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Fiber vs. Vectoring: Limiting Technology Choices in Broadband Expansion

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Abstract

The upgrade of legacy infrastructure is a challenging undertaking in general. The underlying issues are especially prominent for telecommunications networks outside of urban areas. Using German micro-level data, we identify the structural determinants for fiber optics deployment and its extent. We also measure the role of technology competition from the existing infrastructures, VDSL-Vectoring and TV-Cable. In this setting and exploiting a natural experiment, a technologically restrictive policy as proposed by the European Commission is found to be ineffective in promoting fiber deployment. Policy interventions in the form of subsidies targeted at specific local infrastructure projects, however, raise the likelihood of fiber deployment by a substantial margin. A targeted, proactive policy approach is therefore needed to overcome structural and geographical disadvantages.

JEL Classification: D22; L52; L86; L96; 018

Keywords: Fiber expansion; Technology competition; Technology regulation; Subsidies; Regional Infrastructure

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1 Introduction

Communication networks are not only the backbone of today's digital era economy but are also shaping social interactions and with that our society. Investment in those networks therefore exerts positive effects on employment, growth, innovation and other economic indicators. This is achieved by reducing costs of existing business models while simultaneously paving the way for services and applications which rely on more potent networks and transmission rates. For the near future, these requirements are embodied by emerging services such as the Internet of Things, real-time traffic solutions and e-Medicine whose data demands are already foreshadowed today by streaming and cloud services. For this reason, investing in existing communication networks is paramount to cope with the exponential growth of data consumption and provide a hotbed for future innovations.[1] In technical terms, this means upgrading legacy networks, often based on copper, to a state-of-the-art and future-proof fiber-optics based architecture.

Apart from fiber, a consumer's access to a fixed line communication network can be realized by means of copper wires or TV-Cable. While all of these access technologies rely on fiber to some degree, only Fiber-to-the-premise (FttP) directly connects a household with fiber optics.[2] Other hybrid technologies like VDSL2-Vectoring (Vectoring) employ exclusively legacy copper double-wires on the local loop ("last mile") or rely on the hybrid-fiber-coaxial (HFC/TV-Cable) technology. Such existing technologies are readily available and less costly to roll out. This, naturally, affects network operators' calculations and is especially relevant in remote areas where installing fiber to every household might not be efficient.

In an effort to influence operators and accelerate the upgrading process of fixed line networks, the European Commission (EC) formulated a broadband target in 2016 envisioning the coverage of all European households with downlink speeds of at least 100 Mbit/s by 2025. Additionally, this bandwidth has to be provided by an infrastructure which can be technically leveraged to provide Gigabit speed in the near future (see European Commission, 2016a).[3] This Gigabit amendment effectively rules out Vectoring as a viable alternative from the available technologies. The EC (2016b) justifies this restriction by stating that "strategic profit-maximizing considerations at the operator level would delay the transition" to FttP structures. However, the assumption underlying this argument, namely that an incumbent's copper-based Vectoring deployment will act as a substitute to any FttP investment, has not been examined by scientific research so far. Indeed, influences on FttP deployment in particular have not been thoroughly explored, be it regarding structural drivers or effects resulting from infrastructure competition. We aim to close this gap.

This paper is the first, to the best of our knowledge, investigating FttP deployment as a supply side

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[1] Cisco (2017) estimates the data traffic over fixed internet to increase exponentially from 65,94 Petabyte(PB)/month from 2016 up to 187,39 PB/month by 2021. Note that 1 Petabyte(PB) = 1,000 Terabyte(TB) = 1,000,000 Gigabyte(GB).

[2] FttP is a shorthand for Fiber-to-the-Home/Building (FttH/B).

[3] Gigabit speed refers to download rates of more than 1 Gbit/s. Note that 1 Gigabit (Gbit) = 1000 Megabit (Mbit).

outcome at the micro-level. Using municipality-level data from Germany, we examine the influence of structural drivers of FttP deployment at the extensive and intensive margin. We also account for technology competition from the two competing architectures existing in Germany, that is, Vectoring and HFC.

We complement this part of the study with an analysis of policy interventions such as technology regulation and deployment subsidies. For examining effects of a technologically restrictive deployment regulation, a situation deemed favorable by the EC, we exploit a natural experiment in the German telecommunications market from December 2013 to June 2017. Due to exogenous, technological restrictions in the legacy access network, Vectoring was inoperable and banned in certain areas around network nodes, while households in all other areas could be accessed. This provides treatment areas within German municipalities, conform with the new EC mandate, in which higher bandwidths could only be achieved by FttP or HFC structures and control areas in which all technologies were applicable. For the deployment effect of locally targeted subsidies, we use the subset of the federal state of Bavaria which operated a substantial subsidy program over the observation period.

We find the following main results. First, we observe a significant impact of structural characteristics on the extensive probability of FttP deployment and the deployment extent. Of these characteristics, market size and accessibility measures are most pronounced. Notably, an increase of a population's average age by one year in a municipality decreases the investment likelihood by one percentage point. Second, technology competition, especially from Vectoring, appears to increase the likelihood of FttP deployment. However, this positive effect coincides with a negative one at the intensive margin. Hence, Vectoring might signal deployment-worthy municipalities but simultaneously acts as a substitute once both networks coexist, adversely affecting deployment extent. Third, a Vectoring restrictive regulation is ineffective and has neither an effect on the probability of FttP deployment, nor on deployment extent. Lastly, FttP-specific subsidies are demonstrated to be a highly effective policy tool. Every 100.000€ spent as part of the Bavarian subsidy program are associated with an increased likelihood of fiber deployment by three to four percentage points.

The remainder of the paper is structured as follows. Section 2 provides literature findings on the main strands to which we contribute. Section 3 comments on Germany's infrastructure landscape and defines our identification. Section 4 elaborates on the data used in our analyses. Section 5 introduces the empirical strategy whose results are presented in Section 6. Finally, the paper concludes in Section 7.

2 Literature

The vast literature on telecommunications networks establishes the view of the infrastructure as a general purpose technology in the sense of Bresnahan and Trajtenberg (1995). Communication networks are known to exert positive effects on a variety of macroeconomic indicators as well as individual firm or market performances (see Bertschek *et al.*, 2015). Given those positive effects, it is not surprising that the literature identifies different drivers and regulatory frameworks which best foster infrastructure deployment and investments.

We contribute to three different strands of the field. First, we complement the literature on structural drivers for investment in communications infrastructure by investigating these factors for a specific network type, FttP. Second, we examine regulatory approaches and their effect on infrastructure investment. While the effects of access obligations and state funding have been investigated, a technology restricting regulation has not yet been considered in this context. We close this gap. Lastly, we study the interaction of three competing network architectures - FttP, HFC and Vectoring - and their effect on FttP deployment from a supply-side perspective. Previous research has studied inter-technology competition only for the legacy infrastructures, DSL and HFC, and is focused on demand side indicators such as adoption and penetration.

In the first strand, regarding structural drivers, deployment is regularly explained by consumer demand for subsequent services or the costs of an infrastructure roll-out. Demand characteristics are household incomes and population ages, while the costs depend on the density of population and buildings, on topographic characteristics and institutional factors. These properties differ from the national down to the local level, as does actual investment. Cross-country and even regional (NUTS 2) or district-level (NUTS 3) analyses cannot properly capture these effects due to their aggregation. Not surprisingly, such studies either incorporate structural control variables but find no effects (Briglauer *et al.*, 2018, 2013) or abstain from using them (Grajek and Röller, 2012).[4] Empirical studies at the micro-level are scarce due to a lack of suitable data. Nardotto *et al.* (2015) study entry and broadband penetration on the local area level in the UK from 2005 to 2009. They determine significant effects of structural controls such as age, income and population density. Similarly, Bourreau *et al.* (2018) find a significance of population density and income for the number of active fiber operators in French municipalities over the period of 2010 to 2014.

The second strand concerns the options for policy makers to influence providers' decisions where, and to which extent, to deploy broadband infrastructure in general and FttP in particular. In this regard, a regulation restricting technology choice is unprecedented as an instrument to steer the physical deployment of telecommunications infrastructure. Hence, our paper is a first step in assessing the consequences of such a scheme. The most common and most widely studied regulative tool is local loop unbundling (LLU) based on the "ladder of investment" hypothesis (Cave *et al.*, 2001, Cave and Vogelsang, 2003), which postulates a natural evolution from competition in services to competition in infrastructure. However, this hypothesis

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[4] Other cross-country approaches investigating effects on broadband penetration, a demand side measure rather than deployment, take the same approaches. Bouckaert *et al.* (2010) and Briglauer (2014) find structural controls to be insignificant, Distaso *et al.* (2006) do not incorporate them.

finds little support in the literature. Cambini and Jiang (2009) even observe that a systematic trade-off between LLU and investments in broadband infrastructure might exist instead. Cross-country empirical approaches by Grajek and Röller (2012) and Briglauer *et al.* (2018) support this interpretation, as do theoretical analyses highlighting distorted incentives to invest in fiber networks (Bourreau *et al.*, 2012, Inderst and Peitz, 2012). In conclusion, LLU may produce static efficiency of markets but fail to deliver dynamic efficiency and the transition towards infrastructure investment (Bacache *et al.*, 2014). On the other hand, more recent studies by Bourreau *et al.* (2018) and Calzada *et al.* (2018), relying on micro-level data similar to ours, do observe a positive effect of LLU on fiber deployment. Given these ambiguous effects of LLU on infrastructure deployment, Briglauer and Gugler (2013) argue that subsidies might be more effective in promoting fiber deployment. Briglauer (2019) himself provides support for this perspective by observing broadband coverage to increase by 18.4 to 25 % if a municipality receives funding. This study is similar to ours in that it relies on Bavarian municipalities to investigate subsidy effects, although for a different time period and technology.

Lastly, the plethora of empirical studies on inter-technology competition mostly addresses the relationship between copper based (DSL) networks and TV-Cable (see Aron and Burnstein, 2003, Bouckaert *et al.*, 2010, Distaso *et al.*, 2006, Höffler, 2007, Nardotto *et al.*, 2015). These studies focus exclusively on demand side indicators such as broadband adoption or penetration as outcome variable of interest. They all conclude that inter-platform competition promotes the adoption and penetration of broadband. In contrast, studies investigating the effects of existing infrastructure on the deployment of new infrastructure are scarce. Briglauer *et al.* (2013) do investigate the deployment of broadband infrastructure under the competition of cable networks in the EU27 for the period from 2005 to 2011. However, they subsume all kinds of Fttx structures from VDSL to FttH under the broadband tag. Their analysis does consequently not account for technology-specific quality differences which would be crucial in assessing multilateral competitive effects of the infrastructures. Additionally, Calzada *et al.* (2018) study indeed the deployment of FttH in Spain but only projects carried out by the incumbent firm Telefonica. Their assessment of inter-technology competition with respect to Vectoring is based on Bitstream unbundling, the Vectoring based wholesale product. However, this approach implies a negative strategic bias since both FttH and the legacy infrastructure are operated and monetized by the incumbent. Thus, the incumbent's deployment incentives of FttH are systematically limited in areas where Vectoring coverage is high. Our study improves on this in considering firm-independent infrastructure deployments and, therefore, is a first step in understanding the interdependencies between three distinct competing infrastructures and the deployment of FttP.

3 Broadband Infrastructure in Germany & Identification

In this section, we compare the German network landscape to the regulatory demands placed upon it. The EC postulated a broadband target of fixed line connections of 100 MBit/s for every household by the time of 2025 and a reasonable upgrade path to Gigabit connection for the chosen infrastructure (European Commission, 2016a). To this end, we review the fixed line technologies of FttP, HFC and Vectoring and comment on their ability to deliver the EC's conditions. Their deployment extent by December 2013 - the starting point of our observational period - is also summarized. Finally, we elaborate on our identification strategy for a technology-restrictive (Vectoring-free) regulation, which is based upon the technological peculiarities of the historic public switched telephone network (PSTN).

3.1 Infrastructure landscape

The first and most potent technology is fiber, specifically: *Fiber-to-the-premise (FttP).* It subsumes deployments of fiber-optics reaching either the boundary of the end users' homes (FttH) or the respective residential building (FttB). For FttP, the entire "last mile", a shorthand for the wiring from the household's demarcation point to the main distribution frame (MDF), consists of fiber. This currently permits symmetric connections of over 10 Gbit/s in downlink and uplink, although the transmission itself is theoretically restricted only by the speed of light. Consequently, it is considered the most future proof network technology. On the other hand, deployment costs are substantial because existing copper double wires have to be replaced or overbuilt. Additionally, telecommunications infrastructure is traditionally installed underground in Germany, raising deployment costs further.

FttP has first been deployed in Germany in 2011 to the effect that only 2.78% of municipalities had been accessed by December 2013. The geographical deployment pattern is displayed in Panel A of Figure 1. These new networks are being operated by the incumbent - Deutsche Telekom - and other traditional internet providers (Vodafone, United Internet, Telefonica O2), but also by a large number of local carriers. The latter group includes municipality works, specifically founded local companies (M-net, Tele Columbus, NetCologne) and initiatives by municipal administration or citizens.

Hybrid-fiber-coaxial (HFC) networks, the second-most potent technology in Germany, uses fiber as well as coaxial wires of the legacy TV-Cable network (CATV). During our observational period from 12/2013 to 06/2017, two transmission standards - DOCSIS 3.0 and 3.1 - were used simultaneously.[5] While the former

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[5] The German CATV networks were owned by the Deutsche Telekom prior to market liberalization. From 2000 to 2003, Deutsche Telekom sold the CATV infrastructure sequentially in the form of regional sub-networks. From 2013 to 2017, the German CATV were owned by Kabel Deutschland and Unitymedia, which offered regionally differentiated HFC connections.

was introduced in 2006 and offers a maximum downlink of up to 1.5 Gbit/s and uplink of 200 Mbit/s, the latter was introduced in 2013 and permits a maximum downlink of 10 Gbit/s and an uplink of 1 Gbit/s. Hence, HFC both satisfies the current broadband target and offers a reliable upgrade path to Gigabit as well.[6]

Deployment or expansion costs are moderate as most of the legacy CATV wiring is of continuous use and only the equipment installed in network nodes needs to be replaced. However, the network covers only approximately 70% of all German households and by December 2013 only 27.77% of German municipalities had access to a high-speed HFC connection (see Panel B of Figure 1 for the geographical deployment pattern).

The last and most ubiquitous technology in Germany is the legacy copper network, upon which hybrid technologies are based. These are *Very High Data Rate DSL (VDSL)* and *VDSL2-Vectoring (Vectoring)*, which employ fiber up to intermediate network nodes - the so called cabinets - on the copper based local loop. In addition, Vectoring requires special equipment in the cabinets serving as junctions between fiber and copper double wires which filter out additional interference in the wire. The DSL architecture is based on the historical German PSTN, causing it to be near-ubiquitous since the connection of a household to a telecommunications network is a universal service in Germany. Coverage, therefore, is around 99.9% and the technology is the least expensive to roll out as it relies on the existing legacy network for the most complicated and costly part of the local loop, the household access.

However, both architectures suffer from the main shortcoming of copper wires: The higher the frequency of the transmitted signal (and thus connection bandwidth), the shorter the operating distance. VDSL lines provide download speeds close to 50 Mbit/s while Vectoring offers up to 100 Mbit/s downlink over short distances. The maximum operating distance lies at roughly 550m around accessed cabinets, whereas signal strength deteriorates rapidly beyond this. Hence, the upgrade potential of the copper based local loop is limited compared to other architectures. Although the next Vectoring generation G.fast will offer up to 800 Mbit/s over short distances (100m) split in down- and uplink and thus achieve the postulated 100 Mbit/s target, a copper based access technology cannot offer a reliable and widespread upgrade potential towards Gigabit. Under the EC regulation and in long-term consideration, it can therefore only serve as a bridging technology towards a pure fiber-based FttP network.

