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Ryan Hawthorne, Lukasz Grzybowski

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Narrowing the 'Digital Divide': The Role of Complementarities Between Fixed and Mobile Data in South Africa

Abstract

We study substitution between fixed and mobile broadband services in South Africa using survey data on 134,000 individuals between 2009 and 2014. In our discrete-choice model, individuals choose fixed or mobile voice and data services in a framework that allows them to be substitutes or complements. We find that voice services are complements on average but data services are substitutes. However, many consumers see data services as complements. Our results show that having a computer and access to an internet connection at work or school are more important than reducing mobile data prices by 10% in driving broadband penetration.

JEL-Codes: L130, L430, L960.

Keywords: fixed-to-mobile substitution, mobile broadband, fixed broadband.

*Ryan Hawthorne**
University of Cape Town
School of Economics, Rondebosch
South Africa – 7701, Cape Town
ryandavidhawthorne@gmail.com

Lukasz Grzybowski
Telecom ParisTech
46 rue Barrault
France – 75013 Paris
lukasz.grzybowski@telecom-paristech.fr

*corresponding author

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1 Introduction

Mobile broadband is the main means of connecting to the internet in developing countries, where fixed-line coverage is typically limited or non-existent.[1] As a result, governments in developing countries are seeking means by which mobile broadband penetration might be increased. One such intervention is regulating mobile networks on an 'open access' (shared infrastructure) basis, which is similar to the unbundling of the local loop in respect of fixed lines in many developed countries. For example, in Russia, Mexico and Rwanda, the government forced the separation of wholesale upstream mobile network services and downstream retail services by assigning spectrum to wholesale-only upstream ventures.[2] The government in Kenya considered a similar intervention and the government in South Africa has proposed a wholesale open access mobile network.

These interventions may offer a way to catch up with developed countries in respect of broadband penetration. Moreover, the impact of mobile phones and internet access has attracted a lot of attention among policymakers and researchers. Mobile networks are significantly less costly to deploy and can be used to 'leapfrog' fixed lines for broadband access. For instance, Aker and Mbiti (2010) and Blimpo et al. (2017) discuss the role of mobile phones for economic development in Africa. In another recent paper, Hjort and Poulsen (forthcoming) found a positive impact of broadband on employment and labour productivity in African countries.[3]

However, mobile broadband has physical usage constraints due to the limited capacity of radio frequency spectrum, which is not the case for fixed-line broadband. As a result, mobile broadband typically has usage limits and high prices per unit of usage (per gigabyte) which results in lower usage per connection, while fixed-line broadband has significantly lower prices per unit and higher usage per connection. There is therefore a question as to whether mobile broadband can really replace fixed broadband in developing countries, or whether these two technologies complement each other as appears to be the case in developed economies, where most people rely on mobile and fixed broadband access together.

South Africa is an interesting place to study fixed and mobile substitution, because even though mobile broadband is the main means of connecting, there are also limited-coverage fixed-line networks.

[1] We consider fixed lines to be mainly copper or optical fibre connections to homes and businesses. There are a relatively small number of fixed-wireless connections in South Africa, where the end-user device is at a fixed location but the technology may be wireless, such as via satellite or other wireless technology. We consider that mobile broadband is offered in South Africa using EDGE, 3G or 4G connectivity. Most connections over the relevant period were 3G connections.

[2] Regulating open access to mobile networks is not limited to developing countries. For example, in the merger between T-Mobile and Orange in the UK (creating Everything Everywhere, EE), the UK Competition Commission insisted on remedies that forced EE to provide radio-access network sharing with Three UK in order to preserve the latter as an effective competitor.

[3] Additional papers that comment on the impact of mobile phones on economic development include those by Jensen (2007), Muto and Yamano (2009) and Aker (2010).

Fixed lines were rolled out in South Africa almost exclusively to Whites-only areas during apartheid, which came to an end in 1994. Since then, the growth of fixed-line networks has been facilitated by a more open licensing regime and the expansion of sub-sea optical fibre cables, which were connected to the African continent over the past decade.[4] South Africa therefore lies between developing countries in Africa which have very few fixed-lines and developed countries which have close to universal fixed-line coverage.

In this paper, we analyse fixed and mobile substitution for voice and data services. There are many studies on fixed and mobile substitution of voice services in developed countries. But there are no papers that consider substitution between mobile and fixed broadband access using detailed individual-level data in a developing country setting, where fixed-line infrastructure is underdeveloped and people mainly rely on mobile connections.

This research is useful for a number of reasons. First, the assessment of substitution or complementarity between fixed and mobile networks can support ongoing market inquiries into broadband services launched by regulators. For instance, the competition authority and the telecommunications regulator in South Africa separately launched market inquiries in 2017 and 2018 into the cost of data services. Second, it is useful for understanding the means by which broadband penetration can be increased and thus help bridge the 'digital divide'. The 'digital divide' arises within and between countries where access to technology is higher in developed compared to developing countries and is skewed towards high-income consumers within countries (see, for example, Bulman and Fairlie, 2016). This is an especially important problem in South Africa, where fixed-line broadband is available mainly in formerly Whites-only areas. Furthermore, we are able to capture at the individual level the role of factors that drive broadband penetration, including access to computers and access to the internet at work or school, which have not been emphasized previously. This corroborates survey evidence in South Africa and other countries that identify the high cost or lack of equipment, such as computers, as being a barrier to using the internet at home, rather than the price of subscribing to a service.[5]

[4]Licenses were granted to more than 400 licensees in around 2009, when a court ordered that limited-service licences issued under the previous telecommunications law be converted to full-service licences under the new Electronic Communications Act, no. 36 of 2005. In respect of sub-sea cables, the Seacom cable, which connects the North-East coast of South Africa with countries along the East coast of Africa, India and Europe, became operational in 2009. The East African Submarine Cable System (EASSy) lands in the same area in South Africa and connects with countries along the East cost of Africa, ending with Port Sudan in Sudan. Onward routes are provided via third party cable systems. Services on the cable have been operational since 2010. The West Africa Cable System (WACS) landed on the South-West coast of South Africa and began operating in 2012. The cable connects South Africa to countries along the West coast of Africa and in Europe.

[5]For example, in the general household survey run by Statistics South Africa, the most-cited reason for 'not having internet access at home' is 'cost of equipment is too high' (26% of survey respondents that have no internet connection at home). Only 6% of those that do not have internet access at home cite that their reason for this is that the cost of subscriptions is too high. Further evidence corroborating this result is found by Research ICT Africa who find in the 'After Access' survey that the cost of devices is the largest barrier to internet access in South Africa (see report published in 2018 entitled "The State of ICT in South Africa"). For examples of similar

We address these questions using survey data of more than 134,000 individuals for the years between 2009 and 2014. For each individual in the sample, we assess whether fixed and mobile data services are substitutes or complements, which depends on observed individual characteristics. We estimate a discrete-choice model where households may choose one or both fixed and mobile voice and data services. A key problem in the assessment of fixed and mobile substitution is separating out correlation of preferences with true complementarity or substitution.[6] We address this by using factors that shift the utility of fixed-line services without shifting the utility derived from mobile. In particular, we use information on consumers having a fixed-line at work or a gaming console (such as an Xbox) which shift the utility of fixed voice and fixed data access respectively but do not shift utility of having a mobile service.

We find that on average mobile and fixed data services are substitutes. But there is also a substantial share of individuals who perceive them as complements. In particular, we find that fixed and mobile broadband access are complements for a greater share of consumers who are employed, have higher incomes or have a computer, or have access to the internet at work or school. Thus, our analysis confirms that in developing economies people with lower incomes substitute mobile broadband for fixed broadband access. But at higher income levels and once consumers acquire a computer, they will derive higher utility from combining both mobile and fixed broadband access. We conclude that one of the ways of increasing both fixed and mobile broadband penetration is by expanding access to computers and by making internet available at work and educational facilities. In our counterfactual simulations, we show that this is more important than reducing prices of mobile data services by 10% through possible regulatory intervention. Furthermore, since we observe that employed and self-employed individuals derive higher utility from combining fixed and mobile services, having access to both technologies would increase welfare for higher employment levels. This is important since South Africa, like many developing countries in Africa, has very high levels of unemployment (37% using the expanded definition) which leads to high levels of poverty and inequality.

The remainder of the article is organized as follows. Section 2 discusses the relevant literature. Section 3 discusses the telecommunications sector and demographics in South Africa. Section 4 discusses the data used in the estimation. Section 5 introduces the econometric framework. Section 6 presents the estimation results. Finally, Section 7 concludes.

results from surveys in the U.S. see Hauge and Prieger (2010).

[6]See, in general, Samuelson (1974) and Berry et al. (2014) for a discussion on the challenges with identifying complementary goods.

2 Literature Review

A number of papers consider whether fixed and mobile telecommunications services are substitutes or complements. However, much of the literature is focused on voice services and relies on aggregate country-level data (Ward and Zheng, 2012; Grzybowski, 2014; Briglauer et al., 2011).

There are also papers that analyse consumer-level data in order to assess whether fixed and mobile access (mainly voice) are substitutes. Rodini et al. (2003) evaluate fixed and mobile access substitution using panel data on U.S. households. They use a binary logit model to estimate own- and cross-price elasticities of demand and find that fixed and mobile access (mainly voice) services are substitutes. Ward and Woroch (2010) use panel survey data on U.S. households for the years between 1999 and 2001 to test fixed and mobile substitution in respect of voice services. They use various approaches, including a difference-in-difference analysis, to estimate own- and cross-price elasticities of demand. They find that the two services are substitutes and in a simulation find that universal service had a negligible effect on overall phone penetration (fixed and mobile). Suárez and García-Mariñoso (2013) use panel data on Spanish households for the years between 2004 and 2009 to analyse substitution from fixed to mobile access in a binary logit model. They find that larger households and those with older members are less likely to switch to mobile. The authors also find that the availability of the Internet reduces the likelihood of fixed to mobile substitution, while prices and expenditures have only a small or no impact on the substitution decision.

