

Dempsey, Seraphim; Mahon, Ben

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Into a brick wall: mobile connectivity and the thermal efficiency of residential buildings

Seraphim Dempsey^{1,2} and Ben Mahon³

¹Economic and Social Research Institute (ESRI)*[†]

²Trinity College Dublin

³Commission for Communications Regulation (ComReg)

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Abstract

Climate mitigation policies have resulted in increased rates of residential energy efficiency retrofitting. However, building materials with low thermal transmissivity often have higher radio signal attenuation rates which can reduce indoor service quality for mobile phone users. This paper empirically documents this phenomenon in Ireland by linking administrative data on Building Energy Ratings, with reports of in-home mobile quality of service (QoS) issues collected from a nationally representative survey on mobile consumer experiences in Q2 2022. Importantly, we consider local telecommunication infrastructure by exploiting rich market intelligence data from the National

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[†]Corresponding author. Email: seraphim.dempsey@esri.ie Address: The Economic and Social Research Institute, Whitaker Square, Sir John Rogerson’s Quay, Dublin 2, D02 K138, Ireland.

Regulatory Authority. This allows us to account for the quality of outdoor mobile coverage and active fixed line broadband connections at the household level. We find a positive association between living in areas with higher proportions of energy efficient homes and the probability of reporting an issue with indoor mobile phone signal. This highlights the importance of aligning energy efficiency policy with telecommunication policy to ensure future connectivity is safeguarded.

JEL Classification: L96, R28, 013, 018

Keywords: mobile signal attenuation, residential energy efficiency, quality of service

1 Introduction

Climate change is a significant policy challenge faced by the world. In response, the Paris Agreement, which entered into force in November 2016, has been adopted by the majority of countries with the aim of holding “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursuing “efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (Paris Agreement, 2015). Policy measures that improve the energy efficiency of the residential housing stock play an important role in helping to achieve these climate mitigation goals. In 2022, nearly a quarter of all European Union (EU) energy was consumed by households, with just under two-thirds of this energy used for home heating (Eurostat, 2024). The EU Energy Performance Buildings Directive (2024) targets this energy consumption and “promotes the improvement of the energy performance of buildings and the reduction of greenhouse gas emissions from buildings within the Union, with a view to achieving a zero-emission building stock by 2050”. This includes the requirement that all EU countries establish long-term national renovation strategies, and, establishes initiatives such as the Renovation Wave which specifically targets a doubling of the renovation rate by 2030.

Parallel to the challenges posed by climate change, substantial advancements in telecommunication technology have also been observed over the past few decades. This is reflected in the growth of mobile data networks within most economically developed countries. Consequentially mobile data is an increasingly necessary requirement for many of our day-to-day tools, communication, navigation, and social activities.¹ Moreover, this technological trans-

¹ An example of the need for ubiquitous mobile data services which cannot be replaced by fixed line provision, is that since 01 September 2022, Ireland legally requires all taxi drivers to accept card payments (in addition to cash) in the vehicle. These payments typically require the terminal to connect to mobile data.

formation is formally being targeted through the EU Digital Decade which aims to improve connectivity, digital skills, digital business, and digital public services by 2030. Objectives for increased digitisation of public services include; the 100% provision of key public services online, that all EU citizens have access to their medical records online, and that all EU citizens have access to an electronic form of identification. Ensuring access to these services in all locations (as opposed to fixed locations with fixed physical infrastructure) is to be facilitated by investments in digital infrastructure such that “all populated areas are covered by next generation wireless highspeed networks with performance at least equivalent to that of 5G” (European Commission, 2022).

The objectives of increased sustainability and technological progress often go hand in hand (Siedschlag et al., 2024). However, this paper explores a scenario in which the objective of increased connectivity is potentially undermined by the implementation of climate mitigation measures. To illustrate this, it is worth noting that building materials with lower thermal transmissivity are often used to increase the energy efficiency of buildings. Indeed, some of the most efficient home energy upgrades relate to thermal wall- and roof- insulation and window replacement (Lang and Lanz, 2022). However, materials with low thermal transmission properties often exhibit high mobile signal attenuation rates (Rodriguez et al., 2014; Commission for Communications Regulation, 2018; Collins and Dempsey, 2019). Indeed, thick multi-layered insulating external walls and low-emission air-tight windows (often with several layers of glass and metalized coating aimed at the reduction of ultraviolet and infrared radiation), can be particularly problematic for signal attenuation (Kiani et al., 2010; Asp et al., 2014; Haneda et al., 2016). As such, this paper posits that if improving the energy efficiency of the residential housing stock requires the increased utilisation of these signal attenuating materials, it could be the case that outdoor-to-indoor mobile signal attenuation is increasingly negatively affected. Furthermore, the roll-out of 5th generation (5G) cellular networks has the potential to exacerbate outdoor-to-indoor signal attenuation issues further. 5G services use higher frequency bands than 4G to enable the fast transmission of large amounts of data with a low latency. However, high frequency bands have a shorter wavelength of radio waves which can more easily be blocked (Lu et al., 2023).

To date, the literature has predominantly focused on the signal attenuation characteristics of energy efficient buildings materials by modelling and testing the propagation characteristics of specific building materials or case-study buildings. To the best of our knowledge this is the first paper to examine the extent to which the signal attenuation characteristics of energy efficient building materials are reflected in the quality of service (QoS) reported

by individuals who use mobile signal within residential settings. Using Ireland as a case study, we exploit nationally representative survey data on mobile QoS issues collected in Q2 2022, and link respondents to the average energy efficiency rating of the residential housing stock in their surrounding Small Area using a rich administrative dataset of Building Energy Ratings (BER) measurements collected between 2008-2022. Linking to high quality operator data provided by Ireland’s national communications regulator, ComReg, we control for the quality of outdoor mobile coverage and fixed broadband coverage used by each respondent in our survey. This allows us to attribute differences in reports of indoor mobile QoS issues to differences in the predicted energy efficiency of their homes. Importantly, the richness of our survey data additionally allows us to control for a range of other socio-economic and demographic characteristics at the individual level which could jointly determine the probability of reporting an indoor QoS issue, and, the probability of living in a highly energy efficient area. We find that those living in areas characterised by more energy efficient homes, are more likely to report having issues with their mobile signal, relative to those living in areas characterised by lower energy efficient homes.

It is perhaps counter-intuitive that this paper explores mobile coverage in fixed locations (residential buildings). Residential buildings often have access to high quality fixed broadband coverage which can be used as an alternative when mobile QoS issues are experienced. Nonetheless, we are motivated to explore the relationship between QoS issues and the energy efficiency of buildings within the institutional setting of Ireland for several reasons. First, at the time of our survey data collection (Q2 2022) not all residential premises had access to high quality fixed coverage in Ireland. Indeed, a significant regional dimension existed such that respondents living in urban areas were more likely to have access to high-speed broadband compared to respondents living in rural areas (Cullinan et al., 2021; Dempsey and Hoy, 2024). Understanding the relationship between mobile QoS issues and energy efficient homes, can thus help to provide wider insights into the potential benefits associated with widespread high speed broadband rollout. Second, our survey data collection occurs in a post-Covid era in Ireland, in which individuals were increasingly based in their homes due to remote working. Indeed in 2022, Ireland had the highest rate of home working in the EU (Eurostat, 2024), with census data collected in April 2022 indicating 32% of the population was engaged in home working at least once a week (Central Statistics Office, 2023). This labour market shift facilitates a setting in which individuals may have used their mobile devices more intensively and for longer periods of time within their homes. Moreover, the majority of mobile devices sold on the market during this time did not automatically switch to fixed line coverage (e.g. WiFi), emphasising the importance of mobile data. Consequently,

individuals may have been both more likely to experience, and remember experiencing, an issue with their mobile service. Third, Ireland has high levels of mobile data consumption. As such, while we explore indoor QoS issues in residential settings, our findings could help to provide broader insights for connectivity in non-residential indoor settings and indeed the energy efficiency implications of the wider non-residential building stock.

The remainder of our paper is structured as follows. Section 2 outlines the institutional setting, Section 3 describes the data, Section 4 details the estimation strategy, Section 5 presents the results, Section 6 discusses the implications for telecommunication policy, and Section 7 concludes.

2 Institutional Setting

2.1 Ireland: Telecommunications

Ireland is an EU member and is thus subject to EU telecommunications law. Established in 2002, Ireland’s National Regulatory Authority (NRA) is the Commission for Communications Regulation (ComReg). High data usage and good quality infrastructure are reflected in Ireland’s Digital Society and Economy (DESI) score. In 2022, Ireland was ranked 5th in the DESI index, with the highest rate of growth in the EU, indicating a very high level of digitisation (EU Commission, 2022). Reflecting this, Ireland has high mobile data consumption compared to other countries; average mobile data usage per capita in Ireland is 308GB per year, compared to 164GB in the UK and 213GB in the US (Frontier Economics, 2024). This high data usage is likely to continue, with an average of 16.5% growth predicted until 2028 (Frontier Economics, 2024). Usage seems almost ubiquitous across the population with 5,507,826 active phone subscribers (excluding mobile broadband) as of Q2 2022, compared to a national population of 5,149,139 in Census 2022 (Commission for Communications Regulation, 2024b).

High data usage is facilitated by good quality digital infrastructure and mobile networks. Ireland has a competitive mobile market with three mobile network operators (Eir, Vodafone, and Three), all of which provide nationwide coverage. In addition to the three network operators there are a number of Mobile Virtual Network Operators (MVNOs). These MVNOs sell their own retail services but ‘rent’ capacity from one of the three operators networks.² In

² Networks and associated MVNO’s: Eir (Go-Mo), Three (48, Lycamobile, Tesco Mobile, Virgin Mobile), Vodafone (An Post Mobile, Clearmobile, *Sky Mobile entered the market in September 2024, but was not*

2022 Vodafone was the largest operator with a 35.3% market share, followed by 29.8% and 21.6% for Three and Eir respectively. The remainder of the market was made up of MVNO operators.

