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Article

Community Internet of Things as Mobile Infrastructure: Methodological Challenges and Opportunities

Chelsea P. Butkowski [1,*], Ngai Keung Chan [2], and Lee Humphreys [3]

[1] Annenberg School for Communication, University of Pennsylvania, USA
[2] School of Journalism and Communication, The Chinese University of Hong Kong, Hong Kong
[3] Department of Communication, Cornell University, USA

* Corresponding author (chelsea.butkowski@asc.upenn.edu)

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Abstract
From smart devices to homes to cities, Internet of Things (IoT) technologies have become embedded within everyday objects on a global scale. We understand IoT technologies as a form of infrastructure that bridges the gaps between offline spaces and online networks as they track, transmit, and construct digital data from and of the physical world. We examine the social construction of IoT network technologies through their technological design and corporate discourses. In this article, we explore the methodological challenges and opportunities of studying IoT as an emerging network technology. We draw on a case study of a low-power wide-area network (LPWAN), a cost-effective radio frequency network that is designed to connect sensors across long distances. Reflecting on our semi-structured interviews with LPWAN users and advocates, participant observation at conferences about LPWAN, as well as a community-based LPWAN project, we examine the intersections of methods and practices as related to space, data, and infrastructures. We identify three key methodological obstacles involved in studying the social construction of networked technologies that straddle physical and digital environments. These include (a) transcending the invisibility and abstraction of network infrastructures, (b) managing practical and conceptual boundaries to sample key cases and participants, and (c) negotiating competing technospatial imaginaries between participants and researchers. Through our reflection, we demonstrate that these challenges also serve as generative methodological opportunities, extending existing tools to study the ways data connects online and offline spaces.

Keywords
community networks; infrastructure; internet of things; LPWAN; mobile communication; qualitative methods; sensing technologies

Issue
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1. Introduction

Our interactions with the digital and physical worlds are constantly shaped by overlapping infrastructures. They enable our survival, transportation, and connectivity through vast systems that are also implicated in an equally vast array of power relations. Star (1999) defines infrastructure as a far-reaching, relational apparatus that is ubiquitously embedded within our surroundings but also invisible and mundane. Because infrastructures exist to facilitate everyday work and social practices, they also develop over time as outdated technologies fade and new ones emerge. In this article, we examine the Internet of Things (IoT) as one particular type of emerging technology that links online and offline spaces.

IoT can be understood fundamentally as networks and sensors (Bunz & Meikle, 2018) that connect “things” or the physical environment to the internet. It is not just made up of smart refrigerators telling us when we're low on milk, but sensing networks that enable new "addressing, speaking, seeing, and tracking capabilities" (Bunz & Meikle, 2018, p. 4). With radio-frequency identification (RFID) and GPS technologies, for example, we can locate and address where almost anything is, such as cars, phones, products, or deliveries (Frith, 2015, 2019). We can see who is ringing our doorbell when we're not home but also see the soil water content of a field of corn (Bunz & Meikle, 2018). We can track our health and activities with a level of detail and at a scale that was previously unattainable (Neff & Nafus, 2016). As Bunz and Meikle (2018) argue, IoT sensing networks help us make sense of the world around us. Put another way, IoT not only tracks and communicates data about the physical environment that it is embedded in but also invites users to see the world in a particular way through the eyes of such sensing networks (Bunz & Meikle, 2018). From a media and communication perspective, these "technological systems embody ideas about the ways in which we organize ourselves and each other, and they also provide means for us to make meaning about the social organization" (Bunz & Meikle, 2018, pp. 5–6).

The rise of sensor networks has given way to what Andrejevic and Burdon (2015) have called the sensor society, which relies on increasingly ubiquitous, passive detection of an array of different kinds of data and applications. A sensor society is one deeply committed to the logics of big data in which tech companies and corporate interests shape practices of surveillance, power, privacy, and interpretation (Burdon & Andrejevic, 2016). An important critique of the sensor society is that "there are structural asymmetries built into the very notion of a sensor society insofar as the forms of actionable information it generates are shaped and controlled by those who have access to the sensing and analytical infrastructure" (Andrejevic & Burdon, 2015, p. 21). While this might be true for many mobile sensors, especially the ones that are developed by corporate actors for profit-making purposes, community-based IoT can be designed with local knowledge in mind, which offers a new way to think about power, surveillance, and meaning.

In this article, we draw on a community-based IoT network project which aims to use low-cost technology (low power wide-area networks [LPWAN]) to help local communities define and develop their own IoT data networks. As a participatory research project (DiSalvo et al., 2010; Hall, 1992; LeDantec, 2016), this study represents a counterexample of the kind of sensor society that Andrejevic and Burdon (2015) describe. Because community-based IoT networks as infrastructures are deeply embedded in people's daily life (Star, 1999), we ask the following questions: What are the methodological challenges and opportunities for studying an invisible yet ubiquitous IoT at the intersection of online and offline spaces? As IoT is not yet stabilized, both technologically and discursively, how might we delimit the boundaries of IoT? The project involved two primary aspects. First, we studied public discourse around LPWAN. We attended industry conferences and interviewed LPWAN experts and hobbyists. Second, we are working with a community (e.g., non-profits, schools, and local government) to build a public LPWAN network that reflects and prioritizes local needs, not capitalist structures. However, this is not an easy task. In this article, we explicitly examine and reflect on the methodological implications of designing and studying emerging IoT networks as they connect online and offline spaces across communities. To preface our methodological reflections, we situate IoT within literature on mobile infrastructures and science and technology studies (STS) before describing our case study in greater detail.

