How Smart Homes Learn: The Evolution of the Networked Home and Household

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Abstract. Despite a growing desire to create smart homes, we know little about how networked technologies interact with a house's infrastructure. In this paper, we begin to close this gap by presenting findings from a study that examined the relationship between home networking and the house itself—and the work that results for householders as a consequence of this interaction. We discuss four themes that emerged: an ambiguity in understanding the virtual boundaries created by wireless networks, the home network control paradox, a new home network access paradox, and the relationship between increased responsibilities and the possibilities of wireless networking.

Keywords: home networking, smart home, infrastructure

1 Introduction

As computing has migrated into the home, research exploring the implications of domestic technology has grown [2,5,6,8,14,29]. To date most research focuses on individual devices, although recently a few studies on networked systems have emerged [13,17,27]. However, home networking remains under-explored, and in particular, the question of how these networks interact with the home's infrastructure has not been addressed.

This omission seems problematic, given that domestic ubiquitous computing research typically relies on home networking. This home network is oft assumed to be seamlessly integrated into the home's infrastructure—the physical structure and services (*e.g.*, cable and electricity) and all those involved in their establishment and maintenance. In this paper, we report on empirical research that sought to determine whether these assumptions held true. We found that householders' home infrastructures do not readily enable home networking and we identify some of the challenges that the Ubicomp community will need to overcome if domestic ubiquitous computing applications are going to become widespread in people's homes.

We begin by reviewing domestic technology research. Then we describe our methods and participants and present the framework (based on [23]) used to organize our results. We conclude by discussing four themes that emerged: an ambiguity in understanding the virtual boundaries created by wireless networks, the home network control paradox, a new home network access paradox, and the relationship between increased responsibilities and the possibilities of wireless networking.

2 Background: Domestic Technologies and Home Networking

In the last decade, empirical studies of domestic technologies have surfaced a variety of themes. One set of studies has opened up the idea of "home" for investigation, and shows how householder's routines structure domestic life [2,6,29]. These studies have also shown that rooms—part of the home infrastructure—play a role in establishing and maintaining routines.

Other studies have explored the use of technologies such as set-top boxes [20] and VCRs [26]. These studies illustrate how users' adoption is a product of the interaction with the device. They also highlight how adoption is situated within broader contexts of the home (*e.g.,* routines and divisions of labor) [3]. Further, these studies comment on space use in the home, but also pick up on some of the complexities associated with the technical infrastructure required to manage devices.

Another category of studies has focused on the Internet, and its influence on domestic activities. Early studies, dominated by telecommuting, focused on the blurring of boundaries between employment and leisure, showing that work at home was negotiated as spaces changed to support the creation of home offices [30]. As Internet applications have evolved, studies have continued to report the evolving domestic uses of the network at home [7].

Finally, some studies of domestic technologies have deployed systems in the home. For example, systems such as CareNet, an ambient display for elderly health care, involved making a technological intervention within the home [5]. In these studies, home infrastructure comes up in the context of how and where the technologies are used, and also in deployment challenges.

While studies of domestic technologies have surfaced questions of home infrastructure—of which networking is a part—this has not been a primary focus. Smart home research, by contrast, has solved the problems associated with infrastructure through controlling the building of physical and computational infrastructure [14-16]. Yet, these living laboratories—often held up as a solution—also serve as testaments to the complexity of home networking because of the significant commitment required to make the problems "go away" [10]. Further, these smart homes exhibit an interesting duality, in that many of them serve as "offices" where researchers explore the possibilities of their technologies, and where the infrastructure itself might share some advantages of its office counterpart—the presence of administrative support. Yet, even in the office, reports of difficulties in encounters with infrastructure exist, particularly when it breaks [28].

More obviously, smart homes serve as a means by which to compare most housing stock. While smart homes have built in networks, most householders find themselves needing to retrofit their existing homes to accommodate new technologies (or decide whether or not to do this [19]). Relatively little research reports on the challenges associated with using the home's existing infrastructure for networked applications, but what does exist suggests difficulties [13,17,27].

Kiesler *et al.* [17] found that householders relied on family and friends, as well as service providers, to make their home infrastructure accommodate a networked device. More recently, Grinter *et al.* [13] identified problems with home networking including learning that householders relied on 3-7 companies to provide infrastructure support (*e.g.*: Internet Service Providers, cable, phone) on top of the work they did themselves. Although Grinter *et al.* comment on home infrastructure, their findings focused on the networks themselves, with limited attention to the infrastructure required to support it, and we sought to extend their results. We also expanded on Grinter *et al.'s* work, which was limited to dual-income couple households, by focusing on families with children and other household types—allowing us to explore the role of children in infrastructure work. Critically, we focused on home infrastructure centrally—grounding the troubles with networking in a broader context of technologies and services, and those who administer and support them.