Mobile signal is provided by four separate technologies (2G, 3G, 4G, 5G).³ In terms of mobile coverage, Ireland has an extensive 2G and 4G network. Ireland additionally subscribes to the Digital Decade target of full 5G rollout by 2030 (Government of Ireland, 2023). So far, Ireland has had a rapid 5G rollout; in 2021 there was 72% 5G population coverage compared to an EU average of 66% (EU Commission, 2022). In Q2 2022 not all mobile subscriptions included 5G; there were just 664,402 5G mobile subscriptions compared to 5,507,826 total mobile subscriptions (Commission for Communications Regulation, 2022b). In line with other European countries, 3G is being removed by some operators and has seen low investment for the last decade (Commission for Communication Regulation, 2023). 4G and 5G provide substantially better performance than 3G, and 3G traffic now only makes up a very small proportion of data traffic with usage declining in favour of 4G and 5G (Frontier Economics, 2024). Indeed, by 2028, 3G is expected to make up less than 0.3% of mobile data use, down from 3.4% in 2023 (Frontier Economics, 2024).

Despite improving network coverage and the beginning of 5G rollout, the reporting of in-home mobile signal issues remained stable between 2019 and 2022. In 2019, an estimated 35%, and 34% of the respondents reported that they had experienced coverage issues with voice and data respectively (Commission for Communications Regulation, 2019). In 2022, these figures were 37% (voice) and 32% (data) (Commission for Communications Regulation, 2022a). The lack of improvement could partly be due to the Covid-induced increase in home working which may have increased the likelihood of observing an issue with mobile signal. There was additional traffic on mobile networks during the pandemic, likely due to an increase in home working. In response ComReg released additional spectrum, effectively increasing network capacity (Commission for Communication Regulation, 2022).

Although this paper focuses on in-home mobile coverage issues, fixed broadband is often more commonly used within homes. Furthermore fixed broadband coverage might be

active at the time of the survey data collection used in this paper.)

³ While 2G can provide a very low speed data signal, it is mainly used for Voice and Short Message Service (SMS). 4G is the main technology used to provide data coverage and also provides voice calls using Voice over Long Term Evolution (VoLTE). VoLTE allows voice calls to be made over 4G and 5G networks seamlessly for the end-user. 5G is a newer technology providing very fast data speeds.

used as a substitute for mobile coverage when in-home mobile signal issues are observed. This would involve consumers connecting to their Wi-Fi to avail of fixed coverage within their homes for data, and if they enable Wi-Fi calling on their device, for cellular calls. However, although Ireland has extensive fixed-line internet coverage, there is a significant urban-rural divide in this coverage (Dempsey and Hoy, 2024). By the end of June 2022, the time in which our research is set, approximately 72% of households were estimated to have Fibre-to-the-Premises (FTTP) coverage with 54.3% of rural households estimated to have FTTP coverage (European Commission and Directorate-General for Communications Networks, Content and Technology, 2023). The Government of Ireland’s National Broadband Plan is currently subsidising the rollout of FTTP to predominantly rural areas where commercial telecommunication operators have indicated it is uneconomical for them to install FTTP infrastructure. Furthermore, it is worth noting that Ireland has high levels of mobile broadband (MBB) usage.⁴ MBB relies on 4G and 5G networks, and typically uses an in-home modem which receives a mobile data signal and allows users to connect in home, as they would with a fixed line connection. As the modem is in the home, signal passes through external walls, meaning that it can still be attenuated by energy efficient building materials. MBB made up 25% of all mobile data traffic in 2023, and this is likely to continue to grow (Frontier Economics, 2024). There were 385,099 active MBB subscriptions in 2024, making up 18.8% of all active broadband subscriptions (Commission for Communications Regulation, 2024a).

2.2 Ireland: Residential Energy Efficiency

Ireland has made environmental policy a central objective of government policy and aims to achieve net zero carbon emissions before 2050. Successive Climate Action plans have outlined policy towards that overarching goal, a key element of which is improving residential energy efficiency (Government of Ireland, 2019b, 2024). Reflecting this, the Building Energy Rating (BER) certification system was introduced in 2007 with the aim of providing consumers with better information on, and encourage improvements in, energy efficiency. BERs predict the energy efficiency of a residence based on a model which includes more than 140 of the home’s physical characteristics (Mac Uidhir et al., 2020). BER values are scaled from 0 to 450 and graded into a 15 point categorical scale which ranges from most efficient (A1) to least efficient (G) (see Figure A3 for thresholds). The BER system is designed and regulated

⁴Fixed Wireless Access uses a receiver mounted externally on the home to receive signal and would not be impacted by building materials induced loss. Similarly, satellite internet relies on an external receiver. These made up 4.3% and 0.2% of broadband connections respectively in Q2 2022 (Commission for Communications Regulation, 2022b).

by the Sustainable Energy Authority of Ireland (SEAI), with certified inspectors carrying out BER assessments. These rating assessments are legally required after a home upgrade, extension, sale, or when renting except for a small number of excluded historical buildings.⁵

Improving the energy efficiency of the residential housing stock in Ireland is being achieved through several initiatives. One initiative is the requirement that all *new* buildings are to be built to a very high standard, meeting near zero energy building requirements (Government of Ireland, 2024, pp.81).⁶ A second initiative focuses on how the energy efficiency of the *pre-existing* residential dwelling stock can be improved. Indeed, the objective of the National Retrofit Plan is to retrofit half a million homes to a BER rating of B2, by 2030 (Government of Ireland, 2024). To encourage and incentivise homeowners to invest in energy efficiency retrofitting measures, a number of financial grants have been established. Administered by the SEAI as part of the National Retrofit Plan, these financial incentives take the form of three schemes. First, the Better Energy Homes Scheme, which provides a fixed monetary grant for certain energy upgrade actions (e.g. €1200 for installing solar panels). Second, the Better Energy Warmer Homes scheme which is aimed at those on low incomes. Third, the National Home Energy Upgrade Scheme (2022) which targets comprehensive deep retrofits such that a home achieves a minimum B2 BER grade. An important condition of availing of the SEAI grants, is that a final BER assessment must be made upon completion of the works by a BER assessor on the SEAI National Register of BER Assessors. This means that for all residential households who have engaged in energy efficiency retrofits and who have benefited from SEAI grant assistance, a database exists containing details as to their updated BER rating.

Combining BER ratings from energy retrofit grants with the BER ratings from rentals and sales (both new builds and second hand), has resulted in the creation of an SEAI database (BER Research Tool) containing the BER ratings of approximately 35% of all Irish residential dwellings. This paper exploits this rich database to capture the effect of increased energy efficiency on mobile signal attenuation (see Section 3.4 for further details).

⁵ In the case of renting a BER certificate is valid for up to 10 years, unless the owner makes changes that will impact the dwelling's energy performance

⁶ To meet the near net zero energy building requirement all new builds have BER rating of A3 pre-2019, and A2 post 2019 (Government of Ireland, 2019a).

3 Data

Our analysis combines several datasets. First, the Mobile Consumer Experience Survey 2022 (Section 3.1), administered by the Irish national telecommunications regulator, ComReg. From this survey we capture consumer reports of in-home mobile signal issues alongside basic demographics and socio-economic information at the individual level. Second, we use the ComReg Mobile Outdoor Coverage Map (Section 3.2) which estimates the quality of outdoor mobile coverage quality across all mobile signal technologies (2G/3G/4G/5G) for every address in Ireland. Third, we use information on fixed line broadband connections (Section 3.3). This is obtained by ComReg from telecommunications operators as part of a legal requirement to report to the NRA, and is again captured for every address in Ireland. Fourth, to proxy the signal attenuation characteristics of residences we use the National BER Research Tool dataset from the SEAI (Section 3.4) which contains information on the energy efficiency of residential buildings within small geographic regions (Small Areas) containing approximately 100 residences. We link all of these datasets using *Eircodes*. These are address-level spatial identifiers used in the national postcode system of Ireland and identify each address in Ireland with a unique 7 alphanumeric character code.

3.1 Mobile Consumer Experience Survey

We capture consumer reports of mobile signal issues using survey data from the ComReg Mobile Consumer Experience survey (MCE), 2022. The MCE was undertaken as part of ComReg’s strategy for research with a focus on coverage issues.⁷ Conducted by a market research survey company, Behaviour and Attitudes (B&A), interviews were conducted face-to-face via CAPI (Computer Aided Personal Interviewing), for 2,991 survey participants between April and July in 2022. Interviews were carried out at the respondents’ home and lasted for approximately 30 mins. The survey stratification design was based on population density categories according to the Census 2016.⁸ Approximately 600 observations were sampled from each of the five strata, leading to an over-representation of less densely populated areas. This was intentionally designed in order to obtain a higher proportion of rural consumers, who were more likely to experience coverage issues. Interlocking quotas were

⁷ A similar survey was conducted in 2019. However, the 2019 MCE did not collect Eircodes for more than half of respondents, meaning it could not be used for analysis.

⁸ Sample stratification of the survey according to population density (population per square kilometre): Sample 1 = 100+ pop/km², Sample 2 = 50-100/km², Sample 3 = 25-50 pop/km², Sample 4 = 10-25 pop/km², Sample 5 = 0-10 pop/km². According to Census 2016, the total population of each of these samples was: 2,899,576 ; 507,773 ; 650,521 ; 475,702 ; and 54,680.

subsequently applied within each stratum across gender, social class and age, to ensure nationally representative findings of the Irish population aged 18+, according to Census 2016.⁹

To capture reported mobile quality of service (QoS) issues we exploit the MCE question “Thinking about your mobile phone experience over the past month, have you experienced a loss of signal (or no/poor coverage), when using the following services? i) Voice calls or texts on a mobile network, ii) data internet access”, with response options restricted to ‘yes’, ‘no’, and ‘don’t know’. It is worth noting that while the MCE questionnaire distinguishes between coverage issues for voice calls versus coverage issues for data internet access, all Irish network operators are obligated to provide voice over long term evolution (VoLTE) services (Commission for Communication Regulation, 2020). This allows voice calls over 4G networks and removes the historical distinction where voice was provided by 2G, and data by 4G networks. As such, we are interested in coverage issues which are reported for either of these questions, and combine responses from both to indicate that issues with mobile signal have been experienced.

Importantly, those who reported that they had experienced a loss of mobile signal, were subsequently asked a follow-up question in which they were asked to identify the location(s) in which they experienced an issue with their signal, e.g. inside their home, outside their home (gardens, garage, sheds), at work, or while travelling. Crucially this allows us to separate mobile QoS issues that occurred inside the homes of MCE respondents, compared to mobile QoS issues which may have occurred outdoors and/or at any other locations. This facilitates the investigation of our key research question which focuses on the impact of energy efficient residential building materials on indoor mobile signal. To capture in-home mobile signal issues we exploit the following two questions *“How often did you experience a loss of signal (or no/poor signal/coverage) in each of these locations? a) in a specific room/part of my home while other rooms/part of my home have signal, b) throughout my entire home”*. We treat all those who report that they experienced an in-home issue (whether in a specific room or their entire home) as having experienced an issue with their in-home mobile signal.¹⁰

⁹ Social class was categorised according to the occupation of the head of the household using the Association of Irish Market Research Organisations (AIMRO) social grade system. This is an industry standard for Irish survey companies and categorises social class as: A = Professional, Senior Management; B=Newly qualified professional, Middle Management; C1 = Junior Managers, Clerical; C2 = Skilled Workers; D = Semi or unskilled workers; E = State Benefit, Social Welfare only; F50+ = Large farms with 50+acres; F50- = Smaller farms with ≤ 50 acres.

