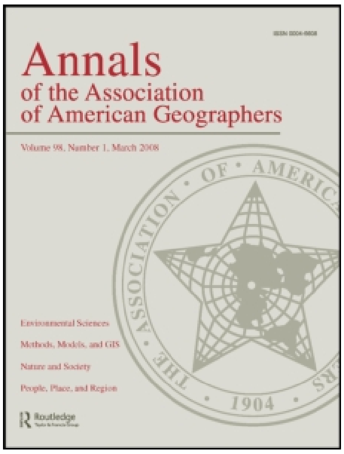

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Wi-Fi Geographies

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Wi-Fi Geographies

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Wi-Fi marries Internet-based networking and radio broadcasting. Although still nascent, the technology is wildly popular. Geography is a central consideration in the functioning of Wi-Fi technology. Yet, its influence is just beginning to be investigated. Examination of the space of Wi-Fi poses problems as wireless data traffic is invisible to the eye and its underlying apparatus is impromptu and veiled to traditional geographic inquiry. A scheme for detecting Wi-Fi infrastructure and transmissions and analyzing their geographic properties is introduced in this article. The application of the scheme to the study of Wi-Fi geography in Salt Lake City, Utah, is described. A dense network of impromptu Wi-Fi infrastructure is found to permeate the city's built environment and the urban area has been blanketed in a fog of Wi-Fi transmissions without any centralized organization. This Wi-Fi cloud is surprisingly resilient to network and physical problems, although the early signs of geographically systematic throughput difficulties are evident in parts of the urban area. Wi-Fi appears to offer a solution to last-mile problems in the city and bucks the trend for polarization of the population on either side of a digital divide, at least for those with access to Wi-Fi-enabled hardware. Wi-Fi was found to strengthen existing urban geography. Activity is most prominent in the city's traditional commercial core. However, Wi-Fi also reaches out to interstitial and peripheral parts of the city. Although commercial penetration of Wi-Fi misses the traditional tourist and retail areas of the city, public Wi-Fi is being used to encapsulate and reinforce civic space in the city. *Key Words: communications geography, cyberspace, Internet and Communications Technologies, urban geography, Wi-Fi.*

无线网络结合了无线电广播和以互联网为基础的网络。虽然还处于萌芽状态，这项技术已经非常流行。地理学是运作无线网络技术的一个重要考虑环节。 然而， 其影响力才刚刚开始被学者进行调查。 研究无线网络的空间将构成问题，因为无线数据流量是肉眼看不见的，其背后的器具是即兴的，也是传统的地理调查所不能揭示的。这篇文章将介绍一个探测无线网络基础设施和传输系统，并分析其地理特性的方案。这项方案形容了盐湖城，犹他的无线网络地理性质。此研究发现整个城市环境渗透着一网稠密即兴无线网络的基础设施。城市地区被没有任何中心组织的无线网络包裹着。虽然地理系统吞吐量的困难在部分市区早已显现，然而无线网络对网络和物理问题的弹性令人惊讶。无线网络似乎是最后一英里问题的一种解决办法。此外，至少在那些可以获得具无线网络功能硬件的地区，无线网络也加深了人口在数字鸿沟两极化的趋势。这项研究发现无线网络能加强现有的城市地理。最为突出的活动区在城市的传统商业核心。然而，无线网络也渗入到了以间质和周边的部分市区。虽然商业无线网络未能渗透到城市里传统旅游和零售业等领域，公共无线网络已被用来概括和强化在城市里公民空间。*关键词：通信地理，网络空间，互联网和通信技术，城市地理学，无线网络。*

Wi-Fi se une a las redes basadas en Internet y a la radiodifusión. Aunque está recién nacida, la tecnología es extremadamente popular. La geografía es de consideración central en el funcionamiento de la tecnología Wi-Fi. Sin embargo, su influencia apenas se está investigando. El análisis del espacio de la tecnología Wi-Fi posee problemas, ya que el tráfico inalámbrico de datos es indetectable por el ojo humano, y su sistema subyacente es improvisado y está encubierto a la indagación geográfica tradicional. En este artículo se presenta un plan para detectar la infraestructura y transmisiones de la tecnología Wi-Fi y el análisis de sus propiedades geográficas. Se describe la aplicación del plan en el estudio de la geografía Wi-Fi en Salt Lake, Utah. Se ha determinado que una densa red de infraestructura Wi-Fi improvisada ha impregnado el entorno citadino, y el área urbana se ha cubierto de una niebla de transmisiones Wi-Fi que carecen de una organización centralizada. Esta nube Wi-Fi es sorprendentemente resistente a los problemas físicos y de red, aunque son evidentes signos prematuros de dificultades geográficamente sistemáticas en la capacidad de procesamiento en partes del área urbana. Wi-Fi parece ofrecer una solución a los problemas de "última milla" en la ciudad y va en contra de la tendencia de polarización de la población en ambos lados de la línea divisoria digital, al menos para aquellos que tienen acceso a equipo capacitado para Wi-Fi. Se determinó que Wi-Fi fortalece la geografía urbana existente. La actividad es más prominente en el núcleo comercial tradicional de la ciudad. Sin embargo, Wi-Fi también alcanza las regiones intersticiales y periféricas de la ciudad. Aunque la penetración comercial de Wi-Fi no toca las áreas turísticas y

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minoristas tradicionales de la ciudad, esta tecnología se está usando para encapsular y reforzar el espacio cívico en la ciudad. *Palabras clave: geografía de comunicaciones, ciberespacio, Internet y tecnologías de comunicación, geografía urbana, Wi-Fi.*

One hundred years have passed since the first wireless voice transmission by radio. Wireless data have been coursing through our cities in analog form for decades since Reginald Fessinden's tests of 1906 (Fessenden 1902; Grant 1907). For many years now, digital data have been hitching a ride on the airwaves. Devices designed to catch and communicate wireless digital data are used by a majority of the population in many countries. In recent years, however, the clouds of wireless data that envelop our cities have taken on a newly disruptive (Christensen 1997) relevance, as new technology for wireless communication has begun to infiltrate the airwaves. Wi-Fi (for Wireless Fidelity) is at the forefront of these developments.

Wi-Fi technology is used to exchange digital data between machines on computer networks as radio signals over the airwaves. In its most popular deployment, Wi-Fi is used to broadcast data packets from the Internet, allowing users to decouple from desktop terminals and fixed, hard-wired, connections to networks. Wi-Fi is most commonly configured in the following fashion. A Wi-Fi access point is connected to a wired network, cabled to Ethernet or a telephone line, for example. The access point essentially behaves as a device that converts data conveyed along that cable into radio waves and broadcasts them into the surrounding environment. Wi-Fi modems operate as two-way radios that can capture radio waves for interpretation on a client device, and can in turn communicate via radio to the access point. The two-way communication allows for data to be exchanged over the airwaves and subsequently routed on the wired Internet to which the access point is tethered. The connection to Internet technology is intrinsic to Wi-Fi with the advantage that Wi-Fi communications can function amid the Internet Protocol (IP), the set of codes that allow data to be packet-switched by routers and proxies (the hardware that collates packets of digital data and routes them to their destinations) and scoured by Webcrawlers and bots (computer programs that search and chart networks and their online content). Different Wi-Fi standards determine the form that the radio wave takes as it passes through the air. There is a trade-off in the ingredients that govern this form, between the frequency of the radio signal, the rate of data exchange (bandwidth) that is capable, and the geographic range over which broadcasts can travel. Lower frequency transmissions tend to have relatively greater spatial reach, but higher frequencies support more bandwidth.

