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Mobile internet connectivity and household wealth in the Philippines

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APPENDIX

Mobile Internet Connectivity and Household Wealth in the Philippines

Zhiwu Wei, Neil Lee, and Yohan Iddawela

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A Auxiliary Data

This section documents our auxiliary data sources that supplement our major data sources from OpenCellId, Infrapedia, and DHS, as described in our data section. We utilize the auxiliary data sources throughout our empirical analyses. We describe these sources and how we measure some important variables below.

Administrative Boundaries We assign georeferenced cell towers, DHS clusters, submarine cable landing points, and other geographic features to administrative regions using boundary data based on the version 4.1 of the Database of Global Administrative Areas (GADM) (GADM, 2022). The GADM database was originally produced as part of the BioGeomancer project through collaboration with the University of California, Berkeley, Museum of Vertebrate Zoology, and the International Rice Research Institute. It maps the administrative areas of all countries, at all levels of sub-division, thus providing a comprehensive coverage of administrative units. For the purpose of this paper, we limit the spatial resolution to units at the Administrative Level 1 (province) and 2 (barangay) across the Philippines. With these regional administrative boundaries, we perform calculations of population, mobile internet coverage, distance, and other geographic characteristics in the WGS84 UTM Zone 51N projection, which creates relatively little distortion when projecting at the scale of the Philippines.

Ookla® Internet Speedtests Data Our mobile download and upload speed data is sourced from the Ookla® Speedtest dataset, provided through the Development Data Partnership (Ookla, 2025). This dataset offers global fixed broadband and mobile (cellular) network performance metrics from 2019 onward, at a quarterly frequency and a spatial resolution of zoom level 16 web Mercator tiles (approximately 610.8 meters by 610.8 meters at the equator). Regarding the data collection method, the download and upload speeds are collected through the Speedtest by Ookla apps for Android and iOS and then averaged for each tile. In this paper, we measure average mobile internet speed within each DHS cluster in 2022. We first generate buffers around DHS clusters with radii of 10 kilometers for rural clusters and 2 kilometers for urban clusters, overlaying these buffers with Ookla's mobile internet speed shapefiles (assembling all four quarters in 2022 together) to calculate the annual average speed within each buffer. The Ookla® data can be accessed via the link: <https://github.com/teamookla/ookla-open-data>.

Foursquare Places: Points of Interest Data We use data on Points of Interest (POIs) from Foursquare OS Places to gauge local economic activities (Foursquare, 2025). Foursquare OS Places is an open database that provides detailed information on 100 million places worldwide, including restaurants, retail stores, landmarks, and other POIs. In the Philippines alone, approximately 0.80 million geocoded places have been recorded since 2009. These POIs are categorized into 1,245 classifications across six levels and we focus on the first level in our analysis. We extract POIs related to Arts and Entertainment, Business and Professional Services, Dining and Drinking, Retail, and Travel and Transportation. We measure economic activities within each DHS cluster from a pool of the 2017 and 2022 waves, using POI density, defined as the number of POIs per 1,000 people. For DHS clusters in 2017, POIs considered were those with entry dates before 2017 and not marked as closed in the database, while for clusters in 2022, POIs were those recorded before 2022 and had not been closed by then.

WorldPop Population Data Some of our analyses rely on geospatial population estimates. We draw on such data from the WorldPop database, developed by a multidisciplinary team of researchers, technicians, and project specialists at the School of Geography and Environmental Sciences, University of Southampton (WorldPop, 2018). We use annual residential population estimates in the Philippines on 3-arc-second grids (approximately 100m at the equator), adjusted to match the official United Nations population estimates prepared by the Population Division of the Department of Economic and Social Affairs. These data allow us to compute population estimates at the regional level. Additionally, we overlay the geospatial population estimates with buffers around cell towers to reckon the population covered by mobile internet. The currently available population data cover the period from 2000 to 2020. When more recent population estimates are needed, we linearly extrapolate population counts to the corresponding year. The data can be downloaded via the link: <https://hub.worldpop.org/geodata/listing?id=69>.

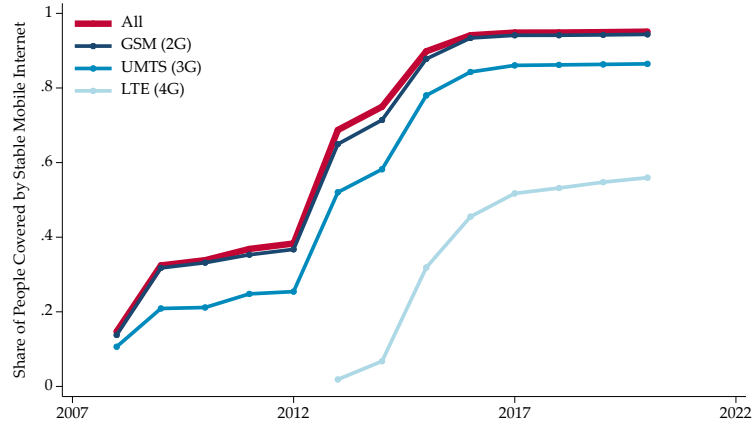
Other Data Sources First, we identify the degree of urbanization of Barangays (the lowest political administrative unit in the Philippines) and obtain their population sizes from the Global Human Settlement Layer (GHSL) Project, an open database developed by the Joint Research Centre of the European Commission that provides global spatial information on human presence over time (Schiavina et al., 2023). The GHSL classifies areas into three main degrees of urbanization, which are further divided into seven sub-levels: (i) city, (ii) dense town, semi-dense

town, suburbs or peri-urban area, (iii) village, dispersed rural area, and mostly uninhabited area. Second, we obtain the percentage of households with internet access across provinces in the Philippines from the IPUMS International census database that collects and distributes census microdata from around the world (Ruggles et al., 2025). Third, our GDP data at the province level are sourced from Philippine Statistics Agency.