Shehan and Edwards [27] propose a variety of futures for home networking. Many, if not all, of their models for the future rely on infrastructure agreements—for example, the outsource model which suggests professional home network provisioning (affordable for all). Inspired, in part, by their models, our research complements theirs by offering empirical evidence about the relationship between home infrastructure—the physical structure and services, and all of those involved in their establishment and maintenance—and home networking.

To analyze our data, we used Rodden and Benford's framework [23], which, although it speaks to Ubicomp broadly (and has been applied at the applications level [24]), emphasizes the relationship between infrastructure and technology. Specifically, Rodden and Benford applied Brand's [4] "layers" theory of home evolution showing how technologies fit in. They suggest that previous domestic research has largely focused on layers that change the most, and argued that little was known about the more stable layers—those focused on utilities. By doing that, Rodden and Benford made home infrastructure visible, highlighting interactions between the technical and physical, and the diversity of people responsible for systems administration. We will return to a discussion of their framework in Section 4. Next, we describe participants and methods.

3 Participants and Methods

Our study consists of 11 households (drawn from the metro-Atlanta area in the United States) with a total of 28 participants, including 5 teenagers who provided their perspectives on engaging with infrastructure (see Table 1). We recruited participants by word of mouth, email, and by visiting a high school parent-teachers association meeting, and we did not offer compensation. Given that our participants come from Atlanta, we recognize that our findings are physically, socially, technically and culturally grounded in household norms, that may not exist in other regions or countries (as others have observed [2, 25]) however, some of our findings echo and build on previously reported encounters with home infrastructure.

Table 1 Participants' demographics (house codes, occupants—occupation and children's ages if relevant—number of computers, wireless or wired computer network—check indicates presence, cross absence—type of Internet connection, and primary caretaker—network administrator—for AV and computer networks).

Home	**Occupants**	**No. of PCs**	**Wired**	**Wireless**	**DSL/Cable**	**Primary Caretaker AV**	**Primary Caretaker Computer**
P1	Boyfriend [Networking Administrator], Girlfriend [Grad. student, technical field]	4	✓	✓	Cable	Both	Both
P2	Husband [Marketing/Sales], Wife [Grad student, technical field]	3	✓	✓	DSL	Husband	Both
P3	Husband [Builder], Wife [Usability Engineer] (Children not living at home)	2	✓	✓	DSL	Husband	Wife
P4	Husband [Prof., technical field], Wife [Homemaker], Son (8), Son (6), Daughter (3)	2	✓	×	DSL	Husband	Husband
P5	Boyfriend [Office Manager in firm], Girlfriend [Grad. student, non-technical field] (engaged)	3	✓	✓	DSL	Boyfriend	Both
P6	Husband [Network Engineer], Wife [Usability Engineer], Son (4), Son (1)	7	✓	✓	DSL	Husband	Husband
P7	Husband [Office worker in business], Wife [Homemaker], Daughter [User Interface Designer] (24)	4	✓	✓	Cable	Daughter	Daughter
P8	BrotherA [Grad. student, technical field], BrotherB [Undergrad. student, technical field], Roommate	5	✓	✓	Cable	Brother A	Brother A
P9	Husband [Prof., technical field], Wife [Instructor, technical field], Son (14), Daughter (11), Daughter (<11), Daughter (<11)	5	✓	✓	DSL	Husband	Husband
P10	Husband [Prof., technical field], Wife [Grad. student, technical field], Son (15), Son (9)	7	✓	✓	Cable	Husband	Husband
P11	Husband [Businessman], Wife [Homemaker], Son (>11), Daughter (<11)	5	✓	✓	Cable	Husband	Wife

For our study, we defined a home network as having one or more computers connected to the Internet and to each other and/or a wireless network. Additionally, we included Audio/Visual (AV) equipment, at minimum a TV and a receiver. We included AV networks for two reasons. First, AV networks have been in homes for a longer time, and we wondered whether experience with them influenced computer networking. Second, and more importantly, AV and computer networks are converging, and we wondered about those challenges.

Clearly, these choices skewed our sample—typically one householder had considerable formal or self-taught knowledge of the technologies (which in and of itself speaks to the usability difficulties associated with home networking), but the other householders varied widely as to their backgrounds and knowledge of networking. We chose these people, despite their high-degree of technical knowledge that existed in most households, because these people were those who were attempting to set up, configure, maintain and evolve their home networks—and relying on household infrastructure to do so. We wanted to understand what real problems these people faced—with particular attention to those ones encountered by the less technical members of each household who might be more typical of the broader middle and upper classes (those who could potentially afford the services and technologies required to create a home network today).

Like Grinter *et al.* [13] we used a two-step data gathering process. First, we asked each household to complete an inventory listing all the computing and AV devices in their homes—allowing us to screen potential participants and customize the protocol for each home. Second, we arranged a home visit (which typically lasted 1-2 hours), which began with each householder sketching the computing, AV, and ideal networks. We noticed that some householders sketches used the physical form of the house to explain their networks (also observed in some of the sketches in [13]). After sketching, participants took us on a tour of their home showing us their networked devices. Proximity to particular parts of the network elicited explanations about the relation between the network and the infrastructure. We audio-recorded the interviews and tours, took photographs of devices, and asked questions. Finally, we finished the visit by asking any outstanding questions. Analysis consisted of transcribing the interviews and examining the resulting data (the interviews combined with pictures, drawings, and inventories) with reference to Rodden and Benford's framework. We report on our results in the next section—grouped around the layers of home infrastructure evolution.