There are also papers that consider fixed and mobile substitution in respect of internet access services. Cardona et al. (2009) analyse survey data for Austria and find high elasticities of demand for DSL services in areas where cable and mobile broadband are available (and lower elasticities where they are not). Their main finding is that cable and DSL form part of the same market but they could not conclude whether mobile broadband by itself can constrain DSL and cable because it had low penetration in Austria in 2006. Grzybowski et al. (2014) use data on 6,446 households in Slovakia to assess fixed and mobile substitution. They find relatively high elasticities of demand for fixed-line services, which means that the market for broadband services includes mobile services. Part of the reason for this is that, in former Soviet countries in Central and Eastern Europe (CEE), the copper networks were of poor quality. However, none of these studies consider Internet and voice services within the same model. Furthermore, these studies do not allow fixed and mobile to be substitutes or complements.

Another stream of recent literature on telecommunications services allows modelling complementarity or substitution of consumer choices. Liu et al. (2010) use panel data on 2,590 households in the U.S between 2004 and 2006 and develop a discrete-choice model that allows for additional utility from obtaining two services from the same provider, and for inertia in the choice of provider. They find that broadband, cable TV and local phone services are complementary. Moreover, consumers prefer obtaining these services from a single provider and they prefer using the same provider over time. They also find that having an internet connection at work results in a greater probability of having an internet connection at home. This may be due to 'learning effects' where users of high-speed internet at work learn applications for high-speed internet at home. In another paper, Macher et al. (2012) use U.S. household data for the years between 2003 and 2010 in a bivariate probit model to analyse whether fixed and mobile connections are substitutes or complements. Analysing cross-price effects, they conclude that mobile and fixed connections are substitutes rather than complements. Grzybowski and Verboven (2016) use survey data on about 160,000 households, collected between 2005 and 2011 in 27 EU countries, to analyse substitution from fixed-line to mobile voice access. While they find significant fixed-to-mobile substitution, their results show significant heterogeneity between households and EU regions. They find stronger substitution in Central and Eastern European countries, where the quality of fixed lines is poorer. They also find that the decline in fixed connections has been slowed by complementarity with broadband internet.

Our approach is similar to the latter paper and follows Gentzkow (2007), where we permit heterogeneity in substitution across households. This allows us to conclude whether fixed and mobile voice and data connections are substitutes, complements or independent from each other among different groups of consumers.

3 Industry

In South Africa over the period between 2009 and 2014, there was one partial-coverage fixed-line operator (Telkom) and two full-coverage mobile operator networks (MTN and Vodacom).[7] There were also two smaller mobile networks, Telkom Mobile (a division of the fixed-line incumbent) and Cell C, which used a combination of their own networks and national roaming on the MTN and Vodacom networks. All mobile operators' services are thus available throughout South Africa. At the same time, the fixed-line network is available mainly in urban areas that were reserved for Whites only during apartheid, which came to an end in 1994. Fixed lines are also available in business areas and in certain areas formerly reserved for Black, Coloured and Indian people where Telkom rolled them out to meet universal service obligations which were imposed on it in the late 1990s. Approximately 5.5 million landlines were rolled out to households in South Africa until 2001 (out of approximately 15 million households in total). In around 2001, the fixed-line incumbent began disconnecting households for non-payment. At that time pre-paid mobile voice services were growing as an alternative to traditional fixed line voice services, at

[7]There were certain other fixed-line networks, however they served largely businesses or small gated communities.

least for low-income consumers (see Hodge, 2005).

Vodacom and MTN began rolling out their Global System for Mobile (GSM) networks in the mid-1990s. Cell C entered the market towards the end of 2001, while Telkom Mobile entered towards the end of 2010. Over the period studied, almost the entire population was covered by 2G or 2.5G (EDGE) internet access by MTN and Vodacom, while Cell C and Telkom Mobile roamed on these networks.[8] But the quality of the smaller networks was lower because customers could lose connectivity when handed over to a roaming partner. MTN and Vodacom covered around 50% of the population with 3G services in 2009 and around 90% by 2014 and the roll-out of 4G began in 2013 (see Figure 3).

According to a survey by the official statistics agency in South Africa in 2017, approximately 60% of households report having at least one member that can connect to the internet, typically via their mobile phone. However, in the same survey, only a small proportion of households reported having an internet connection at home (around 10%), which implies that mobile broadband is used by individuals but not the entire household.[9] This low level of internet penetration at homes reflects the persistence of apartheid policies which excluded the vast majority of the population from basic services such as fixed-line telecommunications.

The lack of connectivity at homes may have led to limited usage of the internet. Almost 40% of consumers that report having an internet connection had not accessed the internet yesterday but rather accessed it 7 days, 4 weeks or 12 months ago.[10] This may be because connectivity via one household member's smartphone or dongle disappears when that member leaves the house. Moreover, mobile networks have capacity constraints related to available spectrum and thus implement maximum usage caps. This suggests that fixed-line broadband may be needed for households to provide all members with unlimited always-on connectivity.

4 Data

4.1 Survey data and demographics

We use six waves of the All Media Products Survey (AMPS) in the estimation. AMPS is a survey of approximately 25,000 consumers each year between 2009 and 2014. An exception is 2013, when data on only half that number is available.[11] The total number of observations is almost 138,000 observations,

[8] EDGE meets the standard for 3G but is often referred to as 2.5G.

[9] Source: Statistics South Africa, 2017. "General Household Survey", Statistical Release P0318.

[10] Source: Respondents to the All Media Products Survey (2009-2014), used in this paper to analyse fixed and mobile substitution.

[11] The AMPS survey is a rolling six-month survey of approximately 12,500 consumers in each period. The committee responsible for the survey omitted several questions used in our model in the July-December 2013 period and this made the observations unusable.

before data processing. This dataset contains information on consumer choices of a range of products and services as well as on personal and household characteristics. The survey samples a greater proportion of higher-income consumers in urban areas than a nationally representatitive sample would.[12] Nonetheless, the survey includes large sample sizes across race, income and other demographic groups (see Table 1).

We use the survey to model choices of fixed and mobile voice and data services. To do this we need to account for the geographic coverage of the networks to define what choices consumers have. As discussed in Section 3, over the period between 2009 and 2014, most of the population in South Africa was covered by mobile broadband services. While a map of cellphone towers shows coverage gaps, these are typically in sparsely populated areas (see Figure 2a).

We do not have information on coverage by the fixed network and we use the survey data to define fixed-coverage areas. A map of Telkom's fixed-line broadband exchanges shows that they are concentrated in cities and towns. There are also a number of exchanges scattered in rural areas, which were often rolled out to serve White farmers during apartheid (see Figure 2b).

During apartheid, the population was segregated according to racial groups, which were Black, White, Indian and Coloured. These patterns of segregation have persisted in the post-Apartheid era, and we rely on this to define fixed-line coverage over the period we study here (2009-2014). In particular, fixed-lines have largely not been rolled out or have been disconnected outside of Whites-only areas due to the theft of copper cables in rural areas and non-payment of postpaid services. As a result of discriminatory policies in this period, White people have significantly higher incomes compared to other racial groups. Indian people were discriminated against during apartheid but benefited from having more access to public resources and from living in urban areas, while many Black and Coloured people live in rural areas with substantially lower funding for education and healthcare. Indian people therefore have lower incomes than White people though both groups have higher incomes than Black and Coloured people. Many Black people were forced during apartheid to live in rural 'homelands' and had to carry pass books to be allowed into urban areas, known as the 'dompas'. These rural homelands were closely associated with race and language groups, and provinces that integrated homelands continue to be characterised by this.

We use this demographic information in order to determine whether a household has fixed-line coverage. First, for the reasons stated above, we consider that fixed lines are available to all White households, including in rural areas. Second, we consider that fixed lines are only available to Black, Coloured and Indian households where the following is reported on the dwelling: (i) has a flush toilet

[12]This is an annual survey conducted by the South African Advertising Research Foundation (SAARF), now called the Marketing Research Foundation of South Africa (MRFSA), on buyers of a range of products, in order to match media companies (such as newspapers, TV stations and radio stations) and advertisers of the various products surveyed. The data was made available to us by DataFirst at the University of Cape Town.

inside or outside, (ii) is a house or flat (and not a hut or a shack), (iii) has a water connection and (iv) indoor plumbing (a built-in kitchen sink) and (v) has an electricity connection (see Figure 4). Furthermore, we consider that Black and Coloured households in rural areas (i.e. living on farms etc.) do not have fixed-line coverage. These assumptions imply that two-thirds of individuals in the AMPS dataset has fixed-line coverage. This number appears to be higher than the true population coverage of the fixed-line network, which as discussed above at its height covered approximately 5.5 million out of 15 million households in South Africa. But we observe that the AMPS survey includes a greater proportion of people living in urban areas who also tend to have higher incomes.

We dropped 1,951 observations where consumers responded having a telephone at home while according to our assumptions they live in areas with no fixed-line coverage.[13] We also dropped 612 observations where consumers reported having a mobile internet connection and at the same time declared not having a mobile network operator. In our model, households with no fixed-line coverage have a choice set limited to mobile services. They can choose between between no mobile, mobile voice only or mobile voice and data provided by one of the network operators. All users within a fixed-coverage area are then also given the option to choose between no fixed services, fixed voice and fixed voice & data services (see Table 2 and Table 3).

The usage of fixed or mobile connections in South Africa varies significantly depending on demographic characteristics (see Table 1). A large proportion of consumers that have computers also have a fixed line or mobile service (48% of consumers that have a computer also have a fixed line, whereas only 14% of consumers that do not have a computer have a fixed line). At the same time, almost all consumers in our sample that have both fixed and mobile data connections also have a computer. This is in line with the experience in other countries: the positive relationship between access to the internet at home and having a computer can also be observed across countries (see Figure 1). The lack of a computer has also previously been reported as a barrier to the adoption of broadband services (see, for example, Hauge and Prieger, 2010).

Similarly, a larger proportion of individuals that have an internet connection at work or school choose fixed and mobile data compared to those that do not. A similar result is found by Liu et al. (2010).