2. Internet of Things and Infrastructures

We approach IoT networks fundamentally as an infrastructure for several reasons. First, our larger project examines the materiality, physicality, location, installment, and hardware that form these networks and the processes involved in their development (Parks, 2015). Focusing on IoT networks as mobile infrastructure forces us to take seriously how the system is materially being built and deployed to link online and offline space. As LPWAN is still largely in the invention stage (Bar & Galperin, 2004; Hughes, 1983), we are interested in the infrastructural imaginaries of IoT networks, that is, "the ways of thinking about what infrastructures are, where they are located, who controls them, and what they do" (Parks, 2015, p. 355). Within mobile media research, there have been calls for researchers to examine infrastructures beyond those that already exist, to study the ways that they are built and unbuilt through political, economic, social, technical, and regulatory means (Horst, 2013). Moreover, as Mattern (2015) argues, new infrastructures often rely on and are built upon previous infrastructures.

Mobile infrastructures are commonly associated with cellular or wireless networks like LTE, 3G, 4G, 5G, or Wi-Fi (Frith, 2015). Communication and media research about these networks has used a technology studies framework to examine the social construction of such networks (Campbell et al., 2021; Horst, 2013). In their study of 5G discourse, Campbell et al. (2021) suggest that 5G networks are closely associated with the connectivity of both people and objects. From cars to packages delivered to your door, their research suggests that the leading telecoms are constructing mobile infrastructure as essential to a better, more healthy, economically prosperous, and socially just world.

There are many examples of IoT systems that are fully commercially deployed as well as in the early development stages. While most people have interacted with IoT through RFID tags or GPS, whether they know it or not (Frith, 2019; Wilken, 2019), newer forms of sensing networks, including LPWAN, the object of the analysis, are being developed and have not yet reached broad commercial deployment. Figure 1 illustrates the distinction between cellular networks, short-range networks (e.g., Bluetooth), and LPWAN. These new IoT networks do not just connect objects but also rely on sensors that "detect and communicate changes in their environment" (Bunz & Meikle, 2018, p. 1). For this reason, they can be powerful tools for collecting environmental data, but they can also enable questionable surveillance practices.

By situating IoT as infrastructure specifically, we align our project with broader technological configurations and social practices. While major US telecoms and internet service providers are investing in LPWAN technology, current emerging community-based IoT networks are very similar to community wireless networks in the early 2000s (Forlano, 2006; Forlano et al., 2011; Powell, 2008). Such networks involved multiple stakeholders such as municipalities, tech hobbyists, and non-profit civic organizations. They try to exist outside the reach of corporate telecoms and internet service providers but sometimes work in tandem with such companies to actualize their goal of creating a community or public network with a sustainable business model. More recently, community-wireless and civic technology projects leverage the power of data and networked technologies for progressive environmental and social action (Gabrys, 2019; Powell, 2021). Ultimately, our work builds on existing methodological scholarship on infrastructure (e.g., Bowker et al., 2010; Horst, 2013; Mattern, 2015; Star, 1999) and STS (e.g., Klein & Kleinman, 2002; Law, 2016) to highlight tensions in the research design and data collection processes when studying new, mobile, and embedded technologies like IoT.

3. Studying the Social Construction of Developing Technologies

Technological development is just as much a social, economic, and political process as it is a technical one (Bijker et al., 1987; MacKenzie & Wajcman, 1999). The social meanings and practical applications of new technologies emerge through consensus and contestation among various social actors and artifacts, including designers, manufacturers, retailers, governing bodies, users, and the material objects themselves (Horst, 2013; Humphreys, 2005). These ideas are central to research in STS, which prioritizes the social and material shaping of technologies, rather than technological determinism alone, as a central force of change (Lievrouw, 2014). For example, the social construction of technology (SCOT) framework is specifically concerned with theorizing this process by defining the social groups most relevant to a developing technology and their differing perceptions of the uses and problems the artifact presents, also known as interpretative flexibility (Pinch & Bijker, 1984). SCOT posits that contested new technologies can stabilize over time as their perceived problems resolve or change across relevant social groups.

Emerging technologies are defined through several attributes, including their novelty and their promising yet uncertain futures (Rotolo et al., 2015), but technological change is also a multidirectional and nonlinear process (Bijker et al., 1987). Our research is dedicated to examining IoT technology as it emerges rather than retrospectively investigating a technology that already plays a relatively stable role in society (Hughes, 1983; Marvin, 1988). IoT is also a distinctly communication-oriented technology, and our project lies at the nexus of communication and STS scholarship. Whereas communication research examines technology primarily through effects research or social constructionist viewpoints, STS positions the social and material elements of technologies on equal footing (Latour, 1992; Lievrouw, 2014). We aim to place a similarly shared emphasis on the people, objects, and spaces that shape IoT, especially because it is a network designed to enable the digital connectivity of "situated things."

Although STS provides important theoretical insights into the social construction of technologies, explicitly methodological scholarship on *how* to best apply these insights in the field is less prominent (Felt et al., 2016). STS is rooted in epistemological—and ultimately methodological—thought, evident in flagship research on the social shaping of the scientific method and its embedded assumptions of objectivity (Harraway, 1988).