Vectoring is deployed predominantly by the Deutsche Telekom since the Bundesnetzagentur permitted its use in 2013. At the start of our observational period, 96,75 % of German municipalities were connected

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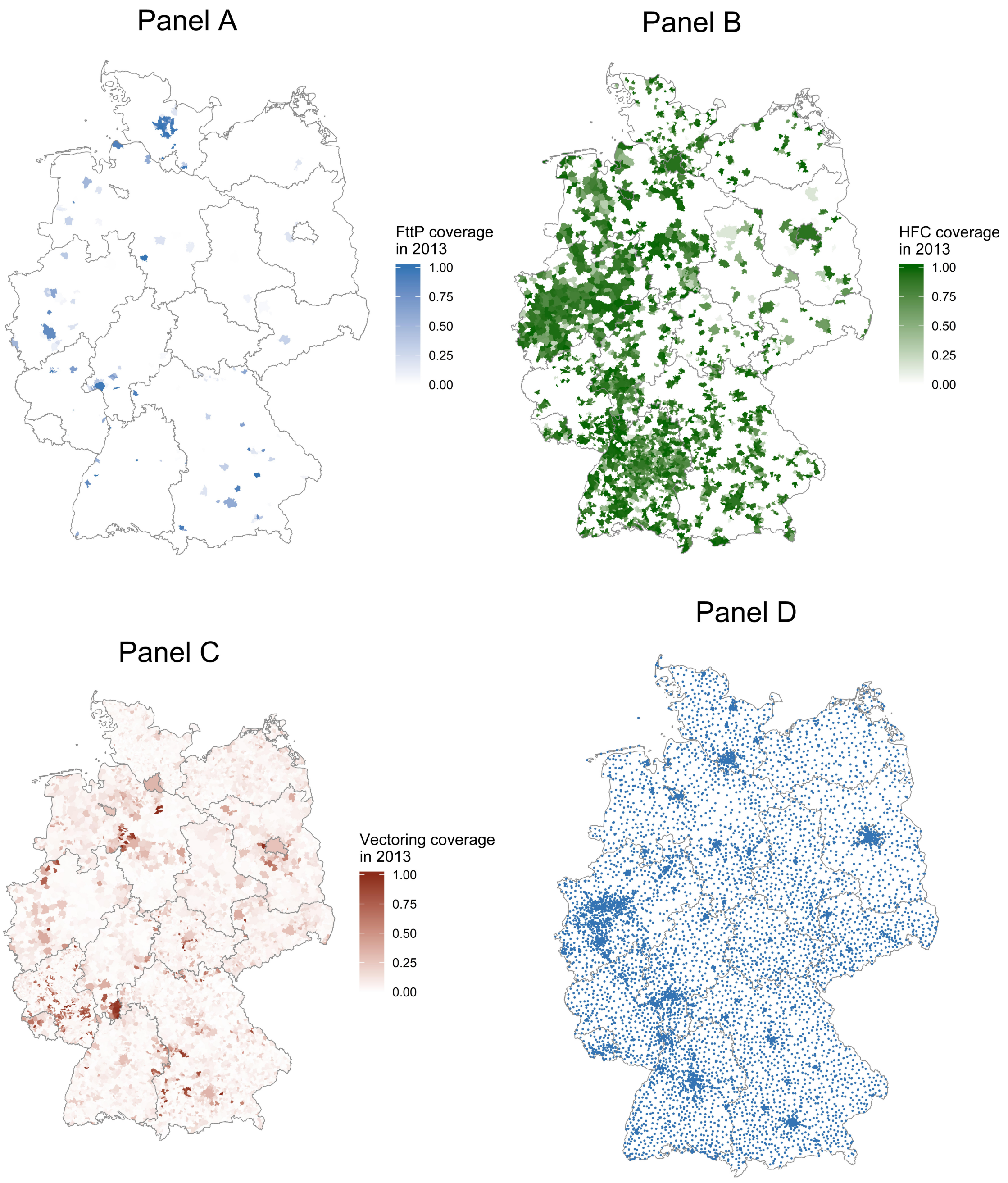
By 2019, both firms - and thus the majority of the historical CATV infrastructure - are owned by Vodafone.

[6] DOCSIS is an abbreviation for Data Over Cable Service Interface Specification and refers to a transmission standard developed by CableLabs, a research lab founded by American cable operators. The European transmission standards (EuroDOCSIS) are based on these but are modified to the European CATV networks which use 8 MHz channel bandwidth compared to the American 6 MHz. However, there are no notable differences regarding downlink and uplink between the two.

Figure 1: Network coverages in July 2013 - levels of FttP, HFC & Vectoring



Notes: Panel A-C display the network coverage of each access technology (FttP, HFC and Vectoring). Panel D illustrates the distribution and locations of all approx. 8,000 MDF in the German access network.

by a VDSL based technology offering 50 Mbit/s downlink or more (Vectoring). Panel C of Figure 1, once again, displays the geographical deployment pattern.

3.2 Identification

With the sequential introduction of Vectoring into the German telecommunications market, a natural experiment is provided which permits the identification of a potential causal relationship between the technology's availability and the deployment of FttP. In August of 2013, the Bundesnetzagentur (2013) initially permitted Vectoring in so called *Remote*-areas, i.e. areas outside of 550 meter wire length starting from the serving main distribution frame (MDF). Vectoring deployments for households within that wiring distance of 550m from the MDF, the so called *Near*-areas, were permitted only in July 2017 (Bundesnetzagentur, 2016). This sequential introduction stemmed from technical limitations of the equipment installed in MDFs which was inoperable with the equipment that needed to be installed in cabinets located too close to the MDF.[7] Prior to the application for Vectoring clearance, this sequential procedure could not have been anticipated by market participants. These circumstances enable the observation of *Near*-areas in which 50+ Mbit/s connections could be provided only by means of FttP and HFC - as the EC target demands - and *Remote*-areas in which all three technologies could be deployed. Panel A of Figure 2 illustrates the classification of *Near*- and *Remote*-areas within municipalities based on MDF placement.

We follow the common definition for *Near*-areas and choose a radius of 550m around each MDF, which is a necessary approximation for the actual Vectoring availability. The technical limitations apply to wiring length, not aerial distance, but wiring may follow street corners or be placed so as to access an entire block most efficiently. The "curvier" such paths, the more likely it becomes that households in the outskirts of the 550m radius defining *Near*-areas are, in wire length, sufficiently distant from their MDF to permit Vectoring. However, only by allowing these false negatives can the households outside the *Near*-areas be properly defined as legally accessible and thus serve as functioning control group.[8] Panel B of Figure 2 displays the schematic structure of the local loop and the special case mentioned above.

The placement of MDFs and thus the selection of households into *Near*- and *Remote*-areas rests on the historical structure of the German PSTN. That structure was determined first in the 1920s and then reshaped in the 1960s following reconstruction after the Second World War and during the German sepa-

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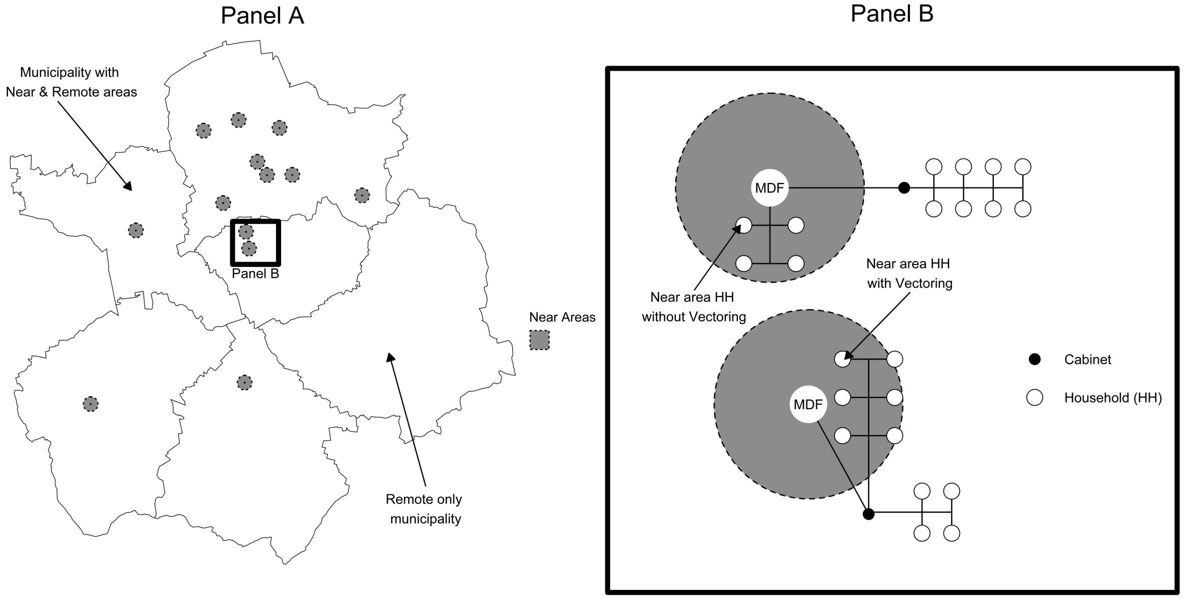
[7] Specifically, this equipment enabling Vectoring is the Digital Subscriber Line Access Multiplexer (DSLAM). Usually, these are installed in cabinets in the form of Outdoor-DSLAM and supply their respective catchment areas. If a MDF is located nearby, the Outdoor-DSLAM has to restrict its transmission spectrum on certain frequencies so as not to interfere with the MDF's signal. This spectral attenuation is normalized in the ITU-Standard G.997.1 and limited the applicability of Vectoring in its early form. Thus, the Deutsche Telekom decided to initially introduce Vectoring in *Remote*-areas only, where the distances to the nearest MDF are sufficiently large.

[8] Furthermore, choosing a radius other than the 550 meters that define the technological limitation would be arbitrary. Only by specifically observing and accounting for wire length could accuracy be improved but this data is not accessible.

Figure 2: MDF placement and Identification



Notes: Panel A illustrates the classification of *Near*- and *Remote*-areas based on MDF placement as well as *Remote*-only municipalities which are not served by an MDF within their own boundaries. Panel B schematically displays the structure of the local loop. The *Near*-area is defined by a 550m radius which allows for an exceptional case where the wire path is so“curvy” that households are accessible with Vectoring despite being theoretically located inside a *Near*-area.

ration. Consequently, existing infrastructure, especially railways, together with population centers at the time shaped the network. Infrastructure influenced wiring paths, while the number of MDFs grew with population size and remained substantially smaller in the GDR. Notably, wiring length had no impact on the quality of telephone services, allowing MDF location choices to be based on structural characteristics and the technological restrictions of the time.[9] MDFs could, for example, house only a limited number of copper twin wires, which caused their number to inflate in larger cities.[10] Sparsely populated areas, on the other hand, required less MDFs or even none at all, shifting the location choice to questions of lots, suitable buildings and topographic issues. Panel D of Figure 1 displays the placement pattern of MDFs in Germany.

Given these relationships, it follows that municipalities with different population shares residing in *Near*-areas also differ systemically in structural characteristics, necessitating a matching procedure prior to estimating a treatment effect. Such an approach is as much precaution as it is necessary by endogeneity concerns. While today’s deployment decisions cannot have influenced MDF placements 60 years - or even a century - ago, today’s infrastructure roll-out might well be based on municipal characteristics. These, in turn, are likely to be time-persistent and could have influenced MDF placement at the time, which serves as selection into treatment. Consequently, despite the treatment being exogenous, it cannot be analyzed

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[9] For reason of this exogeneity, Falck *et al.* (2014) also used the structure of the PSTN for identification purposes.

[10] A main cable from any MDF can contain up to 2,000 copper twin wires.

without accounting for the underlying structural characteristics. Their potential persistence could otherwise bias estimates on today's deployment effects when omitted. Population density, firm agglomeration and topographic peculiarities are all potential causes for such a bias.[11] In conclusion, we chose to augment the identification by conducting a propensity score matching based on the variables best predicting MDF placement (see Section 5.2).

4 The Data

The data we use describe a network operator's deployment decision for a given municipality along four dimensions which we capture in separate variable categories. Technology (T) contains all variables concerning broadband infrastructure. Variables in the market size (Y) category capture relevant influences from the demand side, while accessibility (X) contains deployment cost indicators. All funding related variables are part of the subsidy (S) category. Finally, federal state (*Länder*) fixed effects (L) account for unobserved differences between German federal states. These could be rooted in the structures of local markets or different construction regulations. They also capture intangible factors such as differences in state-level policy and laws or broader trends stemming from the German separation. In what follows we comment on the data sources and the inclusion of a specific variable in a given category.

4.1 Broadband Data

Infrastructure data is sourced from the *Breitbandatlas*, a database funded by Germany's federal government collecting information on household access to broadband technologies. Network operators voluntarily communicate to the database the share of accessed households and available speeds per technology in a given area. This data is provided on an aggregated basis.[12] The operators' offers are accumulated into a total share of households connected to either a certain speed or technology. Speeds are sorted into specific ranges, namely: ≥ 1, ≥ 2, ≥ 6, ≥ 16, ≥ 30 and ≥ 50 Mbit/s of which the last is used in this analysis because it is feasible only with Fiber, HFC and Vectoring. The most granular aggregation level available is the municipality, providing about 11,000 observational units for Germany.

For identification of the Vectoring-specific regulation (see Section 3.2), the municipality coverages were split into *Near*- and *Remote*-areas using virtual circles of 550m radius around the geographical positions of all main distribution frames. Of Germany's 11,187 municipalities in the set, 4972 possess MDFs within their

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[11] Although the decline of coal and steel in the Ruhr valley suggests limitations to persistence with regard to firm agglomeration.

[12] Note that the data used in our analysis was provided by the TüV Rheinland, which had administered the *Breitbandatlas* until December 2018. AteneKOM has since assumed that role, but informed us that they had not received the historical data from TüV Rheinland. For this reason, our data is - to our knowledge - no longer accessible from the *Breitbandatlas*.

boundaries and thus have *Near*- and *Remote*-areas, whereas 6211 do not and are thus classified as *Remote*-only. A further four municipalities are small enough to not surpass their respective *Near*-area boundaries. The average network coverages for each municipality type are summarized in Table 1.

The main specification includes network coverages in 2013 as well as the coverage increase of all three technologies during the observational period. This is equally motivated by our research goal of investigating technology competition as well as literature findings of Bourreau *et al.* (2018) and Calzada *et al.* (2018) who show that deployment and adoption of fiber is crucially impacted by competing infrastructures. Another technology related variable we consider is a municipality's proximity to already existing FttP deployments in 2013. This dummy variable *nearby10k* captures potential spillover effects from these early accessed municipalities to adjacent ones. It takes the value 1 if the centroid of any municipality with FttP deployment in 2013 is at most ten kilometers distant from its own centroid. These variables together with information on MDF distribution define the technology category (T). Summary statistics for all variables contained in T are presented in Table 23 in the Appendix.

Table 1: Average coverages by technologies

Municipality	Count	FttP.13	FttP.17	HFC.13	HFC.17	Vectoring.13	Vectoring.17
Near-only	4	0	0	0.078	0.0823	0.0954	0.1162
Remote-only	6211	0.0118	0.0568	0.1303	0.1538	0.0935	0.3206
Near & *Remote*: *Near*	4972	0.0075	0.0279	0.3582	0.4157	0.0631	0.2716
Near & *Remote*: *Remote*	4972	0.0066	0.0274	0.2826	0.322	0.0589	0.3173
With FttP Expansion:							
Near-only	0	-	-	-	-	-	-
Remote-only	622	0.1087	0.5586	0.15	0.1625	0.099	0.2929
Near & *Remote*: *Near*	637	0.0588	0.2174	0.5536	0.5994	0.0967	0.3943
Near & *Remote*: *Remote*	637	0.0516	0.2141	0.4437	0.4741	0.0827	0.4593

Notes: The average coverage quotas for all broadband technologies in municipalities are shown for *Remote*-only, *Near*-only and *Near* & *Remote* municipalities. The latter group is listed separately with respect to *Near*- and *Remote*-areas. The second part of the table shows the average coverages for all municipalities with positive FttP expansion in the observation period.

The three and a half years covered in the treatment period are sufficient to accommodate for planning cycles and actual deployment, that is, for expansion to occur and treatments to show an effect.[13] However, expansion is still slow. Of all municipalities, only around ten percent receive any investment in FttP. Of those, *Remote*-only municipalities exhibit, on average, 56% coverage of their households, while municipalities with MDFs receive coverage of around 21% by December 2017.[14] For the whole of Germany, average coverage

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[13] The slow expansion of FttP coverage, the most costly and time-consuming technology to roll-out, underlines this assumption (see Table 1).