4 Findings: Networking in the Evolving Home

Our findings are organized by the layers of Brand [4] as used by Rodden and Benford [23]. Brand [4] proposed that buildings are composed of six *layers* from the outside in: *Site*, *Structure*, *Skin*, *Services*, *Space Plan* and *Stuff*. *Site* is the fixed geographic location and boundaries of a building. *Structure* is the foundation and load bearing elements of the building. *Skin* refers to the external surfaces of the home. Embedded in Structure is the *Services* layer—the "working guts' of the building including all the wiring and plumbing. Interior layout is determined by the *Space Plan* layer, which includes walls, ceilings, floors and doors. All other things filling up the interior including furniture, appliances and decorative artifacts are called *Stuff*. Brand [4], differentiates each layer by how often it changes and the people who interact and manage it. For example, Structure changes infrequently because of expense and skill, whereas Stuff moves frequently. Responsibility for making changes tends to shift from professionals at Site to householders for Stuff.

Using these layers, we describe how householders interact with these layers as they setup, maintain and troubleshoot their home networks. Our data did not yield any significant interactions between Skin, the external surface of the building and home networking—it came up for one participant in a discussion of the aesthetics of the satellite dish on P3's roof. Consequently, we omit a section on Skin.

4.1 Site: Shaping Services and Managing Boundaries

For our participants, Site—the permanent restricted geographical setting—affected the types of Services available, and in so doing influenced the home network. Numerous participants described a Service, such as the inability to get a choice of Internet connectivity, *e.g.*, lack of Digital Subscriber Line, as limiting how they connected their home to a broader network. Additionally, Site affected what equipment (Stuff) our participants installed or required. For instance, one of our households, P6, said there were frequent power outages in their area, and consequently they installed Uninterrupted Power Supplies (UPS), a battery backup, to ensure that they could safely power down devices in an outage.

Reciprocally, home networking affected how householders' perceived their Site. Markedly, most of our participants did not know how far their wireless networks reached. Nor did they have a strong sense of the degree of mismatch between that and Site boundaries. And yet, participants realized the potential for mismatch because they saw the networks of other houses bleeding into their own Site.

Households differed in whether and how they managed this mismatch between their physical and wireless Sites. Several participants used Wireless Encryption Protocol (WEP) keys and Media Access Control (MAC) filtering to restrict wireless access to approved people on their own Site—a type of "digital Site boundary". Others expressed less concern about erecting these boundaries, because for example, they used their computer over a secure Virtual Private Network (VPN) to access work data (P1), and more generally they did not view other people as a threat. A more extreme example emerged in one interview where a household (P6) relied on the physical Site to contain and secure the wireless Site. As he put it:

"The only security is like we are 700 feet from the road."

A final reason for leaving the boundaries down emerged during the interviews—some households did not have the knowledge to secure their networks.

Ironically, while some participants expressed concern and took steps to erect digital Site boundaries, those same participants largely saw and used their neighbor's less protected networks. For example, when P9's Internet Service Provider (ISP) connection went down, the administrator used his neighbors open wireless network to contact his ISP and report the problem. In another case, P1 described how whenever their ISP went down, their laptop automatically connected to the neighbor's network, the next strongest signal on their Site. P1's householders reported feeling guilty about being able to see private files on this network but when asked about informing their neighbors about their lack of security one participant spoke of the convenience and utility of having another on-Site connection when their own went down.

In summary, Site affected householder's Services options and influenced Stuff purchases. The interaction between Site and wireless networks showed the most interesting problems (and while we recognize wireless networking is also tied to layers like Services for access to electricity and Stuff since a router is Stuff, we do not focus on these relationships in this paper). The mismatch between physical and virtual Site boundaries led some to find digital means to reassert the type of control that people desire over their physical property (even if that is not always possible either). Others' inability or lack of interest in erecting digital fences, allowed some of our participants to cross into their neighbors' virtual Sites and use their network.

4.2 Structure: Modification and Work Arounds

Households varied on whether, and how, they modified the Structure—load-bearing elements—of their home for networking. For example, P10 installed Ethernet in their home, when it was undergoing remodeling, to get a reliable high-speed network. They also built a basement office with a patch panel to centrally control sharing of cable, telephone and Internet connections throughout the house.

Other participants described more problematic encounters with Structure. For example, P11 explained that they wanted to install Ethernet around the house because of the reliability of connectivity (in comparison with wireless). The primary network administrator, the wife in this household, successfully crawled underneath flooring and drilled holes through wooden panels to connect most of the computers in the home. However, the Structure, and in particular a large wall *en route* to her son's bedroom was a sufficient obstacle, that she abandoned that part of the wired plan, opting for wireless to connect that particular machine.