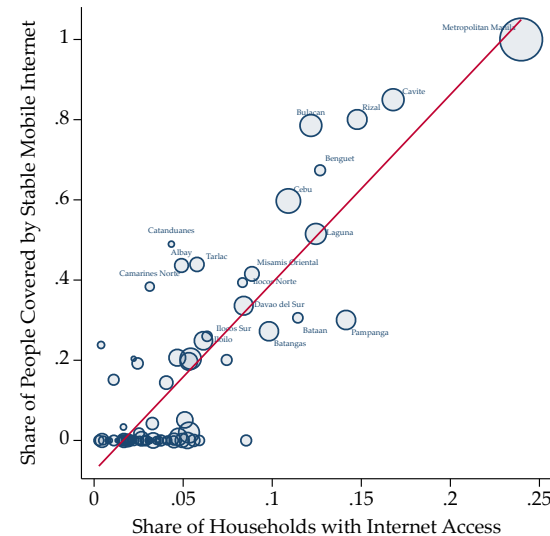
B Mobile Internet Coverage

Figure B.1: Validating Measurement of Mobile Internet Coverage

PANEL A: Mobile Internet Coverage Over Time



PANEL B: Mobile Internet Coverage and Internet Access

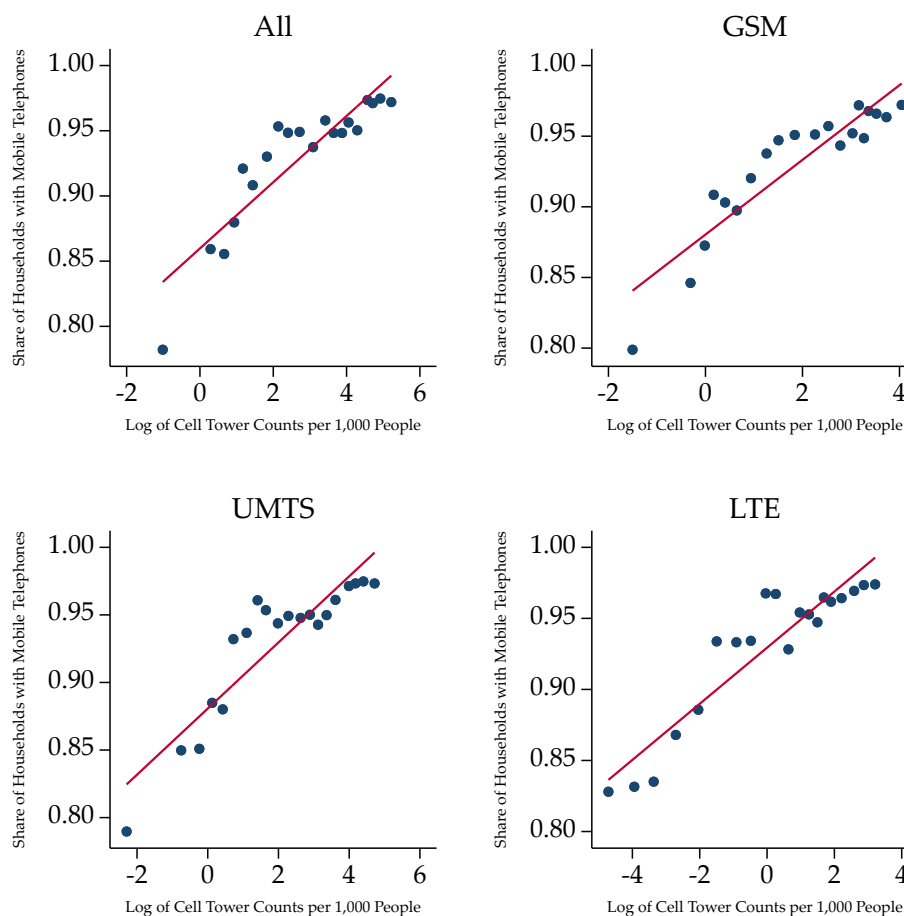


Notes: Panel A shows the share of the population within the coverage radius of cell towers from 2008 to 2020. To calculate these coverage shares, we overlay annual geospatial population data from WorldPop (2018) with cell tower data. Coverage shares represent the percentage of the population within a defined radius of cell towers relative to the total population of the Philippines. The coverage radius is set at 10 km for GSM towers, 5 km for UMTS, and 3 km for LTE. Panel B illustrates the relationship between mobile internet coverage and the percentage of households with internet access across provinces. Data on household internet access comes from the IPUMS International census database (Ruggles et al., 2025). Both shares of households with internet access and our coverage shares in Panel B are measured in 2010.

Source: Authors' calculations.

C Validating Mobile Internet Density and Cell Tower Counts

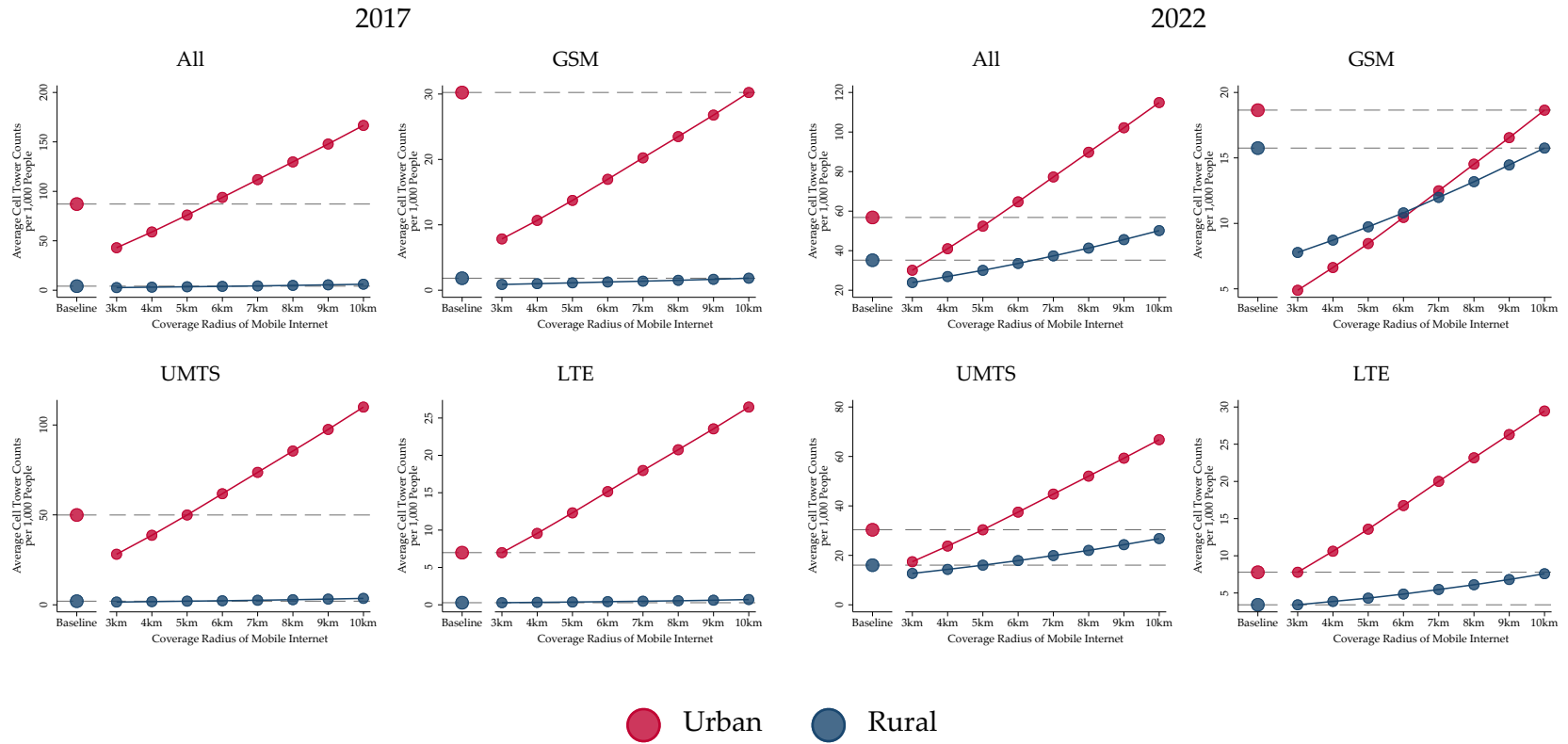
Figure C.1: Validating Measurement of Mobile Internet Density