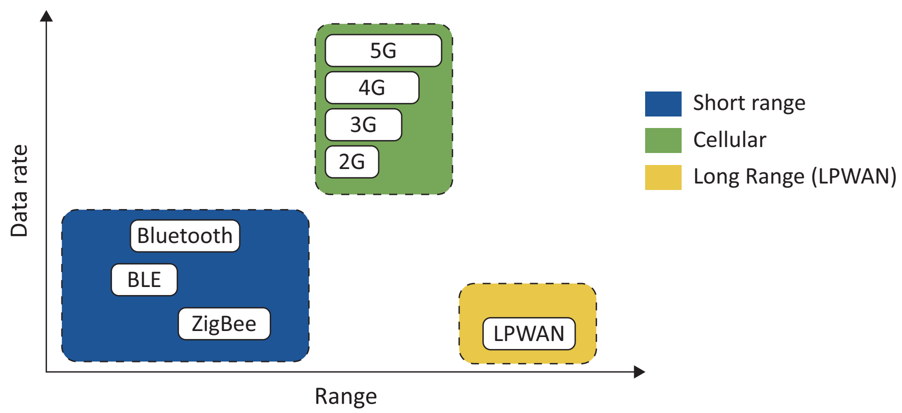

Figure 1. Distinction between different network infrastructures. Source: Hernández (2018).

STS scholarship generally draws on qualitative techniques and a case study approach to facilitate in-depth, specialized engagement with singular technologies and social configurations. Yet it has also attracted criticism for its lack of engagement with methods, including issues of sampling specific to the social study of technologies (Klein & Kleinman, 2002). Recent scholarship has begun to remedy this deficit (e.g., Law, 2016), but more engagement with the methodological considerations of studying technologies across the social and material as well as the digital and physical is needed. We argue that studying emerging mobile infrastructures like LPWAN presents unique methodological challenges to researchers, and we set out to address them by bridging communication and STS approaches.

4. Case Study: Rural Internet of Things and Low-Power Wide-Area Networks

The goal of the project is to build a statewide public IoT network that connects previously unconnected rural spaces to help bridge digital divides. Rural digital divides are often defined as a lack of broadband connectivity (Ali, 2021), but they also include the ways that rural communities can socially, economically, and environmentally benefit from various kinds of networked technologies. Rural computing (Hardy et al., 2019) as well as data feminism (D'Ignazio & Klein, 2020) and sustainable human–computer interaction (DiSalvo et al., 2010) offer frameworks for thinking generatively about network technologies in rural communities. These frameworks feature (a) working with communities to meet their needs and (b) ensuring data networks reflect collective values of environmental and social justice. Rural computing respects and takes seriously the values and landscapes that more agrarian communities embody.

Not all computing needs call for broadband technology. In this project, we are studying LPWAN, a kind of wireless network designed to connect sensors across long distances at low data rates, low power needs, and low cost. Data rates are the speed at which data are transmitted. LPWAN sensors do not transmit data quickly like cellular but can be helpful for monitoring environmental factors like temperature or air quality, which can be tracked over hours, days, and months rather than milliseconds. The material dimension of LPWAN is composed of sensors—battery-operated devices that collect and transmit data on environmental factors such as movement, air quality, and temperature—and gateways—Wi-Fi-enabled intermediary devices that transmit sensing data to data management applications. LPWAN connectivity between sensors and gateways allows sensors to be placed in remote or hard-to-reach locations with limited internet access or electrical power while still transmitting and storing sensing data.

As mobile infrastructures continue to grow and change, we set out to help researchers studying them anticipate the obstacles they may encounter, navigate logistical and ethical research challenges, and build trustworthy qualitative inquiry. Ultimately, we reframe the major challenges of studying IoT deployments and mobile infrastructures more broadly as opportunities to enhance the reflexivity and participatory character of our work while also attending to the physical, digital, and social components of developing networks.

We draw on this LPWAN case study to illustrate the methodological challenges and opportunities of studying emerging mobile infrastructures for several reasons. Firstly, LPWAN has been marketed as one of the key wireless networks for building massive IoT applications, such as fleet management, environmental monitoring, and smart metering, as well as far smaller IoT applications, such as food cabinet monitoring or animal observation, in locations with limited cellular connectivity (e.g., basements and rural areas) and large spaces (Lundqvist et al., 2019). IoT applications, therefore, require a large number of connected devices that can transmit and communicate data signals across long distances at a low cost. Yet both LPWAN and the IoT applications it supports are emerging infrastructural technologies with potential for success and failure, a process which is also accompanied by emergent social norms and practices. Secondly and relatedly, the scalability, flexibility, and cost-effectiveness of LPWAN also allowed our research team and community members to build the infrastructures based on local needs. Thirdly, because of the social and commercial potentials of LPWAN and, more broadly, IoT, these infrastructures constitute complex assemblages of artifacts (e.g., sensors and gateways), physical sites where sensors and gateways are situated, human actors (e.g., developers and users), and organizations (e.g., industry organizations and local governments). Theoretically, these kinds of sensing networks are valuable sites for exploring how infrastructures bridge the gaps between online and offline networks.

