The results summary is presented in Appendix C.
[29] See Appendix C for detail.

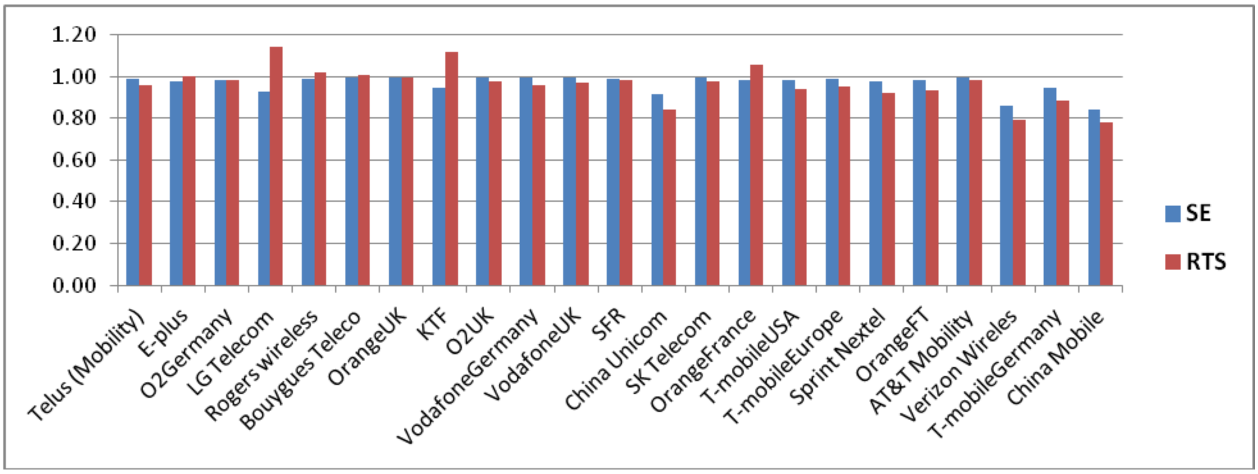

Table 5 presents, using the most recent data we have, a snap-shot of 2007 measures of the firms' economies of scale along with the national regulatory standards for their mobile network markets.[30] The results further emphasize that in a regulatory system featured by active competition among privatized oligopolies, the firms generally operate within the range of constant returns to scale; we find no evidence for substantial unexhausted economies of scale in mobile telecoms.

7. Conclusion

Using stochastic frontier analysis, in this study, we investigated scale efficiency as a measure of scale economies for twenty-two mobile carriers from seven countries over the period 1998-2007. We did not find substantial unexhausted scale economies in mobile telephony in general, especially for firms of medium to large size. Most firms we studied operate at their most productive scale size over their observation years, with a few exhibiting slightly increasing returns along with a few large operators exhibiting decreasing returns.

Regarding the proposed merger of AT&T and T-Mobile, obviously it would have been desirable to have the more localized data necessary to test for the presence of unexhausted economies of density. The conjectures in the literature lean toward the view the in mobile telephony, as in railways, the large, dense networks have exhausted available economies of density, but the empirical evidence for this view is lacking. Nevertheless our results concerning economies of firm size are consistent with those in the literature, suggesting that it is unlikely that T-Mobile, and very unlikely that AT&T, are currently operating in a range where large firm-level economies related to activities such as procurement, marketing, customer service, and administration would have been achievable due to the merger. Regarding both measures, the presence of "immense" unexhausted economies for the two firms seems unlikely indeed. On this

[30] The data information on national regulatory standards were extracted from Li & Lyons's (2012) study.

basis (and on this basis alone), our results support the decision of DOJ to challenge the merger and the scepticism expressed by the FCC staff.

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Table 1: Hypotheses tests for parameters of the SFPF models and final model estimation results

Null hypothesis	$LogL_{H1}$ (unrestricted model)	$LogL_{H0}$ (restricted model)	LR statistics	Critical value	Decision
A. H_0: Cobb-Douglas model is preferred ($\beta_{kj} = \beta_{k\tau} = \beta_{\tau\tau} = 0$, $k, j = 1, 2, 3$)	-19.137	-32.115	25.96	18.31	Reject H_0, in favour of translog model
B. H_0: no technical change (time effects) ($\beta_{\tau} = \beta_{k\tau} = \beta_{\tau\tau} = 0$, $k = 1, 2, 3$)	-19.137	-28.351	18.43	11.07	Reject H_0, significant technical change exists
C. H_0: normal-half normal model is preferred (μ=0)	43.483	25.634	35.69	3.84	Reject H_0, normal-truncated normal model is preferred