P1 who also installed Ethernet to distribute Internet access around the house, explained that he preferred wired connections because of the security vulnerabilities associated with wireless security, also described difficulties working with Structure. He found drilling holes in the walls for cables time-consuming and in some cases, the holes did not lead to places where cables could be run. In this case, he persevered out of a strong desire to hide the wires. Indeed, our participants often spoke of aesthetics as a reason to engage with the Structure, to remove ugly wires that did not "belong" in sight or if not possible to consider the purchase of wireless technologies.

However, embedding the home network into the Structure of the home could and did cause householders' problems. For example, a participant in P4 laid Ethernet throughout his home while it was being built. After the home was completed, he discovered that he had a dead socket in his office. But, unwilling to tear apart the wall, he was unable to fix the broken connection.

A final unusual example of Structure challenges involves a household, P3, who sought to connect multiple buildings on their property—in this case a guesthouse to the main property. In this case, the household chose wireless, but perhaps more unusually, this decision was made by a regular guest to that home—as they explained:

"He works from StateX…then he comes to [sic] in to CompanyX … so he stays in the room above the garage and he's the one that set up the router so that he could have wireless access."

Despite these exceptions, most of our participants did not modify Structure for home networking, citing expense and complexity as deterrents. However, we were surprised by the number of participants who saw advantages in wired network infrastructure, reliability and speed, as compelling reasons to engage in complex home modification or take advantage of remodeling opportunities. And of course, for some, wireless networking was a means for working within or around Structure.

4.3 Services: Making and Designing the Network

Households used a number of Service layer technologies—the cabling and wiring that comes into the home from outside (*e.g.,* electricity) as well as the wiring inside the house. Participants described using Ethernet (a dedicated Service), and PowerLine and X10 technologies that both leverage existing Services in the home, the power network and telephone cables. Interestingly, while both Brand [4] and Rodden and Benford [23] suggest that third parties own the responsibility for this layer, our participants spoke of sharing the responsibility when it came to home networking.

This was most clear in the case of laying Ethernet. While two households contracted outside services to wire their homes—four households wired their own homes. Of all six households, four installed a patch panel to allow them to centrally control a variety of infrastructures implicated in converged home networking, the Internet, cable, and phone lines. All six households described Herculean efforts—working together, spread across the house, to determine which outlet matched which connection on the patch panel or where to drill holes for cables to wire their homes. When asked why some chose to lay their own cable, householders cited cost, specific needs such as high grade cabling, sockets in appropriate places, and to ensure a correspondence between the network and physical layout of the house in addition to not trusting third parties to do a good job.

Before commencing these, or even smaller Service projects, households frequently reported having design problems. Participants told us they found the process of designing how Services would support home networking time-consuming and requiring significant forethought (particularly if they wanted to design for continued growth and evolution of the applications and devices supported by the home networking). Perhaps unsurprisingly then, the most complex "home-grown" Service infrastructures came from people who had graduate degrees in computing.

One consequence of the complexities of planning Service infrastructures was on-line representations of the home networks. The system administrator for P8's network used Microsoft Visio to plan out Services-level changes to their home network. In this household, this diagram then subsequently served as a reference which he used whenever considering an update to the network.

One householder in P11 refined our understanding of what "home-grown" complexity meant. She self-described herself as having a lack of technical training, but yet was able to wire her house with Ethernet. She described the effort as hard physical labor, but not mentally complex. Indeed, what participants seemed to find complex as they took on responsibilities at the Service layer—not to underplay the physical labor—was managing all the constraints imposed by networking technologies. Systems needed to be proximate to multiple Services, such as power or data, and had to share a variety of resources, including in some cases limited outlets. Accommodating home networks' multiple and competing Service needs appeared to be at the heart of the complexity.

Our participants varied in their degree of engagement with Services. However, it was clear that by comparison with other accounts, particularly Brand's [4], householders in our study often needed to increase their engagement with this layer by taking increased responsibility. Specifically, they designed and planned how the home network could most appropriately interact with and leverage the Services.

4.4 Space Plan: Controlling Access and Aesthetics

Space Plan refers to a home's room layout including décor. Rodden and Benford [23] argue that previous domestic technologies studies have surfaced relationships between Space Plan and computing. Consequently, we focus on findings that speak to the less examined relationship between householders' use of Space Plan and the home network (as opposed to individual devices). Critically, home networks supported householders in bringing content into spaces of the house, and consequently we found that rooms played a central role in structuring access and engagement with both the computing and AV networks.

Four households in our study used permanent or portable computers in their kitchens. For example, a P8 participant used a computer in the kitchen to access other machines on both his home and work networks, but also to get recipes and check the commute times. He also described the kitchen computer as a convenient means for checking email and for continuing tasks he had originally begun on the computer in the bedroom upstairs. A P7 householder described why he decided to place his computer, which also serves as a TV, in the kitchen.