Our research on LPWAN is triangulated across multiple modes of data collection. Over the course of 13 months starting in April 2021, we conducted nine interviews with current LPWAN experts, users, and researchers for in-depth insights into LPWAN design and usage; participant observation at five international industry conferences and local community meetings hosted by The Things Network (TTN), an international collaborative open-source network for LPWAN network development; and three participatory workshops with 18 IoT researchers and potential stakeholders within their local communities to examine how users familiar and unfamiliar with LPWAN imagined the technology. Participants in the community workshops included IoT designers and developers, local government officials, business owners, educators, and community advocates centering around topics of agriculture and municipal development.

We drew inspiration from Hardy et al. (2019), who argue for the importance of designing *from* rural communities rather than *for* rural communities, as the communities themselves know better than academic researchers about their local needs, values, and goals. Moreover, we drew on values-in-design work (Flanagan et al., 2008; Wong & Mulligan, 2019) to bring conversations of privacy and surveillance into the community-based discussions of the early network design process to actively avoid personal privacy issues that often arise with sensor networks (Andrejevic & Burdon, 2015; Bunz & Meikle, 2018). Through these methods, we gain insights into the social construction of IoT as a communication infrastructure and observe frictions in its development. Furthermore, we experience frictions within our own work and positionalities as communication researchers in IoT spaces. These methodological challenges furnish insights into the distinctive nature of studying emerging network infrastructures that connect online and offline spaces.

5. Methodological Challenges and Opportunities of Studying Emerging Internet of Things Infrastructures

Through this case study of LPWAN, we have uncovered three key methodological challenges that shape research on emerging mobile infrastructures between offline and online environments. Considerations include navigating structural knowledge gaps between participants, sampling within a shifting technological landscape, and incorporating situated community perspectives into the research process. Ultimately, we understand each of these challenges as furnishing distinct opportunities to bridge imagined and tangible divides between the digital and physical components of mobile infrastructures.

5.1. Transcending Infrastructural Invisibility and Abstraction

At this stage in its development, IoT can be difficult to understand or even imagine, a characteristic that emerges partially by design. Yet this abstraction presents logistical and ethical research challenges in studying IoT sensing networks like LPWAN. The visibility of LPWAN to its users is constrained across multiple levels. On a functional level, LPWAN is an infrastructure, which, according to Star (1999, p. 380), makes it "by definition invisible, part of the background for other kinds of work." Rather, infrastructural systems become visible to their users only when they malfunction in ways that interfere with everyday tasks (Finn, 2018; Frith, 2019; Star, 1999). Even on a technical level, LPWAN sensors are intended as undetectable features of an object or landscape due to their small size, mobility, and replicability. Finally, on a developmental level, LPWAN is also a relatively new and emerging technology. It is not widely known outside of specialist niches, and it requires programming knowledge for installation and upkeep. Recent IoT deployments for personal and domestic use have taken various forms, such as smartwatches or smart assistants. However, municipal and industrial LPWAN applications remain largely abstruse.

Therefore, LPWAN stakeholders and users navigate a complex boundary between technological visibility and invisibility that complicates interview and observational dynamics. While stakeholders set out to build a "seamless" sensing network to facilitate everyday tasks, they must also make LPWAN more visible to spark awareness and adoption among companies, municipalities, educators, and hobbyists. A key aspect of transcending the invisibility and abstraction of LPWAN infrastructure to potential users and communities are "use cases" or examples of how the system works. LPWAN's potentialities are far-reaching but also difficult to perceive and access. "Use cases" vary widely, from tracking livestock in mountainous terrains to monitoring energy consumption in apartment buildings, from sensing trashcan capacity in urban areas to sensing air quality in community gardens. These things could be accomplished with other technologies, but the distinct benefits of LPWAN are largely derived from cost efficiency, as LPWAN gateways are much cheaper than cellular connectivity and battery-operated sensors enable remote accessibility. In our fieldwork, "use cases" were seen extensively in industry conferences and explained by LPWAN advocates. Use cases were not exclusively adopted by technology companies for selling the technology (Sadowski & Bendor, 2019); instead, LPWAN advocates and hobbyists could also articulate desirable futures. For example, while corporate actors at industry conferences discussed the general applications of LPWAN (e.g., "smart utilities" and "smart buildings") and their market potential, local users might consider how LPWAN gateways and sensors could be customized for their home or business use. As such, LPWAN depends on its local users and developers to determine how the sensing network should be deployed based on their own needs and capabilities. Therefore "use cases" both uniquely tie LPWAN to the specific local context (e.g., fields vs. urban streets) while also demonstrating different kinds of sensory data (e.g., location, environmental factors, energy use). Thus "use cases" become illustrative mental models of how data connects online and offline space while also concretizing infrastructural abstraction.

As researchers, we contribute to the de-obfuscation of LPWAN within the data collection process. However, playing the role of technological intermediary imbues our work with added obstacles and responsibilities. When observing and interviewing stakeholders or previous users of LPWAN, we assume the role of student or learner (Lofland et al., 2006). LPWAN's abstraction can make it difficult for researchers to understand, just as it presents complications to users. In turn, teaching us, as researchers, about the "seemingly obvious" features of LPWAN becomes both a generative source of data about the interpretative flexibility of these technologies and a communicative hindrance at times, as we do not want LPWAN-fluent interviewees to believe that we are wasting their time with technological basics. Our project also involves interviewing and facilitating discussions with potential LPWAN users who have not yet adopted the technology to help identify potential localized "use cases" for LPWAN in their communities. In these situations, we become the arbiters of knowledge to make sensing technologies visible to our participants. Our role within this emerging mobile infrastructure compounds questions about the logistics and ethics of studying technological development. We as researchers are often involved in the making of infrastructures with different forms and degrees of engagement, even though we may not work directly with tech companies and designers (Vertesi et al., 2016). Due to the epistemic authority of academia, our presence and data collection can indeed be a form of intervention. For instance, the ways that we described the potential utility of LPWAN and codified what counts as value in a given locality could shape how participants, particularly those with limited knowledge about LPWAN, would perceive the technology.