Maximum-likelihood estimates of translog normal-truncated normal model

β_l	0.068	*(0.107)*	$\beta_{\tau\tau}$	0.003	*(0.002)*
β_m	0.770	*(0.179)*	β_{lm}	-0.316	*(0.095)*
β_k	0.054	*(0.079)*	β_{lk}	0.138	*(0.054)*
β_{τ}	-0.030	*(0.038)*	β_{mk}	-0.018	*(0.056)*
β_{ll}	0.045	*(0.039)*	$\beta_{l\tau}$	0.018	*(0.012)*
β_{mm}	0.220	*(0.074)*	$\beta_{m\tau}$	-0.023	*(0.020)*
β_{kk}	-0.091	*(0.022)*	$\beta_{k\tau}$	0.012	*(0.009)*
λ	6.231	*(1.714)*			
σ	0.568	*(0.119)*			

Note: standard errors are presented in the parentheses next to the coefficients. The first-order coefficient estimates may be interpreted as production elasticities at the sample mean because the data was mean-corrected prior to estimation.

Table 2: List of the names, operating markets and years for observed mobile carriers

Unit-code	Firm name	Regional market	Periods covered	No. years	Unit-code	Firm name	Regional market	Periods covered	No. years
D1	China Mobile	China	98-07	10	D12	E-plus	DE	02-07	6
D2	China Unicom	China	98-07	10	D13	Orange France	FR	02-07	6
D3	Vodafone UK	UK	99-07	9	D14	Bouygues Telecom	FR	01-07	7
D4	O2UK	UK	99-07	9	D15	SFR	FR	98-07	10
D5	Orange UK	UK	02-07	6	D16	SK Telecom	Korea	98-07	10
D6	Orange FT	--	99-07	9	D17	KTF	Korea	98-07	10
D7	T-mobile	--	01-07	7	D18	LG Telecom	Korea	98-07	10
D8	T-mobile Europe	Europe	05-07	3	D19	Sprint Nextel	US	98-07	10
D9	T-mobile USA	US	05-07	3	D20	Verizon Wireless	US	98-07	10
D10	O2Germany	DE	00-07	8	D21	Rogers Wireless	Canada	98-07	10
D11	Vodafone Germany	DE	02-07	6	D22	Telus (Mobility)	Canada	99-07	9

Note: Consolidated information is used for DMU6 and DMU7.

Table 3: Summary statistics of output and inputs for twenty-two mobile carriers from 1998 to 2007

	OutputQ	LQ	MQ	KQ	OutputV	LV	MV	KV
	Mean							
1998	23.13	7890.11	15.07	70.74	2217.42	291.24	1467.84	458.79
1999	34.30	9980.46	23.86	88.26	3351.74	362.25	2315.60	571.66
2000	46.94	14744.36	29.51	126.65	4694.43	468.33	2951.40	809.09
2001	61.24	18211.00	38.64	223.92	6282.31	656.59	3870.76	1321.48
2002	69.66	17336.25	41.30	537.59	7265.85	697.77	4114.11	3172.00
2003	86.20	17802.60	49.82	251.06	9183.40	852.65	5036.10	1437.22
2004	101.63	20665.05	58.69	345.41	11068.81	1033.38	6152.10	1858.38
2005	119.37	22620.09	69.49	425.45	13342.51	1191.90	7587.28	2237.05
2006	134.32	23816.05	75.05	460.50	15398.83	1511.33	8467.77	2640.58
2007	152.31	25495.64	86.14	462.32	17812.51	1672.61	9991.60	2864.78
Average annual change rate	23.82%	14.83%	22.16%	33.47%	26.58%	21.82%	24.46%	32.34%

Note: OutputQ is the quantity of output; LQ, MQ and KQ are the quantities of labour, material and capital inputs, respectively. OutputV is the value of output; LV, MV and KV are the values of labour, material and capital inputs, respectively; all money values are measured in million (US$s).