Other wireless technologies operate with the same basic physics and with similar IP capabilities: cellular telephony, Radio Frequency Identity (RFID) equipment, Bluetooth networking hardware, wireless microelectromechanical systems (MEMS) that operate as smart dust motes on sensor webs, and so on (Kahn, Katz, and Pister 1999; Sharma and Nakamura 2003). Cellular telephony, in particular, has diffused rapidly through the world with the exception of much of Africa beyond South Africa and the Mediterranean coast. The number of cell phone users worldwide is estimated at 1.75 billion (International Telecommunications Union 2006).

Wi-Fi networks, although not as widespread as cell towers, are wildly popular. Wigle.net, a Web site that maintains statistics on the deployment of Wi-Fi access points, contains records of 8.78 million access points at the time of writing. Jones and Liu (2006) reported a total of 5.6 million access points over select cities in the United States. The worldwide user base for Wi-Fi is forecast to climb to 271 million by 2008, with 177 million of those in the United States (Hills 2005). As recently as June 2006, there were an estimated 6 million Wi-Fi users in Spain alone (El Pais 2006), 15 percent of the population. There is rapid growth in use of the technology. Gartner (2004), for example, estimated a tripling in the Wi-Fi user base between 2003 and 2004.

Wi-Fi technology has had a disruptive influence (Christensen 1997) since its introduction in 1996 (O'Sullivan et al. 1996) and the start of its commercial popularity in 1999 with Apple's AirPort access points and modems, representing a challenge to telecommunications standards. The *New York Times* has already begun to speculate that Wi-Fi telephony (such as voice over IP, or VoIP) will displace the current business model used by cell phone providers (Richtel 2006). In business parlance, Wi-Fi is perhaps the killer application (Downes, Chunka, and Negroponte 2000) for networking, for several reasons. There is a primary appeal in the simplicity of its design: it has roots in traditional technology (radio) but retains the ability to interact with current-generation technologies (IP and the Internet). Wi-Fi is powerfully seated at the convergence of these technologies. Barriers to development of Wi-Fi hardware are low. Wi-Fi operates in a relatively unlicensed and experimental space of the radio spectrum. Users of devices in this spectrum are often free from licensing requirements. Moreover, common standards and protocols for development of Wi-Fi devices are relatively open source and thus available to the public. This stands in stark contrast to cellular telephony, which has closed intellectual property, is dominated by major commercial enterprises, and is tightly licensed.

The potential for Wi-Fi to foster equivalent disruption in society is only beginning to be explored, but it is intricately bound to geography. Wi-Fi's innovation relies on its spatial functionality and the potential for wireless connectivity to networks to become ubiquitously ambient. The mobility afforded by Wi-Fi frees users from the geographical inertia of wired hardware, broadening the range of possibilities for Internet and communications technologies (ICTs) to influence human activity. The opening of further digital divides as a consequence of Wi-Fi growth could result in sociospatial polarization, and the erosion of digital divides might level the playing field, geographically, between digital haves and have-nots.

Research into the implications of Wi-Fi diffusion has largely focused, thus far, on business issues and sociological factors. Rheingold (2002), for example, has begun to chart new sociologies of smart mobs, converging around and enabled by the technology. The United Nations has launched an initiative to explore the potential for Wi-Fi to bridge digital divides (Brewin 2003).

Studying the geography of Wi-Fi infrastructure and the space of flows (Castells 1996) over the airwaves is challenging. Both are relatively ethereal. As with wired networks, the infrastructure for Wi-Fi (access points) is sequestered behind the closed doors of businesses and homes, but because the airwaves take the place of wires, Wi-Fi often has little physical presence on communal property. The airwaves serve as the conduits for Wi-Fi data traffic and although ambient, they are invisible to the naked eye and much of the remote sensing technology commonly available to geographers; they cannot be easily observed, counted, or tracked by conventional geographic inquiry. Like Gertrude Stein's (1936) interpretation of Oakland, or William Gibson's (1984) vision for cyberspace, there's no there to study.

Work at the intersection of Wi-Fi technology and geography is in its infancy. Research falls into three broad classes—mapping of infrastructure, coverage, and use. Infrastructure mapping generally involves charting access point locations, or estimating their likely location. Such data are popularly reported in online databases for various cities; worldwidewardrive.org, Wi-Fimaps.com, nodedb.org, and wigle.net are among well-known examples. Anonymous users and enthusiasts contribute to those repositories and there is generally no quality control or assessment of the veracity or reliability of the data they contain. Many community hotspots and commercial providers also maintain maps of the access points that form their network.

A handful of researchers have mounted expeditions to map likely access point locations. LaMarca and colleagues (2004b) at Intel Research examined three small neighborhoods in the Seattle metropolitan area as part of an investigation into the feasibility of Wi-Fi as the basis for an alternative positioning system. Grubesic and Murray (2004) reported access point locations for four noncontiguous districts of Columbus, Ohio, as part of an investigation into the link between Wi-Fi provision and the socioeconomic and demographic geography of the city. Work by Byers and Kormann (2003) is representative of more comprehensive exploration into access point locations; they report data for a large section of lower Manhattan, although whether the data come from a public online database of location submissions or from scanning is not reported. Jones and Liu (2006) have run analyses to estimate the likely location of more than 100,000 access points in northern Atlanta from a commercial database.

Work on Wi-Fi signal coverage involves mapping the potential range of Wi-Fi broadcasts from access points. Lentz (2003) has mapped signal coverage on university campuses in a surrogate fashion by drawing circles around access points to denote the farthest distance at which their signal was sampled. The Information and Telecommunications Technology Center at the University of Kansas have interpolations of signal strength for small parts of Lawrence, Kansas, on display at their Web site (http://www.ittc.ku.edu/wlan/index.shtml). Kamarkis and Nickerson's (2005) investigation of Wi-Fi at Stevens Institute of Technology used interpolation to estimate coverage from thirty access points on that campus.

Relatively few studies have explored the uses to which Wi-Fi infrastructure is put. Sevtsuk and Ratti (2004) studied the rate of use of access points on the MIT network, as compiled from logs of data traffic through the university's servers. Schmidt and Townsend (2003) have examined the number of users on public and commercial Wi-Fi networks in New York, finding comparatively minimal use of commercial resources.

The work reported in this article takes on the challenge of building on this existing foundation of expertise, but also seeks to delve further into the geography of Wi-Fi in urban areas. First, I am interested in mapping and visualizing Wi-Fi presence in urban settings. Second, I explore the underlying infrastructure that supports Wi-Fi data traffic. Third, I study the technical functionality of that infrastructure and its associated cloud of Wi-Fi transmissions. Charting the geography of Wi-Fi coverage across a variety of scales is a fourth objective. The fifth focus is on the uses to which Wi-Fi technology is applied and the extent to which Wi-Fi geography encapsulates urban space for given activities. Sixth, I turn my attention to the spatial structure of Wi-Fi clouds. Spectrum geography is a seventh interest and examination of the security landscape of Wi-Fi is an eighth objective.

The background to the research and its objectives have been detailed in this section of the article. The remainder of the article is organized as follows. The theoretical foundation for the research is laid in the next section. The methodology employed in realizing the objectives of the work is described in detail in the following section. The results of applying that methodology to study of Wi-Fi geography in Salt Lake City are discussed after that, ahead of concluding remarks in the last section.

Wireless Telecommunications and Geography

Exploration into the geography of wireless telecommunications invariably involves consideration of the geography of wired telecommunications. Wi-Fi takes over where wired networks leave off and comes into its own in performing tasks that wired networks cannot accommodate.

