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Communication about sensors and communication through sensors: localizing the Internet of Things in rural communities

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Abstract

Internet of Things (IoT) sensor networks are an emerging technology at the center of the datafication and optimization of far-reaching environmental infrastructures—from "smart cities" to workplace efficiencies. However, this low-power, low-cost technology is also well suited to local deployments in rural communities, which are often overlooked by digital development initiatives. Therefore, we used a social construction of technology approach to study how various U.S.-based IoT stakeholders—including designers and advocates as well as citizen stakeholders—understand and value sensor network technologies. Through observational methods, in-depth interviews, and participatory design research in a rural Upstate New York municipality, we worked to design sensor networks *with* rural community members to generate data *about* and *for* community members to further local knowledge. We found that designing rural sensor networks requires stakeholders to navigate obstacles of communication *about* sensors and communication *through* sensors to facilitate secure, ethical, and localized sensing in rural communities.

Lay Summary

The Internet of Things or IoT has become a popular term to reference new technologies like smart watches or smart fridges. However, it is also used to describe digital networks of sensors that can gather data about environmental conditions such as electricity usage, water levels, location, and temperature without needing a direct internet connection. This makes the sensors especially well suited for use in rural communities, which are often overlooked in the development of new technologies. We studied IoT sensor networks in the United States through interviews with IoT developers and advocates, observation at industry conferences, and design-based workshops with potential users: rural municipal leadership, nonprofits, and farmers. The goals of our research were to understand the technological values and assumptions of IoT sensor stakeholders and to design a rural IoT sensor network *with* and *for* community members in a rural Upstate New York municipality. We found that developing sensor network technologies required stakeholders to confront challenges of communicating *about* sensors—such as the ambiguity of new technologies—and communicating *through* sensors—such as user security and privacy. Our research suggests the importance of localized design in building IoT sensor networks, particularly in rural environments.

Keywords: Internet of Things, technology adoption, urban/rural, community, qualitative methods, smart homes/cities

Internet of Things is a popular buzzword in the tech industry as well as in cities across the world. Central to "smart city" initiatives, "IoT solutions" are being deployed to "improve everything from critical infrastructure and public safety, to efficiencies in city lighting and energy usage, to better traffic flow and mobility" (Locke, 2020). Briefly, IoT is a term used to describe objects or sensors capable of transmitting data without a direct internet connection. Smart objects "augmented with sensing, processing, and network capabilities" are implemented in a wide array of everyday systems, from water and electricity meters to roads and traffic lights (Kortuem et al., 2010, p. 44). These sensors then transmit data regarding the environment or events through networks. We examine a community-based sensor network project in a rural U.S. municipality. From a communication perspective, we examined the development of sensor networks as sociotechnical processes of mediated meaning making. In other words, how does a smart rural community develop and utilize IoT for its local needs?

IoT technologies are designed to ambiently monitor the environmental conditions that surround them. As Bunz and Meikle argue, IoT enables new "addressing, speaking, and tracking capabilities," such as the ability to report air quality conditions or record sleeping patterns (2017, p. 4). The IoT sensor networks in this study consist of battery-operated sensing devices that collect and transmit data remotely through far-reaching network infrastructures at significantly lower cost and data rates than mobile and broadband-based technologies. Rather than solely tracking individual objects or people like radio frequency identification tags, smart watches, and other digitally connected "things" (Frith, 2019), these sensors also perceive particular environmental conditions

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such as temperature or moisture and can measure factors like energy or water use. They can be engineered to observe and quantify things that humans cannot physically see or feel at scale, but in monitoring their physical surroundings, the sensors underscore the entanglement of humans with the datafication of our environments. For example, using IoT sensors to measure electricity usage and improve efficiencies in an apartment complex might also mean tracking the daily behaviors of its residents.

According to Lasswell (1948), "surveillance of the environment" is among the chief functions of mass communication. With the term surveillance, Lasswell was not invoking contemporary notions of a digital panopticon (Andrejevic, 2007; Gandy, 1993), but instead he describes surveillance media as "disclosing threats and opportunities affecting the value position of the community and of the components within it" (Lasswell, 1948, p. 228). This kind of surveillance can help humans to understand and interact with their environments. Media and data can reconfigure social knowledge about people's surroundings (Couldry & Hepp, 2017). However, human actions and environmental conditions inevitably collide, as they do during environmental crises, such as floods or wildfires, and amid everyday processes, such as energy consumption or traffic monitoring (Bunz & Meikle, 2017). The ability to see and understand the world beyond one's immediate senses is a fundamental purpose of what we typically refer to as mediated (rather than mass) communication.

In this article, we study developments and discourses of sensing as it relates to rural communities in the United States. We draw from a social construction of technology framework to examine the social and material shaping of IoT by defining relevant social groups and investigating their divergent perceptions of its usability and significance (Bijker et al., 1987). These relevant social groups include but are not limited to IoT designers, researchers, municipal leaders, educators, community members, and local businesses who may be directly or indirectly affected by municipal IoT deployments. By focusing on these smaller actors, we follow Couldry and Powell (2014) who write, "emerging cultures of data collection deserve to be examined in a way that foregrounds the agency and reflexivity of individual actors as well as the variable ways in which power and participation are constructed and enacted" (Intro, para 2). Through a combination of qualitative approaches, including observational research, in-depth interviews, and participatory design, we study rural municipal IoT as an illustrative case of sensing technologies as mediated communication. In doing so, we position IoT sensor networks as both a discursive subject of communication and a communicative medium in their own right. We study emerging sensor network technologies as they are in the process of emerging to deconstruct this relationship between how we communicate about and through sensors. Therefore, by examining how various relevant social groups understand sensor networks, we can begin to unpack the assumptions and values that are embedded into the design, development, and implementation of IoT as an emerging technology within rural communities.

Communication technologies in rural communities

Communication technologies in rural communities are significantly understudied compared to those of urban communities (Ali, 2018). As Barney (2011) argues, there is a "systematic forgetting of the rural that characterizes most contemporary discussions of technology and politics" (p. 7). Research which does examine rural communication and media tends to approach it from a deficit-mindset—that rural communities are lacking social, political, economic, and technological capabilities compared to their urban counterparts (Su et al., 2021). While differential access to broadband technology is real, the problem is not with the rural communities but with the political economy of Internet Service Providers (Ali, 2021). Indeed, local solutions are often considered the best path forward for rural communities to leverage the possibilities of media and new communication technology rather than relying on urban services, systems, and solutions that are not designed for them (Ali, 2017; Antoniadis, 2016; D'Ignazio & Klein, 2020; Hardy et al., 2019).