¹⁰ While the MCE collects further information on the frequency in which respondents experience each of these issues, e.g. several times a data, once a month, we do not exploit the intensity of having experienced

The MCE contains other important information about respondent telecommunication devices which could reflect an increased propensity for experiencing a QoS issue with their indoor mobile coverage. We use information on whether or not respondents have a landline in their home which might reflect reduced mobile data usage (for calls) in the home. MCE respondents were also asked information about their mobile devices and to identify the type of smartphone they owned. Note, that the in-person interviewer explained how to identify the model using the settings of the device for respondents unsure about the model of their smartphone. We use this smartphone model information to classify MCE respondents’ mobile devices as being 5G enabled or not-enabled, based on latest market information (see Appendix Table A4 for classifications). Information about the mobile device technology of the respondent is important for identifying where a respondent can utilise the 5G outdoor mobile coverage available to them, or not. 5G mobile signal experiences greater attenuation through energy efficient building materials, and as such, we might potentially expect higher rates of QoS issues for those using this type of data coverage. We additionally exploit information on WiFi calling *“Do you ever make calls over Wi-Fi? - a Wi-Fi call is a phone voice call made using a Wi-Fi connection (such as the one in your home or whichever hot-spot or public free Wi-Fi you are connected to) instead of your mobile phone network.”* to account for individuals utilising fixed-line coverage (which will not be subject to outdoor-indoor signal attenuation) via their mobile devices.

In addition to telecommunication variables, the MCE also collects a limited number of demographic and socio-economic variables. This allows us to account for individual characteristics (age, employment status, education level and marital status), in our estimation models.

3.2 Outdoor Mobile Coverage

To proxy actual outdoor mobile coverage, we use the Q2 2022 Outdoor Mobile Coverage Map produced by ComReg. The Outdoor Mobile Coverage Map shows the predicted quality of outdoor mobile coverage that each operator can provide for each type of mobile signal technology (2G, 3G, 4G, 5G), for every residential address in Ireland. The Outdoor Mobile Coverage Map is characterised by five levels of coverage quality (No Coverage, Fringe,

these signal issues due to a higher level of reporting error. However, while consumers might struggle to accurately recall frequency, it is more likely they will correctly identify having had an issue at some point.

Fair, Good, Very Good,).¹¹ The MCE survey collects information on the current mobile network operator (e.g. Vodafone, Eir, Three) utilised by each respondent (i.e. which operator/MVNO they have bought their mobile data plan/package from). Using Eircodes, we link each MCE survey respondent to their outdoor mobile coverage quality according to their reported current mobile network operator. Capturing outdoor mobile coverage quality is fundamental to our estimation strategy. It allows us to attribute differences of in-home mobile QoS issues across individuals, to the outdoor-to-indoor signal attenuation characteristics of energy efficient building materials, while simultaneously accounting for the quality of mobile coverage available to each residence. Note, that while we observe the quality of mobile coverage available to each respondent, we do not observe the exact components of the mobile data plan they have paid for. While all data plans in Q2 2022 will have included 2G, 3G and 4G, not all data plans will have included 5G coverage (see previous discussion in Section 2.1).

3.3 Fixed Line Broadband Coverage

Fixed line infrastructure is not impacted by thermal energy efficiency measures which block and attenuate outdoor-to-indoor mobile signal. As such, local fixed line broadband infrastructure is an important factor to consider when understanding the relationship between consumer reports on the quality of their indoor mobile signal, and the energy efficiency of a home. Indeed, if consumers experience issues with their mobile signal they may be more likely to switch to fixed line broadband, potentially leading to under-reporting of QoS issues by MCE respondents. Importantly, the ability to implement this corrective switching measure will, however, be contingent on the availability of good quality fixed line broadband infrastructure. This paper accounts for this by exploiting Q2 2022 market intelligence data which is uniquely available to ComReg and captures all available (active/non-active), and planned, fixed lines for every residential Eircode in Ireland. The term “active” refers to lines in which the line is being sold to an end user who has a current active broadband subscription. As an NRA, this data is directly reported to ComReg by operators under section 13D of the Communications Regulation Act 2002. The data is used for a variety of regulatory and benchmark purposes and carries legal penalties for incorrect submissions resulting in a high degree of confidence in the accuracy of the dataset.

In addition to identifying active and non-active fixed lines, this dataset also contains a rich

¹¹ See Table 1 for a description of each coverage level. For a technical examination of the coverage categories in the Outdoor Mobile Coverage Map see Rudd and Kirtay (2021)

amount of information on the type of technology used to deliver the broadband (e.g. FTTH, ADSL, VDSL, Cable, Fibre) as well as the maximum download speeds of the broadband available. Given that different broadband technologies can often have different download speeds depending on their location (e.g. the download speed of broadband delivered by VDSL decreases with increased distance between a residence and street cabinet), we choose to focus on the *download* speed of the the fixed line connection. We match this information to each MCE respondent using the Eircode address level identifiers and categorise each respondent as having: (i) no active line, (ii) an active line with less than 1000MB/s theoretical capacity, or (iii) and an active line with 1000MB/s or greater capacity. The last category is based on Article 2(2) of the European Electronic Communications Code’s definition of a Very High Capacity Network and is used to construct national comparisons at an EU level (European Commission, 2018). It is worth noting that the reference category of ‘no active line’ includes both those who have no fixed line infrastructure available to them, and, those with non-active fixed lines (i.e. the infrastructure is available to them but they choose not to pay for it). We hypothesize that in the absence of fixed broadband, this reference category might also have a higher probability of capturing consumers using non-fixed broadband (e.g. MBB) which again, is more susceptible to outdoor-to-indoor signal attenuation.

3.4 Building Energy Rating Data

Data on building characteristics are obtained from the publicly available National BER Research Tool from the Building Energy Rating (BER) scheme which is administered by the Sustainable Energy Authority of Ireland (SEAI).¹² This dataset contains the BER certificates, for all Irish houses which were sold/rented/availed of SEAI retrofitting grants, from 2008 onwards. The data is released at the Small Area (SA) level defined by the 2016 Census (N=18,631). Small Area boundaries are based on population density and divide Ireland into geographic regions containing approximately 80-120 residences (see Figure A4). We include all BER certificates from April 2008 (the earliest date of BER assessment included in the National BER Research Tool) to those collected by December 2022. Note that this means that we include BER certificates collected throughout the entire calendar year in which the MCE Survey took place including the months post survey collection. This is based on the assumption that BER assessments might be conducted a short time after residential renovations/sale transactions have taken place and are thus likely to reflect BER distributions at the time of the MCE survey collection. Appendix A provides further details on the data.

¹² Data accessed December 2024 from: <https://ndber.seai.ie/BERResearchTool/ber/search.aspx>

While BER certificates encapsulate information about building characteristics which have important implications for signal attenuation properties (e.g. building age which predicts the likely radio frequency (RF) values of the building materials used, or the u-value which is a measure of thermal transmission), they also contain information on building characteristics which are less important for signal attenuation (e.g. the space heating systems and heating controls). Accordingly, it could be the case, that buildings which have similar BER certificates have very different signal attenuation characteristics. To overcome this issue, this paper focuses on buildings which are at the top end of the BER scale (B2-A1). We propose that by focusing on these highly energy efficient buildings, we increase our chances of capturing cases where signal attenuation properties caused by energy efficient building materials might be cumulatively occurring and thus more problematic e.g. energy efficient windows will be more problematic if other entry points such as walls have also been ruled out due to thermal efficiency materials. The National Retrofit Plan focuses on the target of retrofitting half a million homes to a minimum B2 standard by 2030. Indeed, by 2022, over a quarter of BERs recorded on the National register were B2 or higher (see Table A3). As such, this paper follows this policy focus, and uses this B2 BER threshold to indicate residential buildings which are highly efficient. The main limitation for the National BER Research Tool database for the purpose of our analysis relates to the fact that BER ratings are only released at the Small Area level. This means we cannot assign each survey respondent their individual household level BER certificate. Rather, we assign each respondent a BER grade based on the average of all BER certificates collected in their Small Area since 2008. More specifically, for each Small Area we calculate the percentage of BER grades which are B2 or higher.

It is important to highlight that the construction of the National BER Research Tool necessarily creates several non-random selection issues. As previously outlined, there is a legal requirement for BER certificates to be reported onto the BER register when selling, renting, buying, or availing of SEAI-funded retrofitting schemes. Consequentially, the observed sample of BER values on the register, might not reflect the underlying BER distribution of the Small Area housing stock which has not been sold, rented, or undergone a subsidised renovation prior to 2008. It is unclear to what extent the observed housing stock might differ from the unobserved housing stock. For example, some Small Areas could comprise housing stock (e.g. housing estates) which are built in similar time periods and thus likely have similar BER ratings. Alternatively, the housing stock within Small Areas might exhibit considerable variation if built in different time periods and/or if energy efficiency renovation rates across the housing stock exhibit differences. Additionally, it is unclear how the ratio of renting/selling/retrofitting to the pre-existing housing stock influences selection effects.

For example, in the case of housing sales, the distribution of BER grades could be reflective of an over-sampling of houses which are highly energy efficient (e.g. the construction of a new housing estate), or alternatively, an over-sampling of old housing stock which is less-energy efficient. Collins and Curtis (2018a) also highlight the issue of bunching (the skewing of BER ratings on the more favourable side of grade thresholds for those availing of retrofitting grants). This could result in an over-estimation of the true underlying BER distribution. Given that we are unable to observe and control for the potential occurrence of these different selection effects, we simply take average BER ratings per Small Area, across the entire period (2008-2022). This maximises the number of sampled BER observations per Small Area, which we argue, should increase the likelihood of capturing the true population mean. Furthermore, given that BER values have mechanically improved over time due to new build legislation, it decreases the potential for the positive bias that would occur if we were to restrict the dataset to the immediate years prior to survey collection.