As can be expected, the usage of fixed and mobile services increases with income which in South Africa is strongly correlated with race. The proportion of consumers that use a mobile service does not vary among racial groups but the proportion using fixed lines does. While 49% of White consumers

[13]We carried out robustness checks to see whether alternative means of developing a proxy for fixed-line coverage would lead to a different outcome. First, we removed the assumption that all White households have fixed-line coverage. This resulted in 2,182 households having a telephone at home while not having fixed line coverage, which is not very different to our baseline assumption. Next, we reinstated the coverage assumption in respect of White households and removed the assumption that Black and Coloured households in rural areas have no coverage, and find that 1,788 households report a fixed-line where there is no fixed-line coverage. Again, this result is very close to our baseline assumption.

have a fixed connection, only 8% of Black consumers do. Fixed and mobile choices among different language groups roughly follow the corresponding race group. While choices of mobile are roughly similar among language groups, a significantly larger proportion of English and Afrikaans-speakers (who are predominantly White, Coloured and Indian) have fixed-line services. In addition, language and race overlap with geographic regions (provinces) in South Africa.[14]

We allow the demographic variables discussed above to influence the degree of complementarity or substitution between fixed and mobile voice, and between fixed and mobile voice and data. The impact of these variables is discussed in more detail in Section 6.

4.2 Prices

Prices used in our model were obtained from Research ICT Africa (2010-2015) and Tarifica.[15] In addition, we completed the database using an online archive service, the Internet Archive. Prices of voice services were matched to consumers by payment method (pre-paid or post-paid) and estimated usage of voice minutes based on cellphone spend. Prices of mobile broadband were assigned based on declared intensity of internet usage.

First, we grouped mobile consumers as pre-paid or post-paid users based on the type of contract they have.[16] In respect of voice services, all pre-paid consumers belong to one segment. Post-paid consumers were divided into three groups: low, medium and high users, according to their declared monthly cellphone spend. Low-usage consumers are assumed to have monthly bills in the range R1-150

[14] There are eleven official languages in South Africa. The languages spoken most often are Zulu, Xhosa, Afrikaans, English, Northern Sotho (Sesotho sa Leboa or Sepedi), Setswana and Sesotho. The languages spoken by relatively smaller minorities are Xitsonga, siSwati, Tshivenda and isiNdebele. The main language in the KwaZulu-Natal province, the most populous province in South Africa, is Zulu. Xhosa-speakers mainly live in the Eastern Cape. Afrikaans and English are spoken mainly in towns and cities including in Gauteng province, and Afrikaans is also spoken in the Western Cape and Northern Cape provinces, including in rural areas particularly among Coloured people. A significant proportion of Sepedi and Tshivenda-speakers live in Limpopo, while Sesotho-speakers largely live in the Free State (a province bordering Lesotho). Setswana speakers largely live in the neighbouring North-West province. Siswati speakers and a significant proportion of isiNdebele speakers live in Mpumalanga province which borders eSwatini (Swaziland). A significant proportion of Xitsonga-speakers also live in Mpumalanga and neighbouring Limpopo. Since the Zulu, siSwati and isiNdebele languages are linked linguistically and geographically, we group these languages together as 'Zulu+'. Sepedi, Setswana, Sesotho, Xitsonga and Tshivenda are largely spoken in the Northern parts of South Africa, and we group these languages as 'Sesotho+'.

[15] Research ICT Africa is a non-governmental organisation that collects data and conducts research on telecommunications in Africa. Tarifica is a market-intelligence firm which collects information on prices of telecommunications services worldwide.

[16] In South Africa, most subscribers are on prepaid plans and are typically unable to choose between prepaid and postpaid because they do not meet the income and employment requirements for a postpaid contract. This is a result of low levels of employment and participation in the labour force. According to the "Quarterly Labour Force Survey" undertaken by Statistics South Africa (publication P0211), the employed population divided by the number of adults in South Africa (aged 15-65 years), i.e. the 'labour absorption rate', varied between 41% and 46% over the period between 2009 and 2014. The unemployment rate varied between 22% and 26% using the official definition (active job seekers) while the expanded definition (i.e. including discouraged work seekers) varied between 30% and 36%.

per month, medium-usage consumers in the range R151-500 per month and high-usage consumers above R500 per month.[17]

Next, we computed average prices per calling minute for each market segment. We assumed different monthly usage of minutes for each segment: 30 minutes for pre-paid (1 minute per day), 180 minutes for low-usage post-paid (6 per day), 540 minutes for medium-usage (18 per day) and 1,080 minutes for high-usage consumers (36 per day).[18] In South Africa, prices differ depending on whether calls are terminated on the same network (on-net), other mobile networks (off-net) or on the fixed network. For pre-paid and post-paid consumers we assume the same distribution pattern of calls where 10% of minutes are terminated on fixed lines and the rest on mobile networks. Calls terminated on mobile networks are distributed according to mobile operator market shares. We also assume that 50% of calls are made in 'peak' times and the balance in 'off-peak' times, for which there are different prices for some tariffs.[19]

This distribution pattern of phone calls is used to compute the average per minute price for all pre-paid tariffs. We then selected the lowest tariff for each operator in a given year. We assume that pre-paid consumers observe prices generated in this way when choosing tariffs from different operators. We compute average prices per minute observed by post-paid low, medium and high voice usage consumers in a similar way.

In respect of mobile data, the price is determined by the cost of bolt-on bundles, which were typically purchased in addition to basic tariff plans. The operators did not differentiate between prepaid and post-paid bolt-on prices over the period between 2009 and 2014. We classify consumers into low, medium and high data-usage categories based on their declaration of internet use in the survey. Low mobile data users reported being connected to the internet via mobile. Medium users declared using mobile internet for instant messaging and email. High users declared using mobile broadband for photos and video (in addition to instant messaging and email).

[17] The South African currency is highly volatile but as of December 2018 one US dollar was approximately 14.6 Rands. Classifying consumers into high, medium and low usage groups is a standard approach to segmenting telecommunications subscribers. The spending bands were selected to broadly reflect regular intervals and available mobile packages, and so as to ensure a large number of observations would fall within each category. Approximately 25% of postpaid customers fall within the first group, around 53% fall within the second category and the remaining 22% fall within the highest spend group. The second category has a greater proportion since almost 25% of postpaid customers spend between R271-R500 per month. Since there are many more packages advertised in the R151-R500 spend level than above R500, it made more sense to allocate the R271-R500 category to the medium-spend group.

[18] These usage categories are similar to the OECD mobile voice call baskets cited below, of 30, 100, 300 and 900 calls per month. The groups are also not far from minutes of use reported by Vodacom in its annual reports between 2009 and 2014, for example, for prepaid and postpaid customers. Prepaid customers on the Vodacom network used between 52 minutes and 116 minutes per month on average, depending on the year, while postpaid consumers used between 182 and 240 minutes per month.

[19] This is in line with the OECD usage baskets mentioned above, which assume that 46% of calls are made during the day, 27% are made during the evening and 27% over the weekend. In South Africa, weekend and evening calls are grouped together under the 'off-peak' period. Source: OECD, 2017, "Revised OECD Telecommunications Price Baskets".

Similarly, data bundles offered by mobile operators were categorized depending on customer segment as low, medium and high. If there was more than one tariff plan available in the segment, we used the lowest available price per gigabyte. Mobile voice and data customers could belong to different voice and data profiles and prices were assigned accordingly. For example, a high usage postpaid customer on the MTN network in 2014 paid R1.02 per minute for a voice call assuming usage of 1,080 minutes as described above, and R79.80 per gigabyte for 5 GB of mobile data.

Fixed-line broadband services were typically bundled with voice services which means there is no 'naked ADSL' option. In most years, fixed-line broadband was offered for three usage profiles: low, medium and high and we used these profiles to group fixed-broadband users. Low fixed-data users reported being connected to the internet. Medium users reported accessing the internet for services such as email, banking and news. High users in addition reported accessing the internet for television and gaming. There is a subscription price for voice only, which includes an allowance of voice minutes, and there are prices for bundles of voice and data. Where there was more than one fixed tariff available, we selected the lowest-price alternative. For example, a high-usage fixed data customer would pay R904 per month and receive 40GB of data over a 10 megabit per second line and unlimited voice calling minutes to other fixed lines.[20] We tested our results against different usage specifications and our estimates of price coefficients are comparable.

5 Econometric Model

We model consumer choices of fixed and mobile voice and data services. We account for the fact that many individuals use fixed and mobile connections together and formulate a discrete-choice model for *bundles* of alternatives following Gentzkow (2007).

In our setup, fixed broadband connections are offered by a single network operator and there are three or four mobile operators depending on the year. An individual consumer i can choose stand-alone voice services on the fixed network ($f = f_v$) or combined fixed voice and data services ($f = f_d$). Thus, with respect to fixed broadband, there are three choice alternatives $f \in F = \{0, f_v, f_d\}$, where $f = 0$ refers to the choice of no fixed services at all.

A consumer can subscribe to mobile operator k and choose stand-alone voice services ($m = m_{vk}$) or combined voice and mobile broadband services ($m = m_{dk}$). With respect to mobile services, in 2009 and 2010 there are three mobile networks and seven choice alternatives $m \in M = \{0, m_{v1}, m_{d1}, m_{v2}, m_{d2}, m_{v3}, m_{d3}\}$, where $m = 0$ refers to the choice of no mobile services at all. Between 2011 and 2014, there were four mobile networks and nine choice alternatives including $\{m_{v4}, m_{d4}\}$. Therefore, in 2009 and 2010 there

[20] Uncapped data plans became available from the fixed-line incumbent (Telkom) towards the end of the period analysed and were very expensive relative to capped plans.

are $7 \times 3 = 21$ choice alternatives in areas that have fixed line coverage and $7 \times 1 = 7$ in areas that do not. Between 2011 and 2014, there are $9 \times 3 = 27$ choice alternatives in areas that have fixed-line coverage and $9 \times 1 = 9$ choices outside of such areas.

Table 2 shows the number of consumers who opt for different choice alternatives in 2014. Table 3 shows how the number of users of fixed and mobile services changes over time.

Individual i's stand-alone utility from a connection to fixed network alternative $f \in F$ is:

$$V_{if} = x_i \beta_f + \alpha_f p_{if},$$

where p_{if} refers to the monthly subscription charge for having voice services only or voice combined with broadband access and x_i is a vector of individual characteristics influencing the utility of the fixed service.

As discussed in Section 4, we define three different usage profiles. Each consumer that has fixed-line coverage is assigned to one broadband usage profile (low, medium or high) and observes two prices (in addition to no service at zero cost): one for the lowest-cost monthly package of voice and another for voice and data.

The stand-alone utility from a connection to mobile operator, denoted k, is:

$$V_{im_k} = x_i \beta_m + \alpha_{m_v} p_{im_{vk}} + \alpha_{m_d} p_{im_{dk}},$$

where $p_{im_{vk}}$ and $p_{im_{dk}}$ are the prices paid by individual i for mobile voice and broadband services from operator k, and x_i is the vector of household characteristics influencing the utility of mobile services.