Ali (2018) argues that we need to think more broadly of media communication when accounting for rural communication. He writes that we need to take "into account not only media and non-conventional media, but modes of transportation and infrastructure, flows of information, of a broad understanding of communication, and how all of these dimensions operate within the wider social totality" (p. 18). It is with this broader framework of mediated communication that we approach our study of community-based sensor networks in rural areas.

From connected to smart communities

Early internet studies demonstrated the rise of community Wi-Fi systems (e.g., Forlano, 2009; Powell, 2008; Sandvig, 2004). Importantly, this research identified alternative models for network connectivity within communities that did not rely on corporate Internet Service Providers for internet access. These early alternative Wi-Fi networks represent digital connectivity embedded with community-based values. Here, connectivity was a shared collective good, which is more efficiently deployed through communities rather than individual consumers. In major city centers, Wi-Fi connectivity is an important part of the urban infrastructure.

Over time, however, the emphasis has shifted from "connected communities" to "smart" cities. As Halegoua (2019) argues, the definition of smart communities or cities has shifted over time. In particular, she notes, "the connotation of smart city has shifted from merely meaning that digital infrastructures and ICTs have been implemented in a city but that these ICTs are intended to optimize every urban system with the goal of enhancing everyday services and quality of life for its residents" (p. 30). While internet connectivity is still seen as a key element of "smart communities," particularly through 5G technologies, smart cities are also looking to deploy different kinds of information technologies, notably sensors, to connect infrastructures, people, places, and data in new ways to optimize efficiency, improve sustainability, and contribute to the economic growth.

Giving rise to what Andrejevic and Burdon (2015) call the sensor society, the proliferation of environmental sensors both on mobile devices and those built into municipal infrastructures lead to unprecedented amounts of data generated about activities, people, and places within the social world. One of Andrejevic and Burdon's primary critiques of the sensor society, however, is the cost of the infrastructures necessarily leads to power imbalance. They write, "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" (p. 21). While there have been open data movements within major urban centers to create public data repositories, like the New York City Open Data (https://opendata.cityofnewyork.us/), the decisions regarding what data to collect are still largely in the hands of those in positions of power.

Our focus on the development of sensor networks within smart rural communities, and the ways that those sensors interact with one another, human actors, and their environments is a fundamentally communication-oriented process (Bunz & Meikle, 2017). Therefore, we describe sensors as a form of media infrastructure (Parks, 2015), that is, the objects, materiality, and labor that make the transfer of messages possible. The datafication of environmental sensing information to meaningful and actionable "data" involves the collection, aggregation, and transformation of such information (Couldry & Hepp, 2017). In particular, our project sought to work with rural community to help create a bottom-up approach to data that emphasizes smart communities rather than just cities. Smart cities initiatives collect and utilize big data as a means of optimizing urban systems (Halegoua, 2019). But what do smart rural communities mean? Large urban centers have dominated the landscape of smart technologies. Precision agriculture is but one example of data-informed rural actions. A goal of our study was to bring intersectional data approaches to upend power imbalances between rural and urban resource allocation (Mayer-Schönberger & Cukier, 2013).

For participatory sensor network design (Schuler & Namioka, 1993), this becomes a mediated meaning-making process facilitated through the combined, and sometimes competing, technological visions of local community members, municipal leaders, and nonprofits, as well as researchers, engineers, and designers.

Case study: public IoT as rural sensor network

Our project focused on combining the values of participatory, community-based network design with the smart rural communities to counter some of the concerns raised by a sensor society, such as asymmetries in data ownership and decision making (Andrejevic & Burdon, 2015). Drawing on data feminism (D'Ignazio & Klein, 2020) and rural computing (Su et al., 2021) frameworks, our project sought to create networks *with* rural communities to generate data *about* rural communities *for* community members and organizations to use to in locally meaningful ways. Within an ethics of care framework (D'Ignazio & Klein, 2020), we prioritized privacy in the design of the network and sought to anticipate potential unintentional uses of these data.

Moreover, collaborating on local network and data governance as community stewardship and sustainability, we strive to work with our community partners to develop a local sensor network that generates locally meaningful data and enhances environmental sustainability. Our project utilized long-range wide-area networks (LoRaWAN), a digital network configuration that connects IoT sensors to the cloud and to one another. LoRaWAN transmits information at low data rates, collecting sensing data ambiently over time as sensors regularly scan their surroundings for relevant information. For example, the air quality sensors described above provide readings at timed increments to gather a general picture of their surroundings over time. It is particularly well suited for rural deployments because LoRaWAN-based sensors have low energy use and do not require a direct internet connection to transmit information. Instead, they communicate through long-range radio frequency with gateways which then transmit that data to servers via the internet. So, sensors can be remotely deployed, while only the gateways need internet access. Thus, we prioritize the social and material implications of this ambient, routine, and slow environmental sensing configuration.

To investigate this case, we aim to answer the following research questions. First, how do stakeholders articulate their values and assumptions about local IoT sensor networks? Second, what challenges and opportunities do community-based design present for IoT sensor network development? Third, what are the implications of rural community-based IoT for wider discourses of sensor networks?

Methods

This research is part of a larger project geared toward building a statewide public IoT sensor network in New York State that connects previously unconnected rural spaces to help bridge digital divides. Therefore, our role in the project was to examine how IoT advocates, researchers, and potential community adopters understand sensor network technologies. We triangulate our research using three complementary modes of qualitative inquiry, which emerged over the course of the study: participant observation, semi-structured interviews, and participatory design research. The goal of this methodological configuration is to assemble discourses of emerging sensing technologies from a variety of perspectives, including corporate and community sources (Butkowski et al., 2022).

Observational research

Data collection began with participant observation at international industry conferences held by The Things Network (TTN), an international collaborative open-source network for LoRaWAN and IoT development. These conferences showcase the latest developments in sensor network technologies, suggest best practices, and illustrate "use cases" for potential adopters. According to the TTN website, the conferences are intended for "builders and buyers" or "players in the LoRaWAN ecosystem." Due to the COVID-19 pandemic, the day-long conferences occurred on a virtual platform with a combination of livestreamed and pre-recorded presentations as well as live chat features. They focused on topics deemed relevant to ongoing IoT development, including "logistics" and "hardware." Overall, the conferences provided a sense of corporate viewpoints on IoT sensor networks, suggesting priorities and challenges within the industry. We attended four conferences between April and October 2021, for a total of 30 hours of observation. During the conferences, we collected detailed fieldnotes and screenshots capturing information about presentations and digital conference interactions, analyzed through close reading and discussion between members of the research team.