Wired telecommunications and geography have an entangled relationship. Wired ICTs allow some activities to be mediated by networks, replacing or supplanting the importance of geography as a central concern in some instances. ICTs have, for example, contributed at least partially to the decentralization of some business activities from urban centers and the outsourcing of others to overseas locations (Castells 1996). This has led to well-published announcements of a decline in the relevancy of distance in shaping human geography (Cairncross 1997). There are, however, a majority of human activities that are immune to the effects of ICTs on their geography (The Economist 2003). Moreover, a plethora of well-documented examples exist to support the notion that wired ICTs have reinforced existing geographies (Graham 2001; Townsend 2003). The Internet backbone has, for the most part, seen its infrastructure concentrated in world cities and regional urban hubs, further cementing their positions atop the central place hierarchy (Graham and Marvin 1996; Moss and Townsend 2000). Existing economic divides have been carried through to form fissures between digital haves and have-nots, with both economic (Zook 2002) and social geography (Castells 1996). Wired ICTs are also shaping new emerging geographies and cyberplaces. A new business model has emerged around a decentralized economic geography amid an information economy adjusted to just-in-time production that relies heavily on networks (Castells 2001). Within the wires, a cyberspace of virtual worlds and telemediated social activity is forming and cementing its influence on popular culture (Rheingold 1993; Kitchin 1998).

Relatively little research has addressed the relationship between Wi-Fi and human geography, but existing progress in this field suggests that the consociation is significant in several respects.

Communications Geography

The latent connection between Wi-Fi and existing communications geography is a primary consideration in charting the potential influence of the technology. The existing territory for most telecommunications has a level of inertia, constrained by the historical geography of previous generations of communication infrastructure (Standage 1998). Fiber-optic lines often follow existing conduits and rights-of-way charted by the installation of copper telephone lines, themselves following a geography based on telegraph routes, which in turn inherited mail routes, and so on (Moss and Townsend 2000). The deployment of the Internet and World Wide Web saw the development of a plait of servers, clients, and proxies bound tangibly to fixed wiring, with fettered communication over networks along those conduits.

Although Internet-based communications have the potential to be always on, charting the geography of these networks has proven to be difficult. The infrastructure, although tangible, is often hidden underwater, within walls and ceilings, underground, or under floorboards (Mitchell 1995). Unlike flows of goods along highways, network flows are immaterial to traditional geographic consideration, conveyed as analog electrical currents or rays of light and veiled in a haze of computer protocols and encryption where they are collated as data on computer hardware.

Communications geography has traditionally focused on the physical space of networks, the geography of their infrastructure (Graham and Marvin 1996; Gorman and Malecki 2000; Moss and Townsend 2000). These spaces are difficult to capture quantitatively, although efforts have been made to visualize such spaces and index their attributes cartographically (Dodge and Kitchin 2000). There is also a body of social theory work in this area (Adams and Warf 1997), particularly associated with vocabularies and metaphors of space and place (Adams 1997).

Wi-Fi, based on a tethered connection to a wired broadband line and so harboring the same abstruseness for research inquiry, is an even more ethereal phenomenon. The conduits for Wi-Fi communication—the airwaves—are ubiquitous, thereby diluting the ease with which their geography as a supporting infrastructure might be charted. It is difficult to trace the journey of a Wi-Fi broadcast once it leaves an access point and is absorbed in the ambient environment.

Urban Geography

The potential for Wi-Fi to influence urban geography is quite profound. Several cities have announced their intent to provide municipal Wi-Fi access, for free, to citizens and visitors. There is an expectation that Wi-Fi can bridge the urban digital divide, attract tourism, and bolster the existing economic and social capital of cities. Citywide hotspots are firmly in the future of Wi-Fi. A distinct protocol for metropolitan-wide Wi-Fi communication has been formulated in recent years: 802.16 for Wireless Metropolitan Area Networks (WMANs), popularly referred to as WiMAX. These protocols provide functionality to support large-scale Wi-Fi coverage.

It has long been argued that ICTs bolster existing links between urban centers of power and influence (Castells and Hall 1994) and this trend appears to continue with the development of successive innovations in telecommunications technology (Townsend 2001). The power of Wi-Fi networks grows, at least conceptually, as the density of their use increases and they reach potency as the volume of collaborators on the network increases. This is the idea behind mesh networks (Sharma and Nakamura 2003). As more users swarm to a Wi-Fi network, adding access points (or client–server devices), the collective benefits to the user community expand. This has led to speculation that urban environments might serve as ideal agglomeration economies for Wi-Fi (Rheingold 2002). Collective capital is more likely to amass when the infrastructure and its protocols are held in the commons (Lessig 2000, 2002). This favors populations living in dense urban areas, because of the sheer volume of devices likely to be deployed and the volume of consumers of network resources. The dominance of large cities would seem to attenuate with a degree of positive feedback in these cases, arguably with a centralizing influence on urban structure with Wi-Fi-oriented activities agglomerating in central cities.

There is, however, a convincing thesis in favor of decentralization of urban structure under Wi-Fi, on the basis of the potential benefits of using Wi-Fi to solve last-mile problems. Hard-wiring rural areas and interstitial sites between urban masses is challenging because of the difficulty of connecting users to the network backbone due to the low density of population in these areas, the relatively large distances of sites from central service facilities, and the economics of providing a costly service to relatively few users. Townsend (2003) has estimated the costs of fiber-wiring homes to be \$2,000 to \$5,000 per house and the figure is presumably more expensive in remote areas where distance to the nearest backbone is greater. The hope is that Wi-Fi can be used to create low-cost wireless lilypads of last-mile coverage as an alternative to threading wires through cities. Various mechanisms have been proposed for deployment, from mounting Wi-Fi broadcast devices on telephone poles to deploying mobile blimps over rural areas (Chang 2006). Wi-Fi solutions to the last-mile problem would seem to level the playing field somewhat, as decentralized settlements covered by Wi-Fi would not necessarily be left wanting for network connectivity for the sake of lack of access to bandwidth. Whether there would be a critical mass of users to rival the collectives in denser urban cores remains to be seen, however.

Digital technologies have popularly been viewed as having significant influences on local urban geography, particularly at the level of architecture and urban design. Mitchell (1995), for example, has long foreshadowed the emergence of cities shaped by data bits. He argues for an architecture that influences and is influenced by the flow of digital data through urban infrastructure. This is a thesis that is shared by Batty (1995, 2003) in his work on computable cities. Crang (2000) discusses the birth of new classes of architecture developed to fit mediated spaces and what he refers to as transmissible cities, a so-called transarchitecture. Castells (1996) has explored the sociological implications of information flows in cities and between cities under a related premise: that the space of flows influences sociology and is, in turn, sociologically determined.

Behavioral Geography

Wired network technologies have influenced human behavior across a range of activities. Telecommuting, although not as widespread as once anticipated (Cairncross 1997), has replaced a significant volume of journey-to-work trips for some areas of the workforce and in some large organizations (OTA 1995). This has had a fundamental influence on trip behavior where used, decreasing rush-hour flows on major arterials and shifting traffic to nonpeak times locally around residential areas (Mokhtarian 1991; Janelle 2004). Wired telecommunications have also had an influence on personal activity patterns. Batty, for example, has argued that humans' sense of space and time has been radically changed by new forms of accessibility that ICTs enable (Batty 2003, 798) and this is particularly true in urban areas. The need for a reconsideration of time geography and human activity spaces as a consequence of ICTs (Kwan 2002; Kwan and Weber 2003) and space–time behavior in cyberspace (Kwan 2000) has also been demonstrated.