Because LPWAN infrastructures are emerging and largely invisible, it can be tempting to answer these methodological questions by focusing solely on discourses and imaginaries surrounding the technology (Parks, 2015). Instead, we problematize LPWAN's invisibility by centering its materiality (Lievrouw, 2014). The value of LPWAN is determined through its material characteristics: the placement, sensitivity, and connectivity of sensors. If LPWAN is not always visible, then it is concrete and interactive. In line with other materially-driven methodologies (e.g., Abildgaard, 2018), we consider materiality as a methodological resource and opportunity for studying emerging mobile infrastructures by making technological knowledge tangible. We employ materiality methodologically by identifying the locales and physical contexts in which both LPWAN sensors and gateways are situated. The specific locations of the network infrastructure can convey the goals of the specific network, for example, on a school campus, within an apartment building, or on public buses. Are sensors widely distributed outdoors across acres of agricultural fields or along waterfronts to help monitor flooding? Are they densely deployed within a tall building to improve energy efficiencies in apartments and businesses? How does the deployment of the network impact the "quality" of the data created through the network? By focusing on the materiality of the sensing network, we examine the mundane decisions that developers and users make to dramatically impact the kinds of data collected and shared. Identifying and describing the material deployment of LPWAN makes visible the kinds of data that mobile infrastructures often hide.

We also worked to de-obfuscate IoT through workshop discussions. In addition to studying how LPWAN has been deployed elsewhere, the aim of our project's participatory workshops was to develop and brainstorm potential future use cases with community members. To do this, we had to first explain what LPWAN was and give a few examples of sensor networks. This occurred to varying degrees both during recruitment as well as in the workshop itself. The choice of "use cases" to share with communities was challenging. While we wanted to inform participants about common kinds of sensors available and envision how they could be used, we did not want to overly determine the uses of such LPWAN implementations. Therefore, we spent the majority of our time explaining how the sensors and gateways connect (see Figure 2) and then gave a variety of different examples which showcased different kinds of sensors based on recent university student projects rather than large-scale municipal LPWAN deployments (see Figure 3). The goal was to demonstrate a breadth of LPWAN examples to generate creative thinking for potential local use cases.

5.2. Managing Boundaries Amid Technological Change

Beyond visibility, LPWAN's status as an emerging technology also positions it as a technology in flux. Although technological change is always a non-linear, multidirectional process (Bijker et al., 1987), emerging technologies—and the institutions behind them—are particularly subject to social and structural transformations (Rotolo et al., 2015). These changes are also in constant dialog with material and physical shifts in the

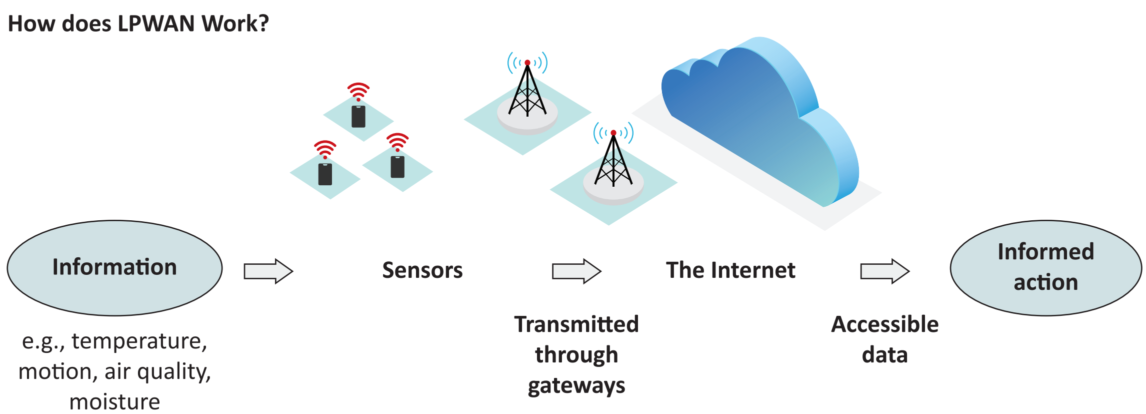

Figure 2. Description of LPWAN network from community workshops.

Figure 3. Slide of example "use cases" from community workshops.