Semi-structured interviews

Simultaneously, we conducted nine semi-structured interviews with sensor network developers, designers, and advocates between September and November 2021. The interviews lasted between 30 and 90 minutes. They were conducted, recorded, and transcribed virtually using Zoom. We utilized a snowball sampling approach to develop our interview sample, beginning with leaders involved in TTN community networks in New York State. From there, we formed connections with a wider network of IoT researchers and educators. Interview participants included five IoT university researchers, three IoT advocates, and one middle school teacher who deployed an IoT sensor network in the classroom. Our interview guide focused on questions about network design and data management as well as challenges and opportunities of industrial sensing technologies. We asked questions such as, "How did you decide to adopt IoT devices?" and "What are the key challenges of developing IoT sensor networks more broadly?" The interviews provided in-depth insights into sensor network design and usage. To protect participant confidentiality, all quotations are attributed to pseudonyms.

Participatory research

Emergent findings from the observation and interview processes led us to develop a series of workshops inspired by traditions of participatory design (Schuler & Namioka, 1993), with the goal that "those who will use information technologies play a critical role in their design" (Robertson & Simonsen, 2012, p. 2). We put this approach into practice to build a "testbed" sensor network situated in a town in Upstate New York and the surrounding rural region (Population: ~13,000). The participatory research involved municipal and community groups in network development from its inception. Conducting several online information sessions about the project with municipal leaders across the state, we set out to build shared visions of an IoT network in New York State between designers and rural community members through a collaborative design process (Hall, 1992). Ultimately, we were constrained to only work with one community because of COVID-19.

This started with conducting a participatory workshop in November 2021 focused on the designers: IoT researchers and advocates from our own research team. Attendees at the one-hour in-person workshop ($N = 12$) included electrical and computer engineers, computer scientists, policy analysts, extension leaders, and economists actively working on IoT sensor network design. We drew from team science research that centers collaborative projects among diverse teams (Wilson et al., 2020) to design a "stepladder" brainstorming activity geared toward answering a central question about visions for the sensor network: "What does a public IoT network in the New York State look like?" The workshop unfolded in three parts. First, we instructed participants to answer the question individually, writing their ideas on a sheet of paper. Then, we partnered participants to read and annotate each other's ideas and then discuss them together. Finally, we combined the pairs into small groups and asked them to consolidate their ideas onto a larger sheet, which they presented back to the full group. The workshop was not recorded, and data produced included participants' brainstorming sheets and notes captured by the first author.

Building on insights from our initial designer workshop, we also conducted two in-person participatory workshops focused on community members in May 2022 after three months of community relationship building in the partner rural municipality. The purpose of the community workshops was to inform community members about the potential functions of LoRa sensor networks and examine whether and how such a network could be useful within their local context. We identified community members to invite to the workshops by attending community meetings and organizing small group presentations through partnerships with local organizations and universities. These short presentations were designed to explain IoT sensing technologies to individuals without specialized technical knowledge. See Figure 1 for a sample of the slides from our community IoT presentations.

We recruited participants for the workshops through presentations at local government meetings, community initiatives, and universities based on their potential interest in IoT and their position within the municipality. We sought out three different sectors with this research: local municipal leaders, small businesses, and nonprofits. After identifying a list of people from these backgrounds in collaboration with community contacts, we organized the two workshops around two themes: (a) agriculture, to capture the prevalence of agricultural businesses and researchers in the area, and (b) municipal concerns, to work with local officials and nonprofits. Each workshop had four participants for a total of eight community members out of 18 who received invitations, including current and former municipal leaders, educators, local vineyard owners, agricultural researchers, and nonprofit leaders. Both workshops focused on the same central question, "What are key challenges for your community, and how could a network of IoT sensors help to address them?" The community workshops followed the same stepladder brainstorming activity employed in the designer workshop. However, we also allotted extra time for discussion throughout and for a brief informational session at the start to ensure that all participants had access to the same baseline information about IoT sensor networks.

Providing this information during data collection required us as researchers to inform participants about the technologies under study. Through an extended process of workshopping with the design team, we carefully selected a modest collection of IoT "use cases" to present to community participants. While we wanted to inform participants about common kinds of sensors and envision how they could be used, we also wanted to avoid overly determining the uses of such network implementations. We shared use cases based on recent university student projects, rather than large-scale municipal sensor deployments. These included apartment electricity metering, agriculture, road surface monitoring, and food cabinet management. At the end of the workshops, we facilitated brief discussions about data ownership and privacy. As with the designer workshop, we collected data in the form of individual and group brainstorming worksheets as well as detailed fieldnotes captured by four members of the research team. The workshops were not recorded. Through these three participatory workshops, we established a collection of three ongoing, community-driven "use cases" to deploy in this municipality alongside a group of community stewards to oversee them.

Findings

We draw from Humphreys and Liao (2011) to explain the complexities of IoT sensor network design as a mediated meaning-making process, building two major themes that emerged in our interview and observational research and extend further into our participatory research. Both themes reflect the social

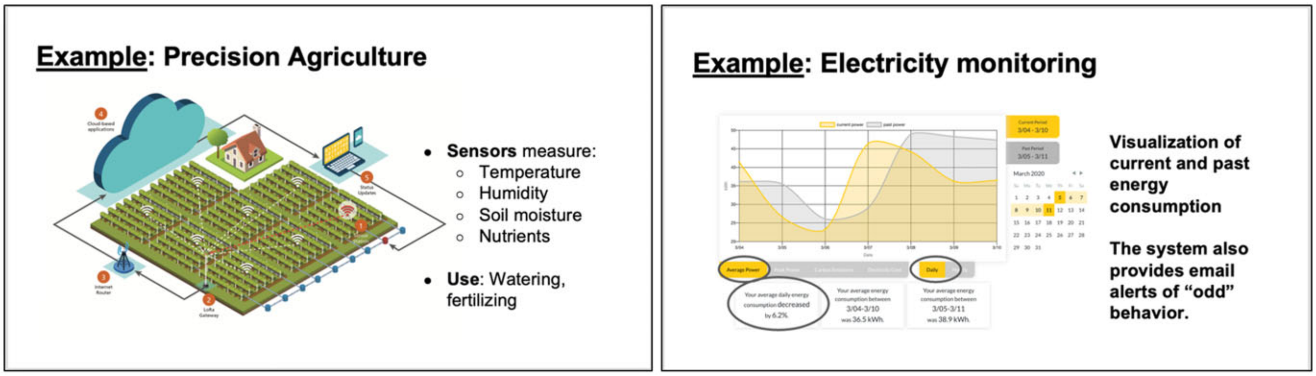

Figure 1. Example slides from rural municipal IoT presentations explaining IoT use cases.