[14] Note that median values for expansion in *Near* & *Remote* municipalities are substantially smaller, at 5% and 6% for the two areas. This reflects the decrease in deployment intensity for larger municipalities on one hand and the high coverage shares for small, primarily *Remote*-only ones. Generally speaking, coverage changes are always subject to size differences between observation units. In our case, a given number of accessed households will translate to a larger coverage change for smaller

drops to 5.7% and 2.7% percent, respectively. The largest increases in coverage can be observed for Vectoring. Notably, an increase in HFC coverage is also observed, but owed not to physical deployment in the ground but to upgrades of existing systems.

4.2 Municipality Data

The supply of broadband connections and the underlying investment decisions are likely based on market size and (presumed) willingness to pay. Given the high fixed costs of deploying fiber networks, a sufficiently large uptake and adoption of those services is necessary to recover costs. The uncertainty regarding these profits very likely constitutes a major cause for the slow expansion of FttP. More importantly, alleviating or reducing these risks will be paramount to network operators. In lieu of the network operators' actual calculations, municipality characteristics are the best approximation for them.

Market size characteristics (Y) include a municipality's population, the amount of residential buildings (Houses), the average age and the average income per capita of its citizens. These variables are known to determine the attractiveness of a municipality in terms of willingness to pay or sales potential for FttP based services (see Bourreau *et al.*, 2018, Briglauer *et al.*, 2019, Calzada *et al.*, 2018). Generally, wealthier people can more easily afford price premiums for higher bandwidths and younger people are on average more interested in data-intensive services. Table 2 presents summary statistics for all variables contained in Y.

Table 2: Summary statistics for market size (Y) variables

Variable	Count	Mean	Median	St. Dev.	Min	Max
Houses	10,956	1,672	556	5,833	0	316,047
Population	10,957	0.731	0.171	4.714	0	342.18
Age	10,940	44.39	44.15	2.490	32.61	58.89
Income p capita	10,945	34.38	33.72	7.144	7.97	142.89

Notes: Summary statistics for all variables contained in the market size (Y) category. The complete list of information on all used variables including their scale of measurement can be found in Table 24.

The set of accessibility (X) variables covers cost drivers for expansion projects. Apart from the prime factor of population density, which is usually found to exert a positive influence on infrastructure deployment in the literature (Bourreau *et al.*, 2018, Calzada *et al.*, 2018), the main specifications also include a municipality's area, the share of newly built houses as well as a ruggedness measure for ground composition and the driving distance (*Min_MZ*) to the next mid-sized town. New housing is included as these houses will be connected to the existing network via FttP which could induce spillover effects for the deployment of

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municipalities than for large ones. However, observing households instead would not improve results since that measure suffers from the reverse: it allows no inference on the intensity of expansion within the constraints of the given municipality, while coverage change does. Moreover, coverage is the policy-relevant measure.

other, already existing houses. Additionally, larger and topographically more uneven municipalities should be more costly to access given the required ductwork. The distance to the next mid-sized town indicates the seclusion of a specific municipality which we expect to raise costs and negatively influence infrastructure deployment.[15]

Related accessibility measures which we consider in robustness specifications include the number of single-family houses, the driving distance to the nearest motorway access and forest as well as industrial areas of a given municipality. Single homes could indicate higher access costs per household due to more ductwork being necessary, whereas larger industrial areas might cause positive spillover effects if they were to be accessed. Forest area and the distance to a motorway access are considered as alternative seclusion indicators to *Min_MZ*. Lastly, we implement also the number of main distribution frames ($HVT.count$) from category T in a robustness specification. Since MDFs are already accessed with fiber, this can also be interpreted as a cost relevant indicator addressing lower wiring expenses for FttP if MDFs are available in large numbers.

German municipalities (*Gemeinden*) provide information on these variables in the *Regionalstatistik* database. Data for 2013 is used to align with the start of the observational period, whereupon expansion decisions would have been based.[16] The distance based seclusion measures (*Min_MZ*, *Min_A*) are sourced from the *INKAR* database and the topographic ruggedness is calculated from the 30 arc-seconds terrain grid provided by Nunn and Puga (2012).[17] Summary statistics for all variables in X are presented in Table 3.

Table 3: Summary statistics for accessibility (X) variables

Variable	Count	Mean	Median	St. Dev.	Min	Max
Density	10,946	1.829	0.929	2.765	0	45.312
Single-Family Houses	10,937	0.748	0.763	0.100	0.320	1.000
New Construction	8,436	0.023	0.019	0.018	0.001	0.494
Area	10,948	31.756	18.645	40.099	0.450	891.700
Forest Area	10,948	9.539	4.270	15.620	0	354.030
Industrial Area	10,948	0.301	0.060	1.027	0	41.840
Ruggedness	11,175	0.683	0.548	0.668	0	7.901
Min_MZ	11,021	12.134	11.450	8.666	0	147.346
Min_A	11,021	15.662	12.734	12.477	0	149.665

Notes: Summary statistics for all variables contained in the accessibility (X) category. The complete list of information on all used variables including their scale of measurement can be found in Table 24.

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[15] The distance measure (*Min_MZ*) has also been used by Briglauer *et al.* (2019), but was not significant for the set used in their study on the provision of broadband coverage.

[16] Note that data is scarce or non-existing for a small number - less than one percent - of mostly small municipalities, which drop out of the sample. Additionally, some of these municipalities have been merged with others, changing unique identifiers or creating entirely new ones. For this reason, we drop these ambiguously defined municipalities, which seems preferable to the inclusion of erroneous data; especially since their modifiers are at times not consistent in the broadband data either. Conveniently, the municipalities in question do not experience FttP expansion.

[17] See http://www.inkar.de/ for the *INKAR* database and https://diegopuga.org/data/rugged/ for the raw data on *Ruggedness* of Nunn and Puga (2012). We are especially thankful to an anonymous reviewer who recommended the inclusion of a ruggedness indicator which improved the quality of our results.

4.3 Subsidies & Bavaria

Data on subsidies for broadband expansion issued by the federal state of Bavaria are used to measure the impact of direct government aid on FttP deployment; as are the subsidies issued by the federal government itself.[18] The latter were often spread out across entire administrative districts and skewed towards more populated regions.[19] Bavaria's subsidies in contrast have a similar volume to the federal program, but for the state and its 2,000 municipalities alone. Additionally, the funding is directed towards less populated, more rural municipalities and is consistently assigned to the specific municipality that applied for it. For a comparison between federal and Bavarian funding choices, see Table 4. Bavaria provides a detailed, publicly available database listing all funded projects and specifying allocation of money, volume, operator (responsible for network installation) and technology deployed. This program, started in 2013, is the only one of such scale and detail in Germany and was also used by Briglauer *et al.* (2019) for their analysis. The specification of technology in particular is a distinct advantage over the federal data, because it allows to assess a technology-specific deployment effect by distinguishing between FttP-specific funding and other deployment projects. To account for planning and construction cycles, we only consider deployment projects that had been approved by the end of 2015. Consequently, we contain the variable *Funding until 15* as the accumulated fiber-specific subsidies a municipality received up to 2015 along with a dummy variable of receiving funding in the subsidy category (S). Figure 3 displays the geographical distribution of the funding associated with this selection of projects.

Table 4: Subsidy Statistics

Bavarian subsidies	Count	Avg.sum (in 1000 €)	Population (in 10,000)	Density (in 100/km^2)
No FttP-Funding	1986	0	0.601	1.85
FttP Funding	142	405.54	0.466	1.32
Federal Subsidies				
No Funding	10882	0	0.629	1.7565
Funding	301	2,656.70	3.8614	3.0152

Notes: Averages for Population variables of subsidized municipalities. In the federal subsidy scheme, any funding directed at a specific municipality was included. The Bavarian set is restricted to funding for projects approved until 2015 and specifically including FttP deployment.

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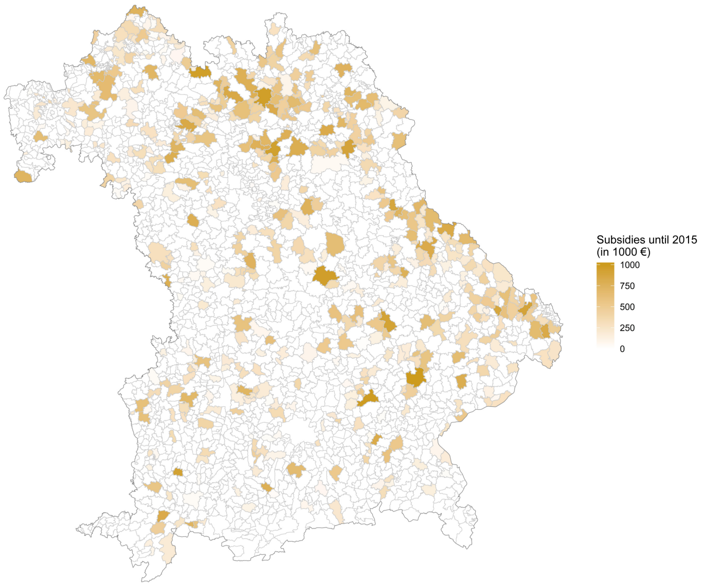
[18] Specifically, by the Ministry of Transport and Digital Infrastructure.

[19] In these cases, when subsidies were allotted to entire districts, the total amount of subsidies was assigned to the corresponding municipalities according to their population- or area-weighted shares. Due to the inherent inaccuracy of this procedure, federal subsidies were also filtered to include only those assigned to specific municipalities in the first place.

Figure 3: Bavarian subsidies accumulated until 2015



Notes: Geographical distribution of accumulated FttP funding originating from the Bavarian subsidy program. All payments of the years 2013, 2014, and 2015 were considered in the accumulation.

5 The Model

The empirical strategy addresses, in turn, our three research questions regarding FttP expansion. First, where does it occur? Second, to which extent? And, third, how does policy affect these outcomes? The first and second translate to the extensive and intensive margin of expansion, which are driven by supply side characteristics and demand indicators like, for example, deployment costs and existing legacy networks. After identifying these structural determinants, we assess two policy interventions in the form of technology restrictions and subsidies. The methods and models used for this process are explained here.

5.1 FttP Expansion

Extensive Margin FttP deployment at the extensive margin is defined as a municipality's probability of receiving FttP access as the variable of interest. This probability is a suitable measure to assess supply side considerations and the effectiveness of policy measures, although it is aggregated over operators and investments are only observed by proxy of their resulting change in coverage.[20]

To this end, operators' decision-making on whether to access a municipality or to expand an existing

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[20] In fact, it specifically indicates a municipality's "resistance to investment", which decreases as the probability of expansion increases.

network is based on the four categories of variables defined in Section 4: Technology (T), market size (Y), accessibility (X) and subsidies (S) while also accounting for federal state (*Länder*) fixed effects (L). These capture, in order, technology-competition, the commercial attractiveness, the access costs, financial support and state-specific market structures and policy for a given municipality. The fixed effects also account for Germany's economic North-South and East-West differences.

The category-specific subsets of characteristics used in the extensive margin equation are indexed with E. They jointly constitute the set of explanatory variables in the following Logit model on the binary deployment decision for each municipality, which is also estimated linearly.[21]

$$Prob(\text{InvF} = 1|X_E, Y_E, T_E, S, L) = f\ (X_E'\alpha_E, Y_E'\beta_E, T_E'\gamma_E, S'\delta_E, L'\zeta_E) \tag{1}$$

Intensive Margin The dependent variable used for FttP expansion at the intensive margin is the change in coverage share from the start of the observation period to its end: Δ FttP = $FttP.17 - FttP.13$.[22] Given that a municipality sees FttP investment, this measure accurately captures the intensity of this resulting deployment.

Technically, deployment effects at the intensive margin are estimated via OLS and with a second subset of the structural variables. The category sets for the intensive margin specification are denoted by the index I. These subsets reflect that certain structural factors are likely irrelevant to the deployment extent, but important to the binary deployment decision - and vice versa. Availability of an already existing competing infrastructure, for example, will affect deployment decisions in general, but matter for the intensity only in the case of an overlap between old and new technology. Similarly, the overall population characterizes market size, but likely does not matter for changes in the coverage for which it is effectively the denominator. Consequently, the model is defined as follows:

$$\Delta\ \text{FttP} = X_I\alpha_I + Y_I\beta_I + T_I\gamma_I + L\zeta_I + u \quad . \tag{2}$$

Additionally, the resulting difference between extensive and intensive margin models allows the use of a Heckman correction model (see Heckman, 1976, 1979), which requires such exclusion restrictions in the

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[21] Other subsets of the characteristics are used outside of the main specification in robustness checks. Note also that this model is restricted ex-post to municipalities without FttP coverage in December of 2013. As elaborated upon in Section 6.1, a municipality with non-zero FttP coverage in 2013 is almost guaranteed to receive further investment on account of the existing access alone. This effect is so strong that it trumps all structural factors, biasing results and necessitating this exclusion.

[22] As with the extensive margin specification, the analysis is restricted to first-time FttP investments (see Section 6.1). Thus, Δ FttP simplifies to its value at the end of the observation period, June 30 of 2017. This alters the intensive margin interpretation to the coverage chosen when a municipality is initially accessed with FttP.

first step. Here, this step is the selection into FttP deployment - the extensive margin. The Heckman correction accounts for the possibiliby of non-random selection by appending a bias correction term to the second step, which reflects the potential effect of selection on the intensive margin. The term is calculated via the standard deviation σ of the error term u and the inverse Mills ratio of the first stage and is defined as follows:

$$\sigma\lambda\left(X_E'\alpha_E + Y_E'\beta_E + T_E'\gamma_E + S'\delta_E + L_i'\zeta_I\right) \quad .$$

5.2 Policy Interventions

Technology Regulation As elaborated in Section 3.2, Germany's sequential introduction of Vectoring provides a natural experiment mimicking a technology-restrictive regulation, permitting the assessment of such a scheme.

However, the identification is valid not on the municipality level - as the control variables are - but for *Near*- and *Remote*-areas within municipalities. These differences in aggregation mandate an adjustment of the data. Specifically, treatment and control groups have to be scaled up to the municipality level required for the analysis, which is accomplished by calculating the shares of a municipality's population residing within (κ) and outside *Near*-areas ($1-\kappa$). Treated are those municipalities which are highly affected by the technological restriction in *Near*-areas and exhibit a share κ of at least one standard deviation above the mean of the distribution of these shares ($\kappa \geq \mu_\kappa + \sigma_\kappa$). This type of municipality is classified as *Near*-heavy. Analogously, municipalities only barely affected by the treatment constitute the control observations, classified as *Near*-light and defined by: $\kappa \leq \mu_\kappa - \sigma_\kappa$. All other municipalities are either of an intermediate κ and classified as *Near*-normal or *Remote*-only which exhibit a share of $\kappa = 0$ by default. Both of these groups are excluded from the analysis regarding technology regulation because they cannot be conclusively sorted into treatment or control groups.[23] The classification of municipality types according to their *Near*-share thresholds is summarized in Equation 3.[24]

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[23] *Remote*-only municipalities in particular are structurally different from municipalities with MDFs and could not be affected by the treatment given their lack of MDFs.

[24] Note that the *Near*-shares are calculated as the ratio of *Near*-area coverage to a municipality's aggregate coverage. Iteratively, all network technologies are used in this calculation to achieve the most accurate result possible. Yet for some municipalities ($< 5\%$) the data is insufficiently precise and thus yields ambiguous results. These observations are dropped prior to analysis.

$$\text{Municipality Type } = \begin{cases} \textit{Near}\text{-heavy} & \kappa_i \geq \mu_\kappa + \sigma_\kappa \\ \textit{Near}\text{-normal} & \mu_\kappa - \sigma_\kappa < \kappa_i < \mu_\kappa + \sigma_\kappa \\ \textit{Near}\text{-light} & 0 < \kappa_i \leq \mu_\kappa - \sigma_\kappa \\ \textit{Remote}\text{-only} & \kappa_i = 0 \end{cases} \tag{3}$$

Table 5 displays key average attributes for the four municipality types defined above. *Near*-heavy municipalities can be characterized as smaller in terms of area and population than *Near*-light (or -normal) ones. This, together with a different age structure, indicates that treatment and control group observations cannot be considered equivalent ex-ante. Since those differing attributes might have influenced MDF placement in the past (see Section 3.2), selection into treatment might be non-random in this regard, necessitating a matching procedure.