"I want it closer to the activities at the house. I didn't want to set it up upstairs. The kitchen is kind of a gathering place for us."

The ability to access new types of content in new places presented some of our participants with another challenge, focused on controlling access. Specifically, householders, particularly those with children, described using the Space Plan to create public and private spaces for computing and AV. Parents purposely placed the computers that their children used in rooms—such as kitchens and dining rooms—where the adults could supervise and monitor usage [18]. Simultaneously, other rooms were designed to be "off-grid" for children. For instance, the mother in P11 allowed her children to use their computers in their bedrooms but without an Internet connection (*e.g.,* by physically removing a wireless card from her son's laptop). This house had an Internet-enabled computer in the kitchen where the mother could monitor her children's online activities.

Householders also used their Space Plan to create more private places for some home network uses. We observed this phenomenon with AV networks, perhaps because the primary family equipment was usually placed in public space—such as the living room—[2,13]. Consequently, parents described watching "unsuitable" programming (for their children), *e.g.,* violent films, on AV networks in their bedrooms, which they characterized as a private part of their Space Plan.

Our participants used the Space Plan to create aesthetic and noise-free places. To mitigate the ubiquity of unsightly wiring, participants designated certain rooms as appropriate for highly networked technologies. For example, in P10 the mother moved her son's gaming systems (wires connecting gaming consoles to controllers, the AV network through the TV, and the Internet) to the basement to make her living room more aesthetically appealing. This move also had the effect of reducing noise levels in the shared and central parts of the house.

Participants also described using wireless networks to create a visually pleasing environment that still supported access to the home network. We see this type of aesthetic concern as speaking to householders' desire to work the home network into the décor of their homes. However, the interactions between wireless technologies and home infrastructure sometimes created problems. Households expressed frustration with poor wireless signals leading to loss of Service that they thought—correctly—were caused by thick walls and possible interference from other electronic equipment nearby (most notably the kitchen, a room full of appliances).

Participants described an interesting relationship between Space Plan and home networking. On the one hand, home networking changed the possible activities that could take place within the Space Plan, and was used to hide some activities in new places. Simultaneously, the Space Plan was used to constrain that same range of activities for some home network users, notably children. Finally, Space Plan was used to make some technologies disappear from certain rooms by designating other places as more appropriate or using technologies that would render the artifacts of home networking perceptually invisible. The latter was not without issue.

4.5 Stuff: Complex and Potentially Isolated

Devices—computing and AV related equipment—are the Stuff of the home network and householders add, move, and disconnect equipment. Householders moved equipment for various reasons. New equipment purchases often triggered the movement of an older equivalent to a different network (in the case of AV) or part of the Space Plan (in the case of the computer network). Inhabitants engaged in device migration for other reasons as well. For example, the P4 household moved their TV and purchased new audio speakers because they felt that the old position was sub-optimal for watching and listening. They reported leaving the old, unused speakers mounted on the wall because removing them was a complicated process.

Participants reported that the Service layer constrained their movement of equipment. For example, power and Ethernet wall plugs determined the position of some home network devices. Additionally, the placement of Service plugs, often determined and shaped the place of non-networking Stuff, used to enhance aesthetics. Participants told us about using carpets, rugs, cupboards and couches to hide the Stuff of home networking. We also observed examples of using Stuff of the home network to obscure other home networking Stuff, such as hiding cables behind TVs.

Complexity of device configuration and interoperability emerged as a theme when we examined the relationship between Stuff and home networking. In a study of AV networks, Petersen *et al.* [21] described how onerous participants found configuring their devices to work together, for example to make surround sound work. We observed similar difficulties emerging with computer network Stuff in this study.

These problems stood in stark and almost ironic contrast to the aspirations of all the participants in our study. Most householders in our study described wanting a fully networked home, one where they could share media between the Stuff of both computing and AV networks. Another surprisingly common theme in our study was the desire of our participants to be able to access, manipulate, and consume media stored on devices in one part of the house on devices in other areas of the home. For example, in household P11, participants connected and distributed speakers throughout the house so that they could listen to sports on the deck without having to place the radio there. Other participants indicated a desire to be able to listen to and watch the TV, located in their living room, from their kitchen while muting the sound in the living room, so as not to awaken their children.

Sadly, despite the desire to connect the Stuff of computing and AV together and across these networks, most of our participants had not attempted to do this in practice. Citing complexity, some households had simply not tried. Other households admitted that they lacked the in-home skill to connect Stuff. Following Brand, and Rodden and Benford's analysis, responsibility for Stuff falls to the householders, and this was certainly true in the case of home networking devices. And yet, participants spoke of a complexity that made this responsibility particularly challenging, a lack of detailed technical knowledge and the difficulties of connecting an eclectic mix of devices. The latter also appeared to exacerbate the former—eclectic Stuff included legacy devices that might be older than some householders themselves (hand-me-downs, or purchases made prior to the arrival of children)—consequently requiring knowledge of the history of the evolution of connection standards, and an awareness of whether and how these older devices could be "made to work" with newer ones.

