Connecting Isolated Communities: Quantitative Evidence on the Adoption of Community Cellular Networks in the Philippines

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ABSTRACT

What determines the success of community cellular networks? We leverage unique circumstances where all households in seven localities were interviewed before the launch of cellular networks. We observed substantial differences in network adoption across communities. Four communities displayed high and regular usage, while usage dissipated shortly after the network launch in three sites. Sixty-five percent of households made or received at least one call or text message. We find that a one standard deviation increase in household wealth is correlated with a three percentage point increase in network adoption and 43 additional cellular network transactions. Agricultural households were ten percentage points more likely to adopt the network than other households and female-headed households were five percentage points more likely to use the network at least once.

CCS CONCEPTS

• **Applied computing → Economics**; • **Networks → Mobile networks**.

KEYWORDS

Cellular Networks; Mobile Phones; Call Detail Records; Socioeconomic Survey; Welfare; Social Networks

ACM Reference Format:
Niall Keleher, Mary Claire Barela, Joshua Blumenstock, Cedric Festin, Matthew Podolsky, Erin Troland, Arman Rezaee, and Kurtis Heimerl. 2020. Connecting Isolated Communities: Quantitative Evidence on the Adoption of Community Cellular Networks in the Philippines. In *Proceedings of Information and Communication Technologies and Development (ICTD '20)*. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3392561.3394645

ICTD '20, June 17–20, 2020, Guayaquil, Ecuador
2020. ACM ISBN 978-1-4503-8762-0/20/06.
https://doi.org/10.1145/3392561.3394645

1 INTRODUCTION

More than 5 billion people have mobile phone subscriptions, yet the expansion of subscribers has slowed in recent years [25]. The reduced pace of growth presents a considerable challenge in the pursuit of ubiquitous communication systems. One of the Sustainable Development Goals is to "significantly increase access to information and communications technology and strive to provide universal and affordable access to the internet in least developed countries by 2020."[1] The World Economic Forum pinpoints a similar goal of "Internet for All" [37]. The GSMA identifies mobile subscriptions as a prerequisite to expanding access to phone and internet communications but cites demographic and geographic challenges to expanding mobile connections [20]. In particular, individuals with limited formal education, low employment potential, and the elderly are less likely to be connected [12, 20]. Rural households are also disadvantaged due to infrastructural constraints.

We examine the potential and constraints to expanding mobile phone access in a set of isolated communities in the Philippines, combining several sources of data to develop a nuanced understanding of the drivers of — and impediments to — mobile phone adoption in these communities. Between September 2017 and January 2019, seven community cellular networks (CCNs) were installed in previously-unconnected villages in the Philippines. CCNs leverage a low-cost technology, the Village Base Station (VBTS), initially developed by [22]. The VBTS provides a practical, open-source GSM (2G) cellular technology (both hardware and software) with three main benefits:

- flexible, low-power deployment requirements that leverage local power generation via solar or wind;
- support for local operation and services within the locality with the potential to run autonomously; and
- a portfolio of SMS and voice services.

Once activated, VBTS towers transmit to a 500-meter radius, though terrain often reduces the actual distance. This technology

[1] https://sustainabledevelopment.un.org/

was adapted for the Philippines by a team of researchers from the University of the Philippines (UP), University of Washington, and University of California Berkeley [5], with the regulatory support of a national mobile network operator. This process included hardware procurement and fabrication, software design and integration, site selection, engineering and construction of towers and solar grids for VBTS boxes in these sites, working with a major telecommunications company and satellite connection providers, and mobilizing local communities to maintain a CCN.

Our aim in this paper is to provide statistical evidence of household-level factors that influence CCN adoption and network usage. In order to glean information about demographics, economic well-being, and social connectedness, we conducted a baseline survey with all households in the CCN project sites. Upon launching the CCNs, we took steps to enable linking the rich socioeconomic data from the baseline survey to Call Detail Records (CDR), which allow us to describe phone-based communication on the community cellular network. Together, this unique data allow us to describe information access before the introduction of cellular networks as well as unpack the baseline household characteristics that correlate with the early adoption of the cellular networks [9–11, 13].

Take-up of the community cellular networks varied greatly across installation sites. Four sites demonstrated rapid adoption and sustained activity on the CCN. Three sites, however, displayed anemic usage statistics. Two of the three sites with low usage had phone ownership rates above 80 percent prior to the CCN installation, thus signaling that these sites may have had lower utility for the CCN.

Our findings highlight the importance of considering socioeconomic characteristics in the expansion of cellular networks. Sixty-five percent of all households used the CCN at least once during the first five months of activity. Across all sites, prior phone ownership increased the likelihood that a household used the CCN by five percentage points. Female-headed households were five percentage points more likely to use the CCN. Furthermore, households involved in fishing and farming were ten percentage points more likely to use the CCN. When we examine the volume of network usage, we find that the wealth of the household and the education level of the household head were the primary drivers of usage. After controlling for other household characteristics, we do not find evidence that pre-existing social network ties influenced CCN adoption.

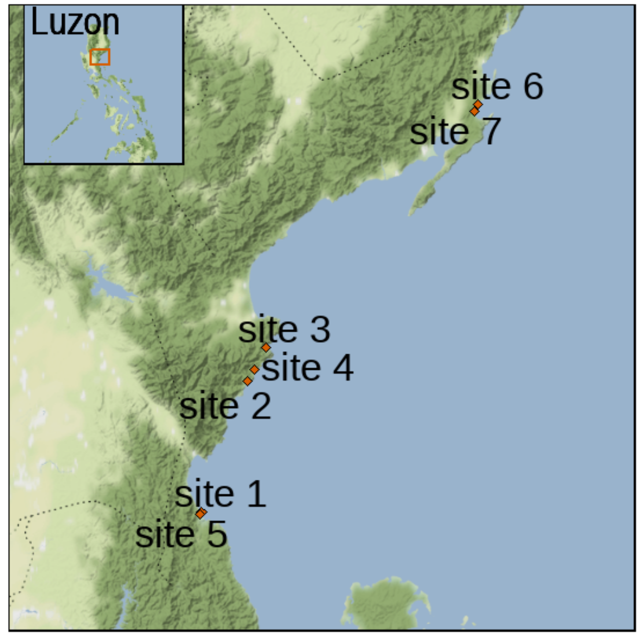

Figure 1: Seven Community Cellular Network Sites: Between September 2017 and January 2019 seven VBTS towers were installed in seven isolated communities in Aurora Province on the island of Luzon in the Philippines. Communities were selected based on the lack of cellular network signal and technical viability of VBTS tower installation. Sites were difficult to reach, often requiring a boat and frequently cut off during typhoon season.

2 RELATED WORK

This paper contributes to a burgeoning literature on low-cost community and mobile phone networks in rural areas of the world. Community networking, the ownership and operation of networking infrastructure by members of the connected community, is an area of active research. While the specific networking technology can vary, including things like 802.11 Wifi [1, 4, 8, 26, 33] or cellular protocols including GSM (2G) [3, 6, 22, 23], UMTS (3G) [32], and LTE (4G) [29, 35], mobile phones remain the dominant network access technology in the developing world [19]. As such, the analysis presented in this paper is intended to complement these ongoing research agendas on the specific technical [21] or operational [27] components of community networks by examining the key social and economic factors in mobile phone adoption.

Prior work on communications networks in developing countries relies on administrative or operational data and lacks demographic and socioeconomic data. Sarker et al. provide an early analysis of cellphone adoption and usage [34]. Ahmad et al. also examine device characteristics of mobile network subscribers on a major network in Pakistan [2]. Vigil et al. explored tribal web traffic among rural indigenous Americans [36]. Johnson et al. explored network usage behavior for an 802.11 community network in Zambia [28]. Heimerl et al., use call detail records from one community cellular network in Indonesia to explore the uptake of the network and the expansion of smartphones [24]. However, the above studies lack detailed socioeconomic data to unpack the determinants of mobile phone usage.

This paper builds on similar statistical analyses that pair survey or census data with CDR to examine social and economic factors that influence mobile phone use [9, 13, 17]. Batzilis et al. provide similar analysis to ours by examining the demographic and economic factors that correlated with mobile network adoption in Malawi; however, their analysis is only possible at the aggregate level of survey enumeration areas [7].