construction of sensor network technologies (Bunz & Miekle, 2017) and their infrastructural attributes (Parks, 2015). Humphreys and Liao analyze the everyday usage of a mobile geo-tagging app as generating “communication about place” and “communication through place” to suggest how digital technologies contribute to the social production of urban space and place. We adopt a similar framework to explain how IoT designers, researchers, advocates, and citizens understand and employ networked sensors. The two themes of (1) communication about sensors and (2) communication through sensors mutually inform discourses and tensions of sensing as a mediated communication technology within the emerging IoT space. Communication about sensors highlights the complications of explaining and, in turn, developing LoRa-based IoT, whereas communication through sensors centers the messages that sensors share through their design, data, and network connectivity. Together these themes underscore how technological frames (Treem et al., 2015) across relevant social groups structure community-based design and wider discourses of sensing, particularly within local community contexts.

Communication about sensors

IoT sensor network designers and advocates are guided by an ethic of possibility, adhering to values of openness and decentralization that are evident in the branding of major LoRaWAN providers. TTN explains its purpose as “a global collaborative open-source Internet of Things ecosystem” while Helium, another popular LoRaWAN provider, calls itself, “the People’s Network.” These networks are driven by largely self-taught volunteer and project-based adopters who set up Wi-Fi-enabled LoRaWAN gateways that propel sensor connectivity in surrounding geographic areas. These experimental, citizen adopters are viewed as powerful innovators, driving novel sensor network applications tailored to their distinct needs. Gerald, an IoT hobbyist, described the significance of installing sensors in his home:

> I’ve been tinkering with this kind of stuff for years, at least since the early 2000s, so it’s something I’ve always thought about. My friends used to tease me when I started putting monitors in the house and detecting when the toilet flushes and stuff like that. I’m like, if we can collect enough data, we can know what’s going on.

Because of their focus on user innovation, IoT designers and advocates tend to favor a “build it, and they will come” approach to technological development. This business adage, which references the 1989 movie *Field of Dreams*, generally suggests that once a product is fully completed, customers will recognize and adopt it. In the case of municipal IoT, it has a more specific meaning. It suggests that widespread yet unspecified LoRaWAN connectivity is necessary to enable widespread citizen and organizational adoption—and subsequent innovation—of IoT sensing technologies.

This results in a fundamental tension of municipal IoT development. On one hand, LoRa sensor networks are a purposefully ambiguous, flexible technology that maximizes the possibilities of potential citizen applications while taking pains not to constrain possibilities. On the other hand, widespread understanding of the technology and its applications among potential citizen adopters is a necessary precondition of growth. Patrick, a public policy researcher studying municipal IoT, underscored this tension, saying: “IoT’s biggest strength is also its biggest problem. It’s so broad and so versatile, it can be used for anything. But by that nature, it doesn’t have a specific application that it can be tied to.” In turn, one of the most consistently pressing obstacles of IoT sensor development is *communication about sensors*, explaining sensors and the wider network apparatus to potential stakeholders unfamiliar with the technology.

Many conditions of municipal IoT contribute to its fundamental ambiguity and communication challenges. Both in spite and because of the ubiquity of sensors in everyday life, participants discussed the difficulties of distinguishing LoRa-based sensor networks from other sensing systems connected through cellular or Bluetooth. These networks are challenging for prospective adopters to imagine and for advocates to explain or justify. Thomas, an IoT advocate and business-owner, attributed this to a disconnect between LoRaWAN designers and users:

> Engineers are lousy communicators. If I could change one thing about LoRaWAN, I’d change the bloody name. That name is the worst name in the world ... If you read the technology presentations of The Things Network or the LoRa Alliance, it’s all gibberish to anybody who’s not inside. It’s just not clear, and I don’t think it’s a lack of clarity of thinking by the people who are doing this because they’re doing their stuff and that works. But it’s a lack of understanding of the other side of the channel: the receivers.

Beyond the conceptual obstacles of explaining IoT sensors, deeper challenges of network structure and stewardship further complicate their deployment. Collectives like TTN offer

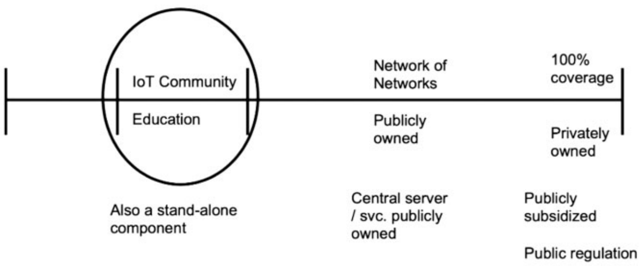

Figure 2. Transcription of a public IoT model drawn by participants in our workshop for IoT researchers, designers, and advocates.

open-source network connectivity, but sensor design and overarching network infrastructure tend to be the domain of large-scale organizations like the LoRa Alliance, a collaborative association of LoRaWAN development companies. Thomas elaborated on the challenges of building IoT between competing financial and structural interests:

> Because [LoRaWAN] is so corporate, there's a constant tension between the corporate types, who are trying to make the world safe for their profit motive and those of us who are techno-anarchists who want to make the world safe for the world.

We saw this echoed in our participatory workshop for sensor network researchers, designers, and advocates as participants collaboratively imagined a public IoT network. We found that participants articulated competing visions of "publicness" via questions of financial sustainability, data ownership, security, and usability. Figure 2 depicts the final output of one group, a diagram imagining different potential models of IoT publicness. The illustration places different models of IoT on a scale from most public to most private, envisioning divergent structures of financial ownership and community management.