Table 4: Summary of DEA and SFA SE & RTS estimates across units over observed years

	China Mobile			China Unicom			Vodafone UK			O2UK			Orange UK		
	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS
1998	0.999	0.943	0.87	0.716	0.955	0.884									
1999	1	0.894	0.819	0.853	0.928	0.853	1	0.996	0.965	0.91	1	1.005			
2000	1	0.852	0.784	0.901	0.87	0.798	1	0.998	0.974	0.978	1	1.003			
2001	1	0.866	0.795	0.865	0.907	0.831	0.977	0.987	0.937	0.944	0.998	0.973			
2002	1	0.811	0.753	0.942	0.871	0.799	0.992	0.991	0.949	0.985	0.961	0.892	0.991	0.994	0.957
2003	0.999	0.829	0.766	0.986	0.924	0.849	0.998	0.999	0.98	0.988	1	1	0.999	0.998	0.978
2004	1	0.799	0.744	0.997	0.925	0.849	0.992	0.993	0.953	0.997	1	0.998	0.995	0.994	0.96
2005	0.966	0.788	0.736	0.994	0.91	0.835	0.999	0.997	0.971	1	0.999	0.987	1	1	1.004
2006	0.774	0.817	0.757	0.999	0.928	0.852	0.978	1	0.989	0.999	0.991	0.95	1	0.997	1.028
2007	0.833	0.852	0.784	1	0.93	0.855	0.968	1	1.004	0.988	1	0.999	1	0.991	1.052
Mean	0.967	0.87	0.804	0.925	0.915	0.84	0.989	0.995	0.969	0.976	0.994	0.979	0.997	0.996	0.996

	Orange FT			T-mobile			T-mobile Europe			T-mobile USA			O2Germany		
	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS
1999	0.901	0.996	0.968												
2000	0.858	0.988	0.941										0.143	0.999	0.981
2001	0.936	0.971	0.908	0.645	0.916	0.84							0.988	1	1.005
2002	0.888	0.969	0.905	0.71	0.84	0.775							0.886	0.928	0.852
2003	0.926	0.981	0.926	0.907	0.977	0.918							0.879	0.992	1.05
2004	0.92	0.974	0.912	0.915	0.984	0.931							0.807	0.991	1.052
2005	0.931	0.984	0.932	0.872	0.973	0.91	0.866	0.994	0.957	0.989	0.986	0.935	0.849	0.994	1.042
2006	0.819	0.99	0.945	0.887	0.972	0.908	0.904	0.992	0.952	0.931	0.987	0.938	1	0.967	0.901
2007	0.884	0.992	0.953	0.845	0.972	0.909	0.902	0.991	0.95	0.968	0.989	0.943	1	1	0.993
Mean	0.896	0.983	0.932	0.826	0.948	0.884	0.891	0.992	0.953	0.962	0.987	0.939	0.819	0.984	0.984

	Vodafone Germany			E-plus			Orange France			Bouygues Telecom			SFR		
	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS
1998													0.947	0.986	0.935
1999													0.933	0.996	0.965
2000													0.977	0.995	0.962
2001										1	0.998	0.976	0.963	0.971	0.907
2002	1	0.992	0.953	0.883	0.898	0.823	1	0.999	1.019	0.92	1	0.994	0.985	0.992	0.951
2003	1	0.997	0.973	0.879	1	1.001	1	0.995	1.039	0.984	1	0.998	0.964	1	0.991
2004	1	0.991	0.948	0.778	0.994	1.041	1	0.993	1.044	0.998	0.999	1.013	0.961	1	0.988
2005	1	0.991	0.948	0.835	0.994	1.043	1	0.984	1.068	0.998	0.994	1.04	0.999	0.997	1.028
2006	0.977	0.993	0.956	0.891	0.993	1.044	1	0.984	1.069	0.999	0.998	1.021	0.998	0.997	1.031
2007	1	0.998	0.973	0.978	0.985	1.067	1	0.949	1.124	0.99	0.995	1.04	0.998	0.983	1.072
Mean	0.996	0.994	0.959	0.874	0.977	1.003	1	0.984	1.06	0.984	0.998	1.012	0.973	0.991	0.983