As discussed in section 4, we define different usage profiles for mobile voice and data services. Each consumer is assigned to one profile and observes different voice and data prices. The prices used in the estimation are voice call prices per minute and prices for one gigabyte of data.

The prices for mobile and fixed-line connections may be endogenous. This is partly mitigated by the inclusion of a rich set of consumer characteristics x_i (see Table 1), which include: demographics (such as income, race, age, gender, education and whether the home is owned or rented); employment status, including whether self-employed or not; and geographic information (such as living in a city, town or rural area). In the estimation, we also address the problem of endogeneity using the control function approach proposed by Petrin and Train (2010).

An individual's utility for a bundle of fixed and mobile services $r \in F \times M$ from different operators is defined as:

$$
\begin{aligned}
u_{ir} &= \varepsilon_{ir} && \text{if } f = 0 \text{ and } m = 0 \\
u_{ir} &= V_{if} + \varepsilon_{ir} && \text{if } f \neq 0 \text{ and } m = 0 \\
u_{ir} &= V_{im} + \varepsilon_{ir} && \text{if } f = 0 \text{ and } m \neq 0 \\
u_{ir} &= V_{if} + V_{im} + \Gamma_{ir} + \varepsilon_{ir} && \text{if } f \neq 0 \text{ and } m \neq 0
\end{aligned}
$$

The term Γ_{ir} is the difference between the individual's total utility from the bundle of services r and the sum of the stand-alone utilities of fixed services, V_{if}, and mobile services, V_{im}.

For the singleton bundles, $r = \{0\} \times M$ and $r = F \times \{0\}$, we set $\Gamma_{ir} = 0$. For the real bundles, the services are complements if $\Gamma_{ir} > 0$, substitutes if $\Gamma_{ir} < 0$, and independent if $\Gamma_{ir} = 0$.[21]

We estimate one value of gamma for a bundle which combines voice services on the fixed-line network with voice services on any mobile network, denoted Γ_{iv}.[22] The second value of gamma, denoted Γ_{id} is estimated for a bundle which combines fixed and mobile broadband services, which by default comes with voice services. Thus, the second gamma is estimated for a subset of users of voice services, as shown on Table 2.

The substitution (complementarity) coefficients, Γ_{ir}, may depend on consumer characteristics x_i. We define $\Gamma_{ir} = \Gamma_r + x_i \gamma_{ir}$, where Γ_r is the stand-alone value common to all individuals, and $x_i \gamma_{ir}$ represents multiplication of vectors which accounts for individual-level variation in complementarity or substitution. The heterogeneity depends on the same individual characteristics which determine utilities of fixed and mobile services.

A key problem in identifying Γ_{ir} is separating the correlation of preferences from true complementarity or substitutability. For example, when we observe consumers buying two services we may simply be observing correlation in preferences rather than complementarity. In order to remedy this, Gentzkow (2007) proposed using variables that shift demand for one service but not the other. We employ one demand-shifter for fixed-voice services and another for fixed-data services. The fixed-voice shifter is having a telephone at work, and the fixed-data shifter is having a gaming console. First, having a fixed-line telephone at work means that members of the household have a cheap means of contacting the individual (fixed to fixed calls are often free or are very cheap in South Africa), thus shifting the utility of having a

[21] At the time of our analysis there were no significant fixed and mobile bundles on the market, and so our estimates are not driven by bundled discounts or other contractual benefits. Telkom Mobile offered fixed and mobile bundles to some extent, but it was by far the smallest mobile operator with a share of 1% or less in the AMPS sample over the period analysed. Thus, the likely effect of these bundled discounts is negligible.

[22] We do not separately estimate gammas for voice on one technology and voice and data on the other, since we are mainly interested in fixed and mobile substitution in respect of voice services overall. We therefore estimate a single gamma for voice services.

fixed line at home but without affecting the utility from having a mobile. Second, gamers require very low-latency connections, which were only possible using fixed-line broadband connections. Thus, having a gaming console shifts out the utility for fixed-line broadband without affecting the utility derived from mobile data services. We denote the shifter for fixed voice as z_i and for fixed data as w_i.

More specifically, the utility from each of the nine bundles is specified as follows:

$$
\begin{aligned}
u_{i0} &= \varepsilon_{i0} \\
u_{ifv} &= x_i\beta_f + z_i\beta_{fv} + \alpha_f p_{if} + \varepsilon_{ifv} \\
u_{ifd} &= x_i\beta_f + z_i\beta_{fv} + w_i\beta_{fd} + \alpha_f p_{if} + \varepsilon_{ifd} \\
u_{imv} &= x_i\beta_m + \alpha_{mv} p_{im_{vk}} + \varepsilon_{imv} \\
u_{imd} &= x_i\beta_m + \alpha_{mv} p_{im_{vk}} + \alpha_{md} p_{im_{dk}} + \varepsilon_{imd} \\
u_{ifv+mv} &= x_i(\beta_f + \beta_m + \gamma_v) + z_i\beta_{fv} + \alpha_f p_{if} + \alpha_{mv} p_{im_{vk}} + \varepsilon_{ifv+mv} \\
u_{ifv+md} &= x_i(\beta_f + \beta_m + \gamma_v) + z_i\beta_{fv} + \alpha_f p_{if} + \alpha_{mv} p_{im_{vk}} + \alpha_{md} p_{im_{dk}} + \varepsilon_{ifv+md} \\
u_{ifd+mv} &= x_i(\beta_f + \beta_m + \gamma_v) + z_i\beta_{fv} + w_i\beta_{fd} + \alpha_f p_{if} + \alpha_{mv} p_{im_{vk}} + \varepsilon_{ifd+mv} \\
u_{ifd+md} &= x_i(\beta_f + \beta_m + \gamma_d) + z_i\beta_{fv} + w_i\beta_{fd} + \alpha_f p_{if} + \alpha_{mv} p_{im_{vk}} + \alpha_{md} p_{im_{dk}} + \varepsilon_{ifd+md}
\end{aligned}
$$

In our model, individuals choose the bundle r that maximizes their random utility. Under the assumption that the terms ε_{ir} are i.i.d. type I extreme value distributed, the random utility maximization results in the following logit choice probabilities:

$$s_{ir} = \frac{\exp(V_{ir})}{1 + \sum_r \exp(V_{ir})} \tag{1}$$

where $V_{ir} \equiv u_{ir} - \varepsilon_{ir}$ is the deterministic component of individual i's utility for bundle r.

The choice probabilities form the basis of the likelihood function applied to the data. The summations in the numerator of (1) are modified to adjust for the limited geographic coverage of fixed broadband and different numbers of mobile operators, depending on the year, discussed in Section 4. Defining $y_{ir} = 1$ if individual i selects voice bundle r, and $y_{ir} = 0$ otherwise, the log likelihood function can be written as:

$$\mathcal{L}(\theta) = \sum_i^N \sum_r y_{ir} \log s_{ir}(\theta) \,. \tag{2}$$

where θ is the vector of all parameters to be estimated. The maximum likelihood estimator is the value of the parameter vector θ that maximizes (2).

6 Empirical Results

6.1 Estimation results

First, we estimate control functions for voice services (Table 4) and data services (Table 5) in order to control for endogeneity between prices and choices. In both cases, we use measures of costs as instruments, and we include dummy variables for the operators and market segments. In the case of voice services, we use the costs of call termination.[23] In respect of mobile data services, we use the number of sites.[24] Termination rates are regulated in South Africa. The number of sites does not respond to short-term demand shocks and is at least partly set in terms of coverage requirements by the regulator. This is in the spirit of Czernich et al. (2011), who use copper network infrastructure as an instrument for broadband penetration. Termination costs and sites are positively related to voice and data prices in the respective control function regressions. In respect of voice, this is consistent with findings in previous papers, including Genakos and Valletti (2015). That there is a positive relationship between sites and data prices is also reasonable, since the average cost (and therefore price) per gigabyte rises with the greater number of sites rolled out. The R-squares are relatively high at 0.68 for the voice and 0.75 for the data regression.

The results from the multinomial logit regression are shown on Table 6. In column (1), the following results are shown: (i) three price coefficients; (ii) a dummy variable for having a fixed connection from Telkom; (iii) fixed broadband speed associated with a tariff plan and controls for quality; (iv) dummy variables for four mobile operators which are estimated relative to not having a mobile phone; (v) a dummy variable for mobile data access on top of voice; (vi) residuals from control function regressions for voice and data; (vii) the shifters for fixed voice (having a telephone at work) and fixed data (having a gaming console).

All three price coefficients, for mobile voice, mobile data and fixed voice and data have the expected negative signs. The coefficients on the dummy variable for having a fixed connection and dummy variables for mobile operators cannot be directly interpreted because of the interaction terms with consumer characteristics shown in columns (2) and (3) and are discussed below. The utility of having a fixed

[23]We computed the termination costs for each mobile operator as follows. First, we consider that 90% of calls are made to other mobile networks (the other 10% are to fixed networks) and that calls to other mobile networks are distributed according to market shares. We further consider that 50% of calls are made during peak hours and 50% are made off-peak, since termination rates were different for these two time slots. Using this information, we computed an average termination cost per minute paid by each mobile operator in each year.

[24]We collected information on the number of sites from operator annual reports and other public sources of information, such as news reports.

connection is higher for greater broadband speed. Having mobile data increases the utility of mobile access. The residuals from the first-stage regressions are positive and significant which indicates that there is a positive correlation between prices and consumer choices of mobile voice and data services. The inclusion of the residuals from the control function regressions results in a significantly more negative mobile voice price coefficient but does not affect the price coefficients on mobile data or fixed services.

The coefficients on the fixed voice and fixed data shifters are significant and positive as expected. They increase the utility of having fixed access but not mobile access, which allows us to identify the Γ_{ir} parameters. The stand-alone gamma coefficient shows that fixed and mobile voice are complements ($\Gamma_v > 0$), while fixed and mobile data services are substitutes ($\Gamma_d < 0$). As shown in columns (4) and (5), the individual-specific gamma coefficients vary considerably. In particular, having a computer not only makes having a fixed or mobile service more likely but also results in complementarity between fixed and mobile data services given that $-1.400 + 1.461 = 0.061$. Having internet at work or school reduces substitution between fixed and mobile data since $-1.400 + 0.432 = -0.968$. This may be due to learning effects, such as learning the benefits of high-volume data use at work or at an educational facility (see Liu et al., 2010). Note that we do not interact having a computer or having internet access at work or school with the fixed and mobile voice gamma since these two attributes are unlikely to shift utility for voice services.