Ultimately, the challenges of communication about sensors can obstruct burgeoning LoRaWAN deployments, further hindering citizen-driven innovation. For example, Jamie, an urban middle school teacher, designed a LoRa-based air quality sensor network alongside his students that required him to communicate about sensors on several levels. On a base level, he had to teach his eighth-grade students how to build a sensor network and interpret the data it produced. However, to get the network up-and-running, Jamie also faced the challenge of explaining the sensors to his colleagues at school and community members outside of it. The school's IT team refused to give Jamie permission to run the gateway that would power the network using the school internet connection because the tech department "doesn't even know what this is." Instead, he had to run the network off a collection of 4G hotspots installed in nearby apartments, which caused inconsistent connectivity and additional upkeep costs. Jamie discussed IoT's ambiguity as both a hindrance and a strength of his educational deployment:

> [Community members] don't even know what you're talking about. They don't think, 'Oh, kids can't do this. Why are you doing this with eighth graders?' That's hard, a little bit of ice breaking with it . . . But it also makes it exciting for the students because it is new, and it's something they can actually work with with actual devices. You can't do that with a cell phone . . . That's why this [sensor network] is great, because the programming is fairly easy, and the devices are easy to build.

As such, communicating about LoRa sensor networks is fundamentally shaped by tensions between purposeful ambiguity and logistical clarity, building technologies that can be challenging to imagine yet easy to learn.

Communication about use cases

IoT researchers, designers, and advocates navigate the purposeful ambiguity of communicating about municipal sensor networks by situating them through "use cases," or examples of potential IoT applications. These "use cases" are a communicative currency intended to make the abstraction of IoT sensor networks "click" for those attempting to understand the technology, to spark ideas for new applications and, at times, to sell sensor products and services. They encompass completed and ongoing IoT applications as well as sociotechnical imaginings of future applications. Use cases are widely variable in scope and topic, from tracking the location of livestock in remote areas or observing the behavior of lab rats under experimentation to monitoring the capacity of community food pantries or sensing water levels to prevent flooding. Gerald discussed the potential of use cases as a tool for innovation in relation to educational IoT deployments by saying, "The kids are actually better at coming up with a lot of these cases of what we do with the sensors than I am." Here, Gerald underscores a common sentiment among several participants, suggesting that young people and, more importantly, nonexperts in IoT sensing are often best suited to innovate the technology through use case development.

Use case logic is often a logic of datafication and optimization (Powell, 2021), through which sensors perform feats of efficiency and sustainability that consolidate the demands of everyday labor. Trading use cases structures how the value of IoT sensor networks can be understood and perpetuated as well as the assumptions built into their development. Communicating about sensors through the language of use cases is a value-laden process that suggests particular visions of sensor networks and the wider systems they are embedded within. This was apparent at industry conferences, where salient use cases were employed to pitch new sensors, network structures, and investments to potential stakeholders and customers already familiar with IoT. For example, Figure 3 illustrates a series of use cases presented during the TTN conference on "Smart Facilities and Compliance" in April 2021. This presentation focused on using LoRa-enabled sensors in the workplace to assess compliance with environmental, social, and employee governance goals. The use cases listed, such as monitoring desk usage, are intended to manage environmental impact (e.g., electricity use). However, in doing so, they also surveil employee activities. Communication through use cases is effective because it activates localized visions of IoT—imagining sensors in our own communities—but these conference use cases and their logics of optimization are not tailored to the local conditions of rural communities.

After observing the prevalence of "use cases" as a communication tool in our IoT observations and interviews, we incorporated them into our participatory research. As stated above, we explained IoT sensor networks to our agricultural and municipal participants using a selection of use cases. However, we also asked participants to generate ideas for

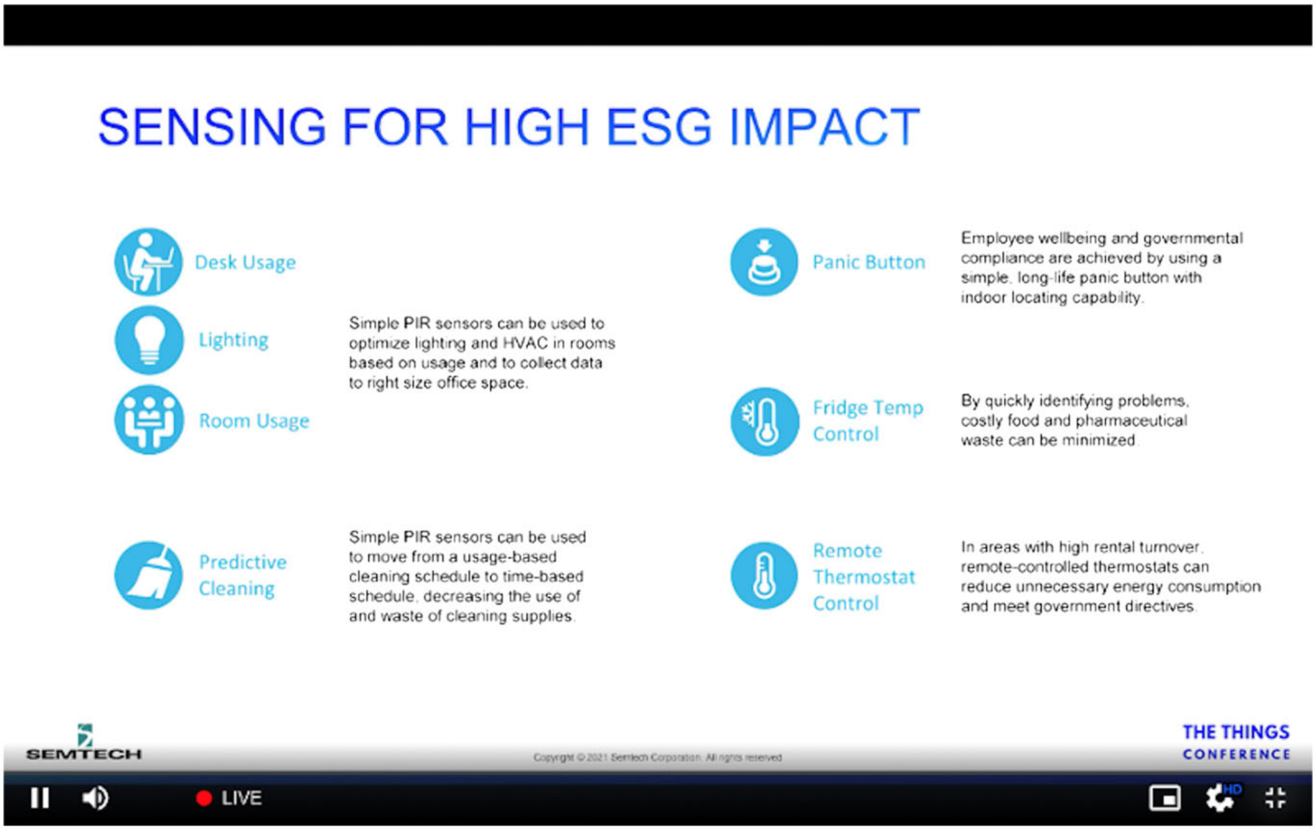

Figure 3. Image of a slide on "Sensing for High Environmental, Social, and Employee Governance Impact" presented at a TTN conference on "Smart Facilities and Compliance" in April 2021.