Notes: This figure presents the relationship between the share of households owning mobile phones (based on the DHS surveys from 2017 and 2022) and mobile internet density across DHS clusters. Mobile internet density is measured as the log of cell tower counts per 1,000 people (to address instances where cell tower counts are zero, we substitute these values with one). To determine the number of cell towers covering each DHS cluster, we create buffers around the clusters (with a radius of 10 km for rural clusters and 2 km for urban clusters) and around cell towers (with radii of 10 km for GSM, 5 km for UMTS, and 3 km for LTE). The cell tower count is based on towers whose buffers intersect with the cluster buffer. The figure displays bin scatter plots of the share of households owning mobile phones against mobile internet density, using 20 equally sized bins, weighted by population. We also break down cell towers by their radio types—GSM, UMTS, and LTE—and calculate the corresponding mobile internet density across clusters.

Source: Authors' calculations.

Figure C.2: Average Cell Tower Counts Per 1,000 People across Urban and Rural Clusters



Notes: This figure presents average cell tower counts per 1,000 people across DHS urban and rural clusters. To determine the number of cell towers covering each DHS cluster, we create buffers around clusters, using a radius of 10 km for rural clusters and 2 km for urban clusters. Buffers are also created around cell towers, with radii set at 10 km for GSM, 5 km for UMTS, and 3 km for LTE as the baseline specification. For comparison, we vary the radius uniformly from 3 km to 10 km for all cell tower types. The count of cell towers is based on towers whose buffers intersect with the cluster buffer. The figure presents average cell tower counts per 1,000 people by cell tower types: “All” includes all types, while “GSM”, “UMTS”, and “LTE” represent each specific type. Baseline levels are marked by grey lines for reference.

Source: Authors’ calculations.

D Validating Household Wealth Index

Table D.1: Possessions by Household Wealth Status (Percent)

	Household Wealth Status					Adjusted Wald Test
	Poorest (1)	Poorer (2)	Middle (3)	Richer (4)	Richest (5)	<i>p</i> -value (6)
PANEL A: Wave 2017						
Own Electricity	67.2	97.1	99.2	99.9	99.9	0.000
Own Radio	32.8	40.9	49.6	60.4	73.2	0.000
Own Television	28.7	68.8	90.4	97.2	99.7	0.000
Own Telephone	0.0	0.3	0.7	4.2	32.7	0.000
Own Mobile Telephone	65.6	86.8	94.3	98.0	99.5	0.000
Own Computer	0.1	1.9	8.0	25.6	78.3	0.000
Own Refrigerator	0.9	9.7	32.2	74.7	98.5	0.000
Own Bicycle	6.4	12.3	18.0	22.6	38.4	0.000
Own Animal-Drawn Cart	2.7	2.7	1.8	1.1	1.2	0.000
Own Motorcycle/Scooter	13.8	28.7	37.8	45.3	53.0	0.000
Own Car/Truck	0.2	0.4	1.2	5.3	44.0	0.000
Own Motor Boat	2.7	2.1	1.5	1.0	1.3	0.001
Own Land for Agriculture	20.0	14.9	13.3	12.5	15.1	0.000
Own Livestock	53.4	41.6	29.9	18.8	14.1	0.000
PANEL B: Wave 2022						
Own Electricity	74.9	99.6	99.9	100.0	100.0	0.000
Own Radio	39.1	43.3	45.3	50.2	58.0	0.000
Own Television	29.7	66.7	83.2	92.8	98.2	0.000
Own Telephone	0.5	1.1	3.7	11.7	45.1	0.000
Own Mobile Telephone	74.7	91.3	96.1	98.5	99.6	0.000
Own Computer	1.5	6.2	15.3	43.4	83.9	0.000
Own Refrigerator	4.4	25.2	51.0	84.5	98.3	0.000
Own Bicycle	7.9	15.7	22.3	30.9	50.5	0.000
Own Animal-Drawn Cart	1.5	1.6	1.1	0.8	1.6	0.015
Own Motorcycle/Scooter	27.3	43.1	48.9	57.5	64.9	0.000
Own Car/Truck	0.3	0.8	2.1	8.7	48.3	0.000
Own Motor Boat	5.4	3.3	2.0	1.0	1.1	0.000
Own Land for Agriculture	19.6	15.3	11.8	12.3	17.2	0.000
Own Livestock	51.4	42.5	27.2	20.9	19.0	0.000

Notes: This table presents the share of households owning specific items or services, categorized by household wealth status measured in quintiles, ranging from the poorest (column (1)) to the richest (column (5)). The household items or services included in the analysis contain electricity, radio, television, telephone, mobile telephone, computer, refrigerator, bicycle, animal-drawn cart, motorcycle/scooter, car/truck, motorboat, agricultural land, and livestock. In column (6), we conduct an adjusted Wald test to assess whether the ownership shares differ significantly across the five wealth groups, presenting the corresponding *p*-values. The results are further broken down by waves of the DHS survey.

Source: Authors' calculations.