Existing exploration into the relationship between wireless ICTs and behavioral geography has mostly focused on cell-phone use and with suggestion by extrapolation that use of wireless networking will continue to transform human geographic behavior. Townsend (2000), for example, has argued that people's use of cellular telephony has accelerated the pace of human activity in urban areas, leading to a quickening of what he calls the urban metabolism. Rheingold (2002) has documented the formation of social and antisocial groups, smart mobs, organized over space and time with the intervention of cellular telephony and text messaging. Location-based services and related geographic information systems (GIS) have been developed to leverage the potential for telemediated human activity spaces (Bartie and Mackaness 2006; Li and Longley 2006), although the likelihood of such uses coming to fruition as practical business models has been questioned (Harris 2006).

Wi-Fi has potentially transformative power over human behavior, particularly through its ability to relate space–time tasks to the person carrying out those activities and the power to network individuals within mobile collectives. The relationship between Wi-Fi and spatial behavior is relatively underinvestigated. There is some evidence that Wi-Fi actually reinforces socio-spatial interaction and face-to-face contact in urban spaces (Schmidt and Townsend 2003). The notion that human behavior can be mediated by Wi-Fi technologies has already begun to influence military management, with the emergence of swarm-based strategies for both humans and vehicles (Arquilla and Ronfeldt 2000). Tagging and tracking of Wi-Fi-enabled devices becomes of critical concern when devices are associated so freely with individual people. Scholars have begun to investigate the potential ramifications of a wireless world watched over by a multitude of Orwellian "Little Brothers" (McCullough 2004, 15; Orwell 1949). There is particular unease regarding the potential implications of tracing human activity patterns en masse (Dobson and Fisher 2003; Fisher and Dobson 2003). This is already a popular concern, as evidenced by growing debate regarding proliferation of Radio-Frequency Identity tags in consumer goods (Markhoff 2006) and the deployment of Global Positioning System devices by rental car firms to track customers and identify and fine speeders (Associated Press 2002).

Socio-Spatial Segregation in Digital Access

Socio-spatial polarization has long been observed in access to wired digital network resources, with a growing digital divide between ICT haves and have-nots evident on global, national, regional, and urban levels (Dodge and Kitchin 2000; Castells 2001; Zook 2002; Crampton 2004). For the most part, these divides mirror (and in some cases exacerbate) segregation in access to other technologies and resources (Warf 2001; Chakraborty and Bosman 2005).

Much of the fanfare surrounding Wi-Fi is anchored in an optimism regarding the ability of the technology to help bridge this divide, particularly in inner-city areas. With relatively lower costs of deployment and broader swaths of coverage compared to wired networks, it is hoped that Wi-Fi can provide network resources ubiquitously in dense urban areas. The City of Philadelphia, for example, used the digital divide as the foundation for their decision to deploy citywide wireless networking, announcing that the "initiative will help overcome a lingering 'digital divide,' the economic and social disadvantage experienced by those without affordable access to technology" (Mayor's Office of Communications

2005). There has been little, if any, research to examine the veracity of such claims, however.

Cyberspace and Cyberplace

A nascent field of cybergeography has emerged to investigate the nature of space and spatial behavior in cyberspace and to explore the portability of existing geographies to cyberspaces (Dodge 2001; Kwan 2001). For the most part, work in this area deals with geography within the wires of Internets and the virtual spaces of computer software (Kitchin 1998).

Some key developments in wireless ICTs have the potential to move cyberspace out from the networks, tangibly, permeating our physical spaces and transforming them into cyberplaces and computable spaces (Batty 1995). Ubiquitous, ambient, pervasive computing (Weiser 1991) is an important catalyst for this transformation, embedding processors and MEMS in the built environment (McCullough 2004). The vision for ubiquitous computing is to blanket the environment with computers and sensors (Ricadela 2005), providing ubiquitous access to information from any device and over any network (Sharma and Nakamura 2003). Wi-Fi becomes ambient infrastructure for spatial interaction with and within the network in such cases and users of mobile Wi-Fi devices become digital beacons, trailed by capta shadows (Dodge and Kitchin 2005) in large clouds of data and communications traffic. Geography and human space–time activity act as context for ubiquitous computing. Indeed, some authors have gone as far as to argue that populations themselves, armed with mobile computing devices, could become the network infrastructure for context-aware computing grids (Bar and Galperin 2004).

Relatively little is known about the spilling over of cyberspace into meatspace, beyond charting the space of possibilities. Dodge and Kitchin have, however, made some initial investigations of this issue. They have uncovered a burgeoning code-space (Dodge and Kitchin 2004a), a diffusion of protocols and rule sets from ICTs into our everyday lives and a fusion of our tangible activity patterns with our data shadows in cyberspace (Dodge and Kitchin 2005). They have documented its influence on air (Dodge and Kitchin 2004b) and vehicle travel (Dodge and Kitchin, forthcoming).

Methodology

There is a clear need for further examination of Wi-Fi geographies. The research described in this article was crafted with three main tasks in mind: to collect data regarding Wi-Fi infrastructure and signals, to analyze those data for geographical properties, and to interpret those results.

Study Area, Sampling Strategy, and Data Collection

Data were collected to allow the geography of Wi-Fi infrastructure in an urban area to be uncovered, specifically the location and geographical configuration of access points. This is relatively difficult to achieve, as access points are often organized impromptu, with no centralized authority or ombudsman, are held in private hands, and are deployed on private land and behind closed doors. The ambient airwaves were also sampled for evidence of Wi-Fi transmissions. This is challenging because Wi-Fi radio broadcasts diffuse relatively freely through the environment, with the ability to pass through physical structures, people, vegetation, and so on. The physical footprint of Wi-Fi data flows is not confined to a conduit or right-of-way that we can focus our attention on. Packet-sniffing on the airwaves (using hardware and software to intercept data packets as they travel through the air) is difficult as well as being futile when those data are encrypted (as is often the case). Most important, it is illegal. Wi-Fi signals do not have any proxy influence on other phenomena that we could analyze—such as, for example, the way gas emissions leave traces in vegetation—so tracing the shadow or footprint of a Wi-Fi signal in this fashion is not feasible. Oscilloscopes might be used to measure signal voltage, but it would be incredibly difficult to distinguish Wi-Fi signals amid the cacophony of radio waves that usually course through an urban area. Even narrowing the search to frequencies on which Wi-Fi travels would be relatively useless, as that part of the spectrum is shared with a host of other devices.

We have devised a scheme for collecting Wi-Fi signals in the ambient environment. From those data, we can infer the location of access points and examine the geography and technical capacity of the airwaves as a network for Wi-Fi communications. Wi-Fi data traffic might originate from many Wi-Fi-enabled devices: access points connected to broadband modems, themselves wired to an Internet service provider's (ISP) network; access points wired to desktop PCs that are part of a local area network; laptop computers functioning as access points; hand-held devices broadcasting in ad hoc mode (a peer-to-peer connection that bypasses servers), and so on (Figure 1). We traveled through the urban environment by walking, cycling, and driving to col-

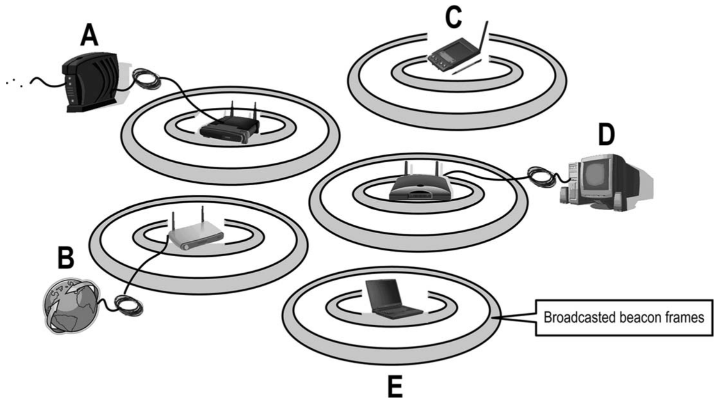


Figure 1. A stylized representation of Wi-Fi devices and the overlapping radio broadcasts that they produce: (A) an access point connected to a wired network via a broadband modem; (B) an access point with a direct connection to the Internet (via Ethernet, for example); (C) a handheld computer that is Wi-Fi-enabled; (D) an access point connected to a local area network via a desktop PC; (E) a Wi-Fi-enabled laptop operating as both an access point and Wi-Fi receiver.

lect data. When driving, antennae were affixed to the roof of the car in its centroid position. In traversing the city, we essentially cut through ambient Wi-Fi radio waves, carrying communications between access points and modems (Figure 2). For any one point in space and time amid that field of signals, we are thus able to sample the radio spectrum to examine what signals are present.