potential use cases that would be relevant and helpful for the community. The techno-optimism that we observed in our interviews and observational research also emerged in the community workshops, which may reflect the use case examples we shared as well as broader discourses of sensing and technological development. In this sense, communicating through use cases fundamentally shapes the value systems used to understand, evaluate, and imagine sensing technologies. When participants described different ideas for a sensor network, one of the key goals they described was to save time and hence resources. For example, by setting up sensors in community gardens, volunteers could know when they needed to water or harvest vegetables without having to check the gardens everyday. This same logic drove ideas to place sensors in community food pantries. These examples demonstrate that local optimization is not just about financial efficiency, but about resource allocation more broadly, including volunteers' time. At the same time, they can also place optimization and civic engagement at odds, as sensor efficiencies can reduce volunteering needs (e.g., habitually tending community gardens).

Optimization, however, was not the only logic that community members use to communicate about sensors. Uses of sensor networks for STEM education and community organizing were also prevalent ideas generated in the workshops. In these cases, the value of sensors is both in the educational application of learning how to set up networks, but also in the creation of *local data*, which enables students to learn about data analysis and statistics and community members to affect local change. In communicating about sensors, participants demonstrated a deep understanding of the various kinds of values that sensors and *local* sensor networks can generate. A list of all participant-suggested use cases can be seen in Table 1.

Communication through sensors

Sensors are also a communication medium that transforms environmental conditions into numerical data for use by humans and machines. This transformation creates a mediated representation of often unseen and untabulated environmental factors. With LoRa-based sensors, messages are transmitted from sensors to gateways through radio waves and from gateways to data repositories through an internet connection. This process, like many other forms of mediation, reflects the ideals of technological designers, revealing biases that surface through the information presented, including what sensors make visible and what they might obscure or reframe (Couldry & Hepp, 2017). Community-based municipal IoT sensors also present opportunities for citizens to directly collect data about their surroundings. As Jamie, said,

> I see sensors as a way to level knowledge. You take away the middleman who may be telling you a different story. An individual can learn things if they want to, and that's, I think, empowering ... Sensors are kind of like our nerve-endings. We're stretching out a little bit further and having a better way to tell what's going on in the world.

Communication through sensors helps people to make sense of the world from an alternative point of view while also

Table 1. IoT sensor network use cases proposed during rural community workshops

Challenges	Use cases	Workshop
Energy		
Housing, public utilities, cost reduction		
	Electricity and gas usage, energy efficiency	Both
	Street light outage monitoring	Agriculture
Plants and growing		
Farms, fields, community gardens		
	Air moisture	Agriculture
	Farm and field temperature	Agriculture
	Grass height (determining when to mow)	Agriculture
	Leaf color and wetness	Agriculture
	Rainfall variation	Agriculture
	Soil quality, nutrients, moisture	Both
	Spray coverage (pesticides)	Agriculture
	Vine density and bud counts	Agriculture
Public services		
Resources, transportation, education		
	Location, availability tracking for public bikes, buses	Municipal
	Resource distribution item availability, space (food, books)	Municipal
	Water pollution	Municipal
	Road surface monitoring	Both
	STEM and data science programs in schools	Municipal
	Traffic	Municipal
Safety		
Environmental justice, community organizing		
	Agricultural runoff	Both
	Fertilizer, pesticide residues	Agriculture
	Air quality near local landfill	Municipal
	Tank leaks	Agriculture
Water management		
Local lake, public beaches		
	Flooding, water levels, extreme weather	Both
	Water consumption	Agriculture
	Water quality, pH	Both
	Water temperature	Municipal

inviting them to see the world in a particular way. This second theme considers how LoRaWAN sensor networks communicate with humans and within themselves.

Unobtrusive and localized

LoRaWAN sensors are often used to transmit messages about their environments, but sensor design and placement also send messages within environments that shape data narratives. At industry conferences, presenters repeatedly discussed advancements toward batteryless and autonomous sensors that operate through alternative energy sources, such as solar or plant energy. These sensor configurations promote sustainability and reduce maintenance needs. They also suggest a vision of sensors as fundamentally unobtrusive, blending into and thriving from their environments. Pablo shared a similar sentiment when describing the deployment of thermal environment sensors in an apartment building. He said:

> It's not really too much of an inconvenience because it's just a small, white device that goes on the wall ... I think we purposely did that. You don't want to be intrusive to the resident's lives. You don't want to disturb them too much ... They were receptive to it, they understood, and they were fine, given that we made our best effort to make it as hidden as possible.

Because of their low-power, low-data design, LoRa-based sensors are also comparatively cheaper than many other kinds of sensors with more complex components. This affordability lends itself to the experimental, citizen science applications promoted by IoT advocates and organizations. It also lends itself to educational applications. The materiality of LoRa-based sensors was a strength in Jamie's classroom. He noted:

> It's low cost. We bought tons of sensors. I still have the sensors, just little pieces here and there we had to buy. Because I didn't care if [students] broke them. We had a lot of burned up sensors because they put the wires on backwards, positive-negative, just real simple stuff. To us, that's part of the learning process, you hope they destroy some of the stuff.

Because of their material qualities, sensors are routinely invisible as mediators of their environments through the traces they transmit. Trace data is subject to various infrastructural challenges, the most notable being challenges of connectivity. Although LoRa-based sensors do not require a direct internet connection, managing and maintaining network connectivity sensor-to-gateway and gateway-to-internet can present a constant puzzle, even in geographic areas with consistent internet access. Sam and Phillip, two interview participants responsible for constructing LoRaWAN networks in different kinds of environments, discussed various factors that can interfere with connectivity, including gateway height and geographic barriers, like hills and trees. These obstacles can create "holes in the data" that limit its usefulness, and network development to circumnavigate them involves computational modeling as well as some degree of trial and error.