E GDP, Population, and New Cell Towers

Table E.1: GDP, Population, and Construction of New Cell Towers

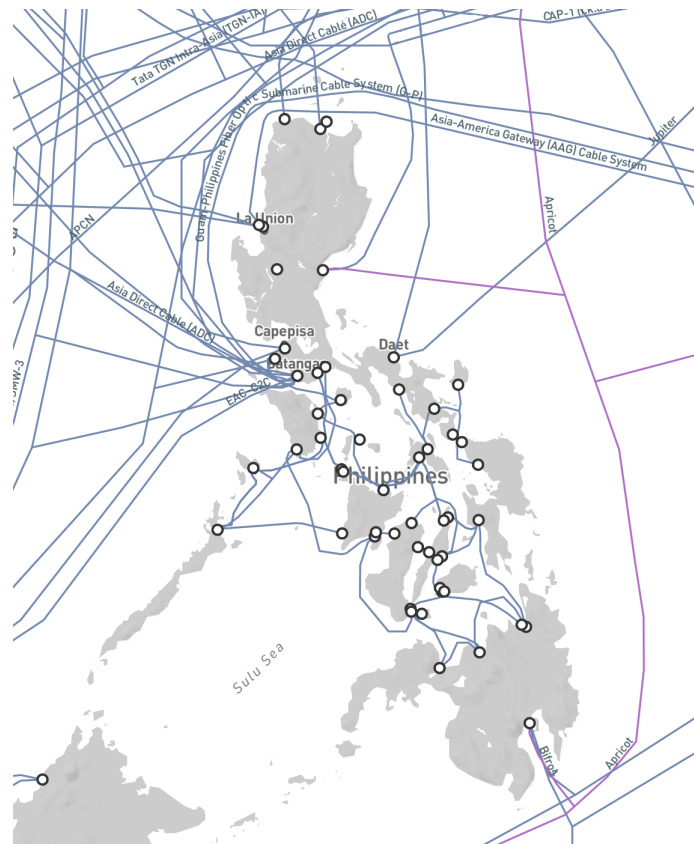
	(1)	(2)	(3)	(4)
Log of GDP per Capita	33.031 (82.616)			
Log of GDP Value		70.710 (114.245)		
Log of Population			-2.882 (107.258)	0.52014 (5.43838)
Year FE	Yes	Yes	Yes	Yes
Provincial FE	Yes	Yes	Yes	No
Barangay FE	No	No	No	Yes
Observations	405	405	405	8235

Notes: This table examines whether economic and demographic factors influence the construction of new cell towers. The dependent variable is the number of cell towers constructed in each year (from OpenCellID). Columns (1) – (3) are estimated at the provincial level, while column (4) is estimated at the district (i.e. 'Barangay' level). GDP estimates are only available at the provincial level. All specifications use year-by-region fixed effects (for provinces and barangays, respectively). This analysis is performed based on cell towers constructed between 2018–2022, since these are the only years for which official provincial GDP is available. We use two-way fixed effects panel regressions to account for unobserved time-invariant characteristics of provinces (provincial fixed effects) and common shocks over time (year fixed effects). We investigate the relationship between tower construction and population at the barangay level (administrative level-2). While GDP data is not available at this level of granularity, population estimates from WorldPop allow us to test for correlations. WorldPop's population estimates are only available from 2000-2020; therefore, we linearly extrapolate population counts to 2022. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

F Submarine Cable Network and Landing Points

Figure F.1: Submarine Cable Network in the Philippines



Notes: This figure provides a snapshot of the submarine cable network across the Philippines, sourced from the Infrapedia database. It visually depicts the geographical distribution and connectivity of submarine cables, illustrating how they link various landing points throughout the archipelago.
Source: Authors.

Table F.1: Submarine Cable Landing Point: Location Name and Ready-for-Service Year

No.	Name	Year	No.	Name	Year	No.	Name	Year
1	Allen	2018	19	Cebu	1996	37	Pagudpud	2022
2	Baclayon	2021	20	Coron	2013	38	Pasacao	2021
3	Bacong	2021	21	Cuyapo	.	39	Pinamalayan	1996
4	Baler	2020	22	Daet	2012	40	Romblon	1996
5	Ballesteros	2009	23	Davao	2017	41	Roxas	2021
6	Batangas	1996	24	Dumaguete	1996	42	Roxas City	1996
7	Bogo	2021	25	Iloilo City	1999	43	San Carlos, Negros	2021
8	Bohol	1996	26	La Union	2009	44	San Fernando City	.
9	Boracay	2021	27	Leganes	2021	45	San Jose	1999
10	Buenavista	2021	28	Legazpi City	1996	46	San Jose de Buenavista	1999
11	Butuan City	1996	29	Lucena	1999	47	San Juan, Batangas	2021
12	Cadiz City	1996	30	Marinduque	1996	48	San Remigio	2021
13	Cagayan	.	31	Masbate City	1996	49	Santa Magdalena	2018
14	Cagayan de Oro	1996	32	Milagros	2021	50	Siquijor	1996
15	Calbayog	1996	33	Naga City, Cebu	2021	51	Tagbilaran	2021
16	Catanduanes	1996	34	Nasugbu	1996	52	Talisay City, Negros	2021
17	Caticlan	2013	35	Ormoc	1996	53	Taytay	2013
18	Cavite	2002	36	Ozamiz City	1996	54	Toledo City, Cebu	2021

Notes: This table lists the location names and ready-for-service years of submarine cable landing points throughout the Philippines. Each landing point may connect to multiple submarine cables, which could be constructed in different years. We assign the ready-for-service year of the earliest connecting submarine cable as the operational year for each landing point. Due to missing data on ready-for-service years for three landing points—Cagayan, Cuyapo, and San Fernando City—these points are excluded from our analysis. The information in this table is sourced from the Infrapedia database.

Source: Authors' calculations.

G Summary Statistics

Table G.1: Summary Statistics

	N (1)	Mean (2)	Std. Dev. (3)	Source (4)
PANEL A: Household				
Poorest	64911	0.256	0.436	DHS Survey
Poorer	64911	0.222	0.416	DHS Survey
Middle	64911	0.193	0.395	DHS Survey
Richer	64911	0.173	0.378	DHS Survey
Richest	64911	0.156	0.363	DHS Survey
Number of Household Members	64911	4.425	2.232	DHS Survey
Household Head: Male	64911	0.793	0.405	DHS Survey
Household Head: Age	64910	49.511	15.033	DHS Survey
Household Head: No Education	64890	0.028	0.166	DHS Survey
Household Head: Primary Education	64890	0.365	0.482	DHS Survey
Household Head: Secondary Education	64890	0.345	0.475	DHS Survey
Household Head: Above-Secondary Education	64890	0.262	0.439	DHS Survey
PANEL B: Cluster				
Cell Tower Count All (per 1,000 people)	2253	31.532	62.314	OpenCellid and DHS Geography
Cell Tower Count GSM (per 1,000 people)	2253	14.536	30.660	OpenCellid and DHS Geography
Cell Tower Count UMTS (per 1,000 people)	2253	14.552	30.204	OpenCellid and DHS Geography
Cell Tower Count LTE (per 1,000 people)	2253	2.443	6.295	OpenCellid and DHS Geography
Arts and Entertainment POI (per 1,000 people)	2253	0.505	2.382	Foursquare Open Source Places
Business and Professional Services POI (per 1,000 people)	2253	3.131	12.629	Foursquare Open Source Places
Dining and Drinking POI (per 1,000 people)	2253	5.255	24.248	Foursquare Open Source Places
Retail POI (per 1,000 people)	2253	2.879	12.034	Foursquare Open Source Places
Travel and Transportation POI (per 1,000 people)	2253	2.577	10.377	Foursquare Open Source Places
Distance to Nearest Landing Point (100km)	3054	0.798	0.851	Infrapedia and DHS Geography
Urban	2253	0.362	0.481	DHS Geography
Rainfall (annual millimeter)	3038	2288.174	665.805	DHS Geography
Day Land Surface Temperature (degree celsius)	3042	30.200	3.181	DHS Geography
Population (thousands)	3069	100.679	157.324	DHS Geography
Population Density (thousands per square km)	3069	31.367	99.622	DHS Geography
Nightlight Luminosity	3069	4.586	9.490	DHS Geography
Slope of Terrain (degree)	3065	2.035	2.116	DHS Geography