Access points (and devices that function as access points) automatically broadcast a test signal of sorts—what is known as a beacon frame—at a rate of about ten frames per second (the interval can vary; the common standard is 100 ms). Frames are wrapped data packets; data packets are small chunks of a discrete unit of data. Most computer networks use IP to disassemble and reconstitute data as they are conveyed across networks and routers. Wi-Fi beacon frames essentially advertise the presence of the access point to clients in the surrounding environment and ensure that it is visible (in spectrum space) to many devices. Because they do not actually carry any substantive data from users of the network (their queries to a search engine, for example), it is legal to capture beacon frames. Indeed, Wi-Fi technology relies on doing exactly this; the beacon frames essentially set up the conversation between device and access point, much as an operator would have done for telephone calls before digital switching. Beacon frames, like all frames broadcast over Wi-Fi, contain tags with some key information that are useful in exploring Wi-Fi signals. Sampling the radio spectrum for beacon frames is passive, as it does not require any tangible connection to or authentication on an access point or any networks or systems that it might be connected to. Beacon frames are also broadcast free from encryption, which means that we can open them up and look inside them once they are captured. The beacon frames do, however, travel through the airwaves with the same characteristics as packets of substantive communications traffic. They are, therefore, wholly representative of Wi-Fi traffic through the airwaves. Our data collection scheme thus functions in much the same way that a single origami paper crane (a beacon frame) would if floated through rapids to test the water ahead of sending a flotilla of cranes (a chunk of digital data divided into packets) in convoy downstream.

We poll the airwaves for the presence of frames using hardware configured as follows. A high-gain omnidirectional antenna is attached to a Wi-Fi-enabled network interface card (NIC; essentially a Wi-Fi radio receiver), enabling the receipt of many signals from the airwaves continuously in 360 degrees of rotation. The NIC is connected to a laptop so that frames pulled from the airwaves can be duplicated and a copy of those data, per frame, per reading, can be stored on a local hard drive for later analysis. A Geographic Positioning System (GPS)

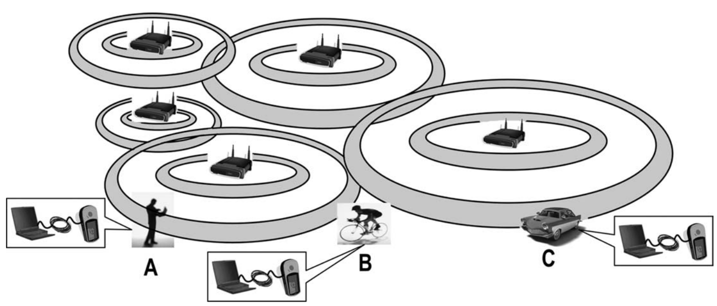


Figure 2. A stylized representation of overlapping Wi-Fi broadcasts from several devices and three discrete space–time samples using a laptop and GPS while walking (A), bicycling (B), and driving (C).

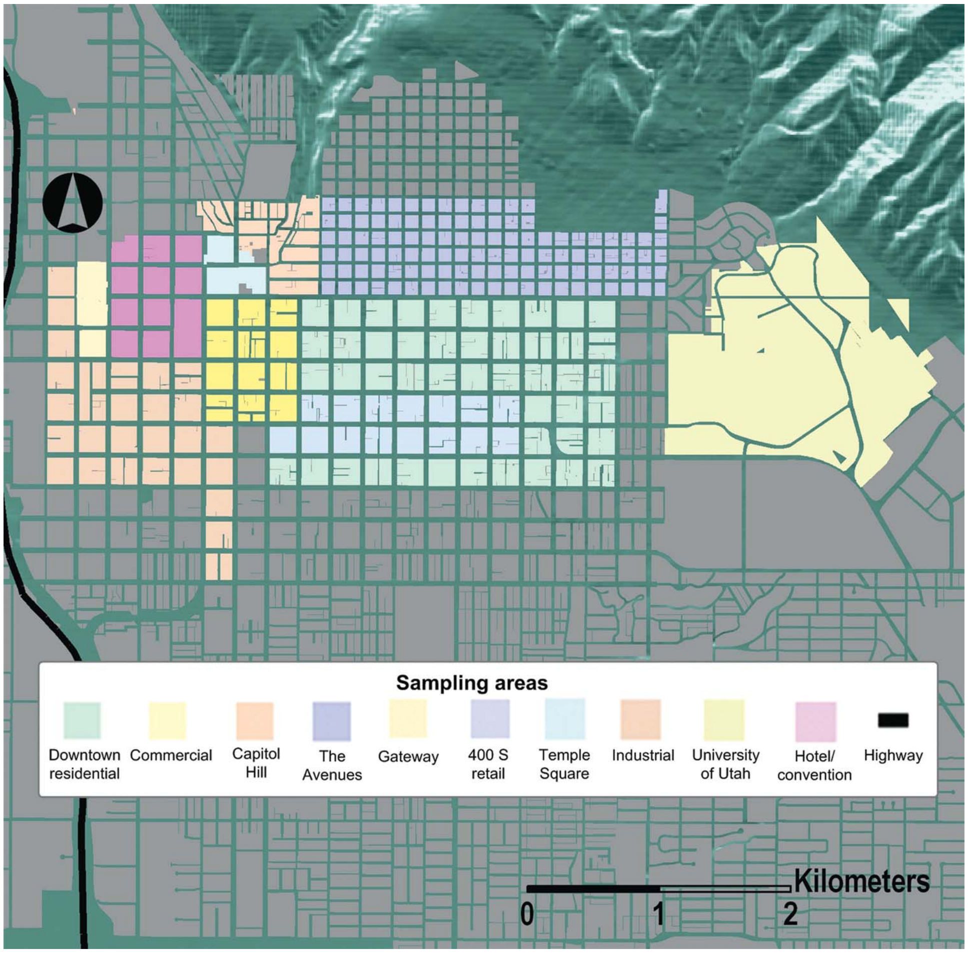


Figure 3. The different districts within Salt Lake City that were sampled, by city block. Sampling across these districts took place contiguously. The areas bounded by color represent the central domain of the city. The land-use and demographic composition of these districts is shown in Table 1.

receiver is also attached to the laptop and the GPS is attached to a separate external antenna and enabled with the Wide Area Augmentation System (WAAS) to ensure accurate positional information. This arrangement of hardware allows us to sample the ambient radio waves, store that information digitally, and both place- and time-stamp it with a fine-scale spatiotemporal resolution (Figure 2).