	SK Telecom			KTF			LG Telecom			Sprint Nextel			Verizon Wireless		
	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS
1998	1	0.967	0.9	1	0.885	1.188	1	0.872	1.2	0.756	0.989	0.943	1	0.877	0.804
1999	0.957	0.997	0.969	1	0.887	1.187	0.907	0.922	1.153	0.762	0.972	0.91	1	0.869	0.798
2000	1	0.993	0.954	1	0.959	1.111	0.988	0.946	1.128	0.844	0.952	0.881	0.927	0.853	0.785
2001	1	0.996	0.966	1	0.966	1.1	1	0.934	1.141	0.942	0.949	0.876	0.908	0.83	0.767
2002	1	0.997	0.972	1	0.974	1.087	0.972	0.951	1.121	0.906	0.965	0.897	1	0.843	0.777
2003	1	1	0.997	1	0.981	1.075	0.766	0.974	1.087	0.916	0.975	0.914	1	0.861	0.791
2004	0.999	0.999	0.981	1	0.974	1.087	0.94	0.939	1.135	0.922	0.983	0.928	1	0.849	0.781
2005	1	1	1	1	0.974	1.088	0.883	0.947	1.126	0.885	0.987	0.938	1	0.861	0.791
2006	0.982	0.999	1.014	1	0.958	1.112	1	0.923	1.153	0.877	0.991	0.949	1	0.869	0.797
2007	0.967	0.998	1.023	1	0.926	1.149	0.814	0.894	1.181	0.791	0.996	0.964	1	0.89	0.815
Mean	0.993	0.986	0.958	1	0.949	1.118	0.927	0.93	1.142	0.872	0.975	0.918	0.984	0.86	0.791

	Rogers wireless			Telus (Mobility)			**Mean**		
	SE_D	SE_S	RTS	SE_D	SE_S	RTS	SE_D	SE_S	RTS
1998	0.932	0.998	0.974				0.928	0.941	0.966
1999	0.851	0.997	0.969	0.859	0.987	0.938	0.918	0.957	0.961
2000	0.826	0.999	0.986	0.817	0.985	0.934	0.876	0.956	0.944
2001	0.829	0.998	0.974	0.63	0.964	0.897	0.914	0.953	0.931
2002	0.82	0.996	1.034	0.873	0.988	0.94	0.938	0.948	0.922
2003	0.762	0.992	1.047	0.98	0.997	0.971	0.947	0.974	0.968
2004	0.777	1	1	1	0.998	0.978	0.95	0.969	0.966
2005	0.89	0.994	1.043	1	0.999	0.987	0.953	0.97	0.973
2006	1	0.978	1.08	1	1	0.992	0.955	0.969	0.975
2007	1	0.962	1.106	0.992	1	0.998	0.951	0.968	0.998
Mean	0.885	0.992	1.014	0.906	0.991	0.96	0.939	0.963	0.959

SE_S is the scale efficiency estimates from SFA; SE_D is the DEA counterparts as a robustness check.
RTS is the overall inputs returns to scale.
RTS = 1 indicates constant return to scale (CRS); RTS < 1 indicates decreasing returns to scale (DRS); and RTS > 1 indicates increasing returns to scale (IRS).

Table 5: Summary firms' SE and RTS, 2007, and national regulatory standard for mobile telecoms

Firm	Ownership	Independent regulator	Number MNOs by 2007	SE (2007)	RTS (2007)	Average annual GDP growth
China		No	2			9.24%
China Mobile	state			0.852	0.78	
China Unicom	state			0.930	0.85	
Korea		Yes	3			4.33%
SK Telecom	private (2002)			0.998	1.02	
KTF	private (2002)			0.926	1.15	
LG Telecom	private (2002)			0.894	1.18	
Unite Kingdom		Yes	5			2.76%
Vodafone UK	private			1.000	1.00	
O2UK	private			1.000	1.00	
Orange UK	private			0.991	1.05	
Deutschland		Yes	4			1.34%
O2Germany	private			1.000	1.00	
Vodafone Germany	private			0.998	0.97	
E-plus	private			0.985	1.07	
France		Yes	3			2.15%
Orange France	private			0.949	1.12	
Bouygues Telecom	private			0.995	1.04	
SFR	private			0.983	1.07	
Unite Sates		Yes	6			2.98%
T-mobile USA	private			0.989	0.94	
Sprint Nextel	private			0.996	0.96	
Verizon Wireless	private			0.890	0.82	
Canada		Yes	5			3.26%
Rogers wireless	private			0.962	1.11	
Telus (Mobility)	private			1.000	1.00	

Note: RTS = 1 indicates constant return to scale (CRS); RTS < 1 indicates decreasing returns to scale (DRS); and RTS > 1 indicates increasing returns to scale (IRS). SE = 1 indicates the most productive scale size.