Notes: This table provides summary statistics for key variables from DHS households and clusters, pooling data from the 2003, 2017, and 2022 waves. Columns (1) to (4) show the number of observations, means, standard deviations, and data sources, respectively. Panel A reports household-level characteristics. Household wealth is categorized by wealth index quintiles (poorest, poorer, middle, richer, and richest), with the percentage of households in each quintile presented. Additional household characteristics include the number of household members, the age, gender, and educational attainment of the household head. Educational attainment is represented by four dummies. Panel B presents cluster-level characteristics. The first set of cluster-level variables are cell tower counts per 1,000 people. We also disaggregate cell tower counts by radio types—GSM, UMTS, and LTE. We source data on five types of Points of Interest (POIs) from Foursquare Open Source Places, categorized at the first level of classification. These categories include: Arts and Entertainment, Business and Professional Services, Dining and Drinking, Retail, and Travel and Transportation. The distance to the nearest existing landing point is measured as the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. The variable "Urban" is a dummy indicating whether the cluster is located in an urban area. We obtain additional cluster-level characteristics from the DHS geospatial covariate datasets, including population, population density, nightlight luminosity, rainfall, daytime land surface temperature, and slope of terrain which are derived by overlaying geospatial data onto DHS clusters and calculating zonal statistics within a 2 km buffer for urban clusters and a 10 km buffer for rural clusters. Source: Authors' calculations.

H Placebo Tests for the Pre-Rollout Period

Table H.1: The Effect of Distance to Nearest Landing Point on Household Wealth

	Standardized Household Wealth Quintile				
	Before Rollout		Rollout		
	(1)	(2)	(3)	(4)	(5)
Distance	-0.104 (0.081)	-0.059 (0.058)	-0.122** (0.050)	-0.089** (0.035)	-0.087*** (0.034)
Observations	11613	11613	53648	53648	53648
Number of cluster	763	763	2308	2308	2308
Wave FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes	Yes	Yes
Household Controls	No	Yes	No	Yes	Yes
Mobile Phone Ownership	No	No	No	No	Yes

Notes: This table presents the reduced-form regression results of standardized household wealth quintile on the distance to the nearest existing submarine cable landing point at the household level, using data from the 2003 DHS survey, prior to the rollout of cell towers in the Philippines (columns (1) and (2)), and from 2017 and 2022 DHS surveys when cell tower rollouts (columns (3) to (5)). Columns (1) and (3) control for factors at the cluster level (an urban dummy, population density, nightlight luminosity, rainfall, temperature, and slope of terrain). Columns (2) and (4) add household-level controls, including the number of household members, the age, gender, and educational attainment of the household head. Column (5) further controls for household mobile phone ownership. Note that the variable of household mobile phone ownership is not applicable in 2003 DHS survey. All specifications incorporate fixed effects for survey wave and province to capture temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

I Assessing Alternative Instrument Variables

Table I.1: Alternative Instrumental Variables

	Standardized Household Wealth Quintile			
	Landing Point Set		Placebo IV	
	(1)	(2)	(3)	(4)
PANEL A: Second-Stage Results				
Mobile internet density	0.201 (0.130)	0.168** (0.068)	0.864 (1.724)	-0.273 (1.183)
Kleibergen-Paap Wald rk F statistic	6.13	19.19	0.56	0.31
AR Test <i>p</i> -value	0.05	0.00	0.49	0.79
Observations	53648	53648	53643	53643
Number of cluster	2308	2308	2308	2308
PANEL B: First-Stage Results				
Distance	-0.300** (0.121)	-0.623*** (0.142)	-0.005 (0.006)	0.015 (0.027)
Wave FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2017 and 2022 DHS surveys, corresponding to periods of cell tower rollouts across the Philippines. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is measured as the log of cell tower counts per 1,000 people within each DHS cluster; for clusters with zero cell towers, we replace zero values with one to enable logarithmic transformation. Columns (1) and (2) use different sets of submarine cable landing points to construct the instrumental variable: column (1) utilizes landing points established before 2003, while column (2) relies on those constructed before 2017. Columns (3) and (4) test placebo instruments; column (3) randomly assigns the baseline instrument values to other clusters within the same survey wave, while column (4) assigns these values randomly to clusters within the same province. The table reports Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to assess the strength and relevance of our instrumental variable. We report both second-stage and first-stage results with Panel A and B. Each regression controls for factors at the cluster level (an urban dummy, population density, nightlight luminosity, rainfall, temperature, and slope of terrain), household-level controls, including the number of household members, the age, gender, and educational attainment of the household head, and household mobile phone ownership. Fixed effects for survey wave and province are applied to account for temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to preserve representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.
Source: Authors' calculations.

J Plausibly Exogenous Framework

We follow the plausibly exogenous framework by Conley et al. (2012) to examine the assumption of instrument exogeneity. This framework contains the following 2SLS model:

$$Wealth_{icpt} = \mu_t \alpha_p \gamma_0 \cdot \widehat{Mobile\ internet\ density}_{cpt} + \delta \cdot Distance_{cpt} + X'_{icpt} \Omega_0 + \epsilon_{icpt}, \quad (3)$$

$$Mobile\ internet\ density_{cpt} = \mu_t \alpha_p \gamma_1 \cdot Distance_{cpt} + X'_{icpt} \Omega_1 + \varepsilon_{cpt}. \quad (4)$$

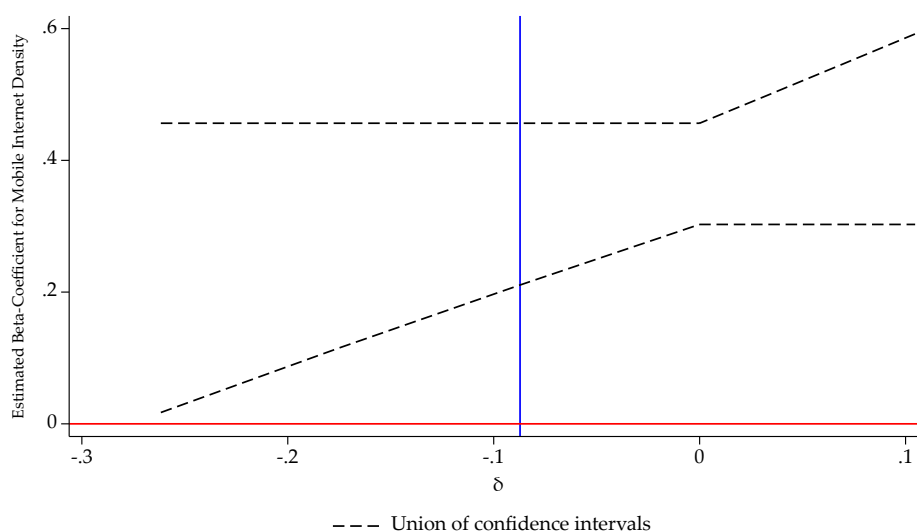
The main idea is to allow our instrumental variable to have direct effects on the main outcomes of interest, i.e., the instrumental variable is involved in the second-stage regression with a coefficient δ . That is, distance to submarine cable landing points can now directly affect household wealth beyond the channel of mobile internet density. If the exclusion restriction assumption holds, δ would be equal to zero with perfect instrument exogeneity. By contrast, various values of δ imply violation of the exclusion restriction. The magnitude of δ therefore allows us to assess how robust our findings are to different degrees of instrumental invalidity.