We have applied this methodology to a study of Salt Lake City. The U.S. Census estimate for the city's population in 2005 was 178,097, garnering a ranking of 122nd for the city nationally. The Salt Lake City–Ogden Metropolitan Statistical Area contained an estimated 1.365 million people in 2003. Salt Lake City is a particularly interesting case study for Wi-Fi for a number of reasons. First, although relatively small, the city ranks highly as a technological hub. Utah ranks first in the nation in terms of presence of computers in the home (74.1 percent of households for the civilian noninstitutional population as of October 2003) and fifth for presence of the Internet in the home (Cheeseman Day, Janus, and Davis 2005). Second, a grassroots organization in Utah is moving ahead with ambitious plans to install a municipally owned fiber-optic network infrastructure in twelve or thirteen cities, at a proposed cost of $540 million (http://www.utopianet.org/; Wallace 2004). This is an effort to promote network connectivity throughout the state. Wi-Fi is an obvious alternative. This relates to the third motivation for selecting Salt Lake City as the study area: the city does not yet have a municipalwide Wi-Fi system.

A sampling strategy was designed to collect data across all of central Salt Lake City. The survey area (Figure 3) encompasses several contiguous districts within the city, with diverse land-use and demographic characteristics (Table 1).

Table 1. Land-use and population characteristics of sampled districts (the geography of surveyed districts is shown in Figure 3)

	% Land use							
	High-density residential	Public or charitable land	Commercial	Low-density residential	Vacant	Industrial	Population (total tract)	% population nonwhite
District								
Hotel/convention	4.1	40.0	27.0	0.3	22.4	4.6	717	11.6
Commercial core	6.2	17.4	59.8	0.0	17.8	0.0	1, 920	12.2
400 S retail corridor	16.4	24.0	45.9	6.8	13.7	2.9	2, 648	21.4
The Avenues	33.5	11.0	6.4	64.1	2.1	0.0	6, 766	8.5
Capitol Hill	18.9	24.1	6.5	24.4	10.0	0.0	2, 400	9.2
Downtown residential	11.4	18.3	24.6	28.1	9.7	0.0	11, 513	15.6
The Gateway	2.8	48.4	10.2	0.0	30.0	0.0	145	34.5
Industrial	0.0	8.2	40.3	0.6	21.5	26.4	1, 820	82.7
Temple Square	0.0	90.9	1.1	0.0	8.1	0.0	1, 532	7.4
University of Utah	0.0	100.0	0.0	0.0	0.0	0.0	1, 478	16.0

We traversed public property in each of the districts illustrated in Figure 3, sampling continuously with records stored at a rate of thirty samples per second. We also recorded additional data slightly outside the geographical boundaries of these districts, to better facilitate spatial interpolation within the boundaries. We did not have rights of access to private property or rights to survey within buildings (also, GPS equipment does not work indoors), so this resulted in samples for the area of the city covered by roads, sidewalks, public plazas, and parks (Figure 4). We were able to gain access to service lanes behind some buildings. This sampling strategy obviously misses signals within buildings, but this is unavoidable. We are interested in Wi-Fi signals to the extent that they become public infrastructure anyway, so the sampling strategy works in this regard. Enthusiasts have been using planes to survey urban areas by air, scanning for access points (Brewin 2002). There is little understanding, however, of the extent to which this accurately depicts conditions on the ground. Samples were collected relatively continuously over the course of several weeks and at varying times of the day and night to reduce the possibility of temporal bias. Output from access points will vary over time, and signals are subject to ambient interference (passing people, vehicles, spectrum traffic) that varies dynamically. Kamarkis and Nickerson (2005) have shown, for example, that Wi-Fi throughput can vary on the order of 2,500 kbs^{-1} over an interval of 10 s. We scanned at a rate of two samples per second to average out temporal variations; this strategy is used in other studies (Kamarkis and Nickerson 2005). When walking, this provides a continuous path of samples; the separation between samples when driving is on the order of a few meters, although more fine-scale when driving slowly or turning corners. This is illustrated for a section of the Temple Square district in Figure 4, where readings have been taken by walking, driving, and bicycling. (Each sample point in Figure 4 represents a point stack with many readings per stack.) Building density, as well as pedestrian and automobile traffic, is at its densest in this part of the city. For much of this area, it is not feasible to get access to the space between buildings (even if rights-of-way were available to us) as they are arranged side-by-side. Sampling in this area is therefore mostly from the street, although we were able to traverse footpaths through public plazas to sample interstitial areas between some buildings.

The sampling procedure produces a series of place- and time-stamped frames from the ambient cloud of Wi-Fi traffic in the city. Captured frames are generally around 50 bytes in size per frame (they can store fifty characters of text). The frames are broadcast as compressed strings. This means that they can yield a lot of data (>50 bytes) when uncompressed. On casual inspection, the frames manifest as unintelligible strings. However, the protocols used to wrap the packets in the frame are open source. We use these protocols as the blueprints for decompressing and unwrapping the frame, examining its contents, and interpreting the information that it contains. These data items and the conditions at the point of sampling then become the raw material for subsequent analysis.

Data collection for this study recovered 500,000 samples from the ambient cloud of Wi-Fi communications over a 12 km^2 area of the city, with an average sampling rate of about 24 samples per m^2 over the study area. This is obviously a huge and rich volume of data.

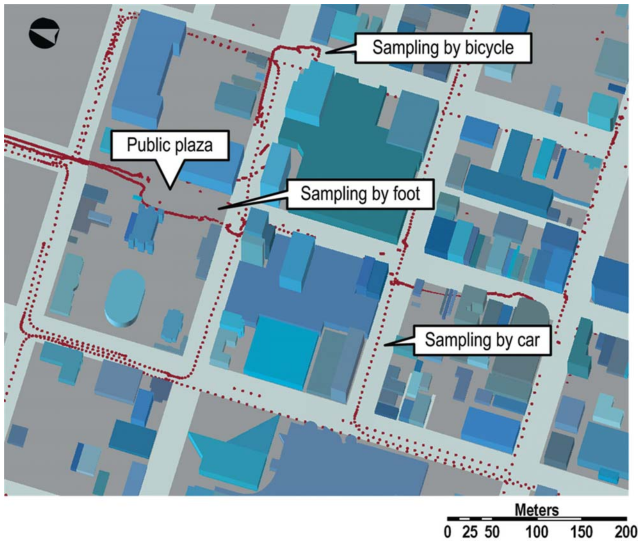


Figure 4. An example of signal sampling for a section of the Temple Square district. Roads are illustrated in light gray, with buildings represented in shades of blue. Darker gray areas are parcel boundaries, many of which represent the confines of public property. (The view in this figure is oblique, illustrating the relative heights of buildings, but this obscures some portions of adjacent sidewalks from which samples were obtained.)

Access Point Geography

Evaluation of access point geography is used to explore the physiography of infrastructure supporting Wi-Fi broadcasts. A threefold approach is used in this endeavor. First, we identify the access points from which signals originate. Second, we estimate the likely location of that access point. Third, we determine the uses to which the access point is put.

The header information of Wi-Fi frames contains a Media Access Control (MAC) address. This is a string of digits embedded in the front of the beacon frame; the string encodes the manufacturer and model of the device and a serial number. The serial number is unique to a given access point. Hence, each of the 500,000 samples that we collected can be associated with a unique access point, regardless of the distance of the sample from that device. This allows us to chart all the sampled transmissions from an access point. We also measure the signal strength of the frame as captured at that point in space and time. In the absence of any booster mechanism, broadcasts from an access point succumb to a relatively regular distance decay with respect to the strength of signal communicated. We can therefore calculate an omnidirectional distance-decay profile per access point and by back-tracing along the distance-decay curve we can estimate the likely location of the access point as being the point along that curve where signal strength is highest. This is a procedure used in other studies with success (LaMarca et al. 2004b). We are limited to detection of the location where our equipment has recorded the highest signal. The true location is likely within a building, on private property to which we have no access. This is the best that we can do without trespassing (and represents the state of the art in similar studies), but the displacement from the true location is small, on the order of a few to ten meters.