Table 5: Average characteristics by municipality type

Municipality Type	Count	Avg. κ	Popul. (in 10,000)	Density (in $100/km^2$)	Area (in km^2)	Houses (abs.)	HVT.count (abs.)
Near-heavy	660	0.665	0.51	2.21	26.46	1256.47	1.13
Near-light	499	0.0741	1.96	2.42	67.94	4023.77	1.47
Near-normal	3369	0.2629	1.69	2.97	55	3652.15	1.59
Remote-only	6206	0	0.14	1.12	15.13	430.31	0

Notes: Comparison of key municipal characteristics by municipality type. For the thresholds defining the respective types, see Equation 3.

The procedure of choice is propensity score matching with the propensity being a municipality's probability of possessing a dense allocation of MDFs and thus a substantial *Near*-area. These likelihoods are estimated via a Logit model regressing this *Near*-heaviness on the more time-persistent structural attributes of German municipalities. This includes accessibility and market size characteristics such as population density, area, number of residential houses and population size, which reflect broader agglomeration trends, but also federal state fixed effects to capture structural differences in MDF placements resulting from the German separation and post-war federalism in West Germany.[25] The Logit model used for the estimation of propensity scores is defined in Equation 4.[26]

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[25] The actual data on municipality characteristics for this period is, unfortunately, not comprehensive, excluding the former GDR entirely and suffering from incomplete data-keeping for West German municipalities. Hence, the reliance on present-day data.

[26] For a more detailed look into the quality and choice of this specification, see Table 20 of the Appendix.

$$Prob(\text{Near} = 1|LXY) = f\left(L'\alpha, \delta_1 Dens, \delta_2 Area, \delta_3 Houses, \zeta_1 Population\right) \quad (4)$$

Based on the propensity scores from this equation, nearest neighbor matching with and without replacement is used to define suitable *Near*-light municipalities as control group for the set of *Near*-heavy treatment municipalities. This procedure is effective in reducing the differences in key variables between treatment and control group municipalities, as can be inferred from Table 6 in comparison with Table 5. Specifically, matching with replacement reduces variation between the groups by 65% to 75%.[27]

Table 6: Average characteristics of matched treatment and control group municipalities

Municipality Type	Count	Avg. κ	Popul. (in 10,000)	Density (in $100/km^2$)	Area (in km^2)	Houses (abs.)	HVT.count (abs.)
Near-heavy	539	0.66	0.51	1.37	27.08	1312.24	1.13
Near-light	173	0.07	0.86	1.46	41.42	2125.54	1.01

Notes: This table depicts average characteristics for municipalities matched with replacement using Equation 4, separate for treatment group (*Near*-heavy) and control group (*Near*-light) observations. The displayed covariates have been used in the calculation of the propensity scores.

Matching-relevant covariates aside, the matched subset is also balanced across federal states, largely drawing treatment and control municipalities proportional to the size of the states. Schleswig-Holstein, which sees above average expansion, is slightly over-represented while the city states Bremen, Hamburg and Berlin drop out. Likewise, the two groups experience deployment roughly to the same degree as other municipality types, implying a common population with respect to actual and predicted deployment decisions.[28]

Since pre-period data for technology-specific network coverages is not available, we cannot test for the fulfillment of the parallel trends assumption directly. However, treatment and control observations are similar to the dropped out but comparable *Near*-normal municipalities with respect to the likelihood of FttP deployment and structural characteristics. Based on this and the conducted propensity score matching, we are confident that the matched sample most likely follows the same trend.

In terms of common support, the two groups have sufficient overlap for a qualified comparison (see Figure 4). Discrepancies do exist in the areas of higher propensity scores, pointing to limitations of the matching. But this deviance in the tails seems acceptable given the higher number of treatment than control observations and the fact that municipalities of a high predicted *Near*-heaviness are typically larger in area and smaller in population - and thus less comparable to *Near*-light municipalities. Furthermore, the matching is more a precaution against an indirect bias resulting from persistence in explanatory variables

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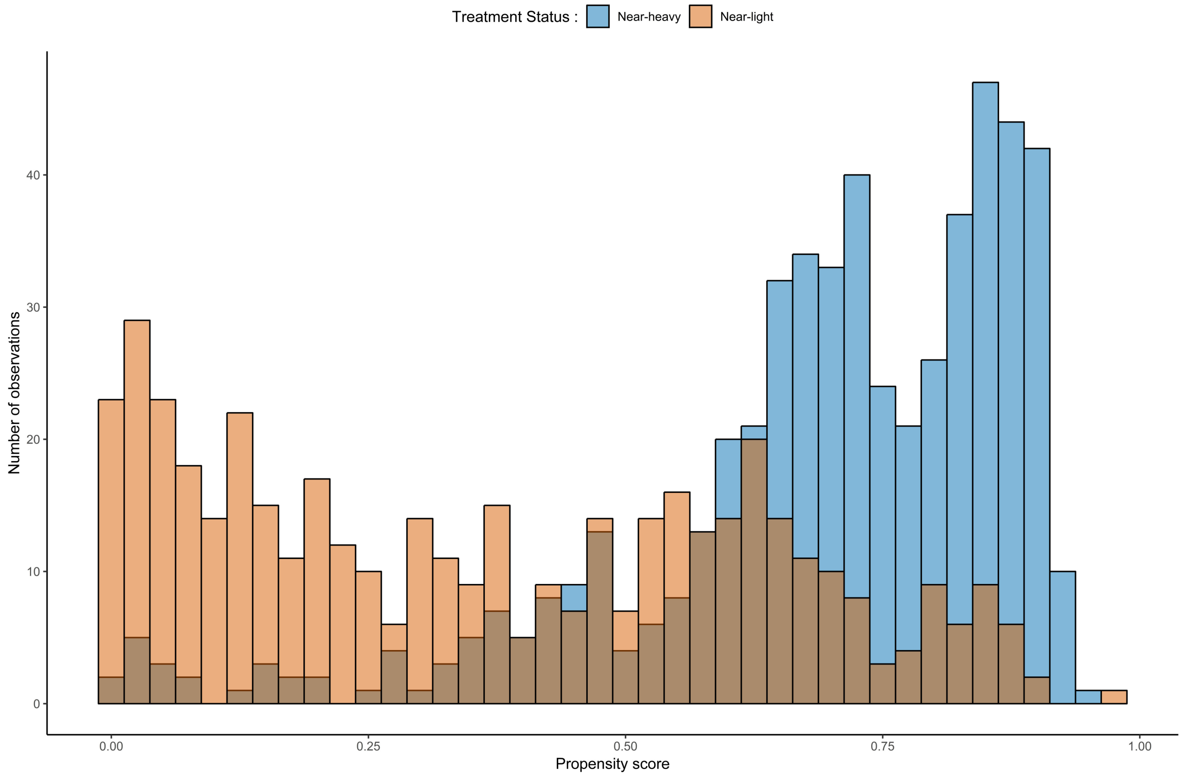
[27] Matching without replacement performs worse, but still significantly reduces divergence.

[28] Figure 5 in the Appendix displays this as a collection of scatter plots for the federal states.

and not against selection into treatment, since MDF location and broadband expansion are decisions taken almost a century apart. Using the matched set, the average treatment effects are calculated as sample means and compared between treatment and control groups. We also apply an OLS estimation for robustness.

Figure 4: Area of Common Support



Notes: Probabilities of being *Near*-heavy for municipalities that have a high share of *Near*-areas (treatment group) and those with a low share of *Near*-areas (control group).

Subsidies The impact of subsidies as a driver of FttP expansion is assessed using the comprehensive program and recordings of the federal state of Bavaria. Extensive and intensive margin models are estimated equivalently to Equation 1 and Equation 2, without the federal state fixed effects. Thus, the subsidies become a singular addition to an otherwise unchanged set of characteristics, permitting comparison across models and subsets.

6 Results

6.1 FttP Expansion

Pre-existing FttP The first result and an ex-post restriction of the main analysis is the special status of municipalities with positive FttP coverage in 2013 (*FttP.13* > 0), the start of the observational period. They are almost guaranteed to receive further - if sometimes miniscule - FttP expansion during the observation period (Δ *FttP* > 0). Out of 311 municipalities which were already accessed with FttP, 303 received further investments into the technology between 2013 and 2017 (see Table 7), while the remaining eight already had high coverage. On average, these municipalities are substantially larger and more densely populated than their counterparts without FttP in 2013. Although these mean characteristics are inflated by Germany's largest cities and skewed by heterogeneity in municipalities, the general trends remain even when observing median values, which suggest a structural distinction between early accessed municipalities and all others.[29]

Table 7: Municipal characteristics by pre-existing FttP coverage

FttP.13$>$ 0, ΔFttP $>$ 0	Count	FttP.13	ΔFttP	Population (in 10,000)	Density (in $100/km^2$)	HVT.count (abs.)
No, No	9916	0	0	0.52	1.67	0.56
No, Yes	956	0	0.295	1.41	2.3	0.96
Yes, No	8	0.696	0	0.02	0.52	0
Yes, Yes	303	0.339	0.002	5.47	5.54	2.93

Notes: Average characteristics for municipalities with and without FttP coverage in 2013 are displayed, separated into those that did (Δ FttP$>$ 0) and did not receive expansion (Δ FttP$=$ 0) during the observational period.

If early accessed municipalities were of a population distinct from all other municipalities, their inclusion in the set of the main analysis might bias results. Structural drivers of investment could no longer be identified correctly. A regression of being an early accessed municipality on subsequent FttP expansion taking place stresses this risk.[30] Existing coverage in 2013 implies an expansion probability of near 100% in linear, Logit and Probit models (see Table 8). Given the dominance of this effect for pre-existing FttP coverage, the exclusion of all municipalities with FttP coverage in 2013 becomes necessary. Hence, the sample is reduced to municipalities not accessed with FttP by the end of 2013 (*FttP.13* $= 0$).

Extensive Margin FttP investment decisions at the extensive margin appear to be driven by elements from three of the four categories defined: Technology, market size and accessibility. Subsidies are insignificant on the federal level. Table 9 shows the estimations for the corresponding Logit and OLS regressions. The

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[29] Median municipality characteristics relating to FttP coverage in 2013 are displayed in Table 14 of the Appendix.

[30] Being an early accessed municipality is captured by the dummy *F2013* which takes the value 1 if *FttP.13*$>$ 0 and a value of 0 otherwise.

Table 8: Influence of pre-existing FttP on the probability of FttP expansion

	Linear (1)	Logit (2)	Probit (3)
	FttP.Exp [0,1]		
(Intercept)	0.09^{***}	-2.34^{***}	-1.35^{***}
	(0.00)	(0.03)	(0.02)
F2013 [0,1]	0.89^{***}	5.97^{***}	3.30^{***}
	(0.02)	(0.36)	(0.15)
R^2	0.21		
Adj. R^2	0.21		
Num. obs.	11183	11183	11183
Log Likelihood		-3274.07	-3274.07
Deviance		6548.15	6548.15

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: Regression of FttP.Exp solely on the existence of FttP coverage in 2013. Note that FttP.Exp is a dummy that takes the value 1 if Δ FttP > 0 and a value of 0 otherwise. Analogously, F2013 is a dummy that takes the value 1 if FttP.13> 0 and the value 0 otherwise. The first model (1) is a linear approximation, whereas the other two are maximum likelihood estimations using logit (2) and probit (3) links, respectively. Note that existing FttP instantly raises expansion probability to 1 in all three models.

following analysis focuses on the OLS results.[31]

In terms of technology competition, the base coverage of Vectoring in the *Near*-area of a given municipality increases the likelihood of FttP expansion by 2.9 percentage points (pp) per 10 pp higher coverage.[32] Likewise, expansion of *Remote*-area Vectoring in the observation period raises the FttP investment probability by 0.5 pp per 10 pp coverage increase. For *Remote*-only municipalities, results are broadly similar: A higher base coverage of Vectoring raises investment probabilities by 1.5 pp per 10 pp higher coverage. Vectoring expansion exerts a positive influence of 0.3 pp (per 10 pp change). In relation to the average predicted investment probabilities of around 10% for *Near* & *Remote* municipalities and 8% for *Remote*-only ones, these effects are substantial.[33]

In contrast to Vectoring, the impact of HFC seems more ambiguous for FttP deployment. While the HFC base coverage in *Near*-areas positively impacts investment probability by 0.7 pp per 10 pp higher HFC coverage, its impact becomes negative in *Remote*-areas and insignificant for *Remote*-only municipalities.

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[31] Robust and federal state (*Länder*)-clustered standard errors have been calculated for these regressions and shown no changes in significance levels. In addition, the Appendix Table 16 summarizes the marginal effects derived from the results of the OLS regressions. In Table 17, marginal effects for the Logit estimations are being displayed. As they are qualitatively similar to OLS, the analysis focuses on the more robust OLS estimators. Expected probabilities of below zero or above one are exceedingly rare, alleviating the potential shortcoming of OLS.

[32] The significant and positive effect of base Vectoring coverage in *Near*-areas does not invalidate the identification. Recall from Section 3.2 that Vectoring may be feasible in the outskirts of a given *Near*-area. Usually, these areas are located near population centers which would make them more attractive for FttP expansion. This provides an explanation for the positive association of Vectoring coverage in *Near*-areas and the probability of FttP deployment.

[33] The averages of the predicted investment probabilities are almost identical between linear and Logit models, which aligns well with the 10 and 9 percent of municipality types receiving deployment over the observation period.

Table 9: Determinants of FttP expansion at the extensive margin

Endogeneous Variable:	FttP.Exp [0,1]			
Municipality	Near & Remote		Remote-only	
Model	Logit	OLS	OLS	Logit
	(1)	(2)	(3)	(4)
(Intercept)	4.32^{**}	0.71^{***}	0.60^{***}	$2.77^{\cdot}$
	(1.59)	(0.13)	(0.09)	(1.46)
Vectoring.13.r	1.00	0.07	0.15^{***}	2.18^{***}
	(0.68)	(0.07)	(0.03)	(0.36)
Vectoring.13.n	1.80^{***}	0.29^{***}		
	(0.55)	(0.06)		
Δ Vectoring.r	0.61^{*}	0.05^{*}	0.03^{*}	0.45^{*}
	(0.26)	(0.02)	(0.01)	(0.21)
Δ Vectoring.n	0.25	0.01		
	(0.30)	(0.03)		
HFC.13.r	-0.85^{*}	-0.07^{*}	-0.03	-0.46
	(0.41)	(0.03)	(0.02)	(0.31)
HFC.13.n	0.84^{**}	0.07^{**}		
	(0.31)	(0.03)		
HFC.Exp.r			0.03^{*}	0.44^{*}
			(0.01)	(0.17)
nearby10k	0.45^{**}	0.05^{***}	0.09^{***}	0.85^{***}
	(0.15)	(0.01)	(0.01)	(0.16)
Age	-0.12^{***}	-0.01^{***}	$-0.00^{\cdot}$	-0.07^{*}
	(0.04)	(0.00)	(0.00)	(0.03)
Density	0.01	0.00	-0.00	-0.01
	(0.02)	(0.00)	(0.00)	(0.05)
Area	0.01^{***}	0.00^{***}	-0.00	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)
Ruggedness	-0.39^{**}	$-0.02^{\cdot}$	$0.01^{\cdot}$	$0.22^{\cdot}$
	(0.14)	(0.01)	(0.01)	(0.13)
Min_MZ	-0.25^{**}	-0.02^{***}	-0.04^{***}	-0.45^{***}
	(0.08)	(0.01)	(0.01)	(0.11)
New Construction	4.77	0.45	0.78^{***}	9.52^{**}
	(3.56)	(0.33)	(0.23)	(3.10)
Länder FE	YES	YES	YES	YES
Log Likelihood	-1145.68			-876.53
Deviance	2291.37			1753.05
Num. obs.	4010	4010	3804	3804
R^2		0.10	0.20	
Adj. R^2		0.10	0.20	

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: Determinants are shown for *Near* & *Remote* municipalities and *Remote*-only ones. The probability of expansion in a given municipality is estimated using Logit - (1) and (4) - and OLS - (2) and (3) -, and separately for the types of municipalities due to type-specific regressors. Within type, the specifications are identical but for the method.