We employ the union of confidence intervals approach by Conley et al. (2012) to assess how our IV estimates are sensitive to violations of the exclusion restriction assumption. We consider a series of values for δ . We first estimate the reduced-form relationship between distance from submarine cable landing points and household wealth, and store the coefficient estimates on the distance (with a negative sign). We then choose the lower bound of δ to be three times larger than the baseline reduced-form coefficient estimate (with a negative sign), implying that a longer distance is associated with a lower household wealth status. The upper bound of δ is set as -1.2 times the baseline reduced-form coefficient estimate (with a positive sign), indicating that a longer distance correlates with a higher household wealth status.

Appendix Figure J.1 estimates the 2SLS equations of the plausibly exogenous framework and presents the upper and lower bounds (i.e., 95 percent confidence interval) for the coefficient estimates on mobile internet density against a series of values for δ . As the figure shows, if $\delta > 0$ (a scenario that is unlikely in practice), the coefficient estimate on mobile internet density becomes larger and does not include zero within the 95 percent confidence intervals. The blue vertical line marks the position of the baseline δ , which indicates all direct effects brought about by the distance from submarine cable landing points. In that case, mobile internet density, instrumented by the distance, still has significantly positive effects on household wealth. On the left-hand side

of the figure, one can see that δ must reach a value approximately three times the size of the baseline reduced-form estimate in order for the 95 percent confidence interval to include zero. Taken together, these results suggest that our IV estimates are robust to high degrees of violation of the exclusion restriction.

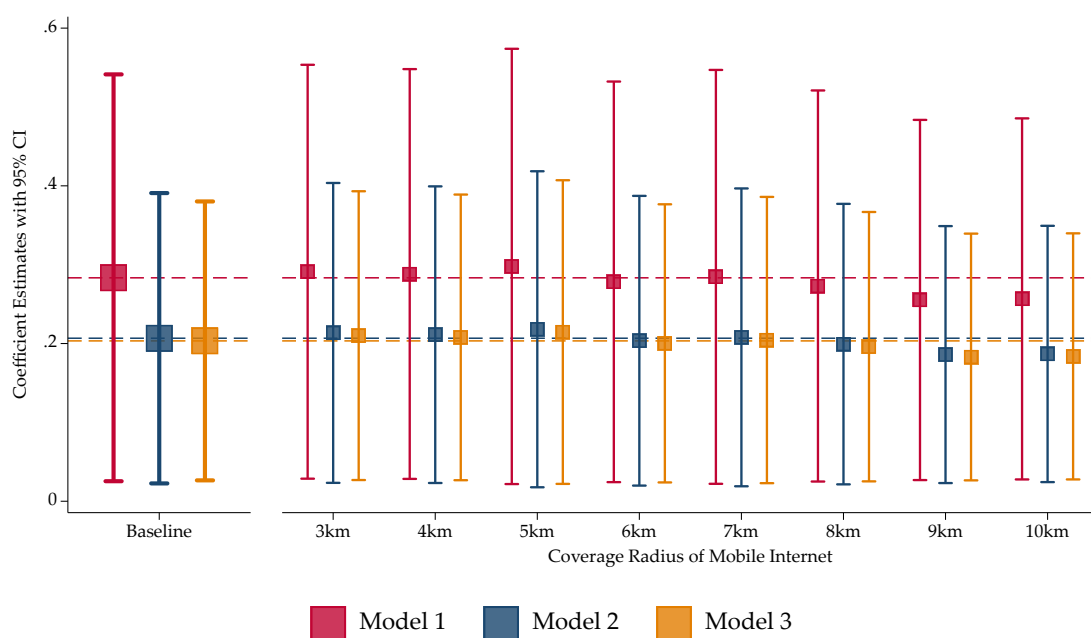
Figure J.1: Plausibly Exogenous Framework



Notes: This figure presents union of 95% confidence intervals of the IV estimates (y-axis) when the exclusion restriction is violated (x-axis). We follow the plausibly exogenous framework proposed by Conley et al. (2012) to estimate the results. The main idea is to allow our instrumental variable to have direct effects on the main outcomes of interest, i.e., the instrumental variable is involved in the second-stage regression with a coefficient δ . If the exclusion restriction assumption holds, δ would be equal to zero with perfect instrument exogeneity. By contrast, various values of δ imply violation of the exclusion restriction. The magnitude of δ therefore allows us to assess how robust our findings are to different degrees of instrumental invalidity. Source: Authors' calculations.

K Additional Robustness Checks

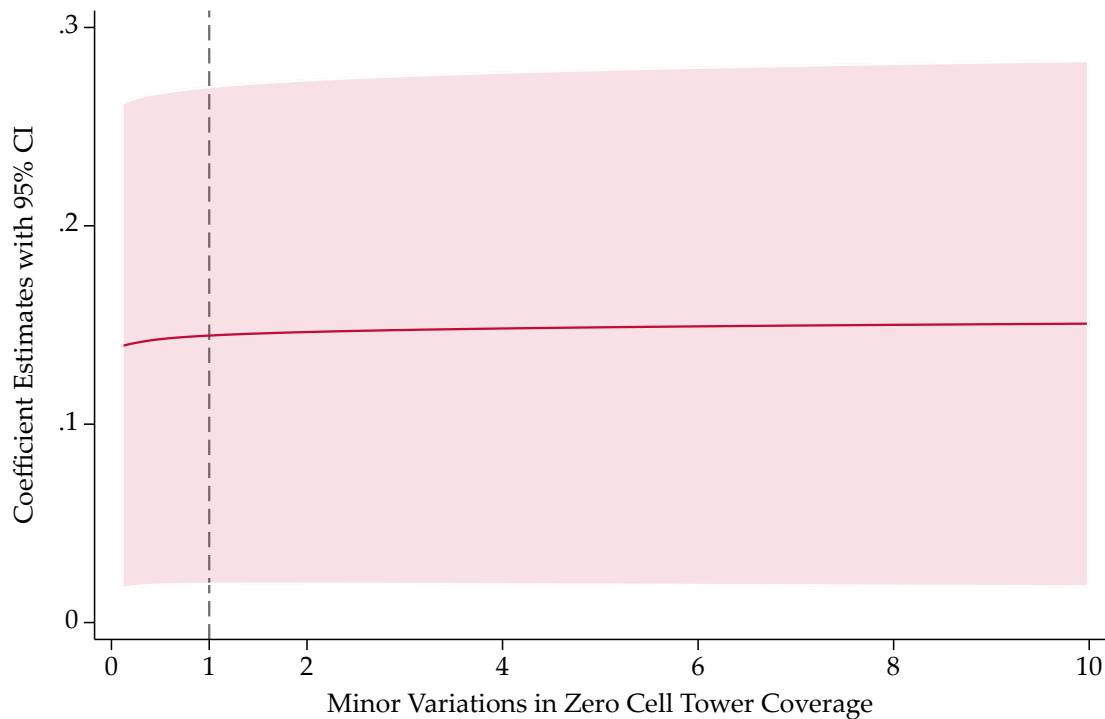
Figure K.1: Mobile Internet Density and Household Wealth, Original Dependent Variables