Nevertheless, the potential of collecting systematic observations of sometimes inaccessible or unobserved environments excites IoT advocates. The low power and low data rates of LoRaWAN allow for versatility and customized character in its sensor deployments. In this sense, the slower-paced, smaller quantities of data collected through LoRaWAN present an opportunity rather than a challenge when compared with other sensor network structures. Thomas explained this in relation to the monitoring of municipal building efficiencies:

> As soon as you monitor a building you discover all the things that have been ignored because the data is right there ... It's analogous to where, if you cut yourself, you have to look at your hand to see if you're bleeding. That's the way a building is. You have to go look at the boiler to see if it's running at the wrong time. You have to go look at your power bill and see what's going on and correlate that to stuff, and everything's at the wrong time scale. It just doesn't work. As soon as you are monitoring data in real time, the mist clears, and you can see what's going on.

LoRaWAN sensors allow their users to witness typically unobserved environmental rhythms and conditions at the hyperlocal level. These observations allow them to learn "what's going on" and to use this information to make informed decisions. Akin to work by Gabrys et al. (2016), they contribute to citizen data that "gives rise to alternative ways of creating, valuing and interpreting datasets" and telling localized data stories (p. 2).

Sensor privacy and risk

Despite their sustainable materialities, sensor networks introduced concerns about privacy and risk that emerged across all the contexts we studied. Visions of public networks included questions about how data can be ethically used and protected, as well as who should be allowed to access it. Concerns in this context fell into two major categories. One area of privacy concern relates to sensor data and, more specifically, how people might be unintentionally implicated in data on the environments they inhabit (Lisovich et al., 2010). The conditions that sensors are built to observe, like temperature, motion, or air quality, are inevitably affected by human activities. While sensors can be utilized for intentional surveillance (Andrejevic & Burdon, 2015), they can also be used to make inferences about people's characteristics and lives that extend outside of the intended scope of a particular use case. Casey, an IoT researcher focused on security and privacy explained this by saying:

> You can learn a lot, just viewing network traffic. When someone's leaving their house reflects what kind of job they have, and how often they're in their kitchen if they have a smart fridge. Those sorts of things. Very easily you can characterize someone's life based on their digital footprint. So, making that as secure as possible so that people who are outside the network can't see it is very important and then sort of blinding it to not attach data to certain people

Municipal leaders who participated in our community workshops similarly considered what sensor data might capture and how it could fall into the wrong hands, even in a community-driven network. For example, they had previously considered deploying public scooter sensors, which allow citizens to track transportation availability. Yet, participants also noted that this data can be utilized by law enforcement to track citizens' whereabouts. Participants opposed surveillant sensor applications, raising questions about data privacy and ownership that align with considerations of inequality brought about by datafication (Powell, 2021). They also expressed concern about putting "this big [network] umbrella over the area" without centralized oversight for these same reasons. Instead, they considered the importance of designated network stewardship and limitations to the publicness of sensor data. This perspective lies in tension with the "build it, and they will come" logic of much IoT design, suggesting that an ethic of possibility also requires ethical limitations.

The second area of privacy concern is not about sensors but rather about the gateways that transmit sensor data to the internet. Gateways are the fundamental building blocks of IoT sensor networks, and their positioning determines the scope of LoRaWAN connectivity in a particular geographic area. One gateway can connect to many sensors simultaneously, but it must also be positioned in the vicinity of those sensors (i.e., within a few miles) while maintaining an internet connection. Therefore, gateways often need to utilize the same internet connections maintained in the spaces that they are used to observe. For example, when deploying the apartment building thermal environment monitors mentioned previously, Pablo faced the challenge of finding someone willing to host the building gateway in their apartment and on their home Wi-Fi. He said:

> I don't know what they thought the threat was, but they thought that there was some sort of privacy threat that could be associated with that. And I don't really think that's a major problem, but I get where they're coming from. Just with IoT devices in general, there are privacy concerns.

Although the threat was abstract and possibly unsubstantiated due to security mechanisms put in place in the sensor network, the thought of connecting sensors for an entire building to the intimate sphere of a home Wi-Fi network presented privacy and security concerns for apartment residents.

Communication about and through sensors

Fundamentally, communication through sensors requires communication about sensors and vice versa; these two themes mutually shape processes of sensor network development. We saw this interrelationship most readily in accounts of the *rhetorical power of data* as a tool for municipal decision and policy-making envisioned as "data-driven." This rhetorical power is not solely drawn from the specificities of the data collected but rather from the *idea of accumulated data* in itself. Within logics of datafication (Van Dijck, 2014), sensor outputs are commodities with value, which undergirds their persuasive strength. Thomas noted that the difficulties of justifying IoT sensor network deployment to potential users virtually vanish once they are exposed to this data. He said,

> Now, what we found is that people who were actually running the [IoT sensor network] experiments, after they find out the data is valuable—and they almost always do—suddenly the barriers to putting a gateway on the premises go away. It was like, 'Oh well, I want this data. I want better coverage. Yeah, I'll just put a gateway up. It's no problem.'

According to Thomas, accumulated data signals value by demonstrating optimization potentials. Throughout our inquiry, logics of optimization served as both a dominant discursive framework for communicating about sensors and a design practice for communicating through sensors. However, the value of data for participants was not just about optimization, but about data's evidentiary nature potentially disrupting power structures (D'Ignazio & Klein, 2020). Particularly for environmental justice advocates in our workshops, air quality data were seen as a powerful means to combat nearby corporate pollution.

IoT advocates in our study emphasized the importance of making data value visible, in part, by getting data in front of potential adopters. They prioritized data accessibility to IoT outsiders rather than broader explanations of the network technologies as fundamental to the success of sensor networks. For example, the primary audience for the TTN conference on "Agriculture" in October 2021 was not farmers themselves but developers and advocates of agricultural sensing technologies. Farmers were repeatedly described as hesitant, laggard adopters who needed to "observe," "wait and see," or "touch and feel" before utilizing sensor networks. Therefore, much of the conference considered the optimization and efficiency of sensor data for rural users through solutions such as integrating data from multiple sensors onto a singular dashboard smartphone application. When successfully collected and presented, the data would speak for itself. However, Phillip, an IoT professional based in the New York City, also highlighted the mixed messages that accessible data can send to users and stakeholders:

> That's another challenge is putting everything in context. People that don't know how to read the data can make, you know, false impressions about what is actually happening. So that's also sort of like the flip side to the benefits of openness.