Appendix A: DEA approach to scale efficiency

In the nonparametric DEA approach, firm scale efficiency can be simply calculated by the ratio of technical efficiency (*TE*) scores measured under constant returns to scale (CRS) over the *TE* scores measured under variable returns to scale (VRS), ie. $SE_i = TE_{ic}/TE_{iv}$.[31] The *TE* of a firm is measured relative to the *TE* of all the other firms in the sample, subject to the restriction that all firms are on or below the production frontier. We calculate the output-oriented *TE* scores by solving the linear programme (LP) problem for each firm, with (one) output, y_i, and three inputs, x_i ($x_i = x_{1i}, x_{2i}, x_{3i}$), under an assumption of CRS. The LP problem is specified as:

$$\text{Maximize w.r.t. } \phi_i, \lambda : \phi_i$$

$$\begin{aligned} \text{Subject to} \quad & \textstyle\sum_s \lambda_s y_s - \phi_i y_i \geq 0,\ s = 1, 2, ..., N \\ & x_i - \textstyle\sum_s \lambda_s x_s \geq 0, \\ & \lambda_s \geq 0, \end{aligned} \tag{1}$$

where λ_s is a vector of optimal weights defined by optimization LP problem (with a constraint $\beta' x_i = 1$ to avoid the problem of infinite solutions), such that the efficiency measure of the *i*-th firm is maximized subject to the restriction that the efficiencies of all firms must be less than or equal to one, and that all weights are non-negative. In the solution, $1 \prec \phi_i \prec \infty$, and the value of $\phi_i - 1$ measures the extent to which outputs could conceivably be increased using the same inputs – relative to other firms in the sample. The value of $1/\phi_i$ is the output-oriented *TE* score for the *i*-th firm.[32] It satisfies $0 \prec 1/\phi_i \leq 1$, where a value which equals one indicates a point on the frontier and hence a technically efficient firm, referring to the Farrell (1957) definition.

Note that the above TE is measured under the assumption of CRS in which assumes all firms are operating at an optimal scale (i.e. corresponding to the flat portion of the long-run average cost curve). However, when not all firms are operating at the optimal scale, the *TE* scores

[31] Follow the literature, we use the subscript '*c*' denotes the CRS assumption; and the subscript '*v*' denotes the VRS assumption.

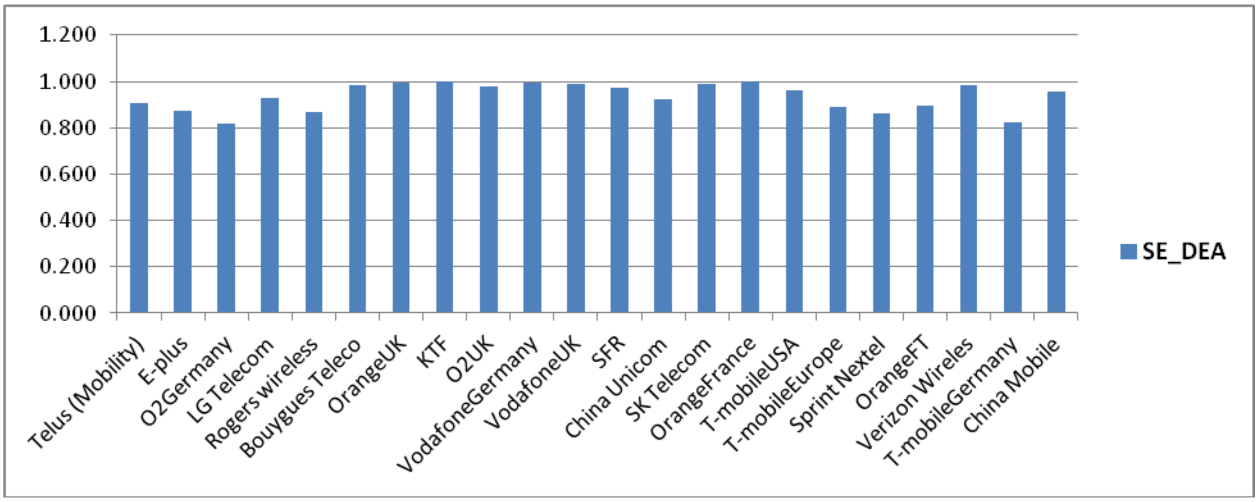
[32] An alternative view of the optimization process is to consider the *input-oriented* efficiency measure, i.e. measuring the extent to which the DMU could reduce inputs to obtain the same output – again relative to the standard of other DMUs in the sample. The LP problem for *input-oriented* efficiency measure is specified as: Min. w.r.t. θ_i, λ: θ_i