Notes: This figure plots the coefficient estimates for the impact of mobile internet density on household wealth. The dependent variable is household wealth status, measured in quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is measured as the log of cell tower counts per 1,000 people within each DHS cluster; for clusters with zero cell towers, we replace zero values with one to enable logarithmic transformation. For all specifications, we instrument mobile internet density using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. The baseline results are replicated from columns (4), (5), and (6) of Table 2, where the coverage radius is set at 10 km for GSM towers, 5 km for UMTS, and 3 km for LTE. To test the robustness of the results, we uniformly vary the coverage radius for all cell tower types from 3 km to 10 km and replicate the same 2SLS regression specifications. Model 1 controls for factors at the cluster level (an urban dummy, population density, nighttime luminosity, rainfall, temperature, and slope of terrain); Model 2 adds household-level controls, including the number of household members, the age, gender, and educational attainment of the household head, while Model 3 further controls for household mobile phone ownership. All specifications incorporate fixed effects for survey wave and province to capture temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to maintain representativeness. The figure also presents the associated 95% confidence intervals. Baseline levels are marked by grey lines for reference.

Source: Authors' calculations.

Figure K.2: Minor Variations in Zero Cell Tower Coverage



Notes: This figure plots coefficient estimates for the impact of mobile internet density on household wealth status, which has been standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is represented as the log of cell tower counts per 1,000 people within each DHS cluster. For clusters lacking cell towers (zero counts), we replace zero values with incremental small numbers ranging from 0.1 to 10, in the step of 0.1, to facilitate logarithmic transformation. To calculate cell tower coverage for each DHS cluster, we establish buffers: 10 km around rural clusters and 2 km around urban clusters, and around each cell tower type (10 km for GSM, 5 km for UMTS, and 3 km for LTE). Cell tower counts are derived from towers whose buffers intersect with cluster buffers. All models instrument for mobile internet density using the Euclidean distance from cluster centroids to the nearest existing submarine cable landing point. Each regression controls for factors at the cluster level (an urban dummy, population density, nighttime luminosity, rainfall, temperature, and slope of terrain), household-level controls, including the number of household members, the age, gender, and educational attainment of the household head, and household mobile phone ownership. Fixed effects for survey wave and province are applied to account for temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to preserve representativeness. The figure includes 95% confidence intervals for the coefficient estimates. Estimates are smoothed using locally weighted scatterplot smoothing (lowess).

Source: Authors' calculations.

Table K.1: Transformation to Measurement of Mobile Internet Density

	Standardized Household Wealth Quintile				
	Inverse Hyperbolic Sine	Neglog	Johnson	Square Root	Cube Root
	(1)	(2)	(3)	(4)	(5)
PANEL A: Second-Stage Results					
Mobile internet density	0.166** (0.074)	0.186** (0.081)	0.353** (0.150)	0.078** (0.033)	0.192** (0.082)
Kleibergen-Paap Wald rk F statistic	19.84	21.19	24.43	20.76	21.37
AR Test <i>p</i> -value	0.01	0.01	0.01	0.01	0.01
Observations	53648	53648	53648	53648	53648
Number of cluster	2308	2308	2308	2308	2308
PANEL B: First-Stage Results					
Distance	-0.526*** (0.118)	-0.469*** (0.102)	-0.247*** (0.050)	-1.122*** (0.246)	-0.454*** (0.098)
Wave FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2017 and 2022 DHS surveys, corresponding to periods of cell tower rollouts across the Philippines. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is subject to several transformations across columns: column (1) applies the inverse hyperbolic sine transformation to cell tower counts per 1,000 people within each DHS cluster; column (2) uses a neglog transformation; column (3) applies a Johnson transformation; columns (4) and (5) use square root and cube root transformations, respectively. Across all specifications, we instrument mobile internet density using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. The table includes Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to evaluate the strength and relevance of our instrumental variable. We report both second-stage and first-stage results with Panel A and B. All regressions include controls for cluster-level factors (urban dummy, population density, nightlight luminosity, rainfall, temperature, and slope of terrain) and household-level characteristics (the number of household members, the age, gender, and educational attainment of the household head, and household mobile phone ownership). All specifications incorporate fixed effects for survey wave and province to capture temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to maintain representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

Table K.2: Alternative Standard Errors

	Standardized Household Wealth Quintile				
	Cluster S.E.	Conley S.E.			
	(1)	(2)	(3)	(4)	(5)
Mobile internet density	0.145* (0.082)	0.145** (0.066)	0.145** (0.069)	0.145** (0.071)	0.145** (0.070)
Kleibergen-Paap Wald rk F statistic	7.69	28.31	28.44	29.74	30.30
AR Test <i>p</i> -value	0.03				
Observations	53648	53648	53648	53648	53648
Number of cluster	163				
Cutoff (km)		50	100	150	200
Wave FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2017 and 2022 DHS surveys, corresponding to periods of cell tower rollouts across the Philippines. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is measured as the log of cell tower counts per 1,000 people within each DHS cluster; for clusters with zero cell towers, we replace zero values with one to enable logarithmic transformation. Across all specifications, we instrument mobile internet density using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. In column (1), standard errors are clustered at the province-by-wave level. Columns (2) through (5) implement Conley standard errors (Conley, 1999), with distance cutoffs set at 50 km, 100 km, 150 km, and 200 km, respectively, to account for potential spatial correlation in the data. The table reports Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to assess the strength and relevance of our instrumental variable. Each regression controls for factors at the cluster level (an urban dummy, population density, nightlight luminosity, rainfall, temperature, and slope of terrain), household-level controls, including the number of household members, the age, gender, and educational attainment of the household head, and household mobile phone ownership. Fixed effects for survey wave and province are applied to account for temporal and regional variations. Sampling weights are applied to preserve representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