Additionally, the expansion of HFC networks is very rare, but nonetheless impacts FttP expansion positively in *Remote*-only municipalities by a 3 pp increase in probability if it occurs.[34]

Thus, the effect of alternative infrastructure technologies on the likelihood of FttP deployment appears to vary with the alternative. While the qualitatively inferior Vectoring exerts a positive influence both in form of coverage level and coverage increase, HFC's effect depends on whether it occurs in *Near*- or *Remote*-areas. Especially the result on Vectoring stands in contrast to Calzada *et al.* (2018) who find a negative influence of the number of Bitstream connections, a Vectoring equivalent, from the Spanish incumbent Telefonica on its own FttH deployment.[35] Based on these findings, extensive Vectoring structures may signal attractive deployment areas to competitors and can be seen as a complementary bridge technology for the extensive margin of FttP deployment.

The set of relevant technology variables is concluded by the dummy variable *nearby10k* which denotes whether a given municipality is adjacent to one with positive FttP coverage in 2013.[36] It captures a possible spillover of early FttP deployments into neighboring municipalities. This effect is found to be highly relevant and significant. The deployment of FttP becomes 5 pp more likely for municipalities with MDF and 9 pp more likely for those without if an early accessed municipality is in the proximity. A similar positive correlation with existing infrastructure has also been observed by Bourreau *et al.* (2018) with regards to legacy DSL connections. The radiating effect can be likened to an "expansion hub" in that an existing local network provider branches out into adjacent areas following a successful early deployment project.

Of the market size characteristics, only age is significant and relevant. Given their lack of impact or significance, other variables of the category are not included in the main extensive margin specification.[37] An additional year of average age within a municipality population reduces the expansion probability by one

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[34] Note that $HFC.Exp.r$ is a dummy variable, capturing solely the event of expansion, not the extent. For robustness, $\Delta HFC.r/n$ have been used but found to be non-relevant.

[35] As mentioned in Section 2, the fact that only FttH of the incumbent is being analyzed by Calzada *et al.* (2018) implies a negative bias of their estimates on infrastructure competition. Since the legacy infrastructure is also being operated and monetized by the incumbent, deployment incentives for FttH are automatically reduced in areas where sales from Bitstream unbundling, the Vectoring based wholesale product, are substantial (or, to put it differently, Vectoring coverage is high).

[36] Using the geographical centroid of a given municipality, the dummy *nearby10k* takes the value 1 if the centroid of at least one municipality with $FttP.13 > 0$ is exactly or less than ten kilometers distant from the given municipality. This threshold of ten kilometers is derived from the first two moments of the area size distribution in the set. For robustness, thresholds of 5 and 25 kilometers were also considered. In an additional robustness check against an overlap with area size or agglomeration effects, variables for proximity to a city of at least 100,000 and 500,000 inhabitants were computed in the same manner. Their inclusion did not alter results.

[37] A broader analysis including all covariates is summarized in Table 15 of the Appendix. Were population included in the main specification, it would also positively impact the deployment likelihood and be significant. However, its correlation with area and population density might cause multicollinearity defects. Area size and population density, on the other hand, are sufficiently uncorrelated on account of the definition of municipality borders. These were driven by the goal of homogenizing population counts during the West-German municipality territory reform in 1967.

Moreover, population is an imprecise measure as it captures not solely the size effect of the customer count, but also a potential stochastic effect: If all households were equally likely to receive FttP, municipalities with larger populations would enjoy a greater deployment likelihood just by increased chance. Inclusion of the variable also does not significantly improve the quality of the extensive margin estimations, while its exclusion does not bias or change results (see Table 15). For these reasons, population is excluded from the main specifications.

pp. Given a lesser interest of older people in digital services such as streaming or video gaming, this result is both intuitive and in line with prior literature.[38]

Accessibility measures appear more relevant in comparison. Only density, typically considered a key factor, is not significant for either municipality type. This divergence from literature may partially result from its influence on legacy infrastructure. Population density also shaped the deployment of cable- and copper-networks which in turn determine, through HFC and Vectoring, the profitability of FttP and the intensity of technology competition today. Hence, these competing technologies are more relevant for FttP deployment than is the density itself. Moreover, the typically observed economies of density are most prevalent in urban agglomerations, of which the largest and most dense are excluded from this analysis due to positive FttP coverage in 2013.

A municipality's area impacts deployment probability positively for *Near* & *Remote* municipalities. This effect becomes insignificant and negative for *Remote*-only observations, reflecting the dual nature of area: If populated, it increases investment opportunities, but an underpopulated rural area signals higher deployment costs.[39] Structural seclusion, measured as Min_MZ, the driving distance to the nearest medium-sized town, reduces deployment probability by 2 pp for 10 additional minutes for municipalities with MDF. This effect doubles for *Remote*-only municipalities, which is one of the most pronounced effects in the analysis and implies a more severe effect for smaller municipalities. Briglauer *et al.* (2019) also used this variable in their analysis and found it to be insignificant for their set of Bavarian municipalities, as do we in the Bavarian subset. This is likely a result of Bavaria's more rural and homogeneous spatial structure.

Similarly, the ruggedness of terrain, a proxy for construction costs of the required ductwork, adversely impacts the likelihood of deployment for municipalities with MDFs by 2 pp per 100 meters of average elevation heterogeneity. Interestingly, this negative influence disappears for *Remote*-only municipalities. The quota of newly constructed residential buildings exerts a positive effect on deployment probability in *Remote*-only municipalities. An additional percentage point in this share corresponds to a higher probability of FttP deployment by 0.78 pp. This *Remote*-only exclusive effect may indicate the higher dependence of those municipalities on new residential housing, which require new wiring, to trigger FttP deployment.[40]

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[38] Literature examples for the effect of age on infrastructure deployment are numerous, but for a specific fiber context see Calzada *et al.* (2018). The observed effect of age is robust to using the share of people older than 60 years, adding a squared age variable or using the mean difference of a population's average age. Lastly, higher population ages could correlate with rural or structurally weak areas, but the age effect is robust to the inclusion of proxy variables for this such as income per capita and industrial area.

[39] More general spatial and political features are captured by the federal state (*Länder*) fixed effects (NUTS 1), which are highly relevant. For robustness, the following alternative fixed effects have been used: *Regierungsbezirke*, *Kreise* and *Reisegebiete*. The first two are less aggregated administrative units (NUTS 2 and 3), whereas the last captures tourist areas and, therein, similarities in geography and structure. Their aggregation level lies between the other two fixed effect alternatives. Overall results remain qualitatively unchanged.

[40] Note that we cannot distinguish from the data whether the expansion occurs solely to connect the new properties or acts

Intensive Margin Once a municipality is chosen for FttP expansion, an operator needs to decide on the deployment extent. That extent likewise depends on factors subsumed under the categories technology, market size and accessibility. Table 10 displays the estimated OLS regression results for FttP expansion at the intensive margin for municipalities which received FttP expansion.[41]

Table 10: Determinants of FttP expansion at the intensive margin

Endogeneous Variable: Municipality	Δ FttP Near & Remote (1)	 Remote-only (2)
(Intercept)	1.41^{***}	1.78^{***}
	(0.37)	(0.38)
Δ Vectoring.r	-0.14^{**}	-0.24^{***}
	(0.04)	(0.04)
Age	$-0.01^{\cdot}$	-0.02^{**}
	(0.01)	(0.01)
Income p. capita	$-0.00^{\cdot}$	0.00
	(0.00)	(0.00)
Density	-0.01^{*}	-0.02
	(0.00)	(0.01)
New Construction	$-1.50^{\cdot}$	-0.24
	(0.77)	(0.70)
Area	-0.001^{***}	-0.005^{**}
	(0.00)	(0.00)
Ruggedness	-0.10^{*}	0.06
	(0.04)	(0.05)
Länder FE	YES	YES
R^2	0.35	0.54
Adj. R^2	0.32	0.51
Num. obs.	409	346

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Determinants of Intensive Margin FttP Expansion in municipalities with *Near & Remote* areas in (1) and *Remote*-only in (2), contingent on them having seen positive FttP deployment in the extensive margin between 12/2013 and 06/2017, that is: $\Delta\text{FttP} > 0$. The endogenous variable is the change in FttP coverage within a given municipality.

From the set of network technology variables, only Vectoring remains significant and relevant for the intensive margin. The change in Vectoring coverage negatively impacts FttP deployment intensity by 1.4 pp per 10 pp increase in coverage for municipalities with MDFs. For *Remote*-only ones, this effect increases to 2.4 pp. Both results imply a substitutive rather than complementary effect of Vectoring for FttP expansion, which would support the European Commission's view. Hence, a simultaneous roll-out of Vectoring appears to partially foreclose - in a lose application of the term - the respective area to FttP deployment. At first

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as an initial trigger for wider deployment.

[41] For these estimates, robust and federal state (*Länder*)-clustered standard errors have also been calculated, but yielded almost identical results for the standard errors. For a detailed look into the different variable categories and their effects on the intensive margin, see Table 18 in the Appendix.

glance, this interpretation may appear contrary to the positive effect of the Vectoring base coverage at the extensive margin, but likely implies a more complex relationship. The level of early Vectoring coverage signals an attractive market, but competition in the form of increasing Vectoring coverage curtails the areas in which FttP could be expanded profitably. Thus, the effect of Vectoring is ambiguous: It may cause FttP investment in municipalities that would not have been sufficiently attractive otherwise, but simultaneously limits the intensity of deployment.

Of the market size characteristics, the average age and available income per capita matter for FttP expansion at the intensive margin. Again, an older population limits the market potential of FttP based services. Available income, however, is barely significant and only for municipalities with MDF but its coefficient has a negative sign, which is implausible, stands in contrast to prior literature findings and remains puzzling to the authors.[42]

The relevant accessibility characteristics all impede deployment intensity. In contrast to the extensive margin results, population density is significant for municipalities with MDFs, its coefficient implying a 1 pp reduction for an additional 100 inhabitants per square kilometer. Density can thus be thought of as a cost driver: Densely populated areas imply a higher degree of urbanization and households requiring connection, complicating construction procedures. While the number of FttP connections increases with density, the share of households connected decreases; hence the lack of significance for *Remote*-only municipalities, which are more sparsely populated in general.[43]

A municipality's area exhibits a negative effect on the intensive margin ranging from 0.1 pp less coverage expansion per 10 km^2 for municipalities with *Near*-areas to 0.5 pp less expansion for those without. As a greater area implies longer cable lengths to connect the households in question, construction likewise becomes more expensive.[44] Terrain ruggedness decreases deployment intensity by 10 pp per additional 100 meters of elevation heterogeneity for municipalities with MDFs, while the variable is non-significant for *Remote*-only municipalities.[45] This reflects both the postulated cost increase of more rugged terrain and divergent cost

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[42] Economic North-South differences in Germany provide a potential explanation for this effect, in that the wealthier but often more remote and rural areas of South Germany appear to receive less FttP expansion.

[43] The estimated negative effect of population density on FttP deployment stands in contrast to findings of Calzada *et al.* (2018) and Bourreau *et al.* (2018) which suggest the interpretation of density as a positive market size increasing measure. However, our distinction between *Remote*-only and *Near* & *Remote* municipalities probably captures this market size effect in the higher deployment probabilities for the latter type, revealing the cost driving effect of population density. Also, the exclusion of early FttP-accessed municipalities, which are on average also more densely populated, further limits the observability of this positive effect.

[44] Proximity to a municipality with FttP in 2013 does not alter results. For this reason, the dummy variable of *nearby10k* is not included in the final specification.

[45] Note that the mean of elevation heterogeneity for municipalities with MDFs is at 0.67 and at 0.4 for municipalities without MDFs.

calculations for *Remote*-only municipalities.

New residential housing also has a negative impact on the intensity of FttP expansion for *Near* & *Remote* municipalities. This mirrors the positive effect for *Remote*-only municipalities observed at the extensive margin in that it induces FttP expansion where it would not have occurred otherwise. Here, it corresponds to a limitation of the deployment intensity and does not seem to trigger additional FttP connections beyond the initial property.

Lastly, as stated in Section 5.1, these results rely on the assumption that the intensive margin effects are independent from selection into expansion. This is tested using a Heckman two-step procedure, which yields similar results to OLS and thus implies that selection is not an issue.[46] In consequence, the first two main results regarding FttP expansion are summarized below.

Result 1: Demographic, structural and topographic characteristics are relevant indicators for FttP deployment on the municipal level. Of these, the population's average age, the ruggedness of terrain, its seclusion and the share of new residential buildings are of major importance.

Result 2: Technology competition from Vectoring has opposing effects. While a high Vectoring base coverage appears to signal attractive markets for FttP deployment and hence increases deployment probability, a simultaneous expansion of Vectoring coverage decreases the deployment intensity of FttP.

6.2 Policy Interventions

Technology Regulation The previous analysis produces significant, yet ambiguous effects of Vectoring on FttP deployment. However, these are only correlations and not necessarily reflective of causal relationships. Utilizing the identifying restrictions in the German telecommunications market (see Section 3.2), the interactions between these two technologies can be defined more clearly. The matching procedure presented in Section 5.2 generates a set of 539 treatment (*Near*-heavy) and 173 control observations (*Near*-light). These match one another more closely not only in terms of treatment probability but also in other relevant structural characteristics.[47] If the matching is conducted without replacement, 451 treatment and control units each remain in the dataset. For both sets, descriptive statistics and mean values for the Vectoring

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[46] The regression results are displayed in Table 19 in the Appendix. Notably, income per capita loses significance when accounting for a potential selection. However, federal state (*Länder*) fixed effects cannot be used in the Heckman approach due to technical issues with the low number of municipalities with investment for smaller federal states, thus restricting the approach to such a degree that it would not be as useful as the main specification. Due to its qualitatively similar results, this is not necessary either.

[47] Due to this desired similarity in observations and resulting lack of variance, most variables with previously significant coefficients in the extensive and intensive margin specifications become insignificant in a supplemental regression based on the matched subset (see Table 21 in the Appendix).

expansion are provided in Table 11. Notably, the predicted probabilities for expansion are similar for treated and non-treated municipalities.[48]

Table 11: Mean characteristics for matched municipalities

Municipality Type	FttP.Exp= 1	Count	Δ FttP	P(FttP.Exp= 1)	Δ Vectoring.r
Municipality statistics, matching with replacement:					
Near-heavy	No	488	0	0.08	0.19
Near-heavy	Yes	51	0.37	0.2	0.23
Near-light	No	156	0	0.09	0.25
Near-light	Yes	17	0.31	0.19	0.29
Municipality statistics, matching without replacement					
Near-heavy	No	412	0	0.08	0.19
Near-heavy	Yes	39	0.38	0.18	0.25
Near-light	No	406	0	0.11	0.3
Near-light	Yes	45	0.2	0.2	0.33

Notes: Descriptive statistics for the matched treatment (*Near*-heavy) and control (*Near*-light) subset based on propensity scores. Sample means for the technology variable of interest are provided for both matching with and without replacement.

The treatment has a significant impact only in the subset generated by matching without replacement (see Table 12 for sample means and p-values). Therein, treated municipalities experience significantly more FttP expansion at the intensive margin. However, this result comes with a caveat as the subset suffers from a deterioration in matching quality. Structural characteristics and predicted extensive margin probabilities differ more substantially when matched without replacement, yielding a control group of, on average, larger and more populous municipalities. That size difference might be partially responsible for the lower change in coverage of the control groups. Since coverage as a measure of expansion is relative to the number of households, it is more costly to achieve a given coverage increase in larger municipalities than it is in smaller ones. All of this limits the validity of the results for matching without replacement.

Table 12: Average treatment effects

		Matching			
		With Replacement		Without Replacement	
		Treat	Control	Treat	Control
	Count:	539	173	451	451
Ext. Margin	FttP.Exp= 1:	0.095	0.098	0.086	0.100
	$Pr(>\|t)$	0.888		0.4923	
	Count:	51	17	39	45
Int. Margin	Δ FttP:	0.367	0.306	0.382	0.205
	$Pr(>\|t)$	0.573		0.040*	

Notes: Mean treatment comparisons via symmetric t-Test for the extensive and intensive margins of FttP expansion. Respective group means as well as test results are provided separate for matching with replacement and without.

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[48] The predicted deployment probabilities stem from the main extensive margin specification in Section 6.1 and are displayed in column 5 of Table 11.

In conclusion, a technology selective regulation, mimicked by the de-facto ban of Vectoring in *Near*-areas, seems to have no measurable impact on the decision to invest into FttP deployment and - at best - a small one on the intensity of such deployment.