There is heterogeneity between consumers across a number of dimensions. First, older consumers are more likely to take up a fixed line service and are less likely to take up a mobile service (at least above the age of 65). This is consistent with the findings of Macher et al. (2012), who suggest that older consumers tend to spend time at home, and are therefore more likely to use a fixed line. The opposite is true of younger consumers, who tend to be more mobile. Fixed and mobile data services are stronger substitutes among older consumers compared to those between the ages of 15 and 25, and this effect intensifies with age. At the same time, fixed and mobile voice are weaker complements for older consumers.

Individuals that have a high school (twelve years) or higher education are more likely to choose a fixed or mobile service and are also more likely to see fixed and mobile voice services as substitutes. There is no significant effect on the gamma for fixed and mobile data. Renters are less likely than home-owners to take up fixed-line services and are more likely to take up mobile services. This result is intuitive, in that renters are more likely to move between houses and therefore are less interested in getting a fixed-line service, which often comes with an installation cost and a term-commitment. At the same time, renters are more likely to see fixed and mobile data services as weaker substitutes since $-1.400+0.360 = -1.040$.

Employed individuals are less likely to choose a fixed service, perhaps because they are not at home as much to use it. But self-employed consumers are more likely to choose a fixed line because they are more likely to work from home. Being employed and being self-employed in particular mean that fixed and mobile data services are weaker substitutes.

Higher-income consumers are more likely to choose a fixed or mobile service. They see fixed and mobile voice services as weaker complements, and see fixed and mobile data as stronger substitutes. It may be that higher income consumers are more willing to pay the high usage price associated with mobile data even when at home, thus reducing the utility from adding a fixed-line data service.

This income-related pattern is also observed among race and language groups, where Indian, Coloured and White consumers are more likely to take up a fixed line service than Black consumers. White consumers are more likely than Black consumers to take up mobile. Afrikaans and Xhosa-speaking consumers are less likely to take up fixed or mobile services than English-speaking consumers. Similarly, Indian, Coloured and White consumers are all more likely than Black consumers to see fixed and mobile as substitutes, whether for voice or for data.

Being female means taking up a fixed or mobile service is more likely. At the same time, females see fixed and mobile voice as weaker complements and fixed and mobile data as stronger substitutes. Individuals in larger households are less likely to take up fixed and mobile services, possibly due to larger households being associated with lower average incomes in South Africa, where children cluster around old-age social pension recipients (see Duflo, 2000).

The number of cellphones in a household makes taking up a mobile service more likely, which is consistent with evidence on the presence of network effects in mobile adoption (see Doganoglu and Grzybowski, 2007). A greater number of cellphones in a household is associated with stronger complementarity in respect of voice and weaker substitution with respect to data services. This is likely because fixed-line services enable more fixed to mobile calls and have greater capacity for cellphones to connect to broadband at home.

Our results suggest that there is considerable heterogeneity among individuals in respect of the complementarity or substitutability of fixed and mobile services, as illustrated on Table 7. In particular, 15% of consumers with a computer, and 27% of consumers that have an internet connection at work or school, see fixed and mobile data services as complements. Substitutability or complementarity also varies substantially by income level and race. While 50% of low-income consumers and 39% of Black and 29% of Coloured consumers see fixed and mobile voice as complementary, only 6% of high-income consumers and only 7% of White consumers do. The reverse is true for data services: while 13% of high-income consumers see fixed and mobile data services as complements, only 2% of the lowest-income group do. Almost 50% of young people see fixed and mobile voice as complements, though this effect dissipates with age. Overall, the pattern of proportions of consumers that see fixed and mobile voice and data services as substitutes or complements follows the discussion on the estimation results above.

These results have important implications for developing countries, where interventions intended to bridge the 'digital divide' are focused on mobile services. Our results suggest that fixed lines are needed together with mobile services at higher levels of employment and when there is access to the internet at work or school and greater access to computers.

6.2 Counterfactual simulations

We use our model to conduct counterfactual simulations in order to illustrate the effects on broadband penetration of (i) reducing mobile data prices by 10%, (ii) expanding fixed line coverage, (iii) rolling out computers, and (iv) expanding internet access at schools and workplaces (as shown in Table 8 and Table 9). The results of this analysis show what might have been possible if Telkom had continued the expansion of fixed-line coverage and met its coverage obligations in the early 2000s (as discussed in Hodge, 2005). In addition, it was intended that the fixed-line network would play an important role in providing access to the internet, facilitated by local loop unbundling.[25] The costs of rolling out fixed lines are likely affordable, even for low-income households, due to relatively low labour costs in South Africa and the large number of fibre to the home operators. For example, one challenger fibre operator in South Africa plans to roll out fibre to the home using exisitng pole infrastructure in a large low-income community in Johannesburg at a price of R80 per month.[26]

Furthermore, while we do not comment on the debate in the literature on the impact of computers at home and at schools on educational outcomes, our simulations are useful in that they may help us understand the means by which the 'digital divide' might be bridged. The 'digital divide' may be especially large in South Africa, where fixed-lines were rolled out mainly to White households during apartheid and fixed-line broadband today is available mostly in the same areas. For example, there is evidence that technology use in schools has positive effects on educational outcomes in developing countries (Banerjee et al., 2007).[27] In addition, there are some papers that show that using technology at home improves educational outcomes, though the evidence overall is mixed. There is stronger evidence that having a computer at home improves computer skills (see, for example, Malamud and Pop-Eleches, 2011), which is unsurprising. Having a computer at home and access to computers and the internet

[25] Local loop unbundling was first recommended in a report prepared by the Ministry of Communications, among others, entitled: "Local loop unbundling. A way forward for South Africa.". This was recommended again in the broadband policy issued by government in 2013, entitled "South Africa Connect: Creating opportunities, ensuring inclusion. South Africa's Broadband Policy".

[26] The operator concerned, Vumatel, has rolled out an extensive fibre network in higher-income areas since 2015, together with more than 30 other new fibre to the home entrants across South Africa.

[27] There is some evidence of this effect in developed countries (see, for example, Goolsbee and Guryan, 2006). The effect in developing countries may be due to high-levels of absenteeism among school teachers, which means that students are receiving a lower-quality education than in developed countries (Bulman and Fairlie, 2016). Chaudhury et al. (2006) find that teacher absenteeism in a study on Bangladesh, Ecuador, India, Indonesia, Peru and Uganda was 19% on average.

at schools and workplaces therefore plays a role in the development of human capital, particularly in developing countries. Providing access to the internet at schools and workplaces is not likely to be very costly, since most communities that have schools have mobile network coverage, and the mobile operators in South Africa use fixed-lines (often fibre) for backhaul to a large extent. Rolling out computers to households would likely be more costly, since only around 22% of 16.2m households have a computer. Such an intervention would nonetheless likely be affordable using more recent low-cost computer technologies combined with the fact that 82% of households have a television in South Africa.[28]

The results of our simulations are as follows. First, a 10% reduction in mobile data prices results in only a small reduction fixed line data penetration, from 21.8% to 21.4%, reflecting the fact the fixed and mobile data services are complements rather than substitutes for large numbers of consumers. Second, expansion of fixed-line coverage (from two thirds to the entire sample) increases fixed-line voice and data penetration but only to a limited extent, from 21.8% to 24.1%. Consumers currently living outside of fixed-coverage areas are unlikely to take up fixed-line services even if they were rolled out. Third, if all consumers were given a computer, fixed broadband penetration would increase to 31.4%, and if in addition all individuals were able to connect to the internet at work or school, fixed broadband penetration at home would increase to 37.1%. Overall, these interventions would result in a gain of 15.3 percentage points in fixed-line broadband penetration.

These outcomes vary depending on various demographic characteristics including income, race and language (see Table 8). For example, expanding fixed-line coverage, access to computers and internet access at school and work would increase fixed-line broadband penetration among Black individuals by 17.4 percentage points from 7.8% to 25.2% but would expand access among White consumers by 12.3 percentage points, from 44% to 56.3%. In expanding internet penetration among particularly poor households, increasing access to fixed lines, computers and internet at work or school may help to reduce the 'digital divide'.

At the same time, a 10% reduction in mobile data prices results in an increase in mobile broadband penetration of only 3.1 percentage points. Due to the complementary nature of fixed and mobile data services for large numbers of individuals, expanding fixed-line data coverage reduces the probability of choosing mobile data by only 0.8%. Expanding access to computers and internet connections at work or school expands demand for mobile data services (Table 9). Computers result in only a small gain in mobile data access (1.3 percentage points). However, computers and access to the internet at work or school result in an expansion of mobile data services by 3.5 percentage points. These benefits are reasonably evenly spread among income and race groups.

[28]Source: Statistics South Africa, "General Household Survey", 2017, statistical release P0318. A Raspberry Pi for example is available in South Africa for R235, a keyboard and mouse for R100, and both can be connected to even old television sets via the 3.5mm jack.

The gain from a 10% mobile data price reduction, in increasing mobile broadband penetration by 3.1 percentage points, is relatively modest compared to gains from expanding access to fixed-line broadband, computers and internet at work or school. The latter interventions result in a similar (3.5 percentage point) expansion in mobile data penetration but also expand fixed-line broadband penetration, which allows for significantly higher usage volumes at lower prices per gigabyte, by 15.3 percentage points. In addition, expanding fixed internet access at homes in South Africa expands individual access to the internet considerably more than mobile services, given the relatively large average household size of 3.3 people in South Africa (rising to 4.3 in rural areas).[29]

The gains from an increase in fixed-line coverage, ensuring that all households have a computer and that workplaces and education facilities have internet connections available to individuals are therefore more important than reductions in retail mobile data prices.