4 Empirical Strategy

4.1 Estimation Sample

Following cleaning procedures in which we drop MCE survey respondents with no mobile phones, those who could not be linked to a mobile operator, and those who did not know if they had experienced a quality of service (QoS) issue, our final linked estimation sample comprise of 2,741 survey respondents. In line with previous telecommunications research in Ireland (European Commission, 2023), we classify rural areas as areas in which the population density is less than 100 people per square kilometer. Using the nationally representative weighting, this assigns 66% of MCE survey respondents as living in urban areas with the remaining 34% living in more rural areas.

Table 2 presents the descriptive statistics which are weighted to be nationally representative for the final linked estimation sample. 80.7% of the sample are under the age of 65. Over half of respondents (51.6%) have a 3rd level education with 42.6% reporting that they have obtained a secondary school or post-secondary school level of education.¹³ 63.5% of respondents are employed, 14.9% are in retirement, with the remaining 21.6% engaged in

¹³ Education categorised as follows; high education (*3rd Level post-graduate (e.g. Master, PhD, etc), 3rd-level under-graduate (diploma, BA, etc)*), medium education (*post- 2nd level course (e.g. certificate, apprentice, etc), 2nd level (e.g. Leaving Certificate etc)*), low education (*primary level, no formal education*).

other activities.¹⁴ 57% of the estimation sample are married with a further 7.2% cohabiting with their partner. 28.6% of the sample are single, with the remaining widowed (4.3%) or separated/divorced (3%).

Nearly a third (31.2%) of MCE respondents in the estimation sample report that they experienced a QoS issue with their mobile signal when using it indoors in their home. Smaller proportions experience QoS issues outside in their gardens (17.5%) and in non-residential settings such as when travelling (11.7%) or when in other indoor settings such as work (17.6%). Given that a relatively higher proportion of individuals report experiencing QoS issues inside their home, it raises questions about why this is the case. Most respondents have access to good quality outdoor mobile coverage as captured by the 5-point scale; 1=No Coverage, 2=Fringe, 3=Fair, 4=Good, 5=Very Good (see Table 1 for detailed description). This is reflected in high averages across the different mobile signal technologies: 3.617 (sd=0.59) for 2G, 2.93 (sd=0.83) for 4G, and 2.76 (sd=1.577) for 5G. Note that the lower average for 5G reflects the incomplete 5G rollout (approximately 20% have no 5G coverage) rather than poorer quality coverage per se. In terms of active fixed line broadband coverage, nearly a quarter (24.7%) have no fixed line coverage, 31.4 % have a fixed coverage with a download speed less than 1000MB, and 43.9% have fixed coverage with broadband speeds of 1000MB or more.

In terms of telecommunications devices 38.5% report that they have a home landline phone with 61.5% indicating that they do not have a landline. 46.9% of respondents owned a mobile device which did not have 5G enabled, 17.6% had a 5G enabled device with missing mobile device information reported for the remaining 35.5%. While 31.2% of MCE respondents reported that they had never used Wi-Fi calling, 68.8% reported that they used Wi-Fi calling. As a note of caution, it is worth observing that significant literature shows that consumers often find it difficult to understand telecommunications terminology and make sub-optimal switching decisions in both Irish and international settings (Lunn, 2013; Lunn and Lyons, 2018; Griffin et al., 2022). As such, poor understanding of telecommunication concepts and terminology may result in misleading survey responses for the Wi-Fi calling variable. This is illustrated by the following example in which Three Ireland did not offer Wi-Fi calling as an option until August 2022 (Three Ireland, 2022) (after the MCE survey took place), yet 61% of Three network customers in the MCE survey indicated that they use

¹⁴ Labour market status classified as; employed (*self-employed (including farmers), full-time work (30+ hours per week), part-time work (<29 hours per week)*), retired, and other (*Home Duties, student, unemployed*).

Wi-Fi calling (unweighted).¹⁵

4.2 Estimation

The objective of this research is to capture the relationship between energy efficient homes and mobile signal issues. Given the policy focus of residential retrofitting aiming to achieve a minimum B2 BER rating, we take B2 as a threshold BER value indicative of highly efficient homes. To estimate the probability of reporting an in-home mobile quality of service issue the following estimation model is employed:

$$\begin{aligned} issue_{i,SA} = & \alpha + \beta BER_{SA} + \\ & + \lambda MobileCoverage_i + \tau FixedCoverage_i \\ & + \theta Device_i + \phi Ind_i + \epsilon_{i,SA} \end{aligned} \quad (1)$$

This estimates the probability of individual i , living in Small Area SA , reporting an issue with the signal in their home, given the proportion of BER ratings B2 or higher in their Small Area. Included as controls are; outdoor mobile coverage quality (λ), fixed coverage download speed (τ), telecommunication device characteristics (θ), and individual characteristics (ϕ). Mobile coverage (λ) captures the estimated quality of the mobile signal (2G, 4G, 5G). This ensures that estimated differences between individuals in the reporting of in-home mobile phone signal do not reflect actual differences in outdoor mobile signal quality. We include coverage as continuous metric in which quality is represented on a 1-5 scale with higher values representing better signal quality.¹⁶ Fixed coverage (τ) accounts for whether the MCE respondent has an active fixed line broadband connection, and the maximum potential download speed (<1000MB, 1000MB+) of this connection. In addition we include respondents' region of residence (urban/rural) to account for poorer fixed coverage quality in rural areas.¹⁷ To control for the possibility that different sub-groups of the population might be more likely to both report experiencing mobile signal issues and live in areas with higher shares of energy efficient residences we also control for the individual characteristics of age (< 65/65+), education (low/medium/high), labour market status (employed/retired/other)

¹⁵ Poor consumer knowledge of telecommunications is common issue across different institutional settings. For example, OfCom, the UK's National Regulatory Authority found that only 46% of consumers who reported having full fibre broadband, actually had full fibre broadband available in their area (OfCom, 2023b). This is despite 67% of respondents saying they were confident or very confident in their understanding of telecoms terminology (OfCom, 2023a, pg.1130).

¹⁶ Alternative specifications of coverage yielded similar results. Results available at the request of the authors.

¹⁷ For example, VDSL broadband infrastructure which exploits the pre-existing infrastructure of copper telephone wires can lead to a dramatic decrease in the speed of the connection in cases where the distance between the premise and the street cabinet is large (as is often the case in more rural dwellings).

and marital status (Cohabiting/Married/Separated/Single/Widowed).

Information on respondent telecommunication devices are also included. Specifically, we include controls for whether or not a MCE respondent has a landline, whether their mobile device is 5G enabled and whether they use Wi-Fi calling. Accounting for these characteristics is important as they not only influence the probability of experiencing a mobile signal issue but might also be endogenous to the probability of experiencing a mobile phone signal issue (i.e. those who experience issues might be more likely to switch to WiFi calling or use a landline). As such, while we include these characteristics of telecommunication devices in a fully specified version of our model, we remain cautious with respect to how much endogeneity they potentially introduce. Furthermore, we remain cautious regarding the accuracy of reporting for Wi-Fi calling as previously discussed in Section 3.1.

5 Results

Table 3 presents the results from our models. All results are weighted to be nationally representative and are estimated using a probit model with marginal effects shown.¹⁸ Model (1) shows the baseline parsimonious specification in which just the quality of mobile coverage and fixed coverage are included as controls. Model (2) additionally includes individual level characteristics (region/age/employment status/education/marital status) to control for observed factors which could effect the probability of an individual living in an area characterised by high levels of energy efficient homes and their likelihood of reporting a QoS issue with their indoor mobile service. Model (3) accounts for any pro-active steps which may have potentially been taken by the survey respondent in response to experiencing an in-home QOS mobile signal issue and includes the mobile device characteristics of the survey respondent in addition to whether or not they have a landline. Caution on these results may be advised due to the issues of endogeneity and reporting error previously discussed. The final of Model (4) is fully specified and includes all controls (mobile/fixed coverage, individual characteristics, telecommunication device characteristics).

Table 3 shows that across all model specifications the probability of reporting an in-home signal issues is positively associated with the share of households reporting a BER rating of B2 or higher per Small Area. The co-efficient remains remarkably stable across all specifications. The most parsimonious specification (Model 1) indicates that on average

¹⁸ Linear probability estimates are shown in Appendix Supplementary Tables A5 and A6

the probability of reporting an in-home QoS mobile signal issue increases by 28.96% if 100% of households had a BER rating of B2 or higher, with the co-efficient slightly decreasing to 27.32% in the fully specified model (Model 4). The magnitude of the effect sizes are considerable and suggest that the mean variation in the reporting of mobile QoS issues can be explained by differences in area level residential energy efficiency characteristics.

5.1 Robustness Checks: Other Locations

The main hypothesis of the paper posits that once mobile and fixed coverage quality are accounted for, any remaining variation in indoor QoS issues across respondents can be explained by building materials. To check the robustness of our results we explore whether the same set of respondents report that they experienced an issue with their mobile phone signal in alternative locations when accounting for the average energy efficiency of residential building within their area (Table 4). First we exploit the question which asks if a loss of signal had been observed *“Outside of my home, but within the vicinity of my home (gardens, driveway, garage, sheds, home farm etc.) (not including your usage via wifi)”*. Table 4 shows that a positive association between BER ratings and QoS issues in outside residential areas is still observed. This could potentially be indicative of respondents who experience BER induced QoS issues, subsequently utilising their device in the garden to improve their access to outdoor mobile coverage.

We next explore whether QoS issues are reported in other locations in particular non-residential indoor settings and exploit responses to those who experienced a loss of mobile signal *“While in another location that you regularly/frequently visit (for work, school, college, recreation, visiting family/friends etc.)”*, and also during travel *“While travelling on a bike or in a car/bus (i.e. any travelling on a road) or in any other form of public transportation (train, Luas, Dart etc)”*. Table 4 shows that living in an areas with a higher proportion of energy efficient residential buildings is not associated with an increased probability of reporting a QoS issue in other locations. The lack of a significant association lends support to the hypothesis that our main findings are not driven by individuals who are an average more likely to experience mobile signal issues also being more likely to live in areas with energy efficient residences. While we cannot rule out the possibility that there is something unique to the areas that respondents live in (such that QoS issues are experienced both outside of their home and inside of their home) the results of Table 4 lend strength to the hypothesis that these QoS issues are uniquely experienced in residential areas characterised

by highly energy efficient homes.