The lack of device or Stuff interconnection had implications for the degree of "online" data interconnection. Most participants described transferring data among devices as being a process that involved USB flash drives, CDs or emailing the document to people with accounts on the target device. In other words, even though participants desired a networked home, they still used physical means or the internet to transfer information between devices, sometimes even in cases when these devices were connected together.

Only two households had connected their AV and computer networks, which they used to stream media from a server to a television. Both households had occupants who were technology aficionados and had created customized Linux solutions that turned machines into media centers. These individuals had also set up a complex system of switches to configure different input and output devices (*e.g.,* switching from DVD input to input from a computer server).

Given the complexity of connecting Stuff (within computer and AV networks, let alone crossing them), households resorted to a number of mechanisms for explaining the state of the network. For example, the P6 participants used notes and post-its on each wire going into various AV devices to remind them how their Stuff network was connected together. Other households, aware of the complexity of operating, let alone administrating or troubleshooting their networks, produced instructions. Participants told us that instructions were given to guests, babysitters, and children, to help them orchestrate the operation of the Stuff in the network. Our participants seemed to accept this work and responsibility, albeit grudgingly, to reap the benefits of home networking. In other words, participants produced instructions and reminders so that they themselves as well as their guests could understand and operate the Stuff that comprised their home networks.

Although Stuff has been a focus of previous research of computing in the home [23], home networking brings a new perspective on how householders' connections shape devices. Movement, while desired by householders, is constrained by Services, and the Space Plan. Additionally, the work of connecting devices is outside the reach of some households and creates a new burden—remembering and explaining the combined functionality to potential users. For our participants, the home network as a whole was more than the sum of its parts—an equation that pitted complexity of dealing with the whole against their own visions of a future with networked services.

5 Discussion: Reconsidering the Layered Smart Home

This paper used Rodden and Benford's framework [23] (based on Brand [4]) to examine the relationship between home networking and home infrastructure. Throughout the analysis we were struck by the need to consider aesthetics in the design not just of Ubicomp technologies, but in the infrastructure required to support them. Aesthetics caused our participants to take up challenging projects, notably hiding things because of their lack of appeal, even if that meant opening up walls. As a community clearly we need to consider the role that aesthetics can play in the easy adoption of the solutions we seek to provide. In this section, we turn to a discussion of four other themes that emerged as householders engaged with infrastructure. First, we discuss an ambiguity in understanding the virtual boundaries created by wireless networks and the need to design systems that help users manage these boundaries more easily. Next, we revisit the home network control paradox, particularly for avid network tinkerers, which suggests that householders may need to be supported through appropriate metaphor and network visualization. We also present a new home network access paradox arising when children are present in the home that affects the types of network management systems we design. Finally, we discuss the relationship between increased householder responsibilities for home networking and how wireless networking and external service providers may help ease the burden of networking the home.

5.1 Re-Placing Site Space: Exploring Physical and Virtual Boundaries

Focusing on Site highlighted a mismatch between physical and virtual boundaries. Physical Site boundaries are, according to Brand [4], the most immutable of outlines, being the least likely to evolve over time because change requires working with governmental agencies to have lines redrawn. By contrast, wireless networks presented our participants with new ways of considering their and other households' Sites by being able to bleed over physical boundaries.

Our participants had mixed responses to what it meant to have a virtual Site to manage. Some did little to prevent others "trespassing" onto their virtual Site, taking advantage of the resources on offer in that other Site but others sought a variety of technical solutions. One was to share their virtual Site, but protect their own access by using technologies such as VPN. Another was to attempt to erect boundaries, akin to virtual fences, using WEP and MAC controls. Finally, we found people who seemed unaware of the implications of this potential mismatch, or that they were creating a new Site, one that was accessible in ways that their physical Site typically is not.

One interpretation of this observation concerns security. Clearly, the difficulties that some of our participants had in using security to establish and manipulate virtual Site boundaries—not to mention the fact that even if they did use WEP, they had not technically secured their network [1]—speaks to the need for usable systems.

Ubiquitous computing for the masses presses particularly on this because the types of applications proposed often contain potentially sensitive data; for example, household rhythms tracked by sensor networks could reveal appropriate times to rob a home, or health data transmitted to the doctors office could expose illnesses—exposure being particularly serious if it reveals that a householder has a socially stigmatized disease.

However, another argument suggests that designs that treat virtual and physical Sites as equal exclude other possibilities. Another interpretation of our findings is that Site concerns speak to another debate, the re-placing of space [9]. Physical Site, grounded in a set of practices about land management seemed natural to our participants—taken for granted as a consequence of a long-ago institutionalized set of governmental arrangements—thus lending themselves to an interpretation of space as a "fact". By contrast, Sites created by wireless networks did not have this property. Instead they produced mixed responses, some seeking to erect walls and some not minding if others used their networks, suggesting that the virtual Site has not become as solidified in people's and practices. Indeed, we would argue that the ambiguity in interpretation of "appropriate behavior" in a virtual Site was even more pronounced among those participants who created their own fences while simultaneously exploiting the lack of boundaries around other's wireless networks.