7 Conclusion

We estimate a discrete-choice model of fixed and mobile substitution for voice and data services in a developing country with high levels of poverty and inequality, South Africa. Our model provides for flexible, individual-level variation in utility derived from fixed and mobile voice services, and fixed and mobile data services. Our results show that fixed and mobile substitution or complementarity depends on a range of individual and household characteristics. We find that half of lower-income consumers see fixed and mobile voice services as complements though only 2% see fixed and mobile data services as complements. The pattern is reversed for high-income consumers, only 6% of who see fixed and mobile voice as complements but 13% of who see fixed and mobile data as complements.

We use our model to conduct counterfactual simulations in order to illustrate the effects on broadband penetration of (i) reducing mobile data prices by 10%, (ii) expanding fixed line coverage, (iii) rolling out computers, and (iv) expanding internet access at schools and workplaces. If mobile data prices were 10% lower, mobile data penetration would increase by only 3.1 percentage points and because fixed and mobile data are complements for large numbers of consumers, fixed-line penetration would decline by a relatively modest 0.4 percentage points. However, if fixed-line coverage were expanded to the entire population and computers were available to all, fixed-line broadband penetration would increase significantly by 9.6 percentage points and mobile broadband penetration would increase by half of a percentage point. Furthermore, having an internet connection at work or school would add an additional 5.7 percentage points to fixed-line broadband penetration, and 3 percentage points to mobile broadband penetration. These results suggest that expanding fixed-line coverage, access to computers and internet at work and

[29]Source: Statistics South Africa, 2017, "Living Conditions of Households in South Africa", statistical release P0310.

schools are more important than reducing mobile data prices by 10%.

Though we do not estimate the impact of broadband penetration on employment, an important finding of this research is that being employed, and being self-employed in particular, makes fixed and mobile data services weaker substitutes. Unemployment in South Africa is currently over 37%.[30] At higher levels of employment and particularly self-employment, more fixed-line services will be needed. This is important in view of the results reported by Hjort and Poulsen (forthcoming), who show that the expansion of high-speed internet access in African countries, including South Africa, results not only in greater employment but also in greater productivity.

These results have several implications for regulators and policymakers in developing countries, particularly in Africa, who are focused largely on interventions in respect of mobile data services. Firstly, it is more important to stimulate demand for broadband services by providing the tools for using them (such as a computer) as it is to reduce the prices of mobile data services. This means that policymakers and regulators might consider activities that ensure that individuals have access to computers and internet at work and educational facilities in order to increase broadband adoption. Second, we find that fixed and mobile are complements for large groups of consumers. The number of consumers that see fixed and mobile data as complements is greater at higher levels of employment and self-employment, and with more access to computers and greater connectivity at work and at schools. This suggests that relying solely on mobile networks to bridge the 'digital divide' is not enough. Policymakers and regulators might consider means of expanding access to computers and internet at workplaces and schools together with expanding access to fixed-line broadband.

[30] Using the expanded definition, i.e. including those who would take a job if offered even though they did not actively seek work in the past month. Source: Statistics South Africa, 2018, "Quarterly Labour Force Survey", statistical release P0211.

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A Appendix

A.1 Figures

Figure 1: Relationship between internet access at home and having a computer, 2012-2016)

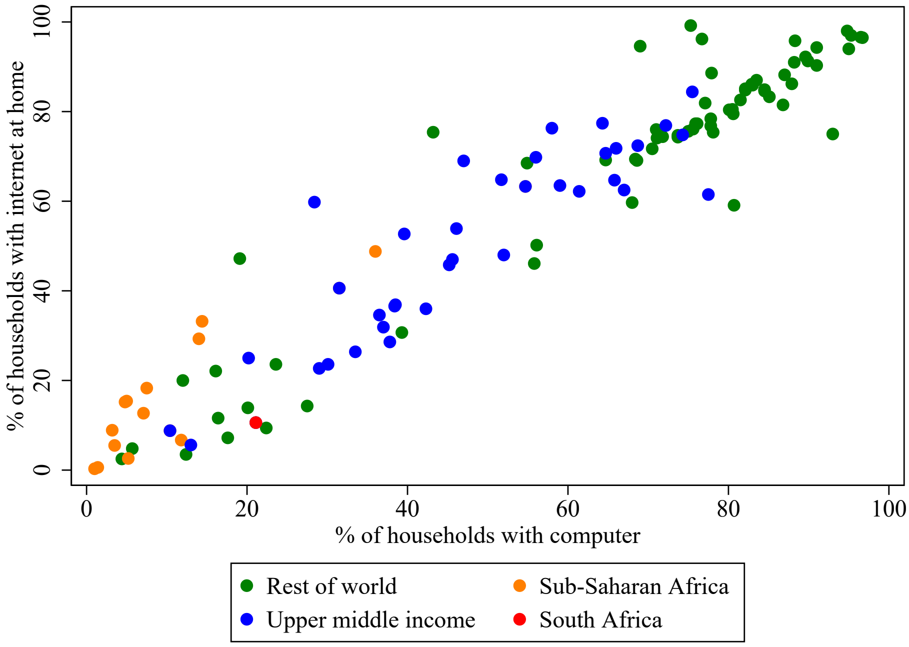


Figure produced using data from the International Telecommunications Union (ITU). Note that for South Africa the ITU estimate of internet access at home is replaced by the estimate from Statistics South Africa. The ITU reports data for the year most recently available, which in most cases is 2016.

Figure 2: Maps indicating cell sites and fixed-line local exchanges

(a) Approximate locations of cell masts (2017) **(b) Telkom fixed-line local exchanges (2014)**

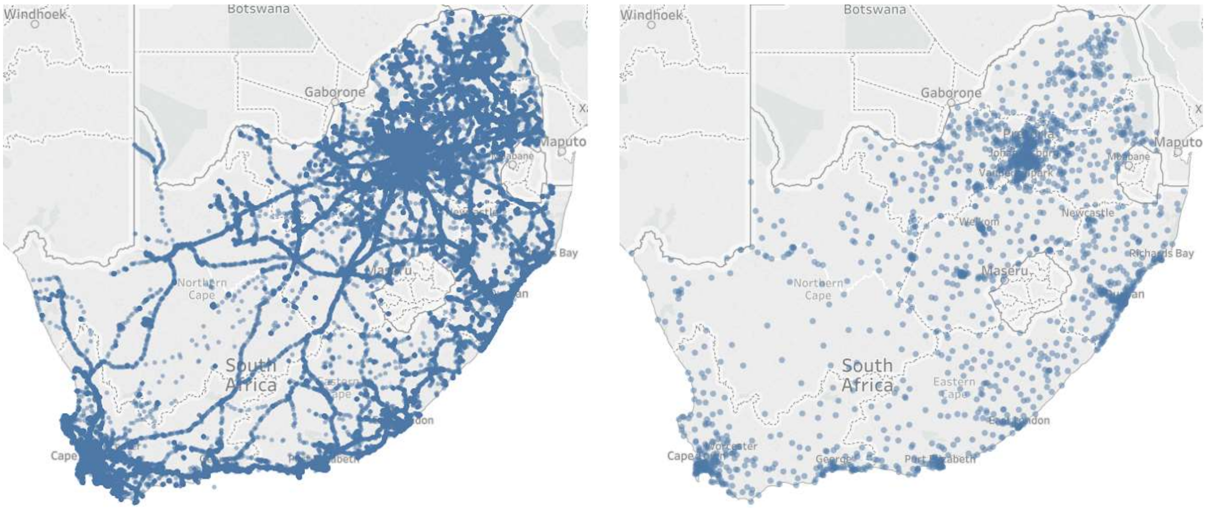
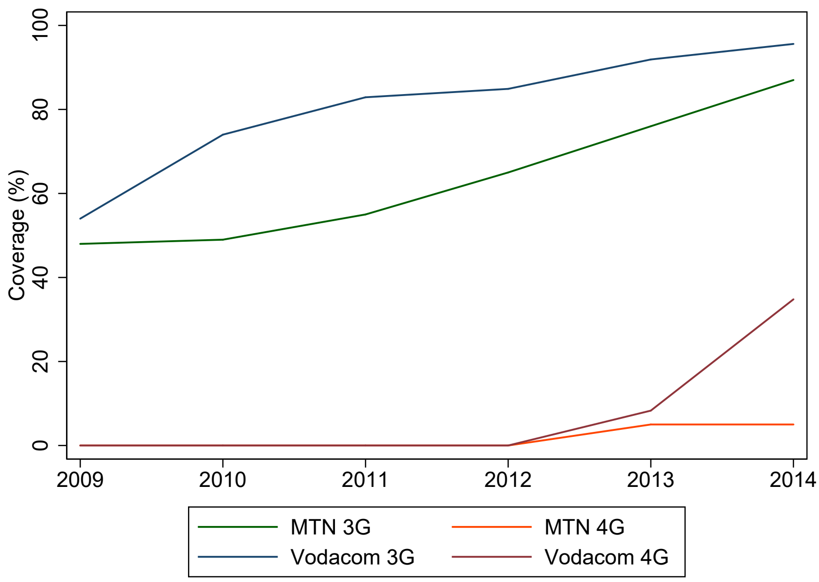


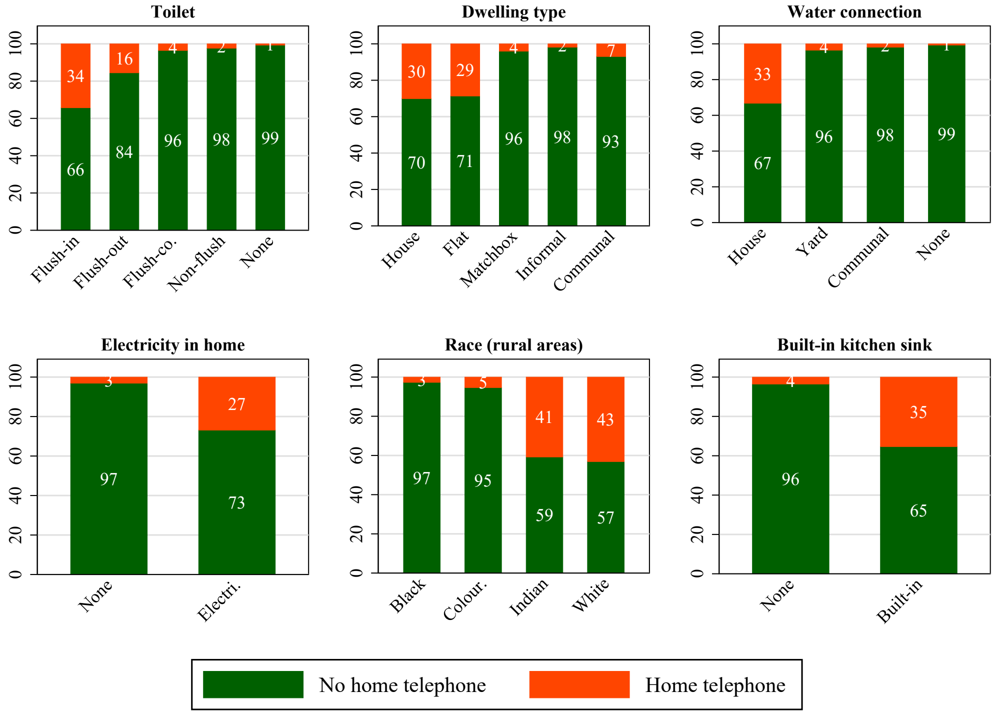
Figure (2b) shows locations of 1,864 local exchanges identified by broadbandstats.co.za in 2014. Figure (2a) shows estimates of positions of high sites and masts obtained from opensignal.com in September 2017. These estimates are based on signal strength to smartphones that have the OpenSignal application installed. Note that number of sites by operator used in the control function for data prices (reported in Table 4) uses number of masts and high sites reported by the mobile operators in annual reports and other public sources.