5.2 Covariates: Discussion

While not the direct focus of the paper, it is interesting to comment on the direction of the relationship for the remaining covariates shown in Table 3. The main telecommunication controls show that as the quality of mobile 2G/4G operator coverage improves, the probability of reporting an in-home mobile signal issue decreases. Surprisingly, improved 5G coverage does not have a statistically significant association with decreased QoS issues. This likely reflects low 5G usage at the time of the MCE survey.¹⁹ In terms of fixed line coverage, those with active fixed line coverage (for all download speeds), are less likely to report that they have experienced an indoor QoS issue with their mobile signal, compared to those who have no active fixed line coverage. Regarding the socio-demographic information of MCE survey respondents Table 3 Models (2) and (4) show that those living in rural areas are more likely to report having experienced a QoS issue. Those who are aged 65 and over are less likely to report an in-home issue. This could be indicative of younger respondents using mobile more intensely, and consequentially more likely to notice signal issues. Similarly, it might also reflect a higher propensity for older MCE respondents to use more traditional forms of fixed line technology (e.g. landlines) which circumnavigate any mobile signal issues (Commission for Communications Regulation, 2022a).

In terms of mobile device characteristics (Table 3 Models 3 and 4), no differences in QoS issues are observed between MCE respondents with mobile devices which can be classified as being “5G enabled” versus those which are not 5G enabled. We expected WiFi calling to reduce mobile signal issues due to the fact that when a fixed line is present, it is not impacted by building materials. However, our results show that Wi-Fi calling is actually associated with an increase in signal issues. We offer two possible explanations for this. First, the use of Wi-Fi calling could be capturing those who have experienced issues with the quality of their mobile signal and as such, have proactively taken measures to mitigate these issues through the use of Wi-Fi calling. Those who have not experienced issues with their mobile signal quality might be less likely to enable Wi-Fi calling on their device. As such, Wi-Fi calling might be endogenous to experiencing issues with mobile signal quality which might explain the observed negative association. Second, a high level of error might be associated with the MCE responses to the Wi-Fi calling variable. Indeed, a likely source of error relates

¹⁹ In Q2 2022 there were 664,000 active subscriptions to 5G (Commission for Communications Regulation, 2022b) compared to 1.59 million in Q1 2024 (Commission for Communications Regulation, 2024a).

to respondents misidentifying instant messaging services (e.g. Whatsapp) as Wi-Fi calling. Those who use such services also may be confident and frequent users of mobile data, and thus more likely to notice issues.

5.3 Limitations

It is important to acknowledge several limitations of the research design. First, and perhaps most importantly, our findings do not capture a causal underlying relationship. While we show that there is a positive association between living in an area characterised by a higher share of energy efficient homes and the probability of reporting an in-home QoS issue, we cannot account for the possibility that there are unobserved joint factors which simultaneously sort individuals who are more likely to experience an in-home mobile QoS issue into specific areas characterised by different levels of residential energy efficiency (omitted variable bias). Although the richness of our data-set allows us to control for some key socio-economic characteristics (e.g. age, education), other important variables such as income and home-ownership could potentially add to the robustness of the results. Indeed, those who are renters are more likely to live in rentals characterised by lower energy efficiency ratings (Burfurd et al., 2012; Petrov and Ryan, 2021; Collins and Curtis, 2018b), which would decrease the probability of reporting a QoS issues. However, the greater flexibility offered by mobile contracts (i.e. contracts are tied to a mobile phone rather than the physical location of a house), might be more attractive for a renter population experiencing less permanence in their location. As such, we suggest that this sub-group of the population could potentially be also more reliant on mobile data contracts which would conversely increase the likelihood of observing a QoS issue. An alternative channel could be that those with higher incomes might be more likely to sort into areas in which the average energy efficiency of homes is higher and simultaneously afford smartphones with higher unobserved differences in smartphone performance. While we control for whether a phone is 5G enabled, there could be other smartphone design features which enhance performance and influence outdoor-to-indoor signal attenuation rates (Jemaludin et al., 2024). Relatedly, it would also be useful to decompose the results by gender to help provide insight as to whether certain sub-groups of the population are driving the results. For example, high proportions of women are engaged in home duties and thus might be more likely to experience in-home issues. Future work and surveys might therefore benefit from the inclusion of these variables.

A second limitation of our results, is that our proxy for the energy efficiency of an MCE residence is based on the surrounding area-level average and does not necessarily reflect the

individual level energy efficiency rating of an MCE respondents’ residence. As previously outlined (Section 3.4), our assumption that the energy efficiency of an MCE respondents’ home is correlated with the average energy efficiency of homes in their surrounding area remains open to discussion. Indeed, in an ideal research setting the exact energy efficiency rating of the individual home would be observed to reduce this potential source of noise. However, an advantage of using the area level average relates to the possibility that it reduces endogeneity at the individual level and acts as an implicit instrumental variable such that these results can be thought of as first-stage findings. Relatedly, while we use the energy efficiency ratings of buildings as a proxy of the signal attenuation characteristics of a building, we do not in fact observe the “signal attenuation rating” of residential dwellings per se. While our research question focuses on the implications of policy aimed at increasing the energy efficiency of the residential housing stock, it is important to bear in mind that not all energy efficiency measures will change the signal attenuation characteristics of buildings.

6 Policy Implications

The findings from this paper helps to inform and contribute to policy discussions taking place against a backdrop in which the energy efficiency of the total household stock is steadily increasing in line with climate migration policy objectives. Furthermore, as the Digital Decade 5G roll-out continues alongside the restructuring of the labour market in favour of remote home working, one could potentially expect to observe an increase in the rate of in-home mobile signal issues. Also of importance, is the ongoing 2G switch-off across Europe. In Switzerland, France, and the Netherlands, at least one network operator has already switched off its 2G network (BEREC, 2023). Similarly, in the UK network operators will not offer 2G services beyond 2033 (BEREC, 2023). While no Irish operator have applied for the 2G switch-off yet, ComReg have recently published a roadmap for operators wishing to switch-off 2G services in the future (Commission for Communication Regulation, 2024a). A major concern with 2G switch off is that it is the main network used around Europe for emergency call answering services (ECAS) (BEREC, 2023). As such, much of the policy focus around the 2G switch-off has focused on enabling ECAS calls on 4G and 5G networks (Commission for Communication Regulation, 2024a) (BEREC, 2023). However, 2G switch-off before coverage in the 700MHZ band becomes universal could have significant impacts on indoor quality of service for basic mobile services. Switching off 2G may reduce ECAS coverage within buildings with problematic signal attenuating characteristics even if 4G/5G coverage is available outside. Existing measurements of coverage from regulators do not take into account building materials, potentially ‘masking’ coverage issues from 2G

switch-off (BEREC, 2020). Our research adds another consideration for regulators both when considering the implications of 2G switch-off and when mapping 4G and 5G quality of service.²⁰

In terms of policy solutions, substitution towards Wi-Fi calling may constitute an efficient and cost-effective policy solution and indeed is already advocated as such by ComReg in Ireland. This solution essentially side-steps any in-home mobile coverage issues through the utilisation of good quality telecommunication infrastructure already available in the form of fixed broadband coverage. It is worth highlighting, that this solution does not improve mobile signal per se, but rather, requires consumers to have access to, and pay for, fixed line coverage. Despite Ireland’s extensive fixed line coverage, however, availability does not always correspond with take-up. Just 57% of premises with FTTP or Cable available had an active FTTP or Cable service at the end of Q4 2024 (Commission for Communication Regulation, 2024b). Understanding the determinants of take-up could be important for informing policy strategies aimed at improving take-up. Other broader considerations of the “fixed-coverage” solution relate to the equity implications of consumers on lower incomes being able to afford paying for both fixed line coverage and mobile coverage.

In Ireland, ComReg has already anticipated the “fixed coverage” solution by putting in place obligations which require operators to deploy and maintain Voice over LTE (VoLTE) and Wi-Fi calling for smartphones.²¹ However, to avail of the “fixed coverage” solution consumers typically need to enable the Wi-Fi calling feature located within their phone settings. Information campaigns which encourage the utilisation of Wi-Fi by specifically informing consumers how to change the settings on their phones could be an important tool for policy makers. A stronger policy response could potentially consider mandating that Wi-Fi calling is enabled by default on all mobile devices sold. A final observation of the Wi-Fi calling solution is that phones which are Wi-Fi enabled are primarily newer models (Commission for Communication Regulation, 2018). As such, if this proposed solution triggers abandonment of older mobile devices models, it could run counter to objectives of environmental sustainability in other policy domains.

²⁰ For a detailed look at considerations around 2G switch off in Europe see BEREC (2023).

²¹ *”With native Wi-Fi calling, calls and texts on a smartphone, rather than going through the mobile network directly, instead use the available Wi-Fi connection. Native Wi-Fi is particularly relevant for Ireland given the challenges in providing mobile connectivity to all premises and the use of modern building materials which can significantly impair the availability of radio signals indoors”.* Page 15 Footnote 21 (Commission for Communication Regulation, 2020)

While the predominant solution advocated in an Irish setting relies on the exploitation of high quality fixed coverage, the appropriateness of this solution might vary across different institutional settings. Not all countries can fund high quality fixed coverage solutions and other alternatives might be important to consider. Across the world, a range of solutions are currently being developed to address the issue of mobile signal loss in energy efficiency buildings. As outlined by Lu et al. (2023), some of these include active solutions, which consume additional energy, such as indoor base stations and repeaters. Mobile phone repeaters were illegal in Ireland until 2018, as they interfered with spectrum bands when not well designed and manufactured. ComReg has since changed regulations to permit specific mobile phone repeaters which amplify signal within the home.²² However, some features of mobile repeaters might limit their wide-spread usage as a solution to indoor QoS issues in Ireland. First, they are expensive, with professional installation also recommended, adding to cost and inconvenience.²³ Second, repeaters in Ireland are limited to 70db, compared to 100db allowed in the UK (Commission for Communication Regulation, 2018). This may limit their efficacy which combined with a high monetary and inconvenience cost means repeaters do not seem likely to enter widespread use.

Others solutions are more energy passive proposals, such as walls embedded with passive antenna systems (Vähä-Savo et al., 2023), or windows with frequency selective surfaces (Yunos et al., 2023) or signal slots. However, while building regulations directly stipulate objectives of increased energy efficiency, regulations have not yet been established with regards to the radio propagation characteristics of energy efficient building materials. Concerns regarding the lack of direction in this aspect have already previously been raised in the UK (Rudd et al., 2014) and Finland (Ministry of Transport and Communications Working Group, 2014). Moreover, Owens et al. (2022) highlight the importance of guidelines establishing metrics of total building penetration loss in order to ensure the success of other energy efficiency improving measures such as the installation of smart meters, might be supported.