LPWAN landscape that shape network functionalities. For example, different kinds of sensors are emerging to work with LPWAN gateways. Companies and organizations are trying to develop and extend their own LPWAN networks beyond just TTN, such as Helium, which runs blockchain incentives and pays people to host gateways in their homes. LPWAN is subject to external political factors like the Covid-19 pandemic or supply chain disruptions. Within TTN, the network coverage and subsequent usability of LPWAN connections regularly grows and shrinks in networks structured largely by user needs and behaviors rather than a centralized provider. In other words, because users volunteer to install and maintain their own gateways, the shape of network connectivity is subject to change. It is also subject to the policies and knowledge of existing institutions and leaders. For example, we interviewed a middle school teacher who deployed a TTN-based neighborhood air quality sensing network alongside his students. He recounted the bureaucratic obstacles of building an IoT network, saying:

> Our [school] tech department doesn't even know what this is, so we can't get past our [school] network security with it. We have to run it off of a hotspot….That's a challenge. We tell our principal or science supervisors, and they don't know what we're talking about, which is good and bad because we can just do it.

As a result of these factors, it can be difficult to define and maintain the boundaries of constantly shifting technologies, mobilities, policies, and priorities. In our role as researchers, these shifting physical, digital, and social boundaries present challenges to systematic sampling of cases and participants.

Sampling is a key focus of methodological scholarship on qualitative inquiry (Lofland et al., 2006) and anticipating change in both the communities of interest and the research project itself is often a part of that process. However, studying an emerging technological infrastructure requires researchers to infer the scope of potential cases and investment of potential participants to make multilevel sampling decisions. We have used several strategies to define cases for analysis within the existing structure of LPWAN deployments. We initially selected TTN as an entry point of analysis because of its decentralized, non-hierarchal organizational structure, which also made it particularly accessible to our research team. While sampling on the organizational level creates natural case boundaries, these organizations are especially vulnerable to change and even failure that can destabilize the distinctions between cases and their individual significance. For example, we observed as TTN and many of its partner organizations attempted to incorporate Covid-19 contact tracing technologies as a potential use case and then slowly removed them as bigger tech companies saturated the contact tracing market. Centering organizations may also cause researchers to overemphasize some users and "master narratives" (e.g., powerful stakeholders and ideas) over others, a criticism that has been leveled at STS research (Klein & Kleinman, 2002; Star, 1999).

We sought to extend our initial sampling strategy by prioritizing offline spatial dynamics. We have built more specified samples based on municipalities—key geographic locations where LPWAN and TTN adoption are expanding. Due to the importance of LPWAN's physical structures that allow sensors and gateways to communicate with one another in offline spaces, geographic sampling enables us to adjust our research to the material characteristics of the local network infrastructure and the needs of localized participants within this network. It also means that participants may have less specific knowledge of LPWAN than the broad swath of already experienced and invested stakeholders that organizations provide. Therefore, sampling participants across organizations and municipalities requires us as researchers to define the relative investment of potential informants in LPWAN. We found ourselves asking questions such as: Which activities constitute usage or potential usage of LPWAN or TTN? What is the minimum amount of LPWAN knowledge required for an interview? How might and should our study and interview experience shape user investment in and perception of LPWAN and TTN? These sorts of operational questions are important to any study, but their urgency intensifies in researching a rapidly changing and unstable technology. Managing boundaries that determine what or who is truly relevant to the study of an emerging mobile infrastructure requires in-depth investigation beyond a singular organization, locality, or apparatus. The goal here was to leverage the multiplicity of infrastructure to consider how LPWAN brings together assemblages of people, organizations, and artifacts.

While we navigate these challenges of boundary management and sampling primarily through sustained engagement with our technologies and communities of interest, we also view them as opportunities to engage with the structural dynamics of LPWAN across its online and offline environments (Klein & Kleinman, 2002). Within our community-based work, we sought out three different sectors within communities: local municipal leaders, small businesses, and non-profits. The aim of our research is to make contributions that can stand the test of technological change, extending beyond LPWAN in its current form to provide insight into wider social dynamics of technological, and specifically mobile and infrastructural, development. In doing so, we set out to examine the people (e.g., municipal leaders, designers, social justice advocates, and data subjects), artifacts (e.g., sensors, gateways), and environments (e.g., physical, technical) that facilitate LPWAN deployment.

5.3. Negotiating Competing Technospatial Imaginaries

A key precept of constructionist theories of technological change is that people in different social positions will have correspondingly different visions of the same technologies (MacKenzie & Wajcman, 1999). The differences between these visions generate insights into the social norms and tensions surrounding technological development. In studying the social construction of a sensing technology like LPWAN, however, the locus of interpretative differences is uniquely positioned between the physical and digital. In other words, physical and spatial considerations are at the center of LPWAN deployment and usage, including questions of how and where sensors and gateways should take up space. These are not just logistical and technological considerations; instead, different social groups may have distinct norms and expectations about how they experience LPWAN (Strengers et al., 2019). Whereas municipal leaders might imagine an LPWAN infrastructure layered over their existing city infrastructure to collect air quality data, for example, they also must store the data digitally and manage the installation and upkeep of sensors situated in space. Municipal residents might focus on their homes and communities, viewing smart cities as intrusive and risky. While the data can inform municipal and personal decision-making across both of them, the different scales and goals of these groups can present obstacles to communication and collaboration surrounding shared spaces and technological change.

In our research practice, we actively consider how competing technospatial visions of LPWAN differ and coincide. However, we also examine how they might be reconciled in scholarship and practice. We aim to make socially situated visions of LPWAN legible both to ourselves as researchers and to the social actors involved. Namely, we consider how individuals and groups in different social positions can communicate across their imagined spatial logics to better define the ethical and logistical implications of sensing networks from a community perspective. We present this as a methodological challenge because it involves constructing situations wherein people with distinct perspectives on LPWAN can articulate their technological visions and reflect on those of others different from themselves. Because of LPWAN's abstraction, communicating across perspectives on technology and space can be difficult. We set out to provide tools to facilitate this communication and furnish insights about LPWAN by putting different perspectives into conversation.