This paper is unique for two reasons. First, through scrupulous efforts to connect survey data with CDR, we present an analysis of household baseline characteristics — such as wealth, income source,

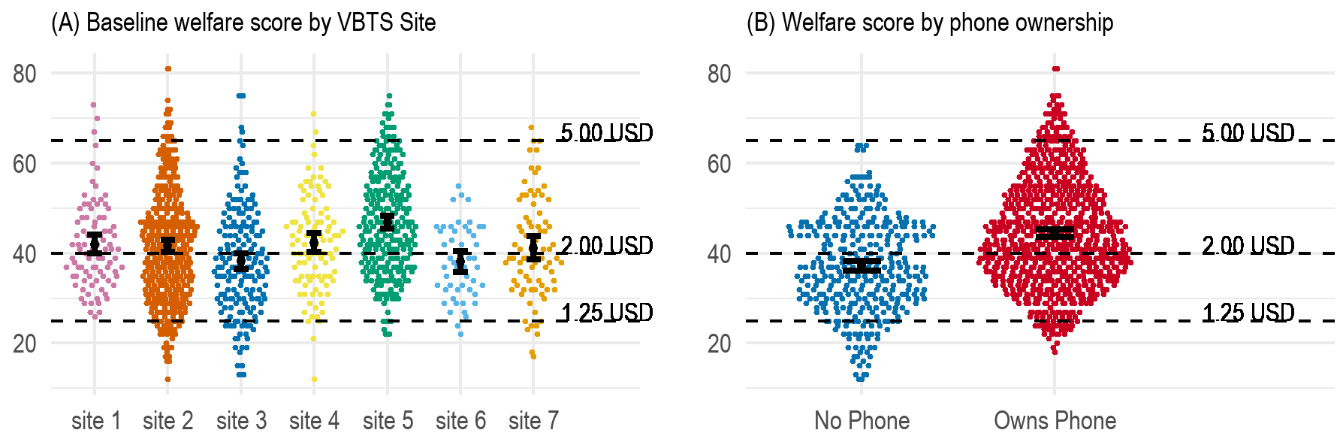

Figure 2: Baseline Welfare by CCN Site and Phone Ownership We estimate a household's welfare level using the Probability Probability Index (PPI). Higher values indicate a lower likelihood of living in poverty. *Panel A:* Across all sites, we see that estimated levels of expenditure were low. 90% of households lived on less than 5 USD per capita per day. Based on this welfare metric, site 3 and site 6 were the poorest communities in the study. *Panel B:* Household welfare was correlated with mobile phone ownership with phone owners less likely to be living on daily expenditures of 2 USD or less.

and prior phone ownership — that may influence cellular network adoption. Second, unlike previous work in which survey data and CDR were analyzed, we also utilize a detailed social network census of all households in the CCN sites to measure social connections prior to the launch of cellular networks.

3 CONTEXT AND SITE IDENTIFICATION

The Philippines provides an ideal setting to study community cellular networks. The country is an archipelago composed of about 7,641 mountainous islands. The topology of the Philippines results in thousands of localities that are isolated from other parts of the country. Approximately 63 percent of the Philippines population subscribe to a mobile network operating system, leaving over 25 million people disconnected [18]. The country faces the "last mile" connectivity gap in differential access to cellular network coverage. This gap is caused by the fact that telecommunications companies, to date, have not found it commercially viable to bring cellular towers to many of the country's small, remote islands nor to the mountainous, coastal regions of its larger islands.

As described in [5], we identified fourteen candidate sites along the east coast of Luzon, the largest island in the Philippines. Sites are "sitios" or "barangays" (local administrative units) located near or along the coast — remote enough to lack cellular network coverage but not so remote as to make the logistics of research infeasible. The province where the sites are located, Aurora Province, is frequently hit by typhoons. During typhoon season, sites are often inaccessible for multiple days. Moreover, the coastal and mountainous terrain make mobile connectivity difficult.

Field teams visited all potential sites to verify eligibility, determine possible logistics, and meet with local government units (LGUs). Our team conducted spectrum analysis to evaluate whether or not a site had pre-existing access to a cellular network. Some sites had nearby access that required walking beyond the community. Our team also assessed potential topographical features that could impede the functionality of a community cellular network. We then randomly selected seven sites that would receive an initial installation of a CCN tower. In this paper, we focus our analysis on the seven project sites that received a CCN tower. Figure 1 shows the location of the seven sites that were selected to receive a Community Cellular Network tower.[2]

The localities where this study was conducted have some of the highest poverty rates in the country. Figure 2 shows our estimates of household welfare across all seven project sites. An estimated 90 percent of households live on less than 5 USD per capita per day. While some variance across sites can be observed, with sites 3 and 6 being the poorest, we assess that the selected sites were among the poorest in the Philippines. While phone owners were, on average, less poor relative to non-phone owners at the time of baseline, the average phone owner lived on less than 2.50 USD per day.

4 DEMOGRAPHICS AND SOCIOECONOMICS AT BASELINE

Prior to the installation of VBTS towers, we conducted a baseline survey with all households in the selected rural communities of Aurora Province. CCN sites range, in size, from 50 to 382 households. The baseline survey involved three parts: (1) a household survey; (2) a listing of all adults, 15 years or older; and (3) and a one-on-one adult survey. Among the seven CCN sites, 1,131 households were interviewed at baseline. A total population of 3,057 adults lived in the CCN sites.[3] To participate in the study, we asked for voluntary consent from all survey respondents. We obtained approvals for human subjects through our academic institutions' Institutional Review Boards.

[2]For more details on the randomized controlled trial, see [14].

[3]In total, we collected baseline data from 2,370 households across the fourteen sites included in the randomized controlled trial.