At a European level, there has been little policy direction. However, the 700MHZ band has been recently re-assigned in every country across the EU except for Poland and Malta (Kronegger, 2024). The lowest band used previously was the 900MHZ band on 2G networks (BEREC, 2023). Spectrum is assigned on a technologically neutral basis but this band can

²² Wireless Telegraphy Act 1926 (section 3) (Exemption of Mobile Phone Repeaters) Order 2018 (Appendix 4: ComReg (Commission for Communication Regulation, 2018))

²³ At the time of writing the least expensive CE complaint repeater available was €210 for 4G only, and €710 for a 5G repeater.

be used in low speed 5G technology. While the assignment of this band is not in direct response to building material induced quality of service loss, its is noted as a distinct benefit with OfCom noting “low frequency spectrum is particularly good at wide-area coverage and in-building penetration” while having lower capacity than higher spectrum bands (OfCom, 2019). Similarly, at a European level it is recognised as offering lower speeds but being particularly useful to “enable nationwide and indoor coverage” (EU Commission, 2023).

It is clear that future-proofing connectivity should take trends in both the telecommunication sector and climate mitigation sector into consideration and propose higher level policy responses anticipating these developments. Care must be taken that issues of mobile signal loss do not adversely effect homeowners decisions to participate in energy efficiency retrofits. For example, recent research from Curtis et al. (2024) highlight the importance of considering the disutility associated with the disruption and mess in the trade-off decision for investing in energy retrofits. As public awareness grows regarding the potential unintended consequence of mobile signal loss, this could be another element of householder preferences to consider. Ensuring that solutions to these issues are clearly outlined and costed could be an important step for policy-makers to consider.

7 Conclusion

While previous research has focused on testing the signal attenuation characteristics of specific energy efficient building materials, we contribute to the literature by investigating the real-world implications of residential energy efficiency policy aimed at improving the nationwide residential housing stock to a minimum B2 Building Energy Rating, for reports of in-home mobile signal loss. Our empirical strategy is strengthened by rich administrative data collected by the National Regulatory Authority, ComReg, which allows us to account for the quality of telecommunication infrastructure (outdoor quality of mobile coverage and download speed of fixed broadband connection) available at each address in Ireland. Linking to a nationally representative survey on mobile consumer experiences collected in 2022 by ComReg we proxy the signal attenuation characteristics of consumer houses using administrative data collected by the Sustainable Energy Authority of Ireland on the average Building Energy Ratings within highly disaggregated spatial regions (Small Areas). This rich data allows us to attribute differences in the probability of experience an indoor mobile QoS issue, to differences in area level mean BER ratings, while accounting for the quality of telecommunication infrastructure uniquely available to each respondent. Using statistical modeling we find a positive association between living in areas with higher shares of energy

efficient homes and the probability of experiencing an indoor QoS issue. Indeed, our estimates suggest that living in a Small Area in which 100% of homes have at least a B2 BER rating, increases the probability of reporting a QoS issue by almost 30%.

8 Tables

Table 1: Quality of Outdoor Mobile Coverage

Coverage Quality	Description
5=Very Good	Strong signal with very good connections/maximum data speeds.
4=Good	Strong signal with good connections/data speeds.
3=Fair	Fair signal and reliable data speeds may be attained, but disconnections and data drop-outs may occur at weaker signal levels.
2=Fringe	Marginal or poor connections/data speeds with disconnections likely to occur.
1=No Coverage	Likely to have no coverage available in this area.

Data Source: Outdoor Mobile Coverage Map Commission for Communication Regulation (2021)

Table 2: Descriptive Statistics

	Summary
N	2,774
QoS issue: Residence (Indoor)	
No	1,910 (68.8%)
Yes	865 (31.2%)
QoS issue: Residence (Outside)	
No	2,288 (82.5%)
Yes	486 (17.5%)
QoS issue: Non-residence	
No	2,287 (82.4%)
Yes	488 (17.6%)
QoS issue: Travelling	
No	2,449 (88.3%)
Yes	325 (11.7%)
B2 Share	0.151 (0.197)
2G Coverage	3.617 (0.594)
4G Coverage	2.935 (0.838)
5G Coverage	2.746 (1.577)
Fixed Line	
No Fixed Line	685 (24.7%)
Fixed Line: Less than 1000MB	871 (31.4%)
Fixed Line: 1000MB+	1,218 (43.9%)
Mobile Device	
5G Device: No	1,301 (46.9%)
5G Device: Yes	489 (17.6%)
5G Device: Missing	985 (35.5%)
Ever Wi-Fi call	
Wi-Fi Call: Never	865 (31.2%)
Wi-Fi Call: Yes	1,909 (68.8%)
Regional Classification	
Urban	1,832 (66.1%)
Rural	942 (33.9%)
Landline	
No landline	1,706 (61.5%)
Has landline	1,069 (38.5%)
Age	
Under 65	2,239 (80.7%)
65+	535 (19.3%)
Labour Market Status	
Employed	1,762 (63.5%)
Retired	412 (14.9%)
Other	600 (21.6%)
Education Status	
Educ: High	1,430 (51.6%)
Educ: Medium	1,183 (42.6%)
Educ: Low	161 (5.8%)
Marital Status	
Cohabiting	199 (7.2%)
Married	1,580 (57.0%)
Separated/divorced	84 (3.0%)
Single	793 (28.6%)
Widowed	118 (4.3%)

Authors' calculations based on estimation sample. Standard deviations in brackets for continuous variables. Descriptives weighted to be nationally representative of the population. Data Sources: MCE Survey 2022 (ComReg), Outdoor Mobile Coverage Map 2022 (ComReg), National BER Research Tool (SEAI), Active Fixed Line Connections (Q2 2022, ComReg).

Table 3: Reported Issues with Home Mobile Signal

	(1)	(2)	(3)	(4)
B2 Share	0.2896*** (0.0798)	0.2934*** (0.0783)	0.2636*** (0.0785)	0.2732*** (0.0770)
2G Coverage	-0.0504* (0.0262)	-0.0390 (0.0253)	-0.0488* (0.0257)	-0.0351 (0.0249)
4G Coverage	-0.0578*** (0.0199)	-0.0537*** (0.0197)	-0.0555*** (0.0195)	-0.0507*** (0.0192)
5G Coverage	0.0047 (0.0081)	0.0081 (0.0083)	0.0024 (0.0080)	0.0078 (0.0082)
No Fixed Line	[ref.]	[ref.]	[ref.]	[ref.]
Fixed Line: Less than 1000MB	-0.1008*** (0.0383)	-0.0879** (0.0379)	-0.1201*** (0.0389)	-0.1066*** (0.0385)
Fixed Line: 1000MB+	-0.0916** (0.0359)	-0.0648* (0.0377)	-0.1136*** (0.0358)	-0.0838** (0.0376)
Wi-Fi Call: Never			[ref.]	[ref.]
Wi-Fi Call: Yes			0.1119*** (0.0279)	0.1101*** (0.0280)
5G Device: No			[ref.]	[ref.]
5G Device: Yes			-0.0522 (0.0427)	-0.0474 (0.0418)
5G Device: Missing			-0.0049 (0.0314)	-0.0102 (0.0305)
No landline			[ref.]	[ref.]
Has landline			0.0340 (0.0301)	0.0582* (0.0301)
Urban		[ref.]		[ref.]
Rural		0.0766** (0.0301)		0.0860*** (0.0300)
Under 65		[ref.]		[ref.]
65+		-0.0793* (0.0418)		-0.0741* (0.0420)
Employed		[ref.]		[ref.]
Retired		0.0114 (0.0551)		0.0062 (0.0524)
Other		0.0902** (0.0378)		0.0879** (0.0377)
Educ: High		[ref.]		[ref.]
Educ: Medium		-0.0331 (0.0300)		-0.0162 (0.0302)
Educ: Low		0.1134 (0.0756)		0.1428* (0.0751)
Cohabiting		0.1259** (0.0611)		0.1236** (0.0607)
Married		[ref.]		[ref.]
Separated/divorced		0.0035 (0.0715)		0.0381 (0.0747)
Single		0.0406 (0.0354)		0.0385 (0.0347)
Widowed		0.0394 (0.0751)		0.0664 (0.0761)
Outcome Mean	0.312	0.312	0.312	0.312
Observations	2,741	2,741	2,741	2,741

Probability of reporting an in-home mobile signal issue. Marginal effects from probit model weighted to be nationally representative. B2 share is the share of households with a BER rating of B2 or higher, per Small Area (Census, 2016). Based on BER ratings collected prior to 2023. Data Sources: MCE Survey 2022 (ComReg), Outdoor Mobile Coverage Map 2022 (ComReg), National BER Research Tool (SEAI), Active Fixed Line Connections (Q2 2022, ComReg). Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.01

Table 4: Mobile Signal Issues in Other Locations

	(1) Garden	(2) Non-Residential	(3) Travel
B2 Share	0.1374** (0.0646)	0.0481 (0.0649)	0.0753 (0.0535)
Outcome Mean	0.175	0.176	0.117
Observations	2,741	2,741	2,741
Mobile Coverage	Yes	Yes	Yes
Fixed Coverage	Yes	Yes	Yes
Mobile Device Controls	Yes	Yes	Yes
Landline	Yes	Yes	Yes
Individual Controls	Yes	Yes	Yes

Probability of reporting signal issues in garden, non-residential locations, and while travelling. Marginal effects from probit model weighted to be nationally representative. B2 share is the share of households with a BER rating of B2 or higher, per Small Area (Census, 2016). Based on BER ratings collected prior to 2023. Data Sources: MCE Survey 2022 (ComReg), Outdoor Mobile Coverage Map 2022 (ComReg), National BER Research Tool (SEAI), Active Fixed Line Connections (Q2 2022, ComReg). Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.01

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A Building Energy Ratings Dataset

We use data from the SEAI National BER Research Tool downloaded 6th December 2024 (<https://ndber.seai.ie/berresearchtool/ber/search.aspx>) which contains data on 1,270,450 Building Energy Ratings (BERs). We restrict the data to observations collected between 2002 and 2008 (986,869 observations) and clean the dataset further by removing observations with provisional assessments (24,998) and missing Small Area codes (n=179,583). This creates a final dataset containing 782,288 BERs from 2008 to 2022 across 18,627 Small Areas. Table A1 shows the number of BERs collected at the yearly level has steadily increased over time, with 87,758 BERs collected in 2022. The majority of Small Areas are sampled each year which reduced concerns that a small number of Small Areas over-represent the dataset. The average number of BERs observed each year for each Small Area is 13.12, with the median number of values falling at 5. Post 2018, the max number of BER observations per Small Area rises substantially (~ 300). These likely represent cases in which a new housing estate is built and thus a large number of houses will simultaneously have their BER recorded as they are sold on the market.