$$\begin{aligned} \text{Subject to} \quad & \textstyle\sum_s \lambda_s y_s - y_i \geq 0,\ s = 1, 2, ..., N \\ & \theta_i x_i - \textstyle\sum_s \lambda_s x_s \geq 0, \\ & \lambda_s \geq 0, \end{aligned}$$

where the scalar θ_i is the *input-oriented* TE score for the *i*-th DMU, satisfying $\theta_i \leq 1$, with a value of one indicating a point on the frontier and thus a technically efficient DMU. However, the *input-oriented* efficiency measure provides the same value as the *output-oriented* efficiency measure under the CRS. In addition, it should be emphasized that the *output*- and *input*-oriented models will estimate exactly the same frontier and therefore, by definition, identify the same set of DMUs as being efficient. It is only the efficiency measures associated with the *in*efficient DMUs that may differ between the two methods if the VRS is assumed. Although the two measures are unequal under the VRS, nevertheless, the influences upon the efficiency scores obtained are only minor (Coelli and Perelman, 1996). This point is also confirmed by my data. Hence, in this study, in order to consist with Färe et al.'s (1994) CRS (*output-oriented*) Malmquist TFP measure (also used in this study), the *output-oriented* efficiency measure is chosen.

measured by CRS model is confounded by scale efficiencies (*SE*). Therefore, the assumption is relaxed to a VRS model proposed by Banker, Charnes and Cooper (1984) by adding a restriction, $\sum_s \lambda_s = 1$, so as to permit the calculation of *TE* devoid of the potential *SE* effects.

Graph 2: Average SE scores across mobile network providers (DEA estimates)