Figure 3: 3G and 4G coverage in South Africa, 2009-2014 (%)



Source: MTN and Vodacom annual reports. Note that EDGE (referred to as '2.5G', though it technically meets the standard for 3G) coverage was close to complete over this period for the MTN and Vodacom networks.

Figure 4: Identifying areas with no fixed-line coverage (%)



AMPS survey respondents, pooled, 2009-2014 (N=137,321).

A.2 Tables

Table 1: Consumer choices of fixed and mobile services, by demographic variables (2009-2014)

	Fixed	Mobile	F&M voice	F&M voice & data	N
No computer	14	79	9	0	90,540
Computer	48	94	34	11	44,202
No Internet at work/school	23	82	16	3	121,203
Internet at work/school	40	98	29	10	13,539
Income <3,000	8	69	4	1	30,871
Income 3-7,999	16	82	11	1	37,743
Income 8-15,999	30	89	22	3	33,081
Income >15,999	46	95	33	10	33,047
Black	8	83	5	1	69,334
Coloured	27	75	19	3	19,398
Indian	55	83	37	6	8,981
White	49	89	35	8	37,029
Afrikaans	32	82	23	4	36,748
English	54	88	38	9	31,487
Zulu, Swazi, Ndebele	8	85	6	1	20,807
Xhosa	7	78	5	1	15,558
Sth., Tsw., Tsn., Ven., Oth.	7	84	5	1	30,142
Age < 26 years	17	85	12	4	39,098
Age 26-50 years	20	89	14	4	59,851
Age 51-65 years	36	81	26	4	23,117
Age > 65 years	54	65	33	2	12,676
No or some High School	16	73	10	1	61,467
High School or more	33	93	24	6	73,275
Unemployed	24	79	16	2	80,866
Employed	26	92	20	5	53,876
Not self-employed	24	83	17	3	121,874
Self-employed	37	93	27	9	12,868
Rural	7	76	6	1	21,031
Towns	32	87	23	5	67,915
Cities	22	83	16	3	45,796
Home owned	28	83	20	4	101,812
Home rented	16	86	11	3	32,930
Male	24	83	17	4	67,171
Female	26	85	18	3	67,571
Household size <=2	30	83	21	4	45,520
Household size > 2	22	84	16	4	89,222
1 earner in household	18	82	12	2	62,430
2+ earners in household	31	85	22	5	72,312
<=1 cell in household	19	59	9	1	35,311
>1 cellphone in household	27	92	21	5	99,431
No work telephone	23	82	16	3	120,465
Work telephone	43	95	33	8	14,277
No console	22	82	15	2	117,234
Console (e.g. Xbox)	47	95	32	13	17,508
Total	25	84	18	4	134,742

The numbers reported are proportions of consumers from a particular demographic having made the choice indicated in the column title, except for the last column which shows the absolute number of consumers in that demographic. Note that proportions are not adjusted for fixed-line coverage.

Table 2: Network operator choices made by consumers in 2014

	No fixed	Fixed voice only	Fixed voice & data	Total
No mobile	1,944	516	54	2,514
Mobile voice only				
Cell C	858	141	84	1,083
MTN	3,343	320	182	3,845
Telkom Mobile	52	12	10	74
Vodacom	3,502	550	319	4,371
Mobile voice & data				
Cell C	1,825	204	358	2,387
MTN	3,673	420	739	4,832
Telkom Mobile	101	20	50	171
Vodacom	4,046	601	1,094	5,741
Total	19,344	2,784	2,890	25,018

We test for substitution or complementarity in two areas: the first is for voice (the light gray cells, including for example where a consumer chooses a fixed voice only service and a mobile voice & data service) and the second is for voice & data, the area shaded dark gray.

Table 3: Fixed and mobile choices made by consumers 2009-2014

	2009	2010	2011	2012	2013	2014	Total
Consumer chooses no mobile service							
No fixed	4,561	3,827	2,821	2,481	1,107	1,944	16,741
Fixed voice	1,203	1,040	886	706	376	516	4,727
Fixed voice & data	83	67	64	55	40	54	363
Total	5,847	4,934	3,771	3,242	1,523	2,514	21,831
Consumer chooses mobile voice only							
No fixed	11,633	11,737	11,740	10,656	4,789	7,755	58,310
Fixed voice	3,076	2,748	2,300	1,783	775	1,023	11,705
Fixed voice & data	1,730	1,435	1,305	1,006	411	595	6,482
Total	16,439	15,920	15,345	13,445	5,975	9,373	76,497
Consumer chooses mobile voice & data							
No fixed	1,224	2,426	3,851	5,467	3,449	9,645	26,062
Fixed voice	558	815	986	1,185	637	1,245	5,426
Fixed voice & data	171	202	473	1,091	748	2,241	4,926
Total	1,953	3,443	5,310	7,743	4,834	13,131	36,414
Total	24,239	24,297	24,426	24,430	12,332	25,018	134,742

Table 4: Control function estimation results - voice services

		Coeff.	(STD)
Termination cost		1.30***	(0.16)
MTN		0.80***	(0.16)
Telkom		0.36*	(0.18)
Vodacom		0.50**	(0.16)
Prepaid		0.68***	(0.16)
Postpaid*	Medium	0.18	(0.16)
	High	0.44**	(0.16)
MTN*	Prepaid	-0.28	(0.22)
	Postpaid medium	-0.21	(0.22)
	Postpaid high	-0.22	(0.22)
Telkom*	Prepaid	-0.42+	(0.25)
	Postpaid medium	-0.21	(0.25)
	Postpaid high	-0.27	(0.25)
Vodacom*	Prepaid	-0.07	(0.22)
	Postpaid medium	-0.14	(0.22)
	Postpaid high	-0.19	(0.22)
Constant		-0.02	(0.14)
Number of obs	88		
R-squared	0.68		

+ p<0.10, * p<0.05, ** p<0.01, *** p<0.001

Table 5: Control function estimation results - data services

	Coeff.	(STD)
Sites	66.41+	(37.59)
Medium usage	-228.26***	(48.35)
High usage	-418.60***	(48.35)
MTN	-514.71+	(270.31)
Telkom	104.82	(91.15)
Vodacom	-520.09*	(245.65)
2010	-168.93*	(76.43)
2011	-353.62***	(82.04)
2012	-452.82***	(97.01)
2013	-692.34***	(120.93)
2014	-731.32***	(134.55)
Constant	828.81***	(99.58)
Number of obs	66	
R-squared	0.75	

+ p<0.10, * p<0.05, ** p<0.01, *** p<0.001

Table 6: Estimation results

Main effects	(1) Coeff. (SE)	Interactions	(2) Fixed Coeff. (SE)	(3) Mobile Coeff. (SE)	(4) Γ_{FMV} Coeff. (SE)	(5) Γ_{FMVD} Coeff. (SE)
Price - mobile	-0.777***	Γ (average)			0.603**	-1.400***
voice	(0.024)				(0.256)	(0.191)
Price - mobile	-0.009***	Computer	0.785***	0.473***		1.461***
data	(0.000)		(0.019)	(0.030)		(0.071)
Price - fixed	-0.004***	I'net work/sch.	0.189***	0.662***		0.432***
	(0.000)		(0.026)	(0.061)		(0.048)
Fixed line	-2.667***	Cities	0.071	0.106***	0.070	0.201
	(0.184)		(0.098)	(0.027)	(0.101)	(0.137)
Fixed broadband	1.030***	Towns	0.350***	0.122***	-0.060	0.005
speed	(0.011)		(0.097)	(0.028)	(0.099)	(0.135)
Cell C	-1.444***	Age 26-50	0.293***	0.326***	-0.257***	-0.443***
	(0.086)		(0.065)	(0.026)	(0.068)	(0.082)
MTN	0.068	Age 51-65	1.110***	0.043	-0.407***	-0.882***
	(0.089)		(0.063)	(0.031)	(0.066)	(0.088)
Telkom Mobile	-4.227***	Age 66+	1.929***	-0.371***	-0.490***	-1.495***
	(0.096)		(0.066)	(0.040)	(0.071)	(0.116)
Vodacom	0.010	High school+	0.526***	0.949***	-0.293***	0.018
	(0.087)		(0.043)	(0.025)	(0.045)	(0.070)
Mobile data	2.535***	Rent	-0.787***	0.120***	-0.013	0.360***
	(0.017)		(0.051)	(0.025)	(0.054)	(0.069)
Residuals - voice	1.065***	Working	-0.303***	0.720***	0.052	0.283***
	(0.031)		(0.061)	(0.028)	(0.063)	(0.079)
Residuals - data	0.001***	Self-employed	0.243*	0.064	0.057	0.424***
	(0.000)		(0.098)	(0.051)	(0.099)	(0.111)
Fixed voice *	0.401***	Coloured	1.214***	-0.286***	-0.319*	-0.883***
work telephone	(0.026)		(0.144)	(0.072)	(0.150)	(0.176)
Fixed data *	0.619***	Indian	1.727***	-0.214*	-0.560***	-1.207***
console	(0.026)		(0.149)	(0.085)	(0.155)	(0.178)
		White	1.310***	0.434***	-0.415**	-0.480**
			(0.145)	(0.075)	(0.150)	(0.170)
		Income 3-8	0.338***	0.019	-0.163*	-0.465***
			(0.057)	(0.026)	(0.065)	(0.123)
		Income 8-16	0.536***	0.039	-0.339***	-0.444***
			(0.064)	(0.035)	(0.071)	(0.111)
		Income 16+	0.728***	0.231***	-0.471***	-0.217+
			(0.080)	(0.051)	(0.085)	(0.116)
		Afrikaans	-0.743***	-0.256***	0.124*	-0.152*
			(0.056)	(0.045)	(0.059)	(0.074)
		Zulu+	0.041	0.148*	-0.363*	-0.584**
			(0.160)	(0.073)	(0.166)	(0.193)
		Xhosa	-0.545**	-0.225**	0.159	-0.262
			(0.168)	(0.073)	(0.175)	(0.209)
		Sesotho+	-0.275+	0.097	-0.279+	-0.345*
			(0.141)	(0.071)	(0.146)	(0.172)
		Female	0.594***	0.546***	-0.462***	-0.418***
			(0.038)	(0.021)	(0.040)	(0.054)
		Hh size	-0.104*	-0.694***	0.013	0.067
			(0.051)	(0.027)	(0.053)	(0.069)
		Hh earners	0.284***	-0.503***	-0.088+	-0.245***
			(0.044)	(0.024)	(0.046)	(0.063)
		Hh cells	-0.372***	2.232***	0.323***	0.504***
			(0.046)	(0.025)	(0.050)	(0.090)