Rationales for the null effect at the extensive margin could be twofold. First, the decision to invest depends primarily on market size and accessibility characteristics as well as the coverage of already existing network technologies. A restriction on Vectoring affects solely the last of these aspects, and only for the less capable technology. Second, Vectoring in Germany is deployed almost exclusively by the Deutsche Telekom, which might use the technology to respond to FttP expansion or HFC offerings by its competitors. This simultaneity might drive the positive correlation of change in Vectoring coverage and FttP expansion at the extensive margin.

The analysis of the technology-restrictive regulation provides only weak support for the previously observed result at the intensive margin of FttP deployment, though. Vectoring expansion can be detrimental to fiber deployment intensity. It seems reasonable to assume that Vectoring exhibits competitive pressure on FttP operators, thus limiting the intensity of their deployments. A policy specifically alleviating this pressure could only be reasonably effective - if at all - at the intensive margin.

Subsidies Repeating the analyses of Section 6.1 for the federal state of Bavaria permits the inclusion of its comprehensive subsidy program on the municipality level. Table 13 displays the estimated OLS regression results for the extensive margin deployment probability of FttP for Bavarian municipalities.

This subsidy program appears to be very effective. Every additional 100,000 Euro of funding for expansion including FttP projects increases the probability of FttP investment by 3 pp.[49] For *Remote*-only municipalities, the effect increases to 4 pp. Note that only five percent of Bavaria's *Remote*-only municipalities and eight percent of its *Near* & *Remote* municipalities see any FttP expansion. Consequently, a subsidy of 100,000 Euro increases the expansion probability of a typical Bavarian municipality by 12.5 to 40 percent. This result supplements the finding of Briglauer *et al.* (2019) who prove the general effectiveness of the Bavarian subsidy program with respect to the occurrence of broadband deployment.

However, this result cannot be translated directly to Germany as a whole since Bavaria has a somewhat non-representative structure. It consists of few large cities or comparable population centers and a large number of smaller towns and surrounding rural areas. Market size measures are not as relevant due to this homogeneity in localities and the exclusion of large cities on account of FttP existing in 2013. Accessibility characteristics, on the other hand, are similar in significance and strength.

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[49] Bavaria also subsidized FttX deployment projects which would have included Vectoring solutions. A regression of such, non-FttP subsidies on FttP expansion probabilities provides no significant effects. This is the expected result and provides no support for the ladder-of-investment hypothesis, although the observation period is admittedly rather short for that evolution to occur.

Table 13: Bavaria subsample: Determinants of FttP expansion at the extensive margin

Endogeneous Variable:	FttP.Exp [0,1]			
Municipality	Near & Remote		Remote-only	
Model	Logit	OLS	OLS	Logit
	(1)	(2)	(3)	(4)
(Intercept)	-6.20	-0.25	-0.48^{*}	-12.19^{**}
	(4.25)	(0.26)	(0.23)	(4.64)
Vectoring.13.r	1.99	$0.18^{\cdot}$	0.24^{***}	3.33^{***}
	(1.35)	(0.10)	(0.05)	(0.76)
Vectoring.13.n	1.67	$0.23^{\cdot}$		
	(1.38)	(0.12)		
Δ Vectoring.r	-0.12	-0.01	0.06^{*}	1.18^{*}
	(0.64)	(0.05)	(0.03)	(0.57)
Δ Vectoring.n	1.65^{*}	0.15^{**}		
	(0.74)	(0.06)		
HFC.13.r	-0.96	-0.07	0.03	0.66
	(1.05)	(0.08)	(0.04)	(0.73)
HFC.13.n	1.13	0.08		
	(0.73)	(0.05)		
HFC.Exp.r			-0.01	-0.22
			(0.02)	(0.46)
nearby10k	0.87^{**}	0.08^{**}	0.07^{***}	1.17^{***}
	(0.31)	(0.02)	(0.02)	(0.34)
Age	0.07	0.01	0.01^{*}	$0.18^{\cdot}$
	(0.09)	(0.01)	(0.01)	(0.11)
Density	-0.03	-0.00	-0.00	-0.09
	(0.05)	(0.00)	(0.01)	(0.15)
Area	0.01^{**}	0.00^{**}	0.00^{*}	0.02^{*}
	(0.00)	(0.00)	(0.00)	(0.01)
Ruggedness	-0.51^{*}	-0.02^{*}	-0.01	-0.22
	(0.23)	(0.01)	(0.01)	(0.25)
Min_MZ	-0.30	-0.02	0.00	0.15
	(0.26)	(0.02)	(0.02)	(0.37)
New Construction	-16.50	-0.84	-0.05	-2.40
	(11.87)	(0.63)	(0.48)	(11.57)
Funding until 2015	0.26^{***}	0.03^{***}	0.04^{***}	0.37^{***}
	(0.06)	(0.01)	(0.01)	(0.08)
Log Likelihood	-221.26			-168.77
Deviance	442.53			337.54
Num. obs.	942	942	905	905
R^2		0.10	0.08	
Adj. R^2		0.08	0.07	

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: Determinants are shown for municipalities with both *Near* & *Remote* areas and *Remote*-only for the subsample of Bavaria. This table is a Bavaria-only replication of Table 9. The probability of expansion in a given municipality is estimated using Logit - (1) and (4) - and OLS - (2) and (3) -, and separately for the two types of municipalities due to type-specific regressors. Aside from the method applied, the specifications are identical for each type.

Technological factors are also less relevant. The coefficients for the HFC base coverage and investment into it are insignificant, which likely results from the technology being less prevalent in Bavaria, limiting variation. Vectoring, both in base coverage and expansion, is more relevant and significant for *Remote*-only municipalities, but only Vectoring expansion in *Near*-areas matters for *Near* & *Remote* municipalities.[50] These findings are reflective of the lower levels of broadband expansion and coverage in Bavaria compared to the whole of Germany during the observation period.

Subsidies also have no significant effect on FttP deployment at the intensive margin.[51] Their coefficient is, however, negative which would seem logical as municipalities accessed only on account of subsidies would likely be less attractive to expand further than those expanded without receiving subsidies. The Bavarian state's tendency to provide subsidies especially to smaller, less densely populated municipalities supports this interpretation.

We summarize the main results regarding policy interventions below:

Result 3: A deployment regulation restricting Vectoring use is ineffective in increasing the likelihood of being accessed with FttP for a given municipality. Deployment intensity is not adversely affected by such a regulation.

Result 4: Subsidies targeted specifically at local FttP deployment projects are effective in increasing the deployment likelihood. An additional 100,000€ funding increases that probability by 3 to 4 pp.

7 Conclusion

Upgrading the telecommunications infrastructure to match digitalization requirements is a prominent aim of national policies. Governments attempt to shape and promote the transition from legacy copper networks to FttP architectures by setting national goals and deployment guidelines, among others. The actual infrastructure provision is, however, carried out on the local level within specific deployment projects, organized under the policymakers' broad agendas.

On the micro-level, structural and topographic conditions are found to be decisive supply-side factors in explaining the locations chosen for FttP deployment and the intensity of that expansion. A population's age, the ruggedness of terrain, the seclusion of a municipality and the share of newly built residential housing are strongly associated with the probability for FttP deployment. Additionally, early fiber-accessed

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[50] See Footnote 32 for the explanation on such expansion.

[51] Table 22 displays the corresponding regression results and compares them to the results for all of Germany. *Remote*-only municipalities are not considered because too few of those with FttP deployment received subsidies in Bavaria for an OLS regression to provide consistent results.

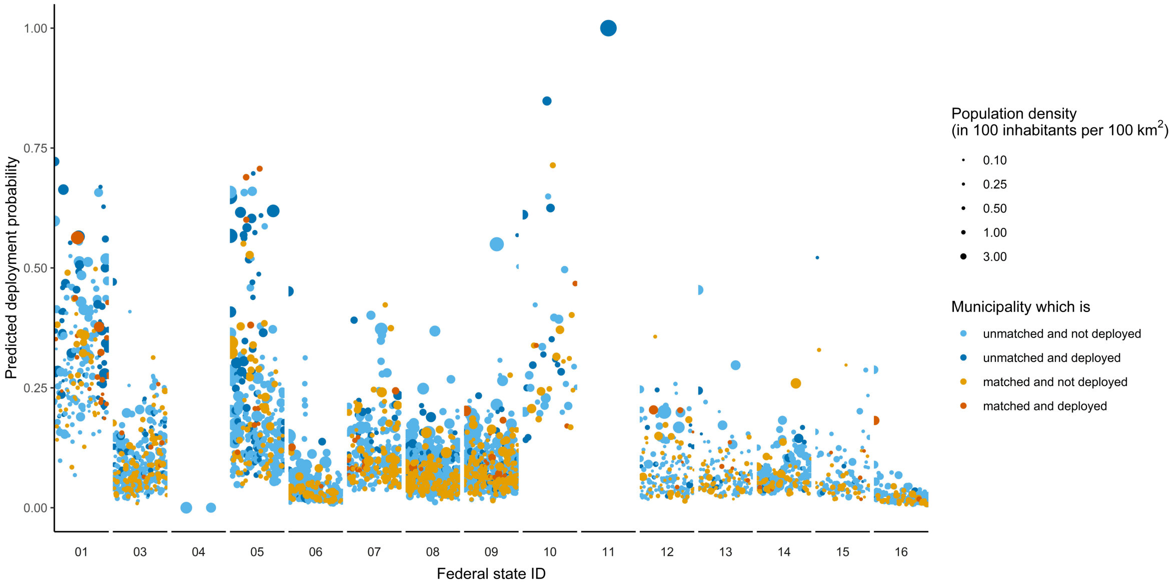
municipalities emit a kind of spillover effect on their neighbors and raise their chance of receiving FttP access. Local competition from other network infrastructures, namely Vectoring and HFC, has more ambiguous effects. While a higher base coverage of Vectoring is associated with a more likely FttP deployment, an increase in coverage reduces the intensity of FttP expansion.

Against these structural factors, a technologically restrictive policy ruling out Vectoring is found to be generally ineffective. Neither FttP expansion at the extensive margin nor at the intensive margin reacts significantly to the deployment restrictions. The removal of Vectoring as a competing infrastructure shows no reliable effect. However, state intervention in the form of subsidies is effective. An additional funding of 100,000€ increases the FttP deployment probability of a municipality by 3 to 4 percentage points, corresponding to a 12.5% to 40% change given the average deployment probability. However, this only applies to funding for FttP-specific projects.

Therefore, the main challenge for policymakers in shaping the infrastructure upgrading process is to offset the structural conditions that determine the FttP roll-out at the local level. Subsidies targeted directly at specific, local FttP projects are able to overcome these structural disadvantages. A general technologically restrictive regulation, on the other hand, is not sufficient. Our results advocate for an increased focus on structural support schemes in the vein of Bavaria's subsidy program. Together with the FttP spillover effects radiating from already fiber-accessed municipalities, a geographically scattered distribution of these subsidies, focusing on local centers, could be optimal. These "expansion hubs" might decrease costs of FttP deployment for neighboring municipalities, reinforcing the positive deployment effect.