Like others who have explored occasions where multiple interpretations exist [11], this ambiguity presents an opportunity for Ubicomp designers and we should perhaps not rush to constrain the virtual to the physical. As Dourish [9] argues, technologies present an opportunity to reconsider our spatial experiences and—for ubiquitous computing—this offers a possibility to explore how we might leverage wireless technologies to help people reconsider what their virtual Site contains. But, solutions that allow people to manage security, while not binding the virtual to the physical, will likely involve creating applications that give end-users a degree of choice in whether to, and if so, how, secure and bind their wireless networks. This calls for further work to understand what types of choices ought to be provided, and how to offer them to end-users in meaningful ways. In addition to partnering with usable security researchers, as a first step, we suggest considering questions of Site and spatiality, something that Rodden and Benford's [23] framework supports.

5.2 Managing Networked Stuff: Revisiting the Control Paradox

In a seminal study of family life in a smart home, Randall [22] identified a control paradox (also suggested by [8]). Simply put, the smart home's systems for controlling the lived experience were so complex that some, if not all, of the householders experienced a lack of control along with an intense frustration. Even the simple functions such as turning lights on and off required complex manipulation of menu-based systems with householders being irritated and uncertain whether they could in fact complete their task.

In our participants' homes, we observed phenomena that suggested a similar type of control paradox, in this case a control of network paradox. On home tours, and in the spaces where we interviewed people—although sometimes they had been tidied away prior to our arrival—we observed evidence of multiple remotes. We also learned about and noticed maps and instructions to support the manipulation of systems. These mechanisms suggest that the control paradox exists in "normal" homes, and as we learned, people respond through persistence in use and by creating a number of representations that explained the network to them.

We also saw a difference between Randall's control paradox and some of the ones that we encountered. In particular, some of our participants' networks seemed to be in a continual on-going project state. Attempts to upgrade and refine the network often seemed to lead to further projects. Intriguingly though, when we asked about these projects, we were sometimes left with an impression that some householders saw the home network as a Do-It-Yourself project. The lack of control that resulted when the project was on-going (sometimes spanning weeks, while the householder did not have leisure time to continue working on the project) led to a certain lack of control that appeared self-inflicted, and based on a desire to explore home networking recreationally. We suggest that these projects constitute part of the nascent *Digital-Do-It-Yourself (DDIY)* culture that will likely exist for the network infrastructure as it already does for the physical infrastructure [12]. And although DDIY-ers do not represent all potential consumers of Ubiquitous computing technologies, they raise questions. For example, what does it mean that the systems that we design will be potentially altered, upgraded, and implicated in projects that restructure the home network and its services? Ubiquitous computing systems are typically designed from end-to-end, as whole solutions implemented to solve a particular problem. But, when they enter certain environments, they may be disassembled, rearranged, and partially upgraded. How do we account for this in our design process?

Irrespective of whether our participants engaged in DDIY, we saw people coping with control by generating representations—notably maps and instructions. But these representations were woefully inadequate for dealing with many aspects of the "seeing" that participants desired in order to make their home network work. They did not have representations that allowed them to see obstacles inside the Structure, or the ability to see the Services offered to their home, let alone the ability to map between their virtual and physical Sites. We see opportunities for reconsidering representations, and in particularly designing new types of network visualization that are householder-centric rather than technologically-centric. Today's network visualizations target network administrators, as opposed to home users, resulting in systems that focus on specialized network-technical details [27]. Taking a household-centered approach, we would argue that exploration of the control paradox through the perspective of layers suggests a variety of complementary visualizations that could support home networking. Visualizing the physical Structure of the home, creating maps that show the range of wireless devices (based on signal type) and representations that support roll-back to previous network states would all increase householders' sense of control. But, we also see the need to understand what types of metaphors would make the most sense to householders, and suggest a need for further research to understand what metaphors could be leveraged.

Beyond representations, control speaks to what it means for the network to work or not. Specifically, networked Stuff adds a dimension of complexity, transforming the network into something that spans the Services and Stuff layers, because it requires devices to provide service to the applications on it. So, unlike Service level failures—electricity and water outages—the network itself, not the applications on it, could partially fail if one device ceased to work. These partial failures, of Stuff in the service of Service, were particularly troubling for participants to diagnose and repair, but all speak to what it means to control the network.

5.3 Space Plan: Introducing the Access Paradox

Our study suggests another paradox related to access to the network. Our examination of Space Plan showed that in homes with children the Space Plan and home network interacted to simultaneously increase and decrease access to content.