+ $p<0.10$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 7: Percentage of respondents that view fixed and mobile as complements (Γ_{ir}>0)

	(1) Fixed & mobile voice	(2) Fixed & mobile voice & data	(3) N
No computer	32	0	90,540
Computer	13	15	44,202
No Internet at work/school	27	3	121,203
Internet at work/school	13	27	13,539
Income <3,000	50	2	30,871
Income 3-7,999	34	2	37,743
Income 8-15,999	15	4	33,081
Income >15,999	6	13	33,047
Black	39	6	69,334
Coloured	29	1	19,398
Indian	2	0	8,981
White	7	7	37,029
Afrikaans	20	4	36,748
English	8	8	31,487
Zulu, Swazi, Ndebele	24	3	20,807
Xhosa	73	5	15,558
Sth., Tsw., Tsn., Ven., Oth.	29	5	30,142
Age < 26 years	49	10	39,098
Age 26-50 years	20	5	59,851
Age 51-65 years	12	0	23,117
Age > 65 years	6	0	12,676
No or some High School	43	2	61,467
High School or more	11	8	73,275
Unemployed	30	3	80,866
Employed	20	8	53,876
Not self-employed	27	4	121,874
Self-employed	19	15	12,868
Rural	38	1	21,031
Towns	19	6	67,915
Cities	31	6	45,796
Home owned	27	4	101,812
Home rented	23	10	32,930
Male	42	9	67,171
Female	10	2	67,571
Household size <=2	19	4	45,520
Household size > 2	29	5	89,222
1 earner in household	32	4	62,430
2+ earners in household	20	6	72,312
<=1 cell in household	22	1	35,311
>1 cellphone in household	27	6	99,431
Entire sample	27	5	134,742

For each individual, we add the Γ_{ir} for each main effect and each control (interaction). Columns 1 and 2 show the percentage of the group (row) who view fixed and mobile as complements ($\Gamma_{ir} > 0$), for (1) voice and (2) voice and data for each demographic variable. The total number of survey respondents belonging to the demographic variable category is shown in column 3, and the total observations in respect of columns 1, 2 and 3 are shown in the bottom row.

Table 8: Fixed-line broadband penetration in counterfactual scenarios in 2014

	(1) Base	(2) -10% price	100% fixed line coverage (3) Base	(4) Computers	(5) Maximum
No computer	7.7	7.3	10.6	22.0	27.3
Computer	47.2	47.0	48.3	48.3	54.8
No Internet at work/school	20.4	20.1	22.8	30.1	36.3
Internet at work/school	39.1	39.0	40.4	47.4	47.4
Income <3,000	11.7	11.5	15.9	23.2	27.7
Income 3-7,999	8.7	8.3	12.1	20.5	25.3
Income 8-15,999	20.3	19.8	21.8	30.3	36.5
Income >15,999	43.2	42.9	43.6	49.0	56.0
Black	7.8	7.7	11.5	19.4	25.2
Coloured	20.4	19.9	23.0	30.5	35.5
Indian	40.2	39.5	40.8	48.2	53.6
White	44.0	43.5	44.0	50.1	56.3
Afrikaans	28.0	27.4	29.2	35.9	41.5
English	44.5	44.0	45.0	51.8	57.9
Zulu, Swazi, Ndebele	7.9	7.8	11.7	20.2	26.1
Xhosa	6.4	6.3	10.4	17.6	22.6
Sth., Tsw., Tsn., Ven., Oth.	6.9	6.8	10.6	18.5	24.2
Age < 26 years	17.7	17.6	19.8	27.2	33.8
Age 26-50 years	18.8	18.7	20.9	28.1	34.2
Age 51-65 years	27.4	26.8	30.1	37.8	43.1
Age > 65 years	34.7	33.4	37.9	44.7	47.4
No or some High School	11.0	10.7	14.6	22.0	26.4
High School or more	29.9	29.6	31.3	38.5	45.2
Unemployed	19.3	18.8	22.0	29.4	34.9
Employed	25.4	25.2	27.1	34.3	40.3
Not self-employed	19.9	19.6	22.3	29.6	35.2
Self-employed	38.8	38.6	40.5	47.7	54.8
Rural	6.1	6.0	11.1	18.5	23.1
Towns	28.2	27.8	29.7	36.7	42.7
Cities	18.9	18.6	21.2	29.0	34.8
Home owned	23.6	23.2	26.1	33.6	39.3
Home rented	16.1	16.0	17.6	24.5	30.2
Male	22.1	21.8	24.2	31.3	36.9
Female	21.5	21.1	23.9	31.5	37.3
Household size <=2	24.8	24.4	26.8	34.1	39.2
Household size > 2	20.1	19.8	22.6	29.9	36.0
1 earner in household	15.6	15.4	18.2	25.7	31.4
2+ earners in household	26.5	26.1	28.6	35.8	41.6
<=1 cell in household	15.3	14.8	19.2	26.6	30.3
>1 cellphone in household	23.5	23.2	25.4	32.7	39.0
Total fixed voice and data	21.8	21.4	24.1	31.4	37.1

In column (1), base scenario probabilities are shown for fixed broadband and in (2) penetration if mobile data prices were reduced by 10% are shown. In column (3), probabilities assuming 100% fixed-line coverage are shown. In column (4), probabilities if there were 100% fixed-line coverage and all individuals had a computer are shown. In column (5), probabilities assuming 100% fixed-line coverage, 100% have computers and all individuals had internet at work or school are shown.

Table 9: Mobile broadband penetration (%) in counterfactual scenarios in 2014

	(1) Base	(2) -10% price	100% fixed line coverage (3) Base	(4) Computers	(5) Maximum
No computer	58.3	61.9	57.1	59.1	62.0
Computer	74.9	76.9	74.8	74.8	78.0
No Internet at work/school	63.1	66.2	62.3	63.5	66.8
Internet at work/school	78.4	80.3	78.3	79.7	79.7
Income <3,000	55.3	59.2	53.9	55.8	59.4
Income 3-7,999	59.7	63.3	58.4	59.5	62.0
Income 8-15,999	65.0	67.9	64.5	65.8	68.6
Income >15,999	74.1	76.2	74.0	75.1	78.4
Black	64.9	68.2	63.7	65.0	67.4
Coloured	59.3	62.5	58.4	59.5	62.8
Indian	61.1	63.8	60.9	62.5	66.5
White	66.2	68.9	66.2	67.4	71.1
Afrikaans	61.7	64.8	61.3	62.3	65.6
English	66.6	69.1	66.5	68.0	71.9
Zulu, Swazi, Ndebele	65.2	68.5	63.9	65.1	67.4
Xhosa	62.7	66.0	61.5	62.9	65.4
Sth., Tsw., Tsn., Ven., Oth.	64.5	67.9	63.3	64.7	67.2
Age < 26 years	72.4	74.7	71.8	73.2	75.8
Age 26-50 years	69.2	72.0	68.6	69.7	72.2
Age 51-65 years	55.1	59.1	54.1	55.4	59.3
Age > 65 years	37.9	42.3	36.7	38.4	43.5
No or some High School	54.7	58.6	53.4	54.9	58.2
High School or more	71.4	73.8	71.0	72.2	75.0
Unemployed	59.6	62.9	58.7	60.0	63.3
Employed	70.9	73.5	70.4	71.7	74.2
Not self-employed	63.4	66.5	62.6	63.9	66.9
Self-employed	71.3	73.9	70.8	72.4	75.9
Rural	57.9	61.9	56.1	57.7	60.6
Towns	66.7	69.4	66.2	67.4	70.5
Cities	63.2	66.3	62.4	63.8	66.7
Home owned	62.9	66.1	62.1	63.3	66.5
Home rented	68.1	70.9	67.7	69.1	71.6
Male	64.0	67.0	63.3	64.7	67.8
Female	64.4	67.5	63.5	64.7	67.7
Household size <=2	60.5	63.8	59.9	61.3	64.6
Household size > 2	66.2	69.1	65.4	66.6	69.4
1 earner in household	63.5	66.8	62.7	64.1	67.0
2+ earners in household	64.7	67.6	64.0	65.2	68.3
<=1 cell in household	48.4	52.3	47.1	49.8	54.5
>1 cellphone in household	68.4	71.3	67.8	68.7	71.3
Total mobile voice and data	64.2	67.3	63.4	64.7	67.7

In column (1), base scenario probabilities are shown for mobile broadband and in (2) penetration if mobile data prices were reduced by 10% are shown. In column (3), probabilities assuming 100% fixed-line coverage are shown. In column (4), probabilities if there were 100% fixed-line coverage and all individuals had a computer are shown. In column (5), probabilities assuming 100% fixed-line coverage, 100% have computers and all individuals had internet at work or school are shown.