We have reframed this challenge as an opportunity to engage with interactive, participatory methods. For example, we conducted workshops with a diverse team of LPWAN researchers and designers from various areas of expertise (e.g., electrical engineering, public policy, sustainability) alongside our workshops with community leaders and business owners to examine the convergences and divergences in their viewpoints on LPWAN. To design the workshops, we drew from literature on group collaboration and technology (Wilson et al., 2020) to engage in a series of scaled brainstorms centered on answering questions about what a public LPWAN should look like. This involved individual, partnered, and group idea generation activities with people from different backgrounds and knowledge bases. Activities centered on "big questions" for discussion including "What are the key challenges for your community, and how could a network of IoT sensors help to address them?" and "What does a public IoT network look like?" The notes that participants captured and presented during the workshops served as our main source of data. While we uncovered many similarities across participants, a major question illustrates points of divergence: LPWAN for whom and by whom? This question points to different participant visions of LPWAN users and stewards and, in turn, how sensing networks should be distributed to meet the needs of these potential stakeholders. This question also reflected concerns about LPWAN relating to security and ethical data use, including for those who may be affected by the technology but do not use it themselves. We collected and actively consolidated these visions through the workshops in materials like the ones depicted in Figure 4.

There were multiple competing perspectives on how LPWAN could help the community. Time and again, different ideas surfaced, which, if deployed, would constitute significant privacy infringements (e.g., tracking children to ensure they get enough active play or exercise as part of a community-wide program to promote children's health). While the goals of many of these visions for LPWAN were admirable, as workshop facilitators, we raised concerns about the privacy infringements such projects would raise. Within the workshops, we also witnessed discussion and debate among participants about the costs and benefits of user privacy ramifications for suggested LPWAN applications. Sometimes the concerns were less apparent, such as the idea of offering financial incentives to those households who consume less water or electricity. However, the monitoring of household utilities has been shown to reveal significant personal information (Lisovich & Wicker, 2008), which, if developed through a public project, could be used in unintended ways. Therefore, as researchers, we made the conscious decision to steer projects away from potentially privacy-infringing use cases.

6. Conclusions

Regardless of the future of LPWAN, mobile infrastructures will continue to shape our everyday experiences of online and offline spaces, as well as the continued study of technological development. We outline some of the key methodological challenges that emerged from our study of LPWAN as a mobile infrastructure. LPWAN relies on networked sensors to observe objects and conditions that physically surround them. This can include motion, temperature, air quality, water levels, and a host of other environmental factors. Studying LPWAN as one kind of IoT-based network, we encountered several key frictions in our roles as researchers. These challenges encompass the invisibility and abstraction of infrastructural, materially embedded, and emerging technologies like LPWAN; defining technological futures and individual investment to sample cases and participants; and translating competing visions of technology and space across social groups. In navigating these obstacles, we reframed them as opportunities to center materiality alongside discourse, engage with structural considerations in sampling, and utilize group interviewing and participatory design across divergent technological expertise and conceptions.

We conclude with some considerations for conducting trustworthy research on emerging mobile infrastructures between online and offline spaces, drawing together the challenges and opportunities illustrated above. First and foremost, studying emerging technologies across physical and digital realms requires close attention to the ways that the design and discourses of