Table K.3: Spillover Effects

	Standardized Household Wealth Quintile			
	(1)	(2)	(3)	(4)
PANEL A: Second-Stage Results				
Mobile internet density	0.163*	0.144**	0.141**	0.181*
	(0.084)	(0.068)	(0.066)	(0.097)
Mobile internet density (1st nearest)	-0.044			-0.036
	(0.032)			(0.027)
Mobile internet density (2nd nearest)		-0.029		-0.022
		(0.021)		(0.018)
Mobile internet density (3rd nearest)			-0.030	-0.027
			(0.022)	(0.022)
Kleibergen-Paap Wald rk F statistic	14.54	19.49	22.20	12.53
AR Test <i>p</i> -value	0.02	0.01	0.01	0.02
Observations	48446	48446	48446	48446
Number of cluster	2070	2070	2070	2070
PANEL B: First-Stage Results				
Distance	-0.528***	-0.627***	-0.643***	-0.464***
	(0.139)	(0.142)	(0.136)	(0.131)
Wave FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes	Yes
Household Controls	YES	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2017 and 2022 DHS surveys, corresponding to periods of cell tower rollouts across the Philippines. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is measured as the log of cell tower counts per 1,000 people within each DHS cluster; for clusters with zero cell towers, we replace zero values with one to enable logarithmic transformation. Across all specifications, we instrument mobile internet density using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. Columns (1) to (3) additionally control for mobile internet density in the first, second, and third nearest neighboring DHS clusters, respectively, while column (5) includes all three simultaneously. The table includes Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to evaluate the strength and relevance of our instrumental variable. All regressions include controls for cluster-level factors (urban dummy, population density, nighttime luminosity, rainfall, temperature, and slope of terrain) and household-level characteristics (the number of household members, the age, gender, and educational attainment of the household head, and household mobile phone ownership). We report both second-stage and first-stage results with Panel A and B. All specifications incorporate fixed effects for survey wave and province to capture temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to maintain representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

L Effects by Educational Attainment

Table L.1: Effects of Mobile Internet Density by Heads' Educational Attainment

	Education		
	<=Primary (1)	Secondary (2)	Higher (3)
PANEL A: Second-Stage Results			
Mobile internet density	0.115** (0.046)	0.159* (0.090)	0.166 (0.117)
Kleibergen-Paap Wald rk F statistic	22.63	15.47	16.59
AR Test <i>p</i> -value	0.00	0.04	0.14
Observations	20591	18957	14100
Number of cluster	2213	2293	2157
PANEL B: First-Stage Results			
Distance	-0.697*** (0.146)	-0.573*** (0.146)	-0.563*** (0.138)
Wave FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2017 and 2022 DHS surveys, corresponding to periods of cell tower rollouts across the Philippines. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The primary explanatory variable, mobile internet density, is measured as the log of cell tower counts per 1,000 people within each DHS cluster; for clusters with zero cell towers, we replace zero values with one to enable logarithmic transformation. Across all specifications, we instrument mobile internet density using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. The table includes Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to evaluate the strength and relevance of our instrumental variable. We report both first-stage and second-stage results with Panel A and B. Column (1) limits the sample to households where the head has less than a primary education, while column (2) limits the sample to households where the head has a secondary education, and column (3) limits to households whose heads have education higher than the secondary. All columns control for factors at the cluster level, including an urban dummy, population density, nighttime luminosity, rainfall, temperature, and slope of terrain, as well as household-level factors, including the number of household members, the age and gender of the household head. All columns control for household mobile phone ownership. Fixed effects for survey wave and province are applied to account for temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to preserve representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

Table L.2: Effects of Mobile Internet Quality by Heads' Educational Attainment, 2022

	Education		
	<=Primary (1)	Secondary (2)	Higher (3)
PANEL A1: Second-Stage Results, Download Speed Based			
Mobile internet quality	0.133** (0.060)	0.139** (0.065)	0.165* (0.088)
Kleibergen-Paap Wald rk F statistic	10.03	14.45	18.40
AR Test <i>p</i> -value	0.01	0.02	0.04
Observations	9885	9502	7335
Number of cluster	1050	1095	1045
PANEL A2: First-Stage Results, Download Speed Based			
Distance	-0.725*** (0.229)	-0.785*** (0.206)	-0.869*** (0.203)
PANEL B1: Second-Stage Results, Upload Speed Based			
Mobile internet quality	0.177* (0.092)	0.171** (0.086)	0.198* (0.108)
Kleibergen-Paap Wald rk F statistic	6.21	10.55	12.33
AR Test <i>p</i> -value	0.01	0.02	0.04
Observations	9885	9502	7335
Number of cluster	1050	1095	1045
PANEL B2: First-Stage Results, Upload Speed Based			
Distance	-0.546** (0.219)	-0.636*** (0.196)	-0.723*** (0.206)
Wave FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Cluster Controls	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes
Mobile Phone Ownership	Yes	Yes	Yes

Notes: This table presents the results of 2SLS regressions at the household level, based on data from the 2022 DHS survey. The dependent variable is household wealth status, standardized from quintiles on a scale of 1 (poorest) to 5 (richest). The endogenous variable is mobile internet quality, measured by the log of cell tower counts per 1,000 people multiplied by mobile internet speed (in mbps). Zero cell counts are replaced with one. The mobile internet quality measure is constructed based on download speed in Panel A1, A2, and upload speed in Panel B1, B2. The speed data are obtained from the Ookla® Speedtest application. To assess mobile internet quality around DHS clusters, we create buffers around clusters, with radii of 10 km for rural clusters and 2 km for urban clusters, overlaying these with Ookla®'s mobile internet speed raster data to calculate the average speed within each buffer. Across all 2SLS specifications, mobile internet quality is instrumented using the Euclidean distance from the cluster's centroid to the nearest existing submarine cable landing point. The table includes Kleibergen-Paap Wald rk F statistics and Anderson-Rubin (AR) test *p*-values to evaluate the strength and relevance of our instrumental variable. We report both first-stage and second-stage results with Panel A2 and B2. Column (1) limits the sample to households where the head has less than a primary education, while column (2) limits the sample to households where the head has a secondary education, and column (3) limits to households whose heads have education higher than the secondary. All columns control for factors at the cluster level, including an urban dummy, population density, nighttime luminosity, rainfall, temperature, and slope of terrain, as well as household-level factors, including the number of household members, the age and gender of the household head. All columns control for household mobile phone ownership. Fixed effects for survey wave and province are applied to account for temporal and regional variations. Standard errors are clustered at the DHS cluster level, and sampling weights are applied to preserve representativeness. * significant at 10%, ** significant at 5%, *** significant at 1%.

Source: Authors' calculations.

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