	All Sites	site 1	site 2	site 3	site 4	site 5	site 6	site 7
Panel A: Households	N=1131	N=88	N=382	N=176	N=100	N=255	N=50	N=80
Adults (15+)	2.70 (1.29)	2.44 (1.18)	2.89 (1.36)	2.81 (1.31)	2.51 (1.15)	2.53 (1.24)	2.56 (1.15)	2.74 (1.38)
Children (0-14)	1.77 (1.49)	1.66 (1.29)	2.06 (1.62)	1.77 (1.51)	1.59 (1.40)	1.45 (1.28)	1.70 (1.52)	1.74 (1.56)
HOH is female	0.36 (0.48)	0.43 (0.50)	0.45 (0.50)	0.32 (0.47)	0.33 (0.47)	0.35 (0.48)	0.13 (0.34)	0.12 (0.32)
HOH has secondary educ.	0.27 (0.44)	0.24 (0.43)	0.33 (0.47)	0.12 (0.32)	0.21 (0.41)	0.36 (0.48)	0.17 (0.38)	0.18 (0.39)
Rooms in dwelling	1.79 (0.81)	1.75 (0.75)	1.96 (0.87)	1.72 (0.78)	1.54 (0.77)	1.72 (0.76)	1.62 (0.67)	1.77 (0.78)
Income - Farming	0.34 (0.47)	0.14 (0.35)	0.40 (0.49)	0.48 (0.50)	0.40 (0.49)	0.29 (0.45)	0.46 (0.50)	0.04 (0.19)
Income - Fishing	0.24 (0.43)	0.42 (0.50)	0.21 (0.41)	0.35 (0.48)	0.30 (0.46)	0.04 (0.19)	0.02 (0.14)	0.62 (0.49)
Income - Wage Labor	0.20 (0.40)	0.16 (0.37)	0.22 (0.41)	0.09 (0.29)	0.13 (0.34)	0.31 (0.46)	0.26 (0.44)	0.06 (0.24)
Welfare Score	42.17 (11.97)	42.00 (9.71)	41.62 (12.61)	38.23 (12.05)	42.31 (10.55)	46.82 (11.55)	38.16 (8.12)	41.19 (11.45)
Wealth Index	-0.11 (1.33)	-0.37 (1.21)	0.19 (1.32)	-0.67 (1.36)	-0.25 (1.25)	0.20 (1.28)	-0.93 (1.05)	-0.32 (1.14)
Electricity in dwelling	0.63 (3.30)	0.89 (0.32)	0.92 (0.28)	0.08 (5.86)	0.82 (0.39)	0.64 (4.89)	0.10 (0.30)	0.31 (0.47)
Owns television	0.52 (0.50)	0.49 (0.50)	0.60 (0.49)	0.40 (0.49)	0.47 (0.50)	0.59 (0.49)	0.22 (0.42)	0.51 (0.50)
Owns radio	0.32 (0.47)	0.23 (0.42)	0.36 (0.48)	0.30 (0.46)	0.29 (0.46)	0.20 (0.40)	0.56 (0.50)	0.50 (0.50)
Owns satellite TV dish	0.31 (0.46)	0.22 (0.41)	0.37 (0.48)	0.13 (0.34)	0.27 (0.45)	0.43 (0.50)	0.12 (0.33)	0.31 (0.47)
Owns cellphone	0.68 (0.47)	0.80 (0.41)	0.69 (0.46)	0.47 (0.50)	0.57 (0.50)	0.85 (0.36)	0.58 (0.50)	0.62 (0.49)
Number of cellphones	1.20 (1.19)	1.20 (0.91)	1.23 (1.22)	0.75 (1.07)	1.13 (1.38)	1.55 (1.11)	0.94 (1.17)	1.21 (1.24)
Owns SIM card	0.64 (0.48)	0.78 (0.41)	0.65 (0.48)	0.43 (0.50)	0.50 (0.50)	0.82 (0.38)	0.56 (0.50)	0.56 (0.50)
Number of SIM cards	1.33 (1.52)	1.34 (1.14)	1.34 (1.51)	0.84 (1.53)	1.21 (1.90)	1.73 (1.30)	1.04 (1.32)	1.38 (1.73)
In-degree centrality	5.40 (29.58)	4.38 (3.56)	6.13 (37.83)	5.15 (4.53)	2.85 (2.89)	6.88 (41.32)	3.18 (3.30)	3.52 (4.06)
Eigenvector centrality	0.09 (0.15)	0.07 (0.16)	0.04 (0.06)	0.17 (0.20)	0.14 (0.21)	0.06 (0.07)	0.21 (0.22)	0.20 (0.18)
Panel B: All Adults	N=2987	N=215	N=1072	N=492	N=246	N=625	N=123	N=214
Female	0.49 (0.50)	0.51 (0.50)	0.48 (0.50)	0.48 (0.50)	0.48 (0.50)	0.52 (0.50)	0.47 (0.50)	0.47 (0.50)
Primary school	0.98 (0.13)	0.97 (0.17)	0.99 (0.09)	0.96 (0.19)	0.99 (0.09)	0.99 (0.11)	0.98 (0.13)	0.98 (0.15)
Secondary school	0.28 (0.45)	0.22 (0.42)	0.33 (0.47)	0.13 (0.34)	0.26 (0.44)	0.38 (0.48)	0.16 (0.36)	0.23 (0.42)
Work/School outside bgy	0.32 (0.47)	0.36 (0.48)	0.33 (0.47)	0.27 (0.44)	0.32 (0.47)	0.32 (0.47)	0.39 (0.49)	0.28 (0.45)
Plans to travel outside bgy	0.45 (0.50)	0.26 (0.44)	0.53 (0.50)	0.35 (0.48)	0.43 (0.50)	0.48 (0.50)	0.42 (0.50)	0.38 (0.49)
Panel C: Adult Survey	N=1615	N=118	N=582	N=264	N=134	N=333	N=64	N=120
Feels isolated	0.30 (0.46)	0.19 (0.39)	0.28 (0.45)	0.18 (0.39)	0.22 (0.41)	0.45 (0.50)	0.51 (0.50)	0.35 (0.48)
Comm. in emergency	0.46 (0.50)	0.53 (0.50)	0.41 (0.49)	0.23 (0.42)	0.31 (0.46)	0.73 (0.45)	0.40 (0.49)	0.65 (0.48)
Travel to neighbor bgy	0.45 (0.50)	0.34 (0.48)	0.40 (0.49)	0.38 (0.49)	0.60 (0.49)	0.45 (0.50)	0.66 (0.48)	0.65 (0.48)
Travel to Manila	0.14 (0.35)	0.30 (0.46)	0.12 (0.32)	0.07 (0.26)	0.18 (0.39)	0.16 (0.37)	0.11 (0.31)	0.19 (0.40)
Total contacts within bgy	6.10 (6.34)	4.95 (2.20)	6.34 (6.47)	5.34 (2.44)	5.44 (3.17)	5.28 (2.86)	6.73 (6.08)	10.41 (15.66)
Total contacts outside bgy	4.02 (7.54)	2.86 (2.09)	4.96 (10.92)	2.65 (2.85)	3.99 (5.93)	2.77 (3.45)	4.62 (4.90)	6.76 (7.67)

Table 1: Baseline Summary Statistics, by CCN Site: The tabel presents summary statistics from the three components of the baseline survey, the household survey (*Panel A*), the listing of all adults (*Panel B*), and the one-on-one adult survey (*Panel C*). *Welfare Score* is the Poverty Probability Index (PPI) score. *Wealth Index* is the value of the first component from the polychoric principal component analysis using household assets. *Feels isolated* corresponds to the question, "Do you feel isolated from the rest of your country?" *Comm. in emergency* corresponds to the question, "Could you communicate with family in case of emergency?" Standard deviations shown in parentheses.

4.1 Household Survey Data

The household survey consisted of modules about household demographic composition, asset ownership, and economic activity. Panel A of Table 1 shows demographic, welfare, asset ownership, and social network characteristics of households before the launch of the CCN. Households comprise, on average, 2.7 adults and 1.8 children under the age of 15. One-third of household heads are women. One-quarter of household heads have a secondary school degree.

Economic activity and sources of income were primarily concentrated in farming and fishing — 58 percent of households reported these sectors as their main source of income. The majority of residents lived and worked within the barangay. Only 25 percent of adults traveled outside of their barangay for work in the twelve months preceding the baseline interview. Individuals do, however, travel for non-work reasons. Half of all adults expected to travel outside the barangay in the 12 months following the baseline interview.

Electricity coverage was fairly widespread, with 63 percent of households having access to some form of electricity. Communication technologies were, however, observed in fewer households. Thirty-two percent of households owned a radio, 52 percent owned a television, and 31 percent owned a satellite dish.

To estimate household welfare, we constructed two commonly-used metrics for assessing the relative wealth of households. First, we included questions from the Poverty Probability Index (PPI) Scorecard. The PPI scorecard is a set of ten questions that, when

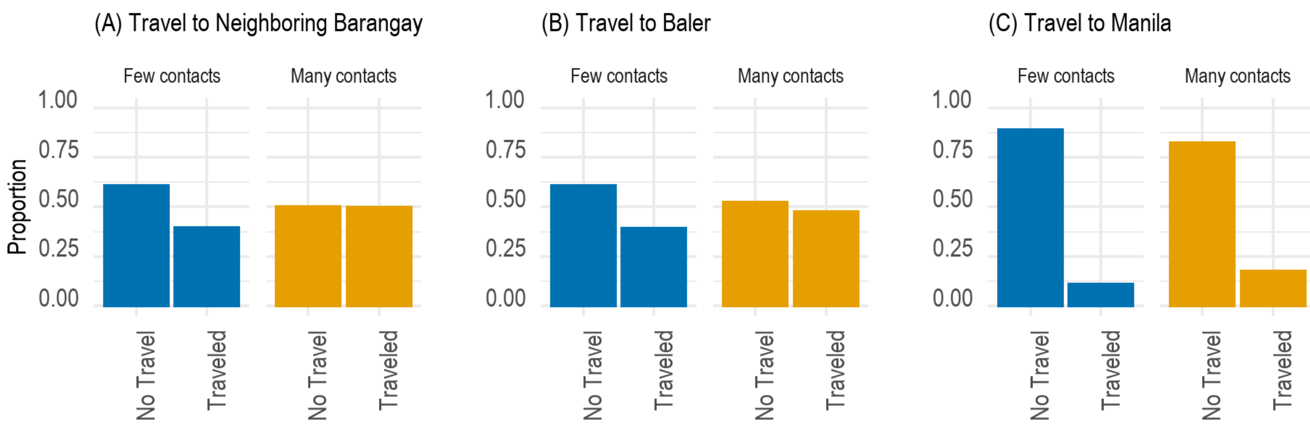

Figure 3: Travel outside of home barangay, by long-distance social network connectivity: We asked all adult survey respondents if they had traveled outside of their home barangay to a neighboring barangay or Baler (the regional capital) in the 12 months preceeding the baseline survey or Manila (the capital of the Philippines) in the 3 years preceeding the baseline survey. We disagregate responses base on whether or not an adult reports below the median ("few contacts") and above the median ("many contacts") number of close friends or family living outside of the barangay. In the figure, we see that socially connected individuals are also more likely to have travel to local and non-local destinations.

considered together, are most predictive of per capita expenditures.[4] The PPI score indicates the probability of a household being below the poverty line. Lower scores indicate that a household is more likely to fall below the poverty line. Among the seven CCN sites, the mean household has a PPI score of 42.17, which translates to a 56.4 percent probability that an individual in the mean household lives on less than USD$2.50 per day.