Appendix B: SFA Input Elasticity breakdown

Input Elasticity (returns to scale) estimates from SFA

	China Mobile				China Unicom				Vodafone UK				O2UK			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
1998	0.28	0.33	0.26	0.87	0.66	-0.11	0.33	0.88								
1999	0.36	0.23	0.23	0.82	0.62	-0.05	0.28	0.85	0.09	0.60	0.28	0.96	0.02	0.77	0.22	1.00
2000	0.37	0.18	0.24	0.78	0.61	-0.12	0.31	0.80	0.08	0.60	0.29	0.97	0.06	0.68	0.27	1.00
2001	0.34	0.32	0.14	0.80	0.52	0.07	0.24	0.83	0.20	0.56	0.17	0.94	0.16	0.57	0.24	0.97
2002	0.40	0.26	0.09	0.75	0.51	0.06	0.23	0.80	0.22	0.57	0.16	0.95	0.39	0.62	-0.11	0.89
2003	0.37	0.33	0.07	0.77	0.34	0.33	0.18	0.85	0.15	0.64	0.19	0.98	0.17	0.68	0.15	1.00
2004	0.41	0.28	0.06	0.74	0.34	0.35	0.16	0.85	0.23	0.66	0.06	0.95	0.17	0.70	0.13	1.00
2005	0.43	0.29	0.02	0.74	0.37	0.26	0.20	0.83	0.23	0.67	0.07	0.97	0.24	0.66	0.09	0.99
2006	0.39	0.32	0.05	0.76	0.36	0.28	0.21	0.85	0.23	0.69	0.07	0.99	0.35	0.40	0.20	0.95
2007	0.34	0.34	0.10	0.78	0.38	0.26	0.22	0.85	0.22	0.72	0.06	1.00	0.23	0.57	0.20	1.00
Mean	0.38	0.24	0.18	0.80	0.47	0.13	0.24	0.84	0.18	0.63	0.15	0.97	0.20	0.63	0.15	0.98
	Orange UK				Orange FT				T-mobile				T-mobile Europe			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
1999					0.04	0.79	0.14	0.97								
2000					0.04	0.72	0.19	0.94								
2001					0.05	0.69	0.17	0.91	0.15	0.69	0.00	0.84				
2002	0.18	0.57	0.21	0.96	0.08	0.69	0.14	0.90	0.31	0.71	-0.24	0.77				
2003	0.16	0.58	0.23	0.98	0.06	0.72	0.15	0.93	0.00	0.78	0.14	0.92				
2004	0.23	0.56	0.16	0.96	0.10	0.72	0.08	0.91	-0.03	0.84	0.12	0.93				
2005	0.17	0.57	0.27	1.00	0.08	0.77	0.09	0.93	0.06	0.78	0.07	0.91	0.08	0.81	0.07	0.96
2006	0.15	0.58	0.29	1.03	0.05	0.84	0.05	0.95	0.10	0.71	0.10	0.91	0.14	0.73	0.09	0.95
2007	0.13	0.63	0.29	1.05	0.08	0.82	0.05	0.95	0.10	0.71	0.10	0.91	0.14	0.73	0.08	0.95
Mean	0.17	0.58	0.24	1.00	0.06	0.75	0.12	0.93	0.10	0.75	0.04	0.88	0.12	0.76	0.08	0.95
	T-mobile USA				O2Germany				Vodafone Germany				E-plus			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
2000					0.38	0.07	0.53	0.98								
2001					0.24	0.51	0.25	1.01								
2002					0.63	0.50	-0.28	0.85	0.22	0.65	0.08	0.95	0.68	0.44	-0.29	0.82
2003					0.21	0.65	0.19	1.05	0.19	0.68	0.10	0.97	0.31	0.64	0.06	1.00
2004					0.21	0.72	0.13	1.05	0.27	0.67	0.00	0.95	0.27	0.73	0.04	1.04
2005	0.18	0.59	0.17	0.93	0.27	0.68	0.09	1.04	0.31	0.62	0.03	0.95	0.30	0.75	0.00	1.04
2006	0.19	0.55	0.20	0.94	0.66	0.22	0.03	0.90	0.33	0.57	0.05	0.96	0.34	0.67	0.04	1.04
2007	0.20	0.53	0.21	0.94	0.44	0.47	0.09	0.99	0.33	0.60	0.04	0.97	0.34	0.68	0.04	1.07
Mean	0.19	0.55	0.19	0.94	0.38	0.48	0.13	0.98	0.27	0.63	0.05	0.96	0.37	0.65	-0.02	1.00
	Orange France				Bouygues Telecom				SFR				SK Telecom			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
1998									0.18	0.67	0.08	0.93	0.31	0.50	0.09	0.90
1999									0.08	0.73	0.15	0.97	0.11	0.72	0.14	0.97
2000									0.11	0.66	0.19	0.96	0.14	0.78	0.03	0.95
2001					0.30	0.16	0.52	0.98	0.21	0.51	0.18	0.91	0.20	0.76	0.00	0.97
2002	0.06	0.76	0.19	1.02	0.23	0.47	0.29	0.99	0.18	0.64	0.13	0.95	0.20	0.79	-0.02	0.97
2003	0.05	0.80	0.19	1.04	0.23	0.53	0.25	1.00	0.13	0.76	0.10	0.99	0.17	0.82	0.01	1.00
2004	0.08	0.83	0.14	1.04	0.21	0.55	0.25	1.01	0.16	0.76	0.07	0.99	0.21	0.79	-0.02	0.98
2005	0.03	0.92	0.12	1.07	0.16	0.64	0.23	1.04	0.12	0.83	0.08	1.03	0.22	0.81	-0.03	1.00
2006	0.07	0.89	0.10	1.07	0.24	0.61	0.17	1.02	0.16	0.77	0.10	1.03	0.20	0.80	0.02	1.01
2007	0.01	0.99	0.12	1.12	0.23	0.62	0.19	1.04	0.12	0.89	0.05	1.07	0.18	0.80	0.05	1.02
Mean	0.05	0.87	0.14	1.06	0.23	0.51	0.27	1.01	0.15	0.72	0.11	0.98	0.21	0.72	0.03	0.96

Lrts denotes labour input elasticity; Mrts denotes material input elasticity; and Krts denotes capital input elasticity. RTS is the overall scale elasticity (returns to scale).

RTS = 1 indicates constant return to scale (CRS); RTS < 1 indicates decreasing returns to scale (DRS); and RTS > 1 indicates increasing returns to scale (IRS).

Input elasticity (returns to scale) estimates from SFA (Continued)