Wi-Fi frames are also broadcast with the network name of wireless local area network (WLAN) within which the access point sits. Mobile devices that wish to communicate with the WLAN need this name to establish a data exchange. The name ascribed to the WLAN is often useful in delineating the use to which the access point is put. Hotspots installed for ad hoc purposes are often labeled with a secure set identifier (SSID) that reflects the uses for which they are intended. SSIDs for commercial and public providers are commonly advertised or available publically. The commercial telecommunications provider T-Mobile labels its SSIDs as "tmobile," for example. We use a database of SSIDs that we have compiled to flag frames as being private, public, or commercial, and affiliated with specific groups within those classifications.

Wi-Fi Spectrum Space

Wi-Fi broadcasts occupy dedicated channels in the radio spectrum. There is, then, geography to their movement through spectrum space. We recorded the frequency over which transmissions are detected when sampling. This allows us to associate frames with frequency channels. Frames are carried in one of eleven channels in the United States. In essence, channels work as paths through the radio spectrum that a frame follows, where the path is carved out by the frequency with which the signal propagates. The frequency lends the transmission a spectral form that dictates the part of the spectrum that it can push through as it is broadcast from an access point. Width of channels is known (as with TV, AM, and FM radio channels). A frame broadcast under the 802.11b or 802.11g protocol in channel 1, for example, varies over 50 MHz (a frequency of 50×10^6 cycles per second) between 2.412 GHz and 2.417 GHz.

Geography of Wi-Fi Coverage

Our analysis of the geography of signal coverage is performed in two ways. First, we use sample data of ambient Wi-Fi transmissions to estimate a field (surface) or manifold of those transmissions for the city. Second, we perform spatial analyses to estimate the spatial structure of that field. This is useful in determining the overall coverage of Wi-Fi signals in the urban area, as well as identifying areas where there are systematic problems with signal propagation.

We calculated (and indexed) a range of attributes for each transmission sample: frequency, 802.11 protocol, SSID, MAC address, security, signal strength, signal in noise units, signal in power units, and likely WLAN use. This produces 500,000 place- and time-stamped data points for each of these variables, with a spatial separation of centimeter-level at a lower bound and a few meters at an upper bound (see Figure 4, for example). Because several signals might be detected per place in space and time, our data collection technique produces a sample point stack in some instances.

These data points are a sample of a continuous field of overlapping Wi-Fi signals in the ambient airwaves. We estimated the likely form of that field for several of these attributes using kriging. (In the case of stacks, we use the maximum sample value per variable per place per time, as we are most interested in the maximal utility of the surface at any given location.) Kriging is a geostatistical interpolation procedure that is guided by inverse distance weighting and the spatial covariance of known data points (Shepard 1968; Cressie 1991). In contrast to density mapping or inverse distance weighting used in isolation, kriging allows us to estimate the properties of Wi-Fi transmissions for points in space not covered by data collection in a statistically robust fashion. Because the separation between sample points is relatively small (a few centimeters at best and a few meters at worst), this produces reliable estimates of the true attributes of the Wi-Fi field.

A spherical model was fit to our sample data for kriging. The spherical model was judged to be most appropriate because an increase in the semivariogram for the sampled data was observed as distance increases, up to a threshold, beyond which the semivariogram leveled out. (The semivariogram pits the average dissimilarity between observations against the distance that separates them.) The spherical model takes on the following form (Cressie 1991):

$$\hat{\gamma}(d) = c_0 + c_1 \left[\frac{3d}{2a} - \frac{1}{2} \left(\frac{d}{a} \right)^3 \right] \quad (1)$$

where $\hat{\gamma}$ is the variogram and d is distance from a sample point (the location i of a known value for a variable) to an interpolated point (j) on the field that is being estimated. n refers to the number of pairs of sample points (i, j) used in analysis. The nugget (c_0) is the variance at zero distance from a sample point. The range (a) is the distance from a sample point beyond which the semivariogram is constant. The sill $(c_0 + c_1)$ is the value of the semivariogram beyond the range. Kriging is usually performed over lag bands, small buffers around a sample point. Given the relatively small average separation between sample points, we used lag bands of 5 m in our analysis (based on the largest separation distance for points in the sample collection).

We then subject the samples and estimated field to spatial analyses of their composition and configuration. Composition is examined in a relatively straightforward manner by mapping the geography of Wi-Fi attributes and hardware and examining their relative spatial densities.

We employ a twofold test for configuration using spatial autocorrelation: one global and one local. Global spatial autocorrelation is measured using Moran's I statistic as follows (Moran 1950; Fotheringham, Brunsdon, and Charlton 2000):

$$I = \left(\frac{n}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \right) \left(\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \right), \quad \text{where } -1 \leq I \leq 1 \quad (2)$$

n represents the number of data points considered in the analysis in Equation (2) (for the sake of tractability we use either the highest or median reading of a variable when several samples are available for a given space–time tuple). w_{ij} refers to the adjacency between readings at points i and j (and $w_{ii} = 0$, $w_{jj} = 0$ by convention). x_i is the value of a variable at point i; x_j is the value at point j. $\bar{x}$ is the mean value considered across all points n. A positive value of I for a given space indicates a configuration in which point-values of x tend to collocate with similarly high or low values (i.e., a homogenously configured space). A negative value of I suggests a heterogeneous spatial configuration of point values for x: high values tend to be found adjacent to low values overall across the examined area. Values of $I = 0$ indicate randomness in the point pattern.

The expected value $E[I]$ and variance $V[I]$ are calculated as follows (Moran 1950; Rogerson 2001):

$$E[I] = \frac{-1}{n-1} \tag{3}$$

$$\left.\begin{aligned}
V[I] &= \frac{nS_4 - S_3S_5}{(n-1)(n-2)(n-3)\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)^2}\\
S_1 &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}(w_{ij}+w_{ji})^2}{2}\\
S_2 &= \sum_{i=1}^{n}\left(\sum_{j=1}^{n} w_{ij} + \sum_{j=1}^{n} w_{ji}\right)^2\\
S_3 &= \frac{n^{-1}\sum_{i=1}^{n}(x_i-\bar{x})^4}{\left(n^{-1}\sum_{i=1}^{n}(x_i-\bar{x})^2\right)^2}\\
S_4 &= (n^2-3n+3)S_1 - nS_2 + 3\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)^2\\
S_5 &= S_1 - 2nS_1 + 6\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)^2
\end{aligned}\right\} \tag{4}$$

We also test for local spatial autocorrelation using Anselin's Local Index of Spatial Association (LISA) for Moran's I. LISA statistics yield local measures of spatial configuration and values of I locally, per point. The LISA for Moran's I is calculated as follows (Anselin 1995):

$$\left.\begin{aligned}
I_i &= \left(\frac{x_i}{m_2}\right)\sum_{j=1}^{n} w_{ij}x_j\\
m_2 &= \sum_{i=1}^{n}\left(\frac{x_i^2}{n}\right)
\end{aligned}\right\}, \text{ where } \sum_{i=1}^{n} I_i = I \quad \text{from}$$

$$\text{Equation (2) and } -1 \le I \le 1 \tag{5}$$

I_i in Equation (5) is the LISA index for a point i; that is, a local measure of Moran's I index for that point.