As our second measure of household welfare, we calculate an asset wealth index using the first component of principal component analysis of 14 asset questions in the baseline household survey.[5] The first component is a reliable predictor of household socioeconomic status [16]. Several of our asset variables are categorical factor variables; thus, we follow the recommendation of Kolenikov and Angeles by using the polychoric correlation matrix in the principal component analysis [30]. The Pearson correlation coefficient between the Welfare Score (PPI) and the Wealth Index (polychoric PCA) is 0.55.[6]

4.2 Adult Survey Data

We conducted private interviews of 1,617 adults. The core adult survey modules were a social network module and a travel diary. Women comprised 62 percent of the adult survey respondents.

We took painstaking efforts to identify local and non-local social network ties at the time of the baseline survey. For local social networks, we asked respondents that participated in the adult survey to name their closest friends and family that lived in the same barangay. We then matched the names of their contacts with names from our household listing. Using these data, we were able to construct a social network graph for each site to identify social ties or "edges" between households. In total, we were able to identify 6,173 edges among the 1,131 households. Most households are included in the largest component of the social network graph. Between 95 and 100 percent of households can be reached via connections in the social network.

Using the social network survey data, we construct two measures of social importance for each household. First, we calculate the in-degree centrality of a household by summing the number of times members of a household were named as a close friend or family member by others during the baseline adult survey. Second, we compute the eigenvector centrality of each household, which is a measure of the position of a social network node that accounts for the centrality of nodes that are connected to it. Thus, households with high eigenvector centrality are connected to central households, which are connected to central households, and so on.

Travel outside of the barangay is common but not universal. Only 45 percent of adults reported that they traveled to a neighboring barangay in the preceeding 12 months. In Table 1, Panel B, we show that 45 percent of adults expected to travel outside of the barangay in the 12 months after the baseline survey. Fourteen percent had traveled to the capital, Manila, in the preceding 3 years. While we see some differences across sites (Table 1 Panel C), it is clear that even travel to neighboring barangays is not universal. Figure 3 shows that the strength of an individual's long-distance social network ties is correlated with the frequency of travel outside the barangay.

[4]The PPI Scorecard can be found at https://www.povertyindex.org/country/philippines. And for details on the PPI methodology, see Kshirsagar et al. [31].
[5]The 14 assets used in the principal component analysis were: land ownership (0/1), number of rooms in the dwelling, access to electricity in the dwelling (0/1), wall type, roof type, floor type, and ownership (0/1) of sala (living room) sets, refrigerator, television set, video player, radio, satellite dish, vehicle, and gas stove.
[6]See Appendix Figure 9 for correlation coefficients between the Welfare Score (PPI) and other variables.

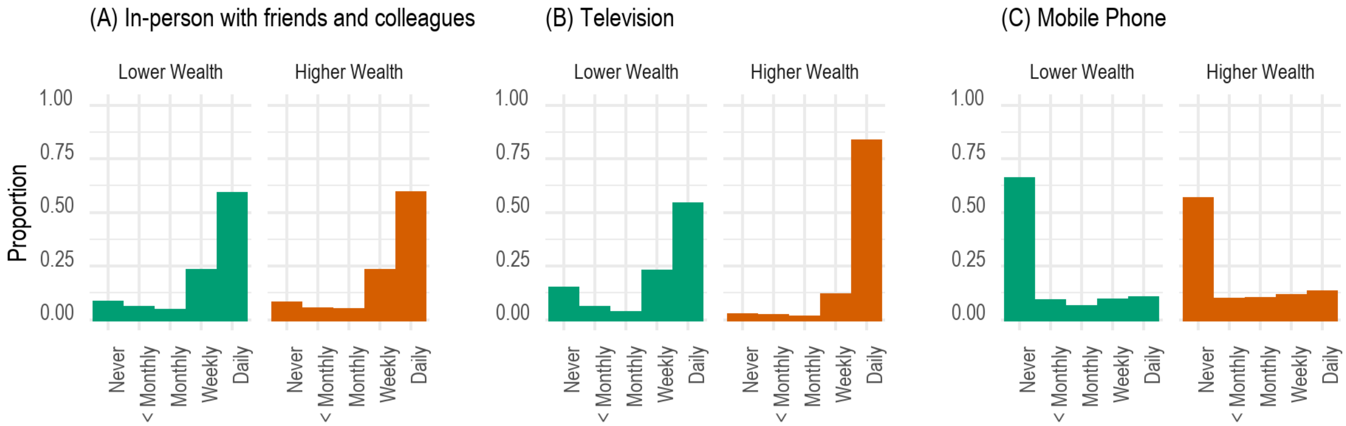

Figure 4: Sources of Information, by Wealth: For a host of different media, we posed the following questions to each adult respondent during the baseline survey, "For each of the following sources, please indicate whether you use it to obtain information (1) daily, (2) weekly, (3) monthly, (4) less than monthly, or (5) never?" *Panel A:* Households below ("Lower Wealth") and above ("Higher Wealth") the median wealth index level communicated with other people in person with equivalent regularity. *Panel B:* However, wealthier households were 25 percentage points more likely to report receiving information through television on a daily basis. *Panel C:* Overall access to information through mobile phones at the time of the baseline survey was low. Yet, households above the median wealth index tended to have more frequent access to information through mobile phones.

5 INFORMATION NETWORKS BEFORE INSTALLATION

Despite the lack of mobile network access prior to the CCN installation, the majority (68%) of households owned a cellphone and a SIM card (64%). Phone ownership varies across sites. In two sites, more than 80 percent of households owned a cellphone at the time of the baseline survey. In only one site, Site 3, was phone ownership below 50 percent of households. On average, households owned 1.2 phones and 1.3 SIM cards. To use the SIM card, people need to travel outside of the site. The CCN provided, for the first time, reliable local cellular network service within the localities.

Households that did not own a phone differ significantly from those that do.[7] Households without phones ranked lower on the welfare score (Figure 2 Panel B) and wealth index.

Households that lacked a cellphone were equally, if not more, central to the local social network — we fail to reject the null hypothesis that in-degree centrality is equivalent but reject the null that eigenvector centrality is equivalent. Phone ownership correlates with non-local communication networks. Adults from households that owned a phone reported that they traveled outside their barangay more than adults from households lacking a phone. Phone owners were more likely to have close friends outside of the barangay. Phone owners reported a greater ability to communicate with family residing outside of the barangay in case of an emergency.

Before the CCN launch, in-person communications and television were dominant sources of information about daily events in the Philippines (see Figure 4). More than 60 percent of adult survey respondents stated that they spoke with friends and family about events and developments in the Philippines and around the world.

[7]See Appendix Table 3 for comparative statistics of households that reported phone ownership versus those that said they did not own a phone at the time of the baseline survey.

Figure 5: A CCN installation in Aurora

As shown in Figure 4, adults from households above the median wealth index were more likely to receive news and information through television. Nearly 90 percent of households received information from in-person communications or through television on a weekly or more frequent basis. The majority of households reported that they never received information via mobile phone prior to the baseline survey.

6 INSTALLATION OF COMMUNITY CELLULAR NETWORKS

Prior to any installation, we needed to secure permission to use of licensed GSM band for the CCN project. The project was granted limited use of spectrum (900MHz band) for the seven CCN sites in Aurora. The test sites were allowed to run on an experimental basis, provided that the subscribers in the community accepted best-effort service without a service-level requirement.

While we used the same frequency as our telecommunications partner, the experimental network was branded as the VBTS Konekt network to differentiate it from our telecommunication partner's mainstream network. The community network only accepted VBTS Konekt SIM cards, with each SIM card pre-assigned with a unique phone number. SIM cards from other networks were barred from camping to the network. Similarly, VBTS Konekt SIM cards could not be used for roaming in our telecommunication partner's network.

Once the sites were identified and baseline survey complete, our team conducted pre-deployment activities that included coordination with local stakeholders. We first reached out to local government units to introduce the project and to seek assistance on-site acquisition and permits processing. Partnership with the local government was crucial because of its administrative control over the sites. We determined that local community partners were needed to handle the day-to-day operations, management, and first-level maintenance for the CCN installations.

To build a sense of local ownership of the CCN, we conducted several consultative meetings with barangay leaders, potential cooperative partners, and community members. At these meetings, we introduce the project, identify key contacts, and discussed respective duties in the management of the community cellular network. Once the maintenance staff and e-load retailers were identified, We trained maintenance staff on the maintenance and troubleshooting of the system. E-load retailers were trained on day-to-day business operations of network and guidelines for customer interactions. Community leaders and cooperative members were also part of the training sessions.