As Phillip points out, communication through sensors generated the need to communicate better about sensors. Our findings underscore the perceived rhetorical power and challenges of sensing data in sensor network development and adoption.

The participatory workshops that we conducted with farmers and rural municipal leaders assembled community-based visions of sensor data rather than collecting or interpreting it. Nevertheless, potential data futures were contested, particularly with regard to conditions when sensor data might become *too accessible* or *communicate too much* about sensor environments. For example, in the municipal workshop, water stewardship and conservation were discussed as important local goals. We brainstormed the possibilities of using sensors to measure flooding or water runoff because of concerns about agricultural chemicals running into a nearby lake after major storms. However, data about the movement of water (and potential contaminants) can become political when it then raises questions about who is responsible for spreading contaminants and cleaning up or managing such water. One of the participants suggested that sensors could be deployed on local water meters to help encourage and perhaps even incentivize individual and household water conservation. Another member of the group responded by raising privacy concerns that public household-level water use could be used to infer the number of people living in a household or other things about the activities of the inhabitants. Both examples of water sensors demonstrate the allure of data to solve community-problems and new problems that such data can also generate.

Discussion

Our project presents four contributions to scholarship on sensor-mediated communication and IoT. First, this project deconstructs sensors as mediated communication by examining IoT sensor networks as both a communicative medium and a communicative subject, focusing on IoT design and deployment in hyper-local, rural contexts. We examine communication about and through sensors to underscore that sensor-mediated communication is not limited to the data that sensors transmit but, like other new technologies (Marvin, 1988), encompasses the values and assumptions embedded in the social construction of sensors as an emerging media technology. The intersections of communication about sensors and communication through sensors offer a generative lens through which to examine the nuances of how sensors are being imagined, developed, and adopted.

Second, we understand IoT and sensor-mediated communication as both communication-oriented and infrastructural technologies (Parks, 2015). IoT is made up of networks of sensors, and the ways that those sensors interact with one another, human actors, and their environments is a fundamentally communication-oriented process (Bunz & Meikle, 2017). Therefore, we describe sensing as a form of *local mediated infrastructure*. The datafication of environmental sensing information to meaningful and actionable "data" involves the collection, aggregation, and transformation of such information (Couldry & Hepp, 2017). For local IoT, this becomes a mediated meaning-making process facilitated through the combined and competing technological visions of the community members, municipal leaders, engineers, designers. As Loukissas (2019) argues, all data are local and require special attention to governance issues. We need to carefully consider what and whom it represents as well as what it lacks, what is missing, and who is missing. When we examine the social analytics (Couldry & Powell, 2014) of data generated through sensor networks, we can appreciate the value of aggregated information as well as real-time data collection for various local social actors, but also recognize the politics and limitations of sensor data within community contexts.

Third, amid prevalent discourses about technology "speeding up" the activities of everyday life (Sharma, 2014; Wajcman, 2015), we study local IoT as a purposefully *slow technology*. Within sustainable HCI (DiSalvo et al., 2010), there is a movement to avoid overdesigning technological artifacts, systems, and networks to help curb the looming environmental crisis. In this vein, our study utilized a low-power, wide-area network suitable for broader areas and using lower data rates to transmit information that does not change in milliseconds but more slowly over minutes. Focusing on a more rural context contributes to the growing knowledge, development, and implementation of more sustainable and local technologies that push back against fast capitalism and environmentally wasteful tech development (e.g., Abildgaard et al., 2021; Hetlinger et al., 2019).

Finally, we consider the Internet of Things beyond the "things" themselves, thinking past the object to examine networked sensing as an *environmentally-mediated sensory phenomenon*. While existing research on IoT has investigated personal devices and object-oriented sensors that "listen" to commands and track location or movement (Frith, 2019), less work has been devoted to understanding what it means to remotely sense the environmental conditions that surround and envelop devices as a primary function. Municipal IoT sensors are less often attached to specific objects or people than they are positioned optimally to pick up on atmospheric factors, from soil quality to energy consumption. IoT sensors are tactile devices that "feel" their relations to the world around them. People are constantly implicated in these environmental sensing configurations, both as users of the data they produce and as bodies within their sensory fields (Powell, 2021). Therefore, the ways that implicated actors understand and experience sensors are fundamental to their social and technological development and use.

Limitations and future directions

While the community-based nature of this study significantly contributes to the ecological validity of the research, our study may be limited in its generalizability. We only worked with one community. While the community's focus on agriculture is not unique to more rural communities, its strong commitment to environmental sustainability may be. Without a comparative case, we do not know how interrelated local commitments are to technological development for sustainable futures. Future community-based IoT research would do well to compare community values and IoT adoption.

Another limitation of this study is that it began during the COVID-19 pandemic, which prolonged the development of community partnerships. Therefore, it is likely that the project funding may end before we can collect long-term use data from the sensor networks. Prolonged engagement is paramount in qualitative inquiry. While our participatory methods help to develop community buy-in and trust in the network, long-term research on sensor network deployments in rural areas is important. Future research should examine long-term effects and developments of community-developed sensor networks.

Questions regarding sustained data governance practices will also be important to explore. Future research on IoT sensor networks should continue building citizen-driven applications across rural and urban environments, with special consideration to citizen values around data ownership and privacy. This rural case suggests the importance of localization in the development of sensor networks, but also in the sustained maintenance of the network and data. This study demonstrates how rural-mediated communication should not be understood as lacking, but as providing different opportunities for technological development and mediated communication.

Conclusion

Using observational research, interviews, and participatory workshops with IoT designers and rural community leaders, this article investigates community-based, rural IoT sensor networks. We examine sensor-mediated communication as rooted in communication through sensors, including how data are mediated and shared, as well as communication about sensors, or the discourses and values that shape sensor development. Furthermore, we focus on rural sensor-mediated communication in this study. Rather than assuming a "deficit mindset," we approach the U.S. rural context as an opportunity for unique communication needs as well as opportunities.

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Data availability

The data underlying this article cannot be shared publicly to protect the privacy of individuals that participated in the study.

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