To gain insight into the underlying trends of the Building Energy Rating categories we use the following thresholds as indicated in the SEAI *BER Research Tool User Information Guide Version 2.0 (Appendix 1, Table 2)*. Rather than using the included “EnergyRating” variable, we recreate the BER categories to ensure consistency in the use of energy rating thresholds. This assigns BER ratings to categories according to the following thresholds: A1 (≤ 25), A2 ($> 25 \leq 50$), A3 ($> 50 \leq 75$), B1 ($> 75 \leq 100$), B2 ($> 100 \leq 125$), B3 ($> 125 \leq 150$), C1 ($> 150 \leq 175$), C2 ($> 175 \leq 200$), C3 ($> 200 \leq 225$), D1 ($> 225 \leq 260$), D2 ($> 260 \leq 300$), E1 ($> 300 \leq 340$), E2 ($> 340 \leq 380$), F ($> 380 \leq 450$), G (> 450).

Figure A1 displays the absolute distribution of BERs at the yearly level between 2008 and 2022. The lower BER counts recorded during the initial time period of the BER database (2009-2012) are likely reflective of the post-2008 recessionary period which lowered housing sales transactions. The total number of BER ratings then increases over the ten-year period between 2013-2022. In terms of BER category thresholds, the absolute number of highly energy efficient residential buildings captured by a BER rating of (A1-A3) can be seen to steadily increase between (in particular post-2016). Similarly, the numbers of buildings which are slightly less energy efficient (B1-B3) also increase over time. These increases in highly energy efficient buildings likely reflect new-build housing regulations (A3 pre-2019 and A2 post-2019), as well as improvements of the energy efficiency of the pre-existing housing stock (subsidisation of energy efficiency retrofitting grants). Figure A2 shows the distribution of BER ratings collected per year. While the proportion of BER certificates falling into the least energy efficient categories (F/G) remains relatively stable over time, the proportion of BER certifications categorised as D displays a substantial decline over time. As of 2022, just over a quarter of BER certifications were recorded as B2 or higher. See Table A2 for full breakdown of distribution.

Table A1: BER Dataset Descriptive Statistics: 2008-2022

	Nationally		BER Observations per Small Area			
	Total BERs	Small Areas	Mean	SD	Min	Max
2008	1,730	588	16.32	19.24	1.00	61.00
2009	37,003	10,290	12.87	19.27	1.00	138.00
2010	33,584	11,415	9.40	27.76	1.00	282.00
2011	43,731	13,082	7.09	8.28	1.00	90.00
2012	35,808	12,860	7.17	12.38	1.00	105.00
2013	52,987	14,465	8.77	11.38	1.00	95.00
2014	62,849	14,585	12.62	15.70	1.00	104.00
2015	58,235	14,540	12.84	19.71	1.00	211.00
2016	54,252	14,798	11.16	17.16	1.00	150.00
2017	59,306	15,155	13.86	23.45	1.00	162.00
2018	60,149	15,371	15.74	33.05	1.00	319.00
2019	65,308	15,578	17.16	35.79	1.00	334.00
2020	61,589	16,010	15.63	32.26	1.00	255.00
2021	67,999	16,820	17.58	43.75	1.00	375.00
2022	87,758	17,761	13.88	35.35	1.00	294.00
Total	782,288	18,627	13.12	27.77	1.00	375.00

Restricted to BER assessments collected between 2008-2022 across 18,627 Small Areas defined by Census 2016 boundaries. Summary statistics (mean, sd, min max) of BER observations per Small Area. Small Areas have at least one BER observation to be included in sample. Based on author's calculations. Data Source: SEAI National BER Research Tool (Accessed 6th December 2024).

Table A2: Baseline Descriptives

	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1	E2	F	G	Total
	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Year																
2008	0	2	47	149	494	389	143	100	70	64	80	49	45	45	53	1,730
2009	0	3	118	576	2,530	4,756	4,429	3,998	3,778	4,035	4,018	2,434	2,004	2,008	2,316	37,003
2010	0	23	200	502	1,219	2,728	4,035	4,476	4,801	4,859	3,934	2,047	1,625	1,490	1,645	33,584
2011	0	3	140	524	781	2,738	5,171	6,872	7,026	6,605	5,180	2,597	1,975	1,836	2,283	43,731
2012	0	2	232	545	901	2,492	4,228	5,022	4,933	5,015	4,212	2,271	1,783	1,792	2,380	35,808
2013	0	28	408	575	1,093	3,544	5,761	6,818	7,129	7,193	6,419	3,833	3,164	3,055	3,967	52,987
2014	0	185	1,155	547	1,169	3,678	7,150	9,090	8,778	8,831	7,525	4,317	3,395	3,164	3,865	62,849
2015	2	418	2,011	602	1,316	3,775	6,882	8,533	7,819	7,652	6,233	3,920	2,962	2,795	3,315	58,235
2016	3	938	3,095	364	1,369	3,921	6,716	7,599	7,021	6,572	5,383	3,085	2,460	2,498	3,228	54,252
2017	17	1,649	5,687	637	1,663	4,278	7,166	7,635	6,896	6,725	5,514	3,194	2,502	2,539	3,204	59,306
2018	31	2,545	7,506	506	1,381	4,551	7,533	7,949	6,724	5,953	4,862	2,748	2,191	2,393	3,276	60,149
2019	63	3,703	7,923	1,058	2,128	5,820	9,059	8,622	6,804	5,912	4,667	2,542	1,993	2,044	2,970	65,308
2020	210	6,479	5,143	1,441	3,100	6,300	7,697	7,016	6,050	5,088	4,303	2,347	1,750	1,876	2,789	61,589
2021	240	8,199	3,989	2,375	4,128	7,124	7,477	7,390	6,552	5,560	4,645	2,662	2,069	2,125	3,464	67,999
2022	714	5,600	5,167	4,741	7,064	10,835	9,949	9,546	8,357	7,138	5,837	3,247	2,581	2,804	4,178	87,758
Total	1,280	29,777	42,821	15,142	30,336	66,929	93,396	100,666	92,738	87,202	72,812	41,293	32,499	32,464	42,933	782,288

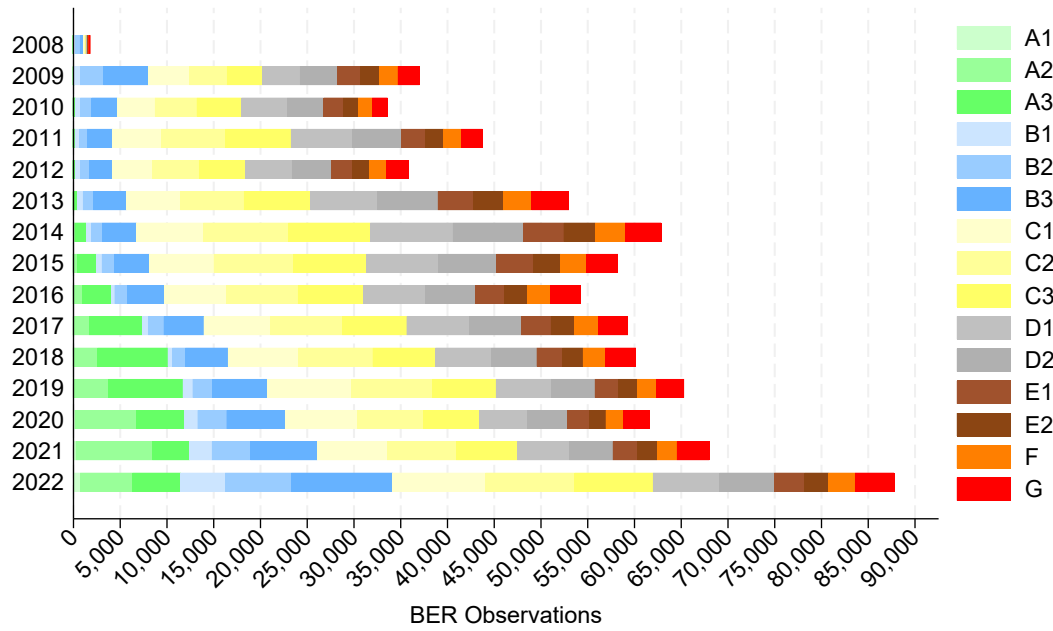
BER Grades 2008-2022. Author's calculations.