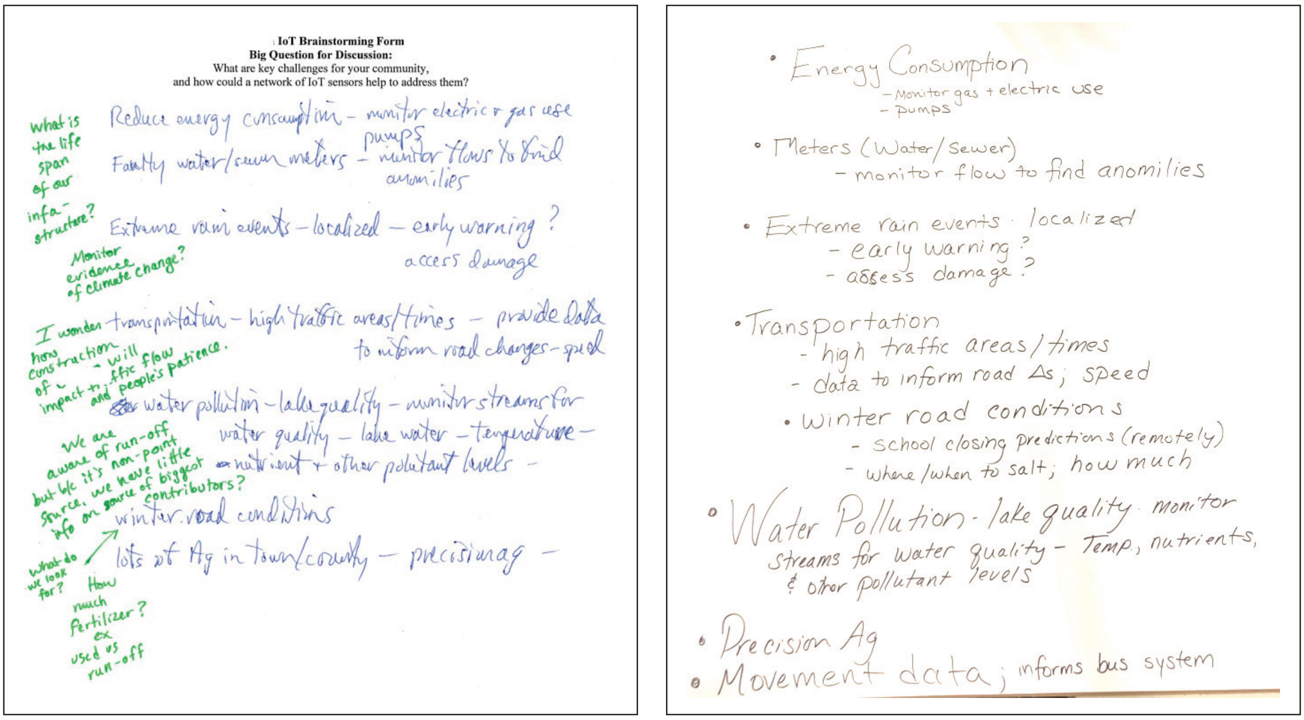

Figure 4. Brainstorming materials from participatory IoT workshops with community leaders: Individual brainstorming sheet with partner feedback (left) and group poster consolidating "use case" ideas produced from it (right).

online and offline spaces mutually shape one another. This includes how emerging technologies become visible, tangible, and legible to potential stakeholders through intertwined processes of material engagement and cultural imagining. In turn, the research process can also reshape and further entangle a technology's physical and digital properties.

Furthermore, establishing and maintaining infrastructures involves many kinds of human and nonhuman actors. Network infrastructures are embedded in local and digital communities with distinct characteristics, and they are shaped by these communities in turn. Following the SCOT approach, a technology opens to plural yet potentially conflicting interpretations, especially before particular meanings come to predominate and stabilize (Pinch & Bijker, 1984). As we illustrated earlier, analyzing the process of infrastructural development in its early stages presented methodological challenges for delimiting the boundaries of what counts as LPWAN and who has the power to speak authoritatively about the technology. Pinpointing the co-production of emerging technical and social orders, Jasanoff (2004, p. 278) argues, "important normative choices get made during the phase of emergence....Once the resulting settlements are normalized (social order) or naturalized (natural order), it becomes difficult to rediscover the contested assumption that were freely in play before stability was effected." As such, the early developmental efforts represent a valuable analytical point of departure for navigating and seeking out a multitude of perspectives on LPWAN across online and offline spaces.

Yet studying a technology as it emerges also involves grappling with the responsibility to make "hidden" physical and digital infrastructures visible as a part of data collection. The effects of infrastructures on local communities can sometimes seem indirect as "ordinary" users experience infrastructures "in the background" and may have little ability to impact their implementation (Star, 1999). Researchers must balance the tradeoffs between involving everyone who might have a vested interest in the network—even if those people are uninformed or unmotivated to understand it—and those with the existing knowledge and power to influence the network. While gaining insight from community members who stand to be affected by a technology can be foundational to design, implementation, and research efforts, the researcher's presence can also impact how technologies will be taken up and understood within communities. Reflexivity about the researcher's role in a field site is always an important consideration in qualitative research (Lindlof & Taylor, 2017; Lofland et al., 2006), but it is especially worthy of attention in this case. It underscores the importance of using community-centered participatory research approaches (Schuler & Namioka, 1993) that directly involve community members in design, data collection, and interpretation of research findings to examine technological uses and effects, but also the values of the research project.

Taking these considerations into account, mobile infrastructures face ongoing issues of sustainability and governance that make their continued study across online and offline spaces especially important. For example, proposed "public" IoT networks could offer broad-based coverage, but they also raise questions of stewardship, funding, data ownership, and security for municipalities, businesses, schools, and individuals, particularly in rural areas. In a mobile ecosystem currently composed of mostly privatized commercial networks, new infrastructural configurations present new avenues for research. Across these different configurations, however, shared methodological models and standards can help to reframe challenging research dilemmas into generative directions for studying technological development.

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Conflict of Interests

The authors declare no conflict of interests.

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About the Authors

Chelsea P. Butkowski (PhD, Cornell University) is a post-doctoral research fellow at the Center on Digital Culture and Society within the Annenberg School for Communication, University of Pennsylvania. She studies how people use digital media technologies to make sense of their identities and environments. Her recent research investigates the everyday politics of mediated self-making, visual media representation and marginality, and the design and discourses of participatory technologies.

Ngai Keung Chan (PhD, Cornell University) is an assistant professor in the School of Journalism and Communication at the Chinese University of Hong Kong. His research interests include critical data studies, the gig economy, platform governance, and digital labor. His current research project examines how precarious workers encounter, interpret, and manage algorithmic technologies as part of their daily work practices.

Lee Humphreys (PhD, University of Pennsylvania) is professor and chair of the Department of Communication at Cornell University. She studies how people integrate communication technologies into their everyday lives. She has published extensively on mobile and social media, exploring questions of identity, time, space, and privacy. She is also founding director of the Cornell's Qualitative and Interpretive Research Institute.