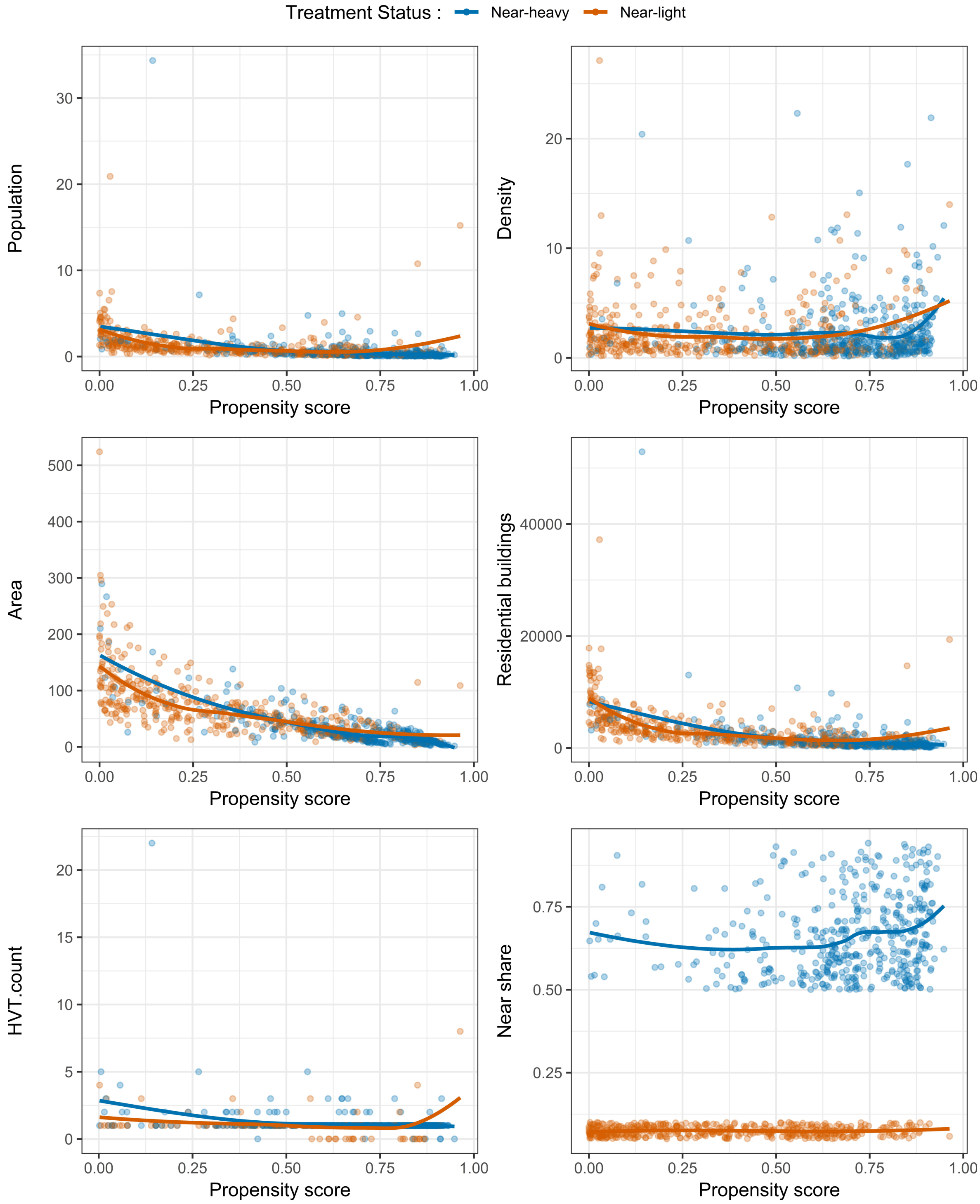
Appendix

Figure 5: Balance of matched municipalities by federal state



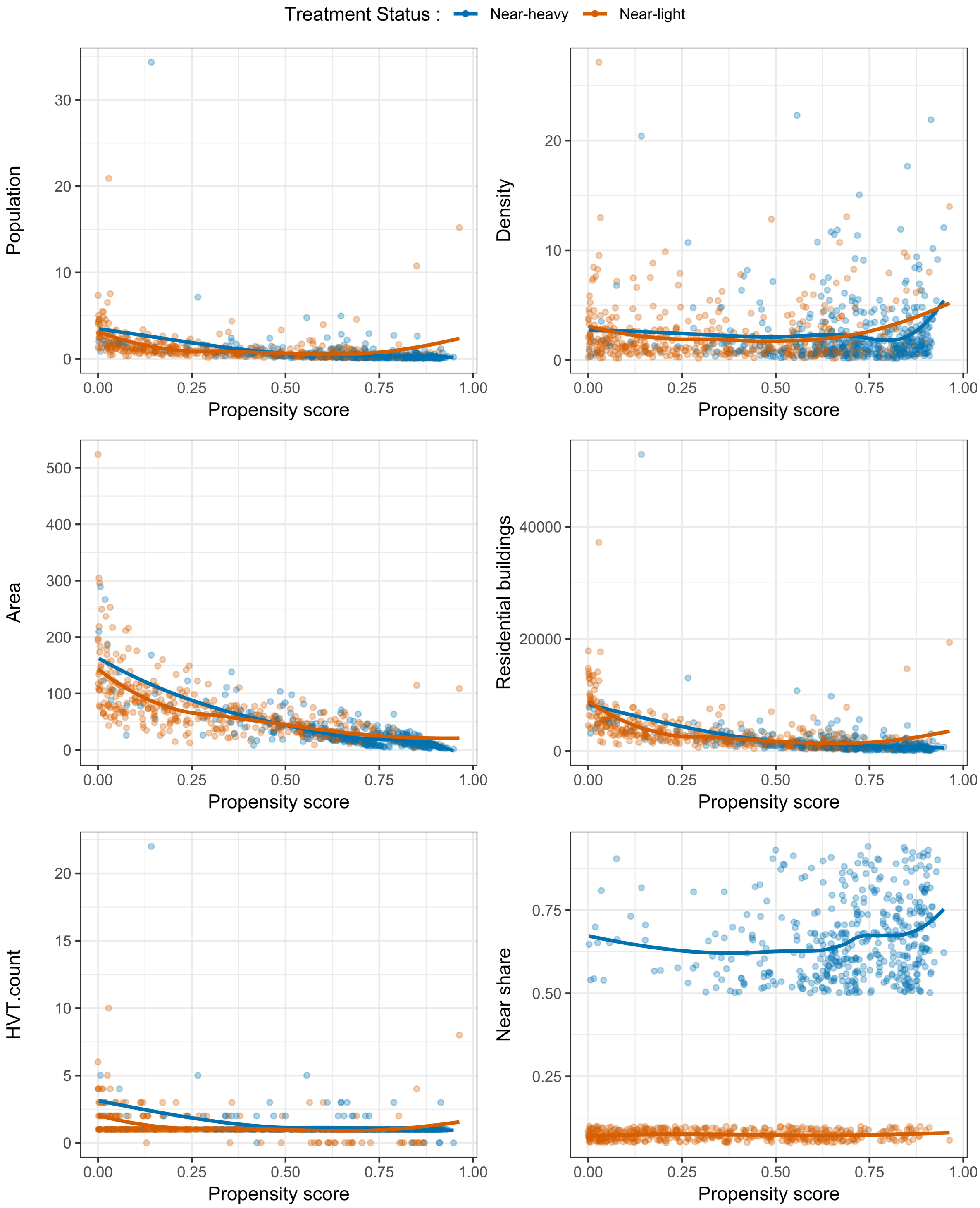
Notes: Municipalities are displayed with respect to their predicted FttP deployment probabilities. Colours refer to their status as either treatment or control group and to their actual deployment status. The scatter plots are sorted by federal state. The IDs correspond to these states in the following manner: 1 = Schleswig-Holstein, 3 = Lower Saxony, 4 = Bremen, 5 = North Rhine-Westphalia, 6 = Hesse, 7 = Rhineland-Palatinate, 8 = Baden-Württemberg, 9 = Bavaria, 10 = Saarland, 11 = Berlin, 12 = Brandenburg, 13 = Mecklenburg-Vorpommern, 14 = Saxony, 15 = Saxony-Anhalt, 16 = Thuringia. Hamburg (ID 2) experienced FttP expansion before 12/2013 and thus drops out of the set.

Figure 6: Covariates of matched sample with replacement



Notes: Comparison of covariate values for treatment (*Near*-heavy in blue) and control (*Near*-light in orange) groups, when matching with replacement. For each of the four covariates used in the matching equation, the values for each municipality are displayed as points, with localities grouped by the tendencies of their *Near*-shares. Additionally, a trend line for each group and covariate is provided. Propensity scores as well as the number of MDFs in a given municipality are also compared.

Figure 7: Covariates of matched sample without replacement



Notes: Comparison of covariate values for treatment (*Near*-heavy in blue) and control (*Near*-light in orange) groups, when matching without replacement. For each of the four covariates used in the matching equation, the values for each municipality are displayed as points, with localities grouped by the tendencies of their *Near*-shares. Additionally, a trend line for each group and covariate is provided. Propensity scores as well as the number of MDFs in a given municipality are also compared.

Table 14: Median municipal characteristics by pre-existing FttP coverage

FttP.13> 0, ΔFttP > 0	Count	FttP.13	ΔFttP > 0	Population (in 10,000)	Density (in 100/km^2)	HVT.count (abs.)
No, No	9916	0	0	0.16	0.9	0
No, Yes	956	0	0.064	0.21	1.15	0
Yes, No	8	0.865	0	0.01	0.36	0
Yes, Yes	303	0.125	0	0.62	2.34	1

Notes: Median characteristics for municipalities with and without FttP coverage in 2013 are displayed, separated in those that did (Δ FttP > 0) and did not receive expansion (Δ FttP $= 0$) during the observational period.

Table 15: Determinants of FttP expansion at the extensive margin - by category and consolidated

Endogeneous Variable:	FttP.Exp [0,1]					
	T (1)	Y (2)	X (3)	S (4)	TYXS (5)	TYXS.cons (6)
(Intercept)	0.17^{**}	0.89^{***}	0.33^{***}	0.32^{***}	0.72^{***}	0.71^{***}
	(0.06)	(0.13)	(0.06)	(0.02)	(0.14)	(0.13)
Vectoring.13.r	0.10				0.06	0.07
	(0.07)				(0.07)	(0.07)
Vectoring.13.n	0.28^{***}				0.28^{***}	0.29^{***}
	(0.06)				(0.06)	(0.06)
HFC.13.r	-0.08^{*}				-0.07^{*}	-0.07^{*}
	(0.03)				(0.03)	(0.03)
HFC.13.n	0.07^{*}				0.07^{**}	0.07^{**}
	(0.03)				(0.03)	(0.03)
Δ Vectoring.r	0.07^{**}				0.05^{*}	0.05^{*}
	(0.02)				(0.02)	(0.02)
Δ Vectoring.n	0.02				0.01	0.01
	(0.03)				(0.03)	(0.03)
Δ HFC.r	-0.04					
	(0.06)					
Δ HFC.n	0.02					
	(0.05)					
Vectoring.Exp.r	0.07					
	(0.06)					
Vectoring.Exp.n	0.02					
	(0.02)					
HFC.Exp.r	$0.04^{\cdot}$					
	(0.02)					
HFC.Exp.n	-0.02					
	(0.02)					
HVT.count	0.01^{***}		0.00		-0.01	
	(0.00)		(0.00)		(0.01)	
Houses		0.00^{***}			0.00	
		(0.00)			(0.00)	
Population		-0.02^{**}			0.00	
		(0.01)			(0.01)	
Age		-0.01^{***}			-0.01^{***}	-0.01^{***}
		(0.00)			(0.00)	(0.00)
Income p. capita		0.00			0.00	
		(0.00)			(0.00)	
Density			0.00		-0.00	0.00
			(0.00)		(0.00)	(0.00)
Single-Family Houses			-0.01			
			(0.07)			
New Construction			0.84^{*}		0.45	0.45
			(0.33)		(0.34)	(0.33)
Area			0.00^{***}		0.00^{*}	0.00^{***}
			(0.00)		(0.00)	(0.00)
Forest Area			-0.00		-0.00	
			(0.00)		(0.00)	
Industrial Area			0.01		-0.00	
			(0.01)		(0.01)	
Ruggedness			-0.02^{*}		-0.01	$-0.02^{\cdot}$
			(0.01)		(0.01)	(0.01)
Min_MZ			-0.03^{***}		-0.02^{**}	-0.02^{***}
			(0.01)		(0.01)	(0.01)
Min_A			0.00		0.00	
			(0.00)		(0.00)	
nearby10k			0.06^{***}		0.05^{***}	0.05^{***}
			(0.01)		(0.01)	(0.01)
Subsidies				0.00^{*}	0.00	
				(0.00)	(0.00)	
Länder FE	YES	YES	YES	YES	YES	YES
R^2	0.09	0.08	0.08	0.06	0.10	0.10
Adj. R^2	0.08	0.07	0.08	0.05	0.10	0.10
Num. obs.	4010	4010	4010	4010	4010	4010

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: This table shows extensive margin regressions for each of the four characteristics classes T, Y, X and S - Technology (1), market size (2), accessibility (3) and subsidies (4), respectively; also shown is a combined specification of these characteristics in column (5). Column (6) shows the consolidated main specification used in the analysis. All specifications are estimated on the set of municipalities with both a *Near* area and no FttP deployment in 2013. For the combined specification, variables with too little variation or without relevance for the variable of interest were excluded to avoid variable inflation and issues with multicollinearity or convergence; though they were included in a robustness regression. For the consolidated specification, this procedure was repeated and other combinations tested using the combined one as basis.

Table 16: Coefficient interpretation for the main extensive margin OLS specification

Variable	Δ	*Near* & *Remote*	*Remote*-only
Vectoring.13.r	10 pp	-	1.5 pp
Vectoring.13.n	10 pp	2.9 pp	
Δ Vectoring.r	10 pp	0.5 pp	0.3 pp
Δ Vectoring.n	10 pp	-	
HFC.13.r	10 pp	-0.7 pp	-
HFC.13.n	10 pp	0.7 pp	-
Age	1 year	-1 pp	-0.4 pp
Density	$\frac{\text{100 Inhabitants}}{km^2}$	-	-
Area	10 km^2	0.6 pp	-
nearby10k	0/1	5 pp	9 pp
Ruggedness	100m	2 pp	1 pp
Min_MZ	10 min.	2 pp	4 pp
New Construction	1 pp	-	0.8 pp
HFC.Exp.r	10 pp	-	0.3 pp

"pp": percentage point; "-": coefficient not significant;

" ": parameter not applicable to municipality

Notes: The table displays the interpretation for the estimated coefficients of the main extensive margin OLS regression (see Table 9). In column 2, the marginal increase per variable is noted in relevant units. In columns 3 and 4, resulting changes in the investment probabilities (Prob(FttP.Exp= 1)) are noted for the two municipality types (*Near & Remote*, *Remote*-only). Average investment probabilities are 10% for *Near* & *Remote* municipalities and 9% for *Remote*-only. The respective median values are at 8 and 5.

Table 17: Average marginal effects for the main extensive margin Logit specification

Endogeneous Variable:	FttP.Exp [0,1]	
	Near & Remote (1)	Remote-only (2)
(Intercept)	0.35^{*}	$0.18^{\cdot}$
	(0.14)	(0.10)
Vectoring.13.r	0.08	0.14^{***}
	(0.06)	(0.02)
Vectoring.13.n	0.15^{**}	
	(0.05)	
Δ Vectoring.r	0.05^{*}	0.03^{*}
	(0.02)	(0.01)
Δ Vectoring.n	0.02	
	(0.02)	
HFC.13.r	$-0.07^{\cdot}$	-0.03
	(0.04)	(0.02)
HFC.13.n	0.07^{*}	
	(0.03)	
Age	-0.01^{**}	-0.00^{*}
	(0.00)	(0.00)
Density	0.00	-0.00
	(0.00)	(0.00)
Area	0.00^{***}	0.00
	(0.00)	(0.00)
nearby10k	0.04^{*}	0.06^{***}
	(0.02)	(0.01)
Ruggedness	-0.03^{*}	0.01
	(0.01)	(0.01)
Min_MZ	-0.02^{**}	-0.03^{***}
	(0.01)	(0.01)
New Construction	0.39	0.61^{**}
	(0.30)	(0.21)
HFC.Exp.r		0.02^{*}
		(0.01)
Länder FE	YES	YES
Log Likelihood	-1145.68	-876.53
Deviance	2291.37	1753.05
Num. obs.	4010	3804

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: The table displays average marginal effects for the Logit models used in the main results displayed in Table 9. The first column shows results for *Near* & *Remote* municipalities, whereas the second column shows results for *Remote*-only municipalities. Coefficients and significance levels are similar to OLS results, thus affirming the decision to use OLS results and effect sizes in the main analysis as the linear specification is more robust.

Table 18: Determinants of FttP expansion at the intensive margin - by category and consolidated

Endogeneous Variable:	Δ FttP					FttP.Exp. [0,1]
	T	Y	X	TYXS	TYXS.cons	TYXS.cons
	(1)	(2)	(3)	(4)	(5)	(6)
(Intercept)	0.55^{***}	1.24^{***}	0.47^{*}	1.26^{**}	1.41^{***}	0.71^{***}
	(0.04)	(0.36)	(0.18)	(0.44)	(0.37)	(0.13)
Vectoring.13.r	0.28^{*}			0.27^{*}		0.07
	(0.13)			(0.14)		(0.07)
Vectoring.13.n	-0.08			-0.09		0.29^{***}
	(0.11)			(0.11)		(0.06)
Δ Vectoring.r	-0.04			-0.04	-0.14^{**}	0.05^{*}
	(0.06)			(0.06)	(0.04)	(0.02)
Δ Vectoring.n	$-0.12^{\cdot}$			-0.11		0.01
	(0.06)			(0.06)		(0.03)
HFC.13.r	-0.11			-0.08		-0.07^{*}
	(0.09)			(0.10)		(0.03)
HFC.13.n	-0.03			-0.02		0.07^{**}
	(0.08)			(0.08)		(0.03)
Houses		-0.00^{**}		0.00		
		(0.00)		(0.00)		
Population		0.02^{*}		$0.02^{\cdot}$		
		(0.01)		(0.01)		
Age		$-0.01^{\cdot}$		-0.01	$-0.01^{\cdot}$	-0.01^{***}
		(0.01)		(0.01)	(0.01)	(0.00)
Income p. capita		$-0.00^{\cdot}$		$-0.00^{\cdot}$	$-0.00^{\cdot}$	
		(0.00)		(0.00)	(0.00)	
Density			-0.01^{**}	-0.00	-0.01^{*}	0.00
			(0.00)	(0.01)	(0.00)	(0.00)
Single-Family Houses			0.10	-0.04		
			(0.22)	(0.23)		
New Construction			$-1.41^{\cdot}$	-1.62^{*}	$-1.50^{\cdot}$	0.74
			(0.74)	(0.77)	(0.77)	(0.33)
Area			$-0.00^{\cdot}$	-0.00^{*}	-0.00^{***}	0.00^{***}
			(0.00)	(0.00)	(0.00)	(0.00)
Forest Area			0.00	0.00		
			(0.00)	(0.00)		
Industrial Area			-0.01	-0.02		
			(0.02)	(0.02)		
HVT.count			0.01	-0.04^{*}		
			(0.01)	(0.02)		
Ruggedness			-0.13^{**}	-0.11^{*}	-0.10^{*}	$-0.02^{\cdot}$
			(0.05)	(0.05)	(0.04)	(0.01)
nearby10k			-0.05	-0.04		0.05^{***}
			(0.03)	(0.03)		(0.01)
Min_MZ						-0.02^{***}
						(0.01)
Länder FE	YES	YES	YES	YES	YES	YES
R^2	0.34	0.31	0.33	0.39	0.35	0.10
Adj. R^2	0.30	0.28	0.29	0.33	0.32	0.10
Num. obs.	409	409	409	409	409	4010

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: This table shows intensive margin regressions for the three characteristics classes T, Y and X - technology (1), market size (2) and accessibility (3). Also shown is a combined specification of these characteristics in column (4). Column (5) shows the consolidated main specification used in the analysis, while column (6) is the extensive margin specification for comparison. The five intensive margin specifications are estimated by OLS on the set of municipalities with both a *Near* area and positive FttP deployment (FttP.Exp= 1).

Table 19: Determinants of FttP expansion at the intensive margin - Heckman selection correction

Endogeneous Variable:	Δ FttP	
Municipality	N&R	R
(Intercept)	1.41^{***}	1.68^{***}
	(0.39)	(0.41)
Land.North	-0.09	0.07
	(0.06)	(0.09)
Land.South	-0.24^{***}	-0.39^{***}
	(0.06)	(0.08)
Land.West	-0.21^{***}	-0.32^{***}
	(0.06)	(0.09)
Δ Vectoring.r	-0.21^{***}	-0.25^{***}
	(0.04)	(0.04)
Age	-0.01	-0.02^{*}
	(0.01)	(0.01)
Income p. capita	$-0.00^{\cdot}$	0.00
	(0.00)	(0.00)
Density	-0.00	$-0.02^{\cdot}$
	(0.00)	(0.01)
New Construction	-1.98^{*}	-0.72
	(0.79)	(0.71)
Area	-0.00^{***}	-0.01^{***}
	(0.00)	(0.00)
Ruggedness	-0.10^{**}	0.05
	(0.04)	(0.05)
IMRI	-0.12^{**}	-0.05
	(0.04)	(0.05)
R^2	0.47	0.80
Adj. R^2	0.46	0.79
Num. obs.	409	346

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: This table shows the second stage - i.e. intensive margin - calculations for a two-stage heckman selection procedure. In the first stage, the extensive margins specification from Table 9 is used for a probit estimation on receiving investment. Under the assumption that this selection into investment does not depend on the change in coverage *given investment*, the intensive margin is calculated with the inverse Mills ratio (IMRI) bias correction. In contrast to the usual extensive and intensive margin specification of Table 9 and Table 10, the German federal states (*Länder*) are grouped into four categories. Since the number of municipalities with investment is very low for smaller federal states, using the *Länder* dummies is problematic. Some of the states drop out entirely, others are captured incompletely. The remaining states are sorted into groups of broadly similar characteristics and underlying trends: North, West, South and East; according to the structural divides in Germany.