Our team collaborated with community members to install equipment and activate the CCN. A typical site had a 12-meter guyed tower where the base station and antennas were attached, solar panels to provide power, a VSAT backhaul, and a small shelter. The shelter housed the rest of the power and network equipment. We chose the location of the VBTS towers to be centrally located in order to maximize coverage across each community.

For each site, we planned a launch and registration event to introduce the community cellular network to the general public. With assistance from local officials we established the date, time, and location for the community registration event. Several days in advance of the registration event, we informed each community of the scheduled launch of the VBTS Konekt network. Community leaders assisted in spreading the word about the registration event. Community members were informed that any resident, 15 years of age or older, would be able to collect one free SIM card at the registration.

The community launch was a significant event for the locality and was well-attended by members of the community. The launch was a good venue to explain the purpose and motivation for the community cellular network, its capabilities and limitations. Community members were informed that the towers were part of a research project and the towers would not necessarily remain beyond the duration of the research study. Moreover, we highlighted the experimental, "best effort," nature of the network service. We described how to use VBTS Konekt and details for utilizing the SIM cards. Afterwards, the floor was opened to address questions and concerns from community members.

Residents that attended the community registration event were then asked to register for their SIM cards. Using the baseline survey data, we pre-assigned one SIM card to every adult in CCN sites. A unique phone number was assigned to a subscriber identifier (IMSI) which was in turn linked to a unique identifier from the baseline household survey.

A team of registration staff verified the identity of individuals interested in acquiring a VBTS Konekt SIM card.[8] VBTS Konekt SIM cards were provided at no cost to customers. No phones were provided to the customers. Registration staff read the user agreement to customers, who were required to accept the terms of the agreement before receiving their SIM card. Subsequently, the registration staff assisted with the installation and activation of SIM cards. Customers were informed them of their unique phone number (MSISDN). SIM cards could be replaced if they were lost or malfunctioned. However, due to the lack of number portability in the Philippines, a new phone number was associated to the replacement SIM card. Replacement SIM cards were also provided at no cost to customers. The old SIM cards were deactivated to ensure that only one phone number was associated per individual at any given time.

The VBTS Konekt network allowed for calls to and from other mobile and landline phones within the Philippines. Customers were informed that they could purchase e-load (phone credit) through local retailers based within the site. Each site had between one and five retailers. A VBTS Konekt subscriber could send text messages to any network but could only receive messages from the local VBTS Konekt and on-network long distance (i.e., through our telecommunication partner's network). Texts from off-network numbers could not be received by VBTS Konekt subscribers, as this type of transaction was unsupported by our telecommunications partner. Local calls and texts were the lowest cost, on-network long-distance calls and texts were billed at a higher rate than local interactions, and off-network interactions were the most costly.[9] All incoming calls and texts were free of charge to the customer; however, the calling party for incoming calls and texts were charged at standard long-distance rates set by our telecommunications partner even if those transactions originated on our telecommunications partner's network. International calls and text messages were prohibited on the VBTS Konekt network.

7 NETWORK ADOPTION

Once a CCN launched, all cellular transactions were logged for the CCN. In this paper, we work with the raw Call Detail Records (CDR) from the seven CCN sites. We were able to link each adult to a unique record from the baseline survey data. The CDR include an identifier for the initiating and receiving parties, the type of transaction, the date-time, the tower used, the cost of the transaction, and the duration of calls. We limit our analysis to call and text message transactions in the first 144 days of the CCN in each site for two main reasons. First, we want to focus on the adoption of

[8]When an interested customer was unidentified in the baseline survey database, we conducted a household visit to verify that the individual was a resident of the CCN site.

[9]See Appendix Table 4 for the schedule of VBTS Konekt tariffs.

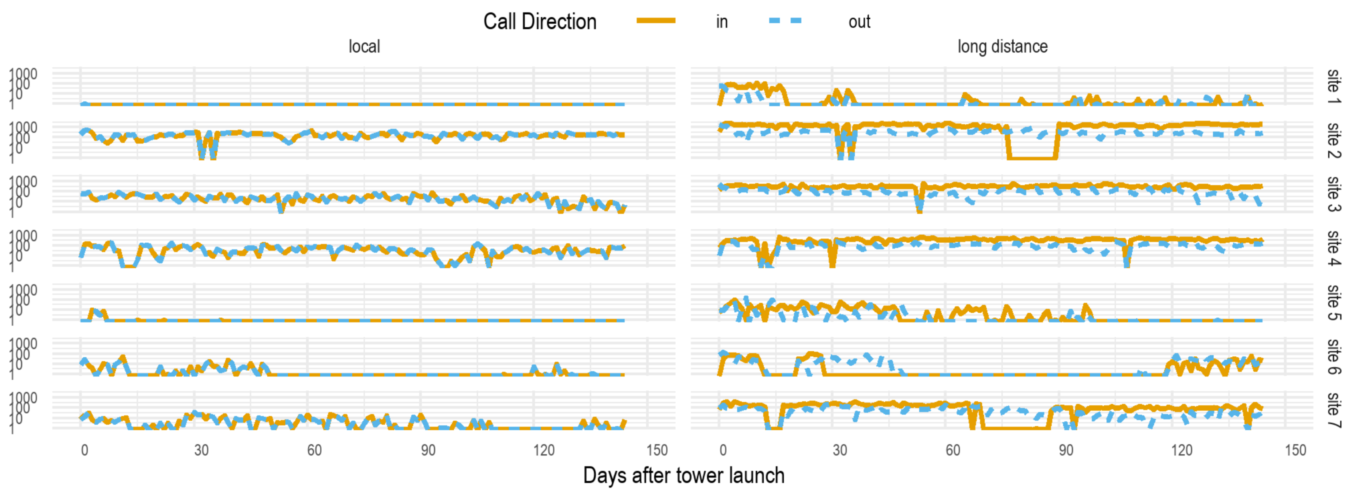

Figure 6: Network Usage by CCN Site: During the initial week in each site phone daily phone calls were above 100. However, the initial levels persisted only in sites 2, 3, 4, and 7. Calls in sites 1, 5, and 6 quickly dropped to near zero after the initial week. We see that incoming calls (solid line) tended to be greater than outgoing calls (dashed line) in each site. The lines in the local call figure are indistinguishable because incoming and outgoing calls are paired within the VBTS Konekt network.

Panel A: Total Activity	All Sites	site 1	site 2	site 3	site 4	site 5	site 6	site 7
All Transactions	954,276	2,073	680,556	110,782	110,284	2,711	4,838	43,032
Outgoing Calls	130,454	287	76,133	19,516	22,768	895	2,219	8,636
Mean Outgoing Call Duration (sec)	30.69	39.44	29.00	33.69	31.26	33.07	26.52	37.84
Incoming Calls	372,398	1,024	238,265	50,555	59,253	1,310	1,671	20,320
Mean Incoming Call Duration (sec)	96.69	144.93	84.06	129.71	118.58	78.48	89.98	98.18
Outgoing SMS	244,373	309	191,584	26,843	15,980	207	576	8,874
Incoming SMS	207,051	453	174,574	13,868	12,283	299	372	5,202
Panel B: Household Use of CCN	N=1131	N=88	N=382	N=176	N=100	N=255	N=50	N=80
Any Transaction	0.65 (0.48)	0.56 (0.50)	0.94 (0.24)	0.73 (0.45)	0.65 (0.48)	0.17 (0.38)	0.70 (0.46)	0.70 (0.46)
Any Outgoing Call	0.56 (0.50)	0.20 (0.41)	0.90 (0.30)	0.66 (0.48)	0.63 (0.49)	0.05 (0.22)	0.64 (0.48)	0.66 (0.48)
Any Outgoing SMS	0.53 (0.50)	0.15 (0.36)	0.90 (0.31)	0.64 (0.48)	0.59 (0.49)	0.02 (0.14)	0.48 (0.50)	0.62 (0.49)
Any Incoming Call	0.61 (0.49)	0.35 (0.48)	0.92 (0.27)	0.69 (0.46)	0.65 (0.48)	0.12 (0.33)	0.62 (0.49)	0.66 (0.48)
Any Incoming SMS	0.60 (0.49)	0.51 (0.50)	0.93 (0.25)	0.68 (0.47)	0.64 (0.48)	0.10 (0.30)	0.52 (0.50)	0.60 (0.49)

Table 2: Community Cellular Network Activity, by Site: Four sites had high usage while usage was low in three sites. *Panel A:* In the first 144 days of network activity, a total of 954,276 calls and texts were successfully operated through the CCNs. More than 70 percent of traffic (680,556 transactions) was generated by site 2. Incoming calls were the most common type of transaction and lasted, on average, 97 seconds. Outgoing calls were less common and shorter (31 seconds). *Panel B:* 65 percent of all households used the CCN at least once. This ranges from 17 percent of households in site 5 to 94 percent of households in site 2.

the mobile network; thus, we concentrate on the earliest period of the network. Second, the dates of CCN launches were staggered for logistical reasons. The last CCN tower was installed in January 2019. Restricting our analysis to the first 144 days of each site maximizes our window of time for this last site while also creating a uniform period of time to examine each CCN site. We also limit our analysis to phone calls and text messages. We drop invalid calls and texts as well as text messages sent to special codes (i.e., to check account balance). In total, 954,276 phone calls and text messages were sent or received by CCN subscribers in the first 144 days of tower activity across all seven CCN sites.