	KFT				LG Telecom				Sprint Nextel				Verizon Wireless			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
1998	-0.09	0.94	0.33	1.19	-0.07	0.90	0.37	1.20	0.08	0.70	0.16	0.94	0.28	0.25	0.28	0.80
1999	-0.12	1.10	0.21	1.19	-0.01	0.94	0.22	1.15	0.10	0.70	0.11	0.91	0.29	0.22	0.29	0.80
2000	0.02	0.93	0.16	1.11	0.04	0.97	0.12	1.13	0.14	0.60	0.14	0.88	0.23	0.36	0.19	0.78
2001	0.03	0.93	0.14	1.10	0.08	0.81	0.25	1.14	0.13	0.59	0.16	0.88	0.27	0.34	0.15	0.77
2002	0.07	0.97	0.04	1.09	0.11	0.79	0.22	1.12	0.12	0.62	0.16	0.90	0.29	0.31	0.17	0.78
2003	0.14	0.93	0.00	1.07	0.23	0.74	0.11	1.09	0.13	0.64	0.15	0.91	0.30	0.33	0.16	0.79
2004	0.14	0.98	-0.03	1.09	0.12	0.91	0.11	1.14	0.14	0.65	0.14	0.93	0.32	0.28	0.17	0.78
2005	0.17	0.95	-0.04	1.09	0.15	0.85	0.12	1.13	0.11	0.78	0.05	0.94	0.32	0.28	0.19	0.79
2006	0.14	1.02	-0.04	1.11	0.11	0.92	0.12	1.15	0.09	0.92	-0.06	0.95	0.36	0.23	0.21	0.80
2007	0.05	1.14	-0.04	1.15	0.06	0.98	0.14	1.18	0.09	0.91	-0.03	0.96	0.34	0.26	0.22	0.82
Mean	0.05	0.99	0.07	1.12	0.08	0.88	0.18	1.14	0.12	0.69	0.10	0.92	0.30	0.29	0.20	0.79

	Rogers wireless				Telus (Mobility)				**Mean**			
	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**	Lrts	Mrts	Krts	**RTS**
1998	0.33	0.32	0.33	0.97					0.22	0.50	0.25	0.97
1999	0.35	0.26	0.36	0.97	0.40	0.29	0.25	0.94	0.18	0.56	0.22	0.96
2000	0.32	0.32	0.34	0.99	0.39	0.27	0.28	0.93	0.21	0.50	0.23	0.94
2001	0.37	0.27	0.33	0.97	0.51	0.19	0.19	0.90	0.23	0.50	0.20	0.93
2002	0.33	0.44	0.26	1.03	0.46	0.13	0.34	0.94	0.28	0.55	0.09	0.92
2003	0.32	0.51	0.22	1.05	0.41	0.17	0.39	0.97	0.20	0.61	0.15	0.97
2004	0.37	0.33	0.31	1.00	0.41	0.16	0.40	0.98	0.22	0.62	0.12	0.97
2005	0.28	0.52	0.25	1.04	0.40	0.20	0.39	0.99	0.21	0.65	0.11	0.97
2006	0.25	0.61	0.22	1.08	0.40	0.21	0.38	0.99	0.24	0.62	0.12	0.97
2007	0.21	0.66	0.23	1.11	0.41	0.23	0.36	1.00	0.21	0.66	0.13	1.00
Mean	0.30	0.42	0.29	1.01	0.42	0.21	0.33	0.96	0.23	0.58	0.15	0.96

Lrts denotes labour input elasticity; Mrts denotes material input elasticity; and Krts denotes capital input elasticity. RTS is the overall scale elasticity (returns to scale).
RTS = 1 indicates constant return to scale (CRS); RTS < 1 indicates decreasing returns to scale (DRS); and RTS > 1 indicates increasing returns to scale (IRS).

Appendix C: Summary of firm SE and RTS over observation years

Firm	SE	RTS	Total Revenue (2007, in bln US$s)
China Mobile	0.85	0.78	48.3
T-mobileGermany	0.95	0.88	47.7
Verizon Wireles	0.86	0.79	43.9
AT&T Mobility	1.00	0.98	42.7
OrangeFT	0.98	0.93	39.9
Sprint Nextel	0.98	0.92	34.7
T-mobileEurope	0.99	0.95	28.4
T-mobileUSA	0.99	0.94	19.3
OrangeFrance	0.98	1.06	13.7
SK Telecom	0.99	0.98	12.9
China Unicom	0.91	0.84	12.6
SFR	0.99	0.98	12.4
VodafoneUK	1.00	0.97	10.7
VodafoneGermany	0.99	0.96	10.5
O2UK	0.99	0.98	10.1
KTF	0.95	1.12	8.8
OrangeUK	1.00	1.00	8.5
Bouygues Teleco	1.00	1.01	6.5
Rogers wireless	0.99	1.02	5.1
LG Telecom	0.93	1.14	4.9
O2Germany	0.98	0.98	4.9
E-plus	0.98	1.00	4.1
Telus (Mobility)	0.99	0.96	4.0

Note: 2007 firm total operating revenues in the mobile service segment are used as a proxy of firm size.