Table 20: Variable composition of the propensity score matching equation

	Cons.Match	XY.Match	MDF.match	MDFxXY.Match	Ext. Margin
(Intercept)	0.41^{***}	0.31^{***}	0.25^{***}	0.26^{**}	0.71^{***}
	(0.01)	(0.09)	(0.01)	(0.09)	(0.13)
Population	0.03^{***}	0.03^{***}		0.01	
	(0.00)	(0.00)		(0.00)	
Density	-0.00^{*}	-0.00		-0.01^{***}	0.00
	(0.00)	(0.00)		(0.00)	(0.00)
Area	-0.00^{***}	-0.00^{***}		-0.00^{***}	0.00^{***}
	(0.00)	(0.00)		(0.00)	(0.00)
Houses	-0.00^{***}	-0.00^{***}		-0.00^{***}	
	(0.00)	(0.00)		(0.00)	
Age		0.00		-0.00	-0.01^{***}
		(0.00)		(0.00)	(0.00)
Income p. capita		-0.00		0.00	
		(0.00)		(0.00)	
Single-Family Houses		0.09^{*}		$0.06^{\cdot}$	
		(0.04)		(0.04)	
New Construction		-0.00		-0.03	0.45
		(0.20)		(0.19)	(0.33)
Forest Area		0.00		0.00	
		(0.00)		(0.00)	
Industrial Area		0.01^{**}		0.01^{*}	
		(0.00)		(0.00)	
HVT.count			-0.01^{**}	0.03^{***}	
			(0.00)	(0.01)	
HVT.density.geo			1.53^{***}	1.47^{***}	
			(0.07)	(0.09)	
Vectoring.13.r					0.07
					(0.07)
Vectoring.13.n					0.29^{***}
					(0.06)
Δ Vectoring.r					0.05^{**}
					(0.02)
Δ Vectoring.n					0.01
					(0.03)
HFC.13.r					$-0.07^{\cdot}$
					(0.03)
HFC.13.n					0.07^{**}
					(0.03)
nearby10k					0.05^{***}
					(0.01)
Ruggedness					$-0.02^{\cdot}$
					(0.01)
Min_MZ					-0.02^{***}
					(0.01)
Länder FE	YES	YES	YES	YES	YES
R^2	0.16	0.17	0.20	0.26	0.10
Adj. R^2	0.16	0.16	0.20	0.25	0.09
Num. obs.	4011	4011	4011	4011	4011

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: Comparison of propensity score matching equations (columns 1 to 4) in linear form. The logit results are qualitatively identical. Column 5 shows the best extensive margin equation to highlight similarities and differences between determinants for a high *Near* share and the probability of FttP deployment. Column 1 depicts the model used in the main analysis, whereas column 2 shows an expanded version including a broader range of market size and accessibility variables. In column 3, the *Near* shares are regressed on the number and geographical density of MDFs within a given municipality. This serves as a quality control for the model used since the MDF placements define the *Near* shares, but are themselves a consequence of infrastructure decisions made in the past century. In column 4, this control equation is expanded by including market size and accessibility variables from column 2. In comparison, the lack of explanatory power between the consolidated (1) and full market size/accessibility models (2) is negligible, while models including MDF information are more precise - as would be expected - but not exceedingly so.

Table 21: Specification comparison: Matching set vs. main set on extensive and intensive margin

Endogeneous Variable:	FttP.Exp [0,1]		Δ FttP	
	(1)	(2)	(3)	(4)
(Intercept)	1.35^{***}	0.71^{***}	0.20	1.41^{***}
	(0.23)	(0.13)	(0.93)	(0.37)
Vectoring.13.r	-0.11	0.07		
	(0.12)	(0.07)		
Vectoring.13.n	0.37^{***}	0.29^{***}		
	(0.11)	(0.06)		
Δ Vectoring.r	0.01	0.05^{*}	-0.37^{**}	-0.14^{**}
	(0.04)	(0.02)	(0.14)	(0.04)
Δ Vectoring.n	0.00	0.01		
	(0.05)	(0.03)		
HFC.13.r	-0.09	-0.07^{*}		
	(0.06)	(0.03)		
HFC.13.n	0.11^{*}	0.07^{**}		
	(0.05)	(0.03)		
Age	-0.02^{***}	-0.01^{***}	0.02	$-0.01^{\cdot}$
	(0.01)	(0.00)	(0.02)	(0.01)
Density	-0.00	0.00	0.01	-0.01^{*}
	(0.00)	(0.00)	(0.01)	(0.00)
Area	0.00	0.00^{***}	$-0.00^{\cdot}$	-0.00^{***}
	(0.00)	(0.00)	(0.00)	(0.00)
nearby10k	0.05^{*}	0.05^{***}		
	(0.03)	(0.01)		
Ruggedness	0.01	$-0.02^{\cdot}$	-0.16	-0.10^{*}
	(0.02)	(0.01)	(0.14)	(0.04)
Min_MZ	-0.01	-0.02^{***}		
	(0.01)	(0.01)		
New Construction	0.16	0.45	1.98	$-1.50^{\cdot}$
	(0.57)	(0.33)	(2.48)	(0.77)
Income p. capita			$-0.01^{\cdot}$	$-0.00^{\cdot}$
			(0.01)	(0.00)
Länder FE	YES	YES	YES	YES
R^2	0.14	0.10	0.46	0.35
Adj. R^2	0.12	0.10	0.32	0.32
Num. obs.	991	4010	97	409

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: This table shows a comparison of the main extensive and intensive margin specifications between the set used in matching for the impact of Vectoring - (1) and (3) - and the complete set used in the main analysis - (2) and (4). For the extensive margin, linear specifications are used; the intensive margin is likewise an OLS model. In both comparisons, the signs of the coefficients remain the same. Effect sizes also differ little, though exceptions exist with regards to technology and new construction. Both can be attributed to the subset used in the matching procedure excluding larger municipalities, which possess - on average - more extensive legacy networks.

Table 22: Determinants of FttP expansion at the intensive margin - Bavarian subset

Endogeneous Variable:	Δ FttP			
	Bavaria	Germany	Bavaria	Germany
	TYXS		TYXS.cons	
(Intercept)	1.50	1.26^{**}	$1.49^{\cdot}$	1.41^{***}
	(0.91)	(0.44)	(0.87)	(0.37)
Vectoring.13.r	0.92^{***}	0.27^{*}		
	(0.25)	(0.14)		
Vectoring.13.n	-0.60^{*}	-0.09		
	(0.26)	(0.11)		
Δ Vectoring.r	-0.01	-0.04	-0.01	-0.14^{**}
	(0.10)	(0.06)	(0.08)	(0.04)
Δ Vectoring.n	-0.03	-0.11		
	(0.11)	(0.06)		
HFC.13.r	-0.12	-0.08		
	(0.16)	(0.10)		
HFC.13.n	0.01	-0.02		
	(0.11)	(0.08)		
Houses	-0.00	0.00		
	(0.00)	(0.00)		
Population	$0.27^{\cdot}$	$0.02^{\cdot}$		
	(0.14)	(0.01)		
Age	-0.03	-0.01	-0.03	$-0.01^{\cdot}$
	(0.02)	(0.01)	(0.02)	(0.01)
Income p. capita	0.00	$-0.00^{\cdot}$	-0.00	$-0.00^{\cdot}$
	(0.00)	(0.00)	(0.00)	(0.00)
Density	-0.00	-0.00	0.01	-0.01^{*}
	(0.01)	(0.01)	(0.01)	(0.00)
Single-Family Houses	-0.37	-0.04		
	(0.37)	(0.23)		
New Construction	-1.63	-1.62^{*}	-2.58	$-1.50^{\cdot}$
	(2.29)	(0.77)	(2.36)	(0.77)
Area	0.00	-0.00^{*}	-0.00	-0.00^{***}
	(0.00)	(0.00)	(0.00)	(0.00)
Forest Area	-0.00	0.00		
	(0.00)	(0.00)		
Industrial Area	-0.10	-0.02		
	(0.10)	(0.02)		
HVT.count	-0.02	-0.04^{*}		
	(0.06)	(0.02)		
nearby10k	-0.04	-0.04	-0.03	
	(0.05)	(0.03)	(0.05)	
Ruggedness	-0.01	-0.11^{*}	-0.03	-0.10^{*}
	(0.07)	(0.05)	(0.06)	(0.04)
Min_MZ	0.02		0.05	
	(0.04)		(0.04)	
Min_A	0.00		0.00	
	(0.00)		(0.00)	
Funding until 15	0.01		-0.00	
	(0.01)		(0.01)	
Länder FE	NO	YES	NO	YES
R^2	0.40	0.39	0.14	0.35
Adj. R^2	0.14	0.33	-0.01	0.32
Num. obs.	74	409	74	409

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Notes: This table compares the OLS intensive margins estimations between Bavaria (columns 1 and 3) and the whole of Germany, including Bavaria, in columns (2) and (4). Columns (1) and (2) use all available regressors, whereas columns (3) and (4) follow the consolidated specification used for the main results (see Table 10). The specifications consider only municipalities with *Near* & *Remote* areas. The Vectoring base coverage (Vectoring.13.r) and population are more important in Bavaria than in Germany as a whole, whereas nearly all other regressors lose significance. For the consolidated specification, the variables are jointly non-significant. Given the low number of observations, the apparent larger relevance of Vectoring and the general lack of FttP expansion in Bavaria, this not too surprising.

Table 23: Summary statistics for technology (T) variables

Variable	Count	Mean	Median	St. Dev.	Min	Max
F2013	11,183	0.028	0	0.164	0	1
FttP.Exp	11,183	0.113	0	0.316	0	1
FTTP.13.r	11,183	0.009	0	0.085	0	1
Δ FttP.r	11,183	0.034	0	0.161	0	1
FTTP.13.n	4,972	0.008	0	0.069	0	1
Δ FttP.n	4,972	0.020	0	0.131	0	1
Vectoring.Exp.r	11,183	0.957	1	0.202	0	1
Vectoring.13.r	11,183	0.078	0.029	0.146	0	1
Δ Vectoring.r	11,183	0.241	0.071	0.318	0	1
Vectoring.Exp.n	4,972	0.935	1	0.247	0	1
Vectoring.13.n	4,972	0.063	0.034	0.114	0	1
Δ Vectoring.n	4,972	0.208	0.041	0.276	0	1
HFC.Exp.r	11,183	0.402	0	0.490	0	1
HFC.13.r	11,183	0.157	0	0.297	0	1
Δ HFC.r	11,183	0.031	0	0.137	0	1
HFC.Exp.n	4,972	0.511	1	0.500	0	1
HFC.13.n	4,972	0.304	0	0.415	0	1
Δ HFC.n	4,972	0.057	0	0.209	0	1
HVT.count	10,972	0.656	0	2.185	0	132
HVT.dens.geo	10,948	0.019	0	0.038	0	0.80
nearby10k	9,937	0.118	0	0.322	0	1

Notes: Summary statistics for all variables contained in the technology (T) category. The complete list of information on all used variables including their scale of measurement can be found in Table 24.

Table 24: Variable List

Variable	Description	contained in:	appears in Analysis Table:
Technology (T)			
FttP.13	FttP coverage in 2013 in Municipality	T	7, 14
F2013	Dummy, whether FttP coverage was positive (1) by the end of 2013	$T_{E,13}$	7
FttP.13.r	FttP coverage in 2013 in Remote area	T	
FttP.13.n	FttP coverage in 2013 in Near area	T	
FttP.Exp	Dummy, whether FttP coverage changed (1) from 2013-17	Dep.var	7 - 9, 11 - 13, 15
Δ FttP	Change in FttP coverage from 2013-17	Dep.var	10 - 12, 14, 17, 19
Vectoring.13.r	Vectoring coverage in 2013 in Remote area	T	9, 13, 15 - 17, 18, 20 - 22
Vectoring.13.n	Vectoring coverage in 2013 in Near area	T	9, 13, 15 - 17, 18, 20 - 22
Vectoring.Exp.r	Dummy, whether Vectoring coverage changed (1) from 2013-17 in Remote area	T_E	15
Vectoring.Exp.n	Dummy, whether Vectoring coverage changed (1) from 2013-17 in Near area	T_E	15
Δ Vectoring.r	Change in Vectoring coverage from 2013-17 in Remote area	T_E, T_I	9 - 11, 13, 15 - 22
Δ Vectoring.n	Change in Vectoring coverage from 2013-17 in Near area	T_E	9, 13, 15 - 18, 20 - 22
HFC.13.r	HFC coverage in 2013 in Remote area	T_E	9, 13, 15 - 18, 20 - 22
HFC.13.n	HFC coverage in 2013 in Near area	T_E	9, 13, 15 - 18, 20 - 22
HFC.Exp.r	Dummy, whether HFC coverage changed (1) from 2013-17 in Remote area	T_E	9, 13, 15 - 17
HFC.Exp.n	Dummy, whether HFC coverage changed (1) from 2013-17 in Near area	T	15
Δ HFC.r	Change in HFC coverage from 2013-17 in Remote area	T	15
Δ HFC.n	Change in HFC coverage from 2013-17 in Near area	T	15
HVT.count	Amount of MDF in a municipality	$T, (X)$	7, 14, 15, 18, 20 - 22
HVT.dens.geo	Density of MDF based on Area (in MDF per km^2)	T	20
nearby10k	Dummy, whether a neighboring municipality within 10km is accessed with FttP (1) by the end of 2013	$T_E, (X)$	9, 13, 15 - 17, 18, 20, 21
Market size (Y)			
Houses	Absolute number of residential houses	Y	15, 18, 20 - 22
Population	Absolute number of inhabitants (in 10.000)	Y	7, 14, 15, 18, 20 - 22
Age	Average age of a municipality's population (in years)	Y_E, Y_I	9, 10, 13, 15 - 22
Income p capita	Average income per inhabitant (in 1.000 Euro)	Y_I	9, 10, 15, 18 - 22
Accessibility (X)			
Density	Population density (in 100 inhabitants per km^2)	X_E, X_I	7, 9, 10, 13 - 22
Single-Family Houses	Share of one-family housing, relative to all residential houses	X	15, 18, 20 - 22
New Construction	Share of newly built residential housing, relative to all such houses	X_E, X_I	9, 10, 13, 15 - 22
Area	Area of a municipality (in 10 km^2)	X_E, X_I	9, 10, 13, 15 - 22
Forest Area	Forest area of a municipality (in 1 km^2)	X	15, 18, 20 - 22
Industrial Area	Industrially used area of a municipality (in 1 km^2)	X	15, 18 - 22
Ruggedness	Topographic heterogeneity, defined as differences in elevation (in 100m)	X_E, X_I	9, 10, 13, 15 - 21
Min_MZ	Distance to the nearest *Mittelzentrum* (mid-sized town) in driving time (10 min. steps)	X_E	9, 13, 15 - 22
Min_A	Distance to the nearest *Autobahn* access in driving time (1 min. steps)	X	15, 22
Subsidies (S)			
Subsidies	Accumulated municipality-specific subsidy payments of the federal and Bavarian programs	S_E	15
Funding until 15	Accumulated subsidy payments received through the Bavarian program until 2015	S_E, S_I	13, 22

Notes: This table summarizes all used variables for the estimations and analyses. Descriptions and unit of measurement are provided in the second column. The third column links the variable to its category and to its sub-categories in the main specifications. Column four lists all tables detailing analyses in which the respective variable has been used.

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