7.1 Site-level Network Usage

Table 2 provides aggregate statistics of usage in each site during the first 144 days of service. We see that site 2 accounted for more than 70 percent of total activity. However, sites 3, 4, and 7 displayed high volumes of transactions in the analysis period.

With the exception of site 6, incoming calls were much more common than outgoing calls. Incoming calls were approximately three times longer in duration as compared to outgoing calls. Outgoing texts tended to be more common than incoming text messages. This

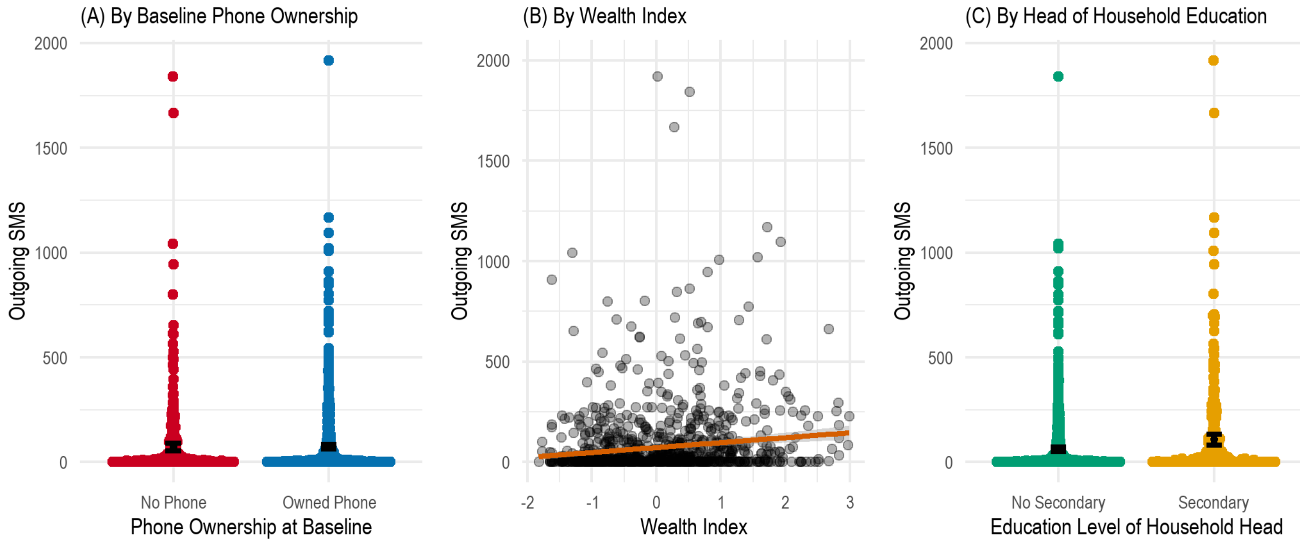

Figure 7: Bivariate analysis of household network usage: The figures display the relationship between outgoing SMS per adult household member and three socioeconomic characteristics of households. *Panel A:* Households that owned a phone at the time of the baseline survey, that is, prior to the CCN launch, were 5 percentage points more use the network. However, total volume of these households was no greater, on average, that in household that did not own a phone at the time of the baseline survey. *Panel B:* Baseline wealth of a household was positively correlated with adoption and volume of usage, as measured by the total number of calls and text messages in the first 144 days of the CCN. *Panel C:* Households where the head of household completed secondary school sent, on average, 107 text messages per adult household member, 46 more than households where the head of household did not complete secondary school.

pattern of communication comports with practices observed elsewhere in that low-income households concentrated their network usage on text messages to avoid more costly phone calls [15].

Figure 6 shows daily calls and text messages for each of the 7 CCN sites. The actual dates when the periods begin range from September 2017 for Site 1 to January 2019 for Site 7. There is a clear and marked difference in site-level usage. Sites 2, 3, and 4 consistently had more than 1,000 transactions per day. Site 7 also shows high activity with over 100 transactions on most days. In contrast, user activity in Sites 1, 5, and 6 dropped to below ten daily transactions by the third month of the network operation.

In Figure 6, we also show that sites differed in their use of local and long-distance communications. By long-distance, we mean any transaction that is outside of the VBTS Konekt network subscribers, i.e., to a phone number that is registered with another mobile network operator. Across all sites, long-distance communications were more common. In two sites, Sites 1 and 5, local calls and texts were avoided almost entirely. The solid lines in Figure 6 represent incoming transactions, while the dashed line represents outgoing transactions. Local calls and SMS messages are paired; thus, the outgoing and incoming lines are indistinguishable.

Through focus group discussions the reasons for site-level difference were made salient. Residents of low-usage sites mentioned that they had access to network via signal boosters. Others mentioned that the 2G service was inadequate to meet their needs (e.g. for social media and for receiving remittances).

7.2 Household-level Network Usage

Nearly two-thirds of households initiated or received at least one call or text message during the first 144 days of the cellular network. As shown in Table 2, network adoption ranges from 17 percent of households in site 5 to 94 percent of households in site 2.

Households that reported owning a phone at the time of the baseline survey had, on average, 150 more transactions than households that did not report phone ownership during the baseline survey. Figure 7 shows the relationship between household socioeconomic characteristics and outgoing text messages per adult household member. The bivariate analysis suggests that wealth and education are positively correlated with network activity.

We now turn to multivariate regression analysis of the determinants of household usage of the CCN. Our dependent variable, Y_i, is one of six quantitative measures of cellular network usage. *Any Transaction* is a binary variable that takes the value of one if a household has at least one transaction (call or text) in the CCN call detail records. $TotalTransactions_i$ is the count of all incoming and outgoing calls and texts associated with phone numbers registered to a given household. $OutgoingCalls_i$, $OutgoingSMS_i$, $IncomingCalls_i$, and $IncomingSMS_i$ correspond to count values at the household level for outgoing calls, outgoing text messages, incoming calls, and incoming text messages, respectively.

$$Y_i = \beta_1 OwnedPhone_i + \beta_2 WealthIndex_i + \beta_3 Contacts_i^{LD} + \beta_4 NetCentrality_i^{Local} + \beta_5 HHSize_i + \beta_6 FemaleHOH_i + \beta_7 SecSchoolHOH_i + \beta_8 FarmFishIncome_i + v_s + \epsilon_i \tag{1}$$

We include several household characteristics from the baseline survey as covariates in our regression specification. $OwnedPhone_i$ is a dummy variable indicating whether household i reported owning a phone at the time of the baseline survey. $WealthIndex_i$ is the first component of the principal component analysis described in Section 5. For our regressions, we transform the wealth index to a standardized value. $Contacts_i^{LD}$ is the number of contacts outside the household's barangay reported in the adult survey. For households with more than one adult survey, we use the highest number of contacts reported by an adult in household i. $NetCentrality_i^{Local}$ is a measure of social network centrality using social ties within the site. For our regressions, we use eigenvector centrality; results are similar using in-degree centrality. $HHSize_i$ is the number of adults and children living in the household. We include a dummy variable, $FemaleHOH_i$, to indicate if the head of the household is a woman and a dummy variable, $SecSchoolHOH_i$, that equals one if the head completed secondary school. We include dummy variables for the primary source of income at baseline. $FarmFishIncome_i$ is equal to one if the household reports farming or fishing, respectively, as the primary income source for the household. We also include site fixed effects, v_s, in all regressions.[10]

We find that CCN adoption was correlated with household wealth. Controlling for other household characteristics and site fixed effects, we find that a one standard deviation increase in the wealth index is correlated with a 3 percentage point increase in network adoption. Households that reported farming or fishing as their main source of income were 10 percentage points more likely to adopt the network than other households.

We also see that households that owned a phone at baseline were five percentage points more likely to have at least one transaction on the CCN. We find that larger households and female-headed households were more likely to have used the CCN. The result for female-headed households is encouraging as it suggests that female-headed households were five percentage points more likely to join the cellular network compared to male-headed households, controlling for other covariates.