Expected values $E[I_i]$ and variance $V[I_i]$ are calculated as follows (Anselin 1995):

$$E[I_i] = \frac{-w_i}{(n-1)} \tag{6}$$

$$\left.\begin{aligned}
V[I_i] &= \frac{w_{i(2)}(n-b_2)}{(n-1)} + \frac{\frac{2w_{i(kh)}2(b_2-n)}{(n-1)(n-2)-w_i^2}}{(n-1)^2}\\
w_{i(2)} &= \sum_{j\neq i}^{n} w_{ij}^2\\
b_2 &= \left(\frac{m_4}{m_2^2}\right)\\
2w_{i(kh)} &= \sum_{k\neq i}^{n}\sum_{h\neq i}^{n} w_{ik}w_{ih}\\
m_4 &= \sum_{i=1}^{n}\left(\frac{x_i^4}{n}\right)
\end{aligned}\right\} \tag{7}$$

w_i in Equation (7) is the sum of row elements in an adjacency matrix w_{ij}, $\sum_{j=1}^{n} w_{ij}$. k and h are point locations.

We also test for spatial configuration using nearest neighbor analysis. This involves calculating the observed straight-line separation between point locations, and comparing the findings to a random point pattern. This is calculated as follows (Clark and Evans 1954; Rogerson 2001):

$$R = \frac{R_0}{R_e} = \frac{\bar{x}}{\frac{1}{2\sqrt{\lambda}}},\ 0 \le R <, \cong 2.14 \tag{8}$$

Application of Equation (8) produces a ratio of clustering R, where R_e is the expected value of nearest neighbor separation (R), R_0 is the observed value, $\bar{x}$ is the mean separation between points, and λ is the number of points per unit area. A value of $R = 1$ indicates a condition of randomness in the pattern of nearest neighbors. When $R = 0$, points form a point stack with no separation between them. $R = 2.14$ is a theoretical maximum separation (Rogerson 2001). We can calculate a Z test to evaluate a null hypothesis of randomness in the pattern of nearest neighbors as follows:

$$Z = \frac{(R_0 - R_e)}{\sqrt{V[R_e]}}, \quad \text{where } V[R_e] = \frac{4-\pi}{4\pi\lambda n} \tag{9}$$

The Network Properties of Ambient Airwaves

We are also interested in the capacity of the ambient airwaves to support Wi-Fi communications traffic as an indicator of Wi-Fi network properties in the environment. We use frame slot time to determine the data rate at which frames pass through the air from an access point to a receiver. Frames broadcast under the protocols for 802.11b and 802.11g are broadcast with the same frequency (2.4 GHz–2.5 GHz), but at different data rates (a maximum of $11\text{Mb}^{-1}\text{s}$ for b and 54 Mb^{-1}s for g). Access points pause slightly before frame broadcasts. The slot time governs the length of this gap. The data rates are a function of the slot time between broadcast of one frame from an access point and the next in a sequence of broadcasts. By default, 802.11b access points operate with a slot time of 20 μs, 802.11a with 9 μs, and 802.11g with 9 μs (although 802.11g can operate with a slot time of 20 μs when in mixed mode, allowing backward-capability with 802.11b protocols). Lower values of slot time offer higher throughput and thus a greater data rate.

We also record the signal strength of the radio wave carrying the frames sampled in data collection. Signal strength is a measure of the strength of lossless signal on receipt at the client device, in this case at the receiving modem. We measure signal strength natively on our equipment in units of sound level, as decibels relative to 1 milliwatt (dBmW), and in units of power.

Although beacon frames are broadcast free from encryption, part of the frame body carries a marker that declares whether the access point from which the frame originated intends to encrypt subsequent communication frames and what encryption protocol it intends to use. We can therefore note whether an encryption protocol is used without decrypting the packet.

The frame also carries the SSID of the WLAN from which it originated. We use the SSID to determine the intended use of Wi-Fi access points and signals by comparing SSIDs to public records. Many access points ship with default configurations, including a default SSID. The default names of SSIDs (and their default configurations) are publicly available from several manufacturers of these devices. Presence of a default SSID often implies the use of a default password for the access point's controls, signaling possible security vulnerability. We can determine the vulnerability of an access point to potential hijack by noting the SSID and comparing it to a database of default SSIDs that we have constructed.

Findings

Our data collection and analysis scheme allows us to unveil the otherwise secret geography of Wi-Fi. We are able to visualize and, moreover, measure, this geography by examining the relative positioning of the underlying infrastructure that feeds wireless communications to the airwaves, the overlapping coverage of Wi-Fi radio broadcasts, the spectrum space of Wi-Fi communications as they travel through the air, and the network functionality of Wi-Fi as an ambient urban data cloud.

The Geography of Wi-Fi Infrastructure

Access points were found to be relatively ubiquitous across the study area (Figures 5 and 6). A dense constellation of access points supports Wi-Fi communications in the city, feeding it with signal broadcasts. In the study area, 1,739 individual access points were detected.

The number of access points was high where office and household density was high. A large number of access points were detected in the industrial district, apparently serving offices there (based on SSID data). The University of Utah campus was the only area found to be sparsely populated with access points, which is understandable given the large area of the campus covered by park.

Access point density is particularly high across the study area, with an average of seven access points available within 100 m of most points in the city (100 m is an important range as it is the lower end of spatial extent for 802.11b access point broadcasts) and as many as forty-three access points were available in parts of the city (Figure 5). Access point density was highest around the commercial core. It was also found to be high on the sections of the University of Utah campus where college dormitories are located. Deploying access points in close proximity can degrade broadcast performance when they operate on the same frequency. Certainly, having as many as forty-three access points within 100 m of each other is problematic. Nearest neighbor analysis was run on likely access point locations and compared to a random pattern. The ratio of observed separation to randomly derived separation was 0.27, with a Z score of –57.96; this is indicative of general clustering. Access points tend to be located in close proximity over the study area.

These findings have some significant implications. The infrastructure necessary to blanket the entire central city with Wi-Fi is considerably less than that needed to hard-wire a city with copper or fiber-optic wiring. If we were to budget \$100 per access point (a reasonable price for a high-gain access point), that would total a cost of \$173,900 to install an unplanned network in central Salt Lake City. This is much cheaper than the millions of dollars that was tabled for the development of a municipal wired network in the city (Wallace 2004).

The infrastructure is dense enough to support an alternative positioning system. If the exact location of only a small portion of the 1,730 detected access points were known and fixed, it would be sufficient to triangulate position based on time of arrival (TOA) of Wi-Fi packets. Existing work has demonstrated that Wi-Fi can support positioning services with accuracy of 1.5 m indoors (Bahl and Padmanabhan 2000) and 18.9 m outdoors (LaMarca et al. 2004a) in just this way and several companies are developing location-based services that rely on Wi-Fi as a positioning scheme. New cell phones in the United States must be equipped to triangulate location of the device over radio waves in a similar fashion, to facilitate emergency services (so-called E911). Malaysia has begun to convert automobile license plates to wireless technology based on RFID in a bid to track stolen cars (International Herald Tribune 2006). Radio communications are advantageous for these purposes; GPS do not operate indoors or in areas obscured from line of sight with orbiting satellites. Wi-Fi, by contrast, is capable of transmitting through building materials and is also much cheaper to deploy and maintain.

The Geography of Wi-Fi Transmissions

Wi-Fi broadcasts are designed, first and foremost, to provide local lilypads of network access around an access point. Theoretically, wireless coverage should extend symmetrically around an access point, radiating out in a circular fashion with equidistant radii in all directions. The strength of the signal of radio broadcast would decay monotonically with distance from the access point under normal conditions. Our analysis found Wi-Fi broadcasts around individual access points to differ substantially from their "textbook" geography. Specifications for coverage around three detected access points are provided in Table 2 as an example. Each operates under the same protocol, in the same spectral band (~2.4 GHz) and at the same data rate. Moreover, they achieve almost identical signal high-points