Adult participants in our study described how their network allowed them to reconfigure their use of space increasing their opportunities for networked-based activities from a variety of rooms within the home, such as the kitchen. Simultaneously, these same adults described two types of restricted access that turned on manipulating the Space Plan—and the behaviors appropriate or possible within that—in conjunction with the home network. First, they described carving out a private space for the consumption of sensitive media, such as films deemed too violent for children. In this case, the home network again supported a redirection of activities, out of public spaces and into more private ones. Second, they described using the Space Plan to restrict their children's access to and use of the very content that the home network provided. By disconnecting machines from the network that were in isolated parts of the Space Plan, and by placing connected computers in public settings such as the kitchen, adults described how that provided them a sense of control over the access that their children had to the Internet in particular.

Contrast this with some visions of Ubiquitous computing, and the networks that support it, that tend to emphasize increased access. In homes with children, increased access is not always desirable, instead the ability to control and manipulate access is desired. In some cases, this might be possible by simply disconnecting devices, but when that is not the case, we need to be open to the design of systems that can be virtually disconnected (which again speaks to a relationship between Ubiquitous computing and the usable security community).

Beyond access controls, Space Plan highlights the relationship between technical and social infrastructures. This has been commented on before with a focus on particular devices in rooms (*e.g.*, [2,6,20]). Our study suggests that the home network is also implicated in this relationship and must be deeply considered to both provide and facilitate content provision while simultaneously restricting access. In particular, the home network is technically neutral, providing the possibility of access throughout the Structure and Site, but it is the Space Plan that seemed to highlight and shape the access paradox. In particular, the householders' manipulation of the Space Plan framed their decisions about access. We suggest that this insight offers an opportunity for reflection by the Ubicomp community. How will Space Plan shape the ways in which householders seek to adopt and use, or restrict and deny, access to systems based on their presence in various rooms of the home? Minimally, we argue that considering these questions in the deployment of systems in homes, particularly those with children, may yield implications for the results of these experiments.

5.4 Service and Responsibility, Structure and Wireless

The Service and Structure layers also spoke to issues that we wish to revisit. The Service layer revealed a changing shift in responsibility. In comparison with Brand's description of this layer—one where external parties made changes, and thus guided its evolution—we observed a greater degree of household responsibility for designing and delivering the Service of the home network.

One reason why participants took up the work of designing the Service was that they told us that they did not trust external parties. External service providers had not, in the eyes of our participants, yet reached the stage where they were able to design a home network that met our householders' needs. One explanation of this situation relies on a temporal argument that some people, our participants, at least in this region, at this time, have such "cutting edge" expectations of what a home network should be that they cannot find an appropriate contractor. This suggests that in time the situation could change and eventually outside sources will be sufficiently sophisticated to make modifications to the Service layer—retrofitting houses for Ethernet and so forth with the technical ability required to produce home networks for complex and varied needs (although, as Shehan and Edwards observe there are downsides to this particular approach [27]). But, if this is the case, then the Ubicomp community might take heed of, and potentially encourage the emergence of these outside service providers, to ensure that they enable ubiquitous computing services. Further, the evolutionary properties of home networking suggest that the external service providers will also have to evolve their services to meet the demands of the changing home network or supply enough access that householders can do this work.

Another potential explanation is that responsibility is permanently shifting for this layer. Outsiders will not emerge to provide Service, and householders will either develop their own knowledge and skill, or be unable to have home networks. This latter argument poses significant challenges for the Ubicomp community—if a class of people cannot or choose not to accept this responsibility for Service, and if external providers do not fill the need, or if their services are not largely affordable—we have a situation where our user base is the manifestation of the next digital divide. This divide would be based on financial and technical literacy needed for home networking Service and all the applications it makes possible.

Into this mix comes the hope of wireless technologies. Within this study, we observed participants using wireless technologies to work around the constraints and complexities imposed by interactions between wires and virtually every layer of the home. Yet, we were surprised to find, despite wireless, there was an enthusiasm and need for wired solutions. Participants spoke of reliability, speed and security as reasons for wanting wires. Further, participants showed us legacy equipment that was not ready for (or ever would be) for wireless solutions. Old computers, and favored AV equipment such as receivers and amps, ranged in ages by as much as decades.

Again, we can view this as a temporal anomaly and assume that with time, the oldest of machines will be out of the house, and the new so-called "old" machines will be running 802.11b wireless technologies. One problem with this argument is that by the time this occurs, there is a distinct possibility that the newest of technologies will no longer support that wireless standard. More generally, wireless hints at a problem that the age range of technologies, that are not as uniformly new as those found in the workplace, presents challenges for the types of systems that the Ubicomp community seeks to design.

6 Conclusions

We used Rodden and Benford's framework [23] to explore the relationship between home networking and home infrastructure. We discussed four themes: an ambiguity in understanding the virtual boundaries created by wireless networks, the home network control paradox, a new home network access paradox, and the relationship between increased responsibilities and the possibilities of wireless. More generally, we offer this research as a starting point for discussions within the Ubicomp community about for whom and how the home network will be designed.

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