When we look at the volume of CCN usage, we observe that wealth and education are primary determinants of cellular network activity. As shown in Figure 8, the household wealth index is positively correlated with all types of transactions. A one-standard-deviation increase in the wealth index is associated with 43 additional cellular network transactions. The majority of increased transactions come from outgoing and incoming text messages as well as incoming calls. Put another way a standard deviation increase in household wealth is associated with one additional outgoing text message every two weeks and one additional outgoing call every month for each adult household member.

[10] See Appendix Table 5 for the multivariate regression results from Equation 1 on our main outcomes of interest.

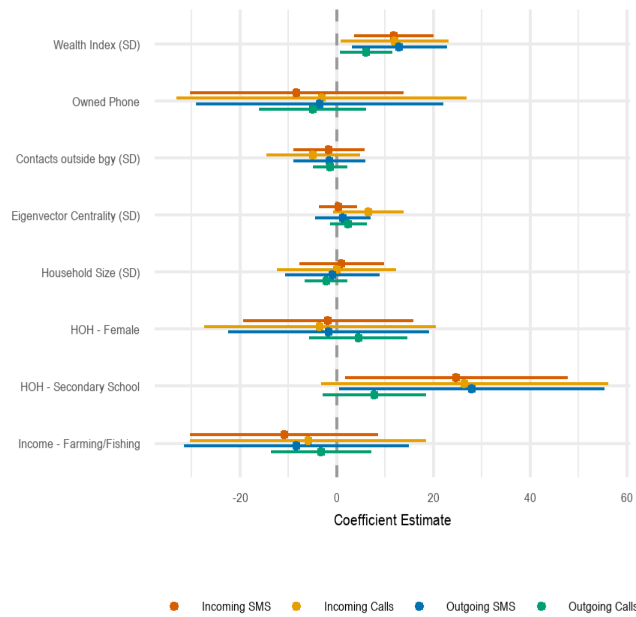

Figure 8: Regression Coefficients from Equation 1: The dots represent the coefficient on respective covariates in the model. Whisker lines represent the 95 percent confidence intervals on the coefficient. The outcome variables are measured in terms of per adult household member. We find that the wealth of a household is positively correlated with VBTS Konekt network activity. Additionally, households where the head of the household completed secondary school participated in more transactions per adult household member. Appendix Table 5 displays the regression results.

As mentioned earlier, all households in the setting of the project are poor relative to the rest of the Philippines. We find that among the poorest households in the CCN sites, there is a base level of demand for phone transactions. Analyzing the responsiveness of activity to prices, we find that the poorest of the poor consume less network time but are *less* responsive to prices (i.e., less price elastic).

After controlling for wealth, income source, and other covariates, we do not observe any measurable correlation between non-local and local social network measures and CCN usage. However, we do observe that households where the head has a secondary school degree were more active on the cellular network. Notably, these households were more likely to send more text messages.

8 CONCLUSION

This paper presents findings from the largest installation of CCNs in a research setting. We believe that the four most successful sites serve as good examples of how a low-cost cellular network can provide lasting revenue to sustain operability and involve a wide swath of subscribers. The analysis provides insight into the promises and challenges of expanding cellular networks to the remaining 10% of the world's population that currently lacks phone service. It will be important to consider not only technical constraints to expanding network access but also demand constraints from users. Our analysis suggests that site-level characteristics (pre-existing access to mobile networks and long-distance social networks) are important factors to consider. Moreover, socioeconomic differences tend to drive adoption and usage of the cellular network.

We observe several characteristics influenced whether or not a household participated in the CCN. Foremost among these were the wealth of the household, the number of people living in the household, the primary income source, and whether the household head was a woman. The volume of network usage was primarily driven by the wealth of the household and the education level of the head of household.

ACKNOWLEDGMENTS

The team from Innovations for Poverty Action was critical to the smooth implementation of the research discussed in this paper. Allan Lalisan provided excellent leadership and recommendations during the baseline and implementation periods. Ana Sheila Pacris, Yuna Liang, and Ann Mayuga provided incredible support during the endline survey. Implementation of the project would not have been conceivable without the tireless efforts of Giselle Marie Dela Cruz, Philip Martinez, Ronel Vincent Vistal, and other team members at the University of the Philippines. This study was made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. Additional funding for data collection was provided by the Bill and Melinda Gates Foundation, the Center for Global Action at UC Berkeley, and the University of California Berkeley Hellman Fellows Fund.

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A APPENDICES ON FOLLOWING PAGES

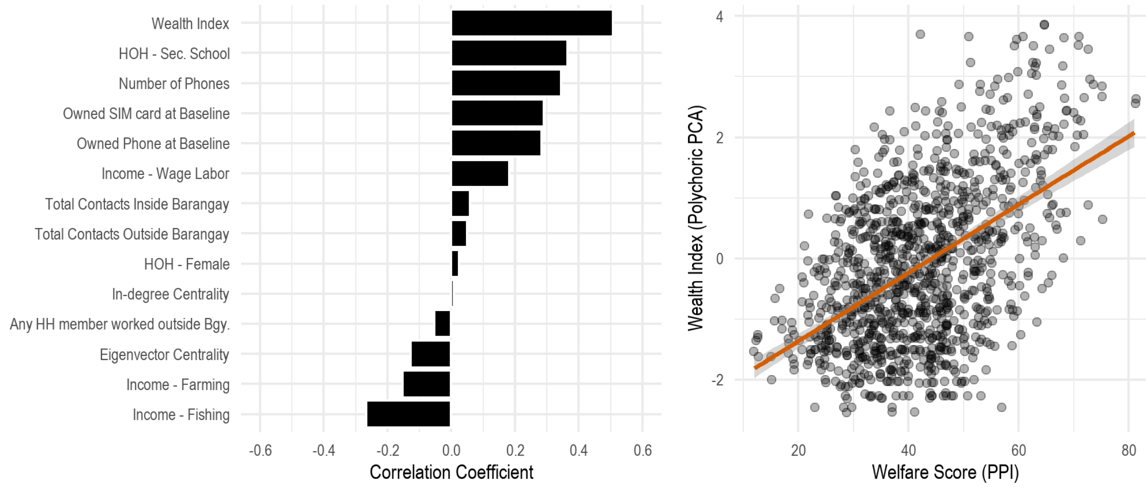

Figure 9: Correlation with Welfare Score

	All	No Phone	Owns Phone	
Panel A: Household Summary Statistics	N=1131	N=364	N=767	p-value
Adults (15+)	2.70 (1.29)	2.26 (0.98)	2.91 (1.37)	<0.01
Children (0-14)	1.77 (1.49)	1.75 (1.61)	1.78 (1.43)	0.76
HOH is female	0.36 (0.48)	0.39 (0.49)	0.35 (0.48)	0.19
HOH has secondary educ.	0.27 (0.44)	0.12 (0.33)	0.34 (0.47)	<0.01
Rooms in dwelling	1.79 (0.81)	1.60 (0.73)	1.88 (0.83)	<0.01
Income - Farming	0.34 (0.47)	0.37 (0.48)	0.33 (0.47)	0.14
Income - Fishing	0.24 (0.43)	0.28 (0.45)	0.22 (0.41)	0.03
Income - Wage Labor	0.20 (0.40)	0.14 (0.35)	0.22 (0.42)	<0.01
Welfare Score	42.17 (11.97)	37.25 (10.48)	44.51 (11.93)	<0.01
Wealth Index	-0.11 (1.33)	-0.70 (1.12)	0.17 (1.33)	<0.01
Electricity in dwelling	0.63 (3.30)	0.42 (4.10)	0.74 (2.83)	0.18
Owns television	0.52 (0.50)	0.37 (0.48)	0.59 (0.49)	<0.01
Owns radio	0.32 (0.47)	0.27 (0.45)	0.34 (0.47)	0.03
Owns satellite TV dish	0.31 (0.46)	0.18 (0.39)	0.37 (0.48)	<0.01
Owns cellphone	0.68 (0.47)	0.00 (0.00)	1.00 (0.00)	-
Number of cellphones	1.20 (1.19)	0.00 (0.00)	1.77 (1.04)	<0.01
Owns SIM card	0.64 (0.48)	0.01 (0.07)	0.95 (0.23)	0.00
Number of SIM cards	1.33 (1.52)	0.01 (0.07)	1.95 (1.47)	<0.01
In-degree centrality	5.40 (29.58)	5.64 (34.69)	5.29 (26.83)	0.87
Eigenvector centrality	0.09 (0.15)	0.11 (0.18)	0.09 (0.13)	0.01
Panel B: Adult Survey Module	N=1617	N=516	N=1101	p-value
Do you feel isolated from the rest of your country?	0.30 (0.46)	0.31 (0.46)	0.30 (0.46)	0.88
Could you communicate with family in case of emergency?	0.46 (0.50)	0.38 (0.49)	0.50 (0.50)	<0.01
Travel to neighbor bgy	0.44 (0.50)	0.38 (0.48)	0.48 (0.50)	<0.01
Travel to Manila	0.14 (0.35)	0.07 (0.25)	0.18 (0.38)	<0.01
Total contacts within barangay	6.10 (6.34)	5.91 (4.46)	6.19 (7.05)	0.35
Total contacts outside barangay	4.02 (7.54)	3.33 (4.60)	4.34 (8.56)	<0.01
Panel C: Household usage of CCN	N=1131	N=364	N=767	p-value
Any Transaction	0.65 (0.48)	0.66 (0.47)	0.64 (0.48)	0.47
Any Outgoing Call	0.56 (0.50)	0.60 (0.49)	0.55 (0.50)	0.14
Any Outgoing SMS	0.53 (0.50)	0.56 (0.50)	0.52 (0.50)	0.29
Any Incoming Call	0.61 (0.49)	0.63 (0.48)	0.60 (0.49)	0.32
Any Incoming SMS	0.60 (0.49)	0.61 (0.49)	0.60 (0.49)	0.81