Table A3: Baseline Descriptives

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
BER Ratings																
A1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.4	0.8	0.2
A2	0.1	0.0	0.1	0.0	0.0	0.1	0.3	0.7	1.7	2.8	4.3	5.8	10.9	12.4	7.2	4.0
A3	2.8	0.3	0.7	0.3	0.7	0.8	2.1	4.2	7.4	12.4	16.8	17.9	19.2	18.3	13.1	9.4
B1	11.4	1.9	2.2	1.5	2.2	1.9	3.0	5.2	8.1	13.5	17.6	19.5	21.6	21.8	18.5	11.4
B2	40.0	8.7	5.8	3.3	4.7	4.0	4.9	7.5	10.6	16.3	19.9	22.8	26.6	27.8	26.5	15.3
B3	62.5	21.6	13.9	9.6	11.7	10.7	10.7	14.0	17.9	23.5	27.5	31.7	36.8	38.3	38.9	23.8
C1	70.8	33.5	25.9	21.4	23.5	21.5	22.1	25.8	30.2	35.6	40.0	45.6	49.3	49.3	50.2	35.8
C2	76.5	44.3	39.3	37.1	37.5	34.4	36.6	40.4	44.2	48.4	53.2	58.8	60.7	60.2	61.1	48.6
C3	80.6	54.6	53.5	53.2	51.3	47.9	50.5	53.8	57.2	60.1	64.4	69.2	70.5	69.8	70.6	60.5
D1	84.3	65.5	68.0	68.3	65.3	61.4	64.6	67.0	69.3	71.4	74.3	78.2	78.8	78.0	78.8	71.6
D2	88.9	76.3	79.7	80.1	77.0	73.5	76.5	77.7	79.2	80.7	82.4	85.4	85.8	84.8	85.4	80.9
E1	91.7	82.9	85.8	86.1	83.4	80.8	83.4	84.4	84.9	86.1	86.9	89.3	89.6	88.7	89.1	86.2
E2	94.3	88.3	90.7	90.6	88.3	86.7	88.8	89.5	89.4	90.3	90.6	92.3	92.4	91.8	92.0	90.4
F	96.9	93.7	95.1	94.8	93.4	92.5	93.9	94.3	94.0	94.6	94.6	95.5	95.5	94.9	95.2	94.5
G	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total																

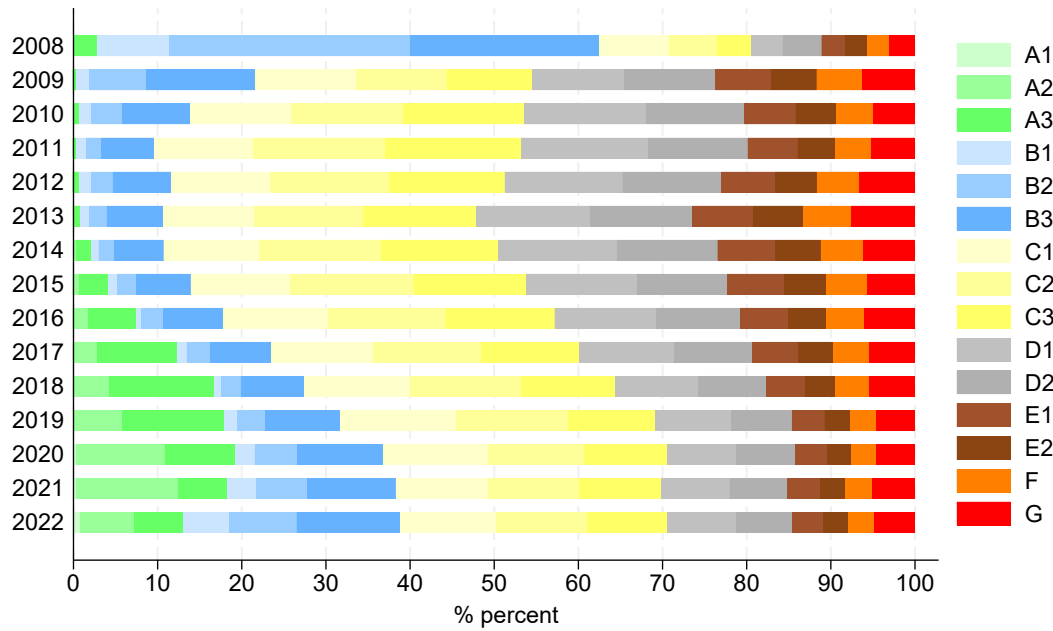
Cumulative percentages of BER Grades 2008-2022. Author's calculations.

Figure A1: Total number of BER observations, per year



Authors' Calculations. Data Source: SEAI National BER Research Tool (Accessed December 2024).

Figure A2: Yearly Distribution (%) of BER Ratings



Authors' Calculations. Data Source: SEAI National BER Research Tool (Accessed December 2024).

B Supplementary Tables

Table A4: Categorisation of 5G enabled devices

5g Enabled	Device Model
No 5G	Google Pixel 3 & 3Xl, Google Pixel 4, Google Pixel 4A, Google Pixel 5 , Google Pixel 6, Huawei P50 Or P50 Pro, Iphone 11, 11 Pro, 11 Pro Max, Iphone 13, 13 Pro, 13 Pro Max, 13 Mini, Iphone Se, Iphone Xr, Iphone Xs, Xs Max, Samsung Fold Lte Model, Samsung Galaxy Fold, Samsung Galaxy Note 20 Fe, Samsung Galaxy S20, S20+ And S20 Ultra, Samsung Galaxy Z Flip
5G Enabled	Huawei P40 Or P40 Pro, Iphone 12, 12 Pro, 12 Pro Max, 12 Mini, Samsung Galaxy Note 20 Fe 5G, Samsung Galaxy Note 20 Ultra, Ultra 5G, Samsung Galaxy S21 Fe 5G, Samsung Galaxy S21 Ultra 5G , Samsung Galaxy S21+ 5G , Samsung Galaxy Z Flip3 5G, Samsung Galaxy Z Fold2 5G, Samsung Galaxy Z Fold3 5G, Samsung Note 20+

Categorisation of MCE survey respondents devices

Table A5: Mobile Signal Issues in Other Location: Linear Probability Model

	(1) Garden	(2) Non-Residential	(3) Travel
B2 Share	0.1474** (0.0744)	0.0546 (0.0694)	0.0839 (0.0672)
Outcome Mean	0.175	0.176	0.117
R-Squared	0.058	0.036	0.041
Observations	2,741	2,741	2,741
Mobile Coverage	Yes	Yes	Yes
Fixed Coverage	Yes	Yes	Yes
Mobile Device Controls	Yes	Yes	Yes
Landline	Yes	Yes	Yes
Individual Controls	Yes	Yes	Yes

Probability of reporting signal issues in garden, non-residential locations, and while travelling. Linear probability model model weighted to be nationally representative. B2 share is the share of households with a BER rating of B2 or higher, per Small Area (Census, 2016). Based on BER ratings collected prior to 2023. Data Sources: MCE Survey 2022 (ComReg), Outdoor Mobile Coverage Map 2022 (ComReg), National BER Research Tool (SEAI), Active Fixed Line Connections (Q2 2022, ComReg). Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.01

Table A6: Reported Issues with Home Mobile Signal: Linear Probability Model

	(1)	(2)	(3)	(4)
B2 Share	0.3080*** (0.0896)	0.3143*** (0.0886)	0.2833*** (0.0883)	0.2959*** (0.0873)
2G Coverage	-0.0556** (0.0277)	-0.0460* (0.0270)	-0.0537** (0.0273)	-0.0417 (0.0269)
4G Coverage	-0.0583*** (0.0202)	-0.0541*** (0.0199)	-0.0573*** (0.0200)	-0.0528*** (0.0197)
5G Coverage	0.0043 (0.0081)	0.0077 (0.0081)	0.0022 (0.0080)	0.0072 (0.0081)
No Fixed Line	[ref.]	[ref.]	[ref.]	[ref.]
Fixed Line: Less than 1000MB	-0.0993*** (0.0378)	-0.0861** (0.0378)	-0.1154*** (0.0381)	-0.1016*** (0.0382)
Fixed Line: 1000MB+	-0.0924** (0.0362)	-0.0671* (0.0383)	-0.1130*** (0.0359)	-0.0839** (0.0381)
Wi-Fi Call: Never			[ref.]	[ref.]
Wi-Fi Call: Yes			0.1130*** (0.0278)	0.1072*** (0.0277)
No landline			[ref.]	[ref.]
Has landline			0.0338 (0.0299)	0.0580* (0.0299)
5G Device: No			[ref.]	[ref.]
5G Device: Yes			-0.0502 (0.0420)	-0.0466 (0.0415)
5G Device: Missing			-0.0041 (0.0315)	-0.0103 (0.0307)
Urban		[ref.]		[ref.]
Rural		0.0737** (0.0299)		0.0803*** (0.0296)
Under 65		[ref.]		[ref.]
65+		-0.0745* (0.0405)		-0.0708* (0.0410)
Employed		[ref.]		[ref.]
Retired		0.0042 (0.0520)		0.0013 (0.0504)
Other		0.0888** (0.0375)		0.0862** (0.0375)
Educ: High		[ref.]		[ref.]
Educ: Medium		-0.0280 (0.0297)		-0.0126 (0.0299)
Educ: Low		0.1141 (0.0747)		0.1386* (0.0738)
Cohabiting		0.1255** (0.0612)		0.1248** (0.0614)
Married		[ref.]		[ref.]
Separated/divorced		0.0035 (0.0675)		0.0411 (0.0664)
Single		0.0417 (0.0347)		0.0404 (0.0345)
Widowed		0.0302 (0.0721)		0.0552 (0.0715)
Outcome Mean	0.312	0.312	0.312	0.312
R-Squared	0.052	0.076	0.066	0.090
Observations	2,741	2,741	2,741	2,741

Probability of reporting an in-home mobile signal issue. Estimated with linear probability model weighted to be nationally representative. B2 share is the share of households with a BER rating of B2 or higher, per Small Area (Census, 2016). Based on BER ratings collected prior to 2023. Active fixed line connections (Q2 2022, ComReg). Data Sources: MCE Survey 2022 (ComReg), Outdoor Mobile Coverage Map 2022 (ComReg), National BER Research Tool (SEAI), Active Fixed Line connections (Q2 2022, ComReg). Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.01

C Supplementary Figures

Building Energy Rating (BER)

BER for the building detailed below is:

C2

Address

Street Name One, Street Name Two,
Town Name One, Town Name Two,
County Name One, County Name Two.

BER Number XXXXXXXXX

Date of Issue Day Month Year

Valid Until Day Month Year

BER Assessor Number XXXXXX

Assessor Company No XXXXXX

The Building Energy Rating (BER) is an indication of the energy performance of this dwelling. It covers energy use for space heating, water heating, ventilation and lighting, calculated on the basis of standard occupancy. It is expressed as primary energy use per unit floor area per year (kWh/m²/yr).

'A' rated properties are the most energy efficient and will tend to have the lowest energy bills.

Building Energy Rating

kWh/m²/yr

MOST EFFICIENT

<25	A1
>25	A2
>50	A3
>75	B1
>100	B2
>125	B3
>150	C1
>175	C2
>200	C3
>225	D1
>260	D2
>300	E1
>340	E2
>380	F
>450	G

198.69 kWh/m²/yr

C2

LEAST EFFICIENT

Carbon Dioxide (CO₂) Emissions Indicator

kgCO₂/m²/yr

BEST

0

Calculated annual CO₂ emissions

37.76 kgCO₂/m²/yr

WORST

>120

The less CO₂ produced, the less the dwelling contributes to global warming.

IMPORTANT: This BER is calculated on the basis of data provided to and by the BER Assessor, and using the version of the assessment software quoted below. A future BER assigned to this dwelling may be different, as a result of changes to the dwelling or to the assessment software.

DEAP Version: X.X.X

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Figure A4: Small Area Boundaries, Census 2016 (n=18,641)