Table 3: Summary Statistics, by Phone Ownership

Network Interaction Type	Tariff (PHP)
Call from a Konekt number to another Konekt number	1.00/minute
Call from a Konekt number to a long-distance on-network number	3.00/minute
Call from a Konekt number to an long-distance off-network number	5.50/minute
Text from Konekt number to Konekt number	0.25/message
Text from Konekt number to long-distance on-network number	0.50/message
Text from Konekt number to long-distance off-network number	1.00/message
All incoming calls	FREE
Incoming text messages (on-network local and long-distance)	FREE
Incoming text messages (off-network)	NOT SUPPORTED

Table 4: VBTS Konekt Tariff Schedule: Customers were required to pay for outgoing transactions on the VBTS Konekt network. The table shows the per minute cost to the subscriber for calls made through the network and per text message cost for SMS sent over the network.

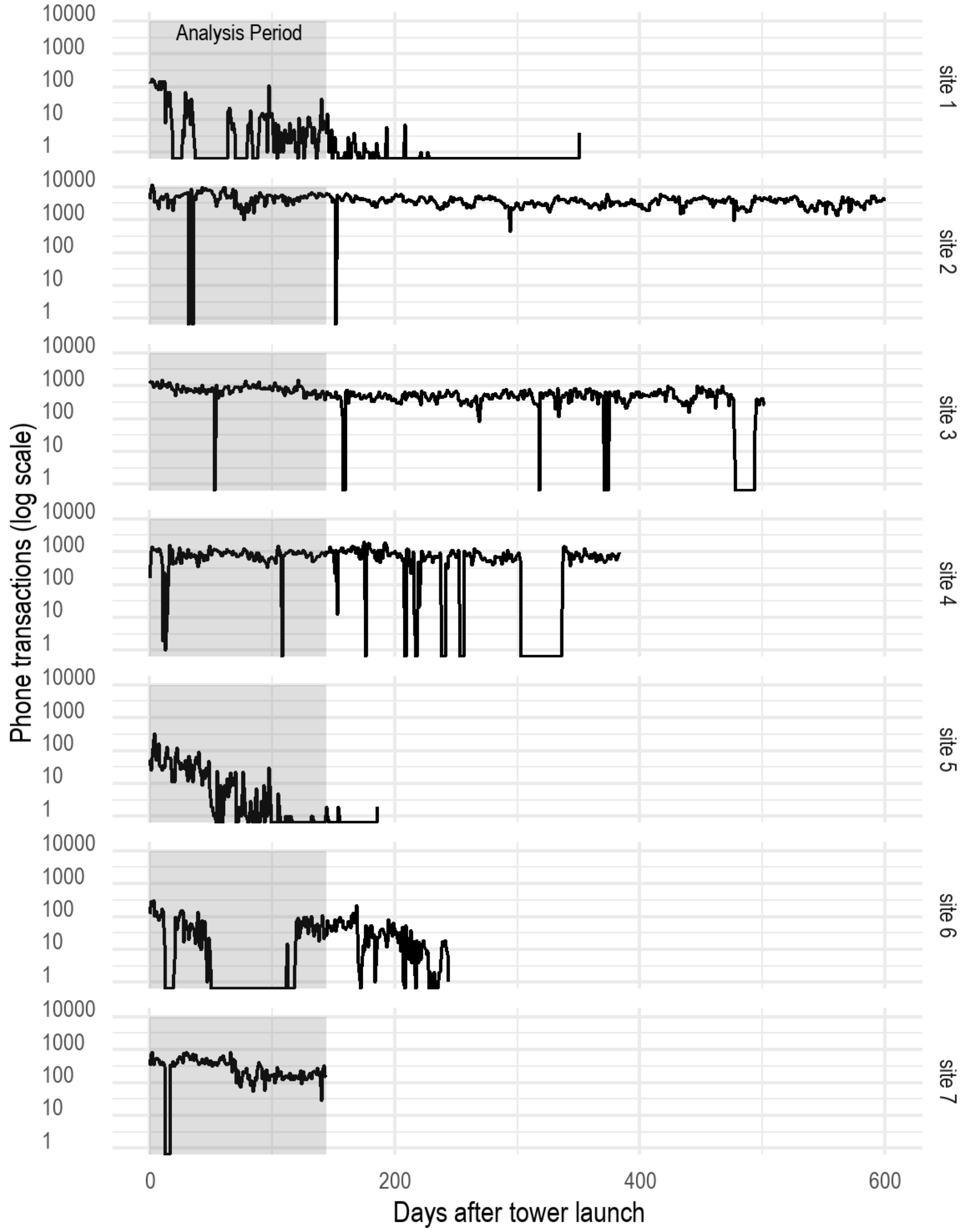

Figure 10: Site Activity: We have shaded in gray the period of analysis – the first 144 days after the network launch.

	(1) Any Transaction	(2) Total Transactions	(3) Out Calls	(4) Out SMS	(5) In Calls	(6) In SMS
Wealth Index (SD)	0.03^{*}	42.87^{**}	6.10^{*}	12.97^{**}	11.95^{*}	11.85^{**}
	(0.01)	(14.19)	(2.77)	(4.99)	(5.70)	(4.17)
Owned Phone at Baseline	0.05^{*}	−19.90	−4.98	−3.51	−3.13	−8.28
	(0.03)	(39.48)	(5.63)	(13.02)	(15.31)	(11.23)
Contacts Outside Barangay (SD)	−0.00	−9.44	−1.39	−1.55	−4.89	−1.61
	(0.01)	(12.43)	(1.80)	(3.80)	(4.93)	(3.76)
Eigenvector Centrality (SD)	0.02	10.41	2.40	1.25	6.49	0.28
	(0.01)	(8.96)	(1.95)	(2.92)	(3.71)	(2.03)
Household Size (SD)	0.04^{**}	−2.14	−2.21	−0.95	−0.00	1.02
	(0.01)	(15.39)	(2.29)	(4.96)	(6.29)	(4.45)
HOH - Female	0.05^{*}	−2.38	4.46	−1.61	−3.46	−1.77
	(0.02)	(30.69)	(5.20)	(10.59)	(12.22)	(8.98)
HOH - Secondary	−0.00	86.85^{*}	7.78	27.91^{*}	26.41	24.75^{*}
	(0.03)	(39.28)	(5.49)	(13.98)	(15.14)	(11.72)
Primary Income Source - Farming or Fishing	0.10^{***}	−28.23	−3.15	−8.33	−5.89	−10.87
	(0.03)	(33.06)	(5.29)	(11.85)	(12.44)	(9.94)
R^2	0.39	0.27	0.16	0.21	0.22	0.23
Num. obs.	1131	1131	1131	1131	1131	1131
Mean of Outcome	0.65	773.75	100.78	201.99	299.37	171.61
Std. Dev. of Outcome	(0.48)	(1462.65)	(203.43)	(481.14)	(576.33)	(413.95)

Table 5: Determinants of Mobile Network Usage: The table shows regression resuelts for the linear regression models specified in Equation 1. Dependent variables with (SD) are in standardized units. CCN site fixed effects included. Eicker-Huber-White robust standard errors in parentheses. Significance level of the test that the coefficient is equal to zero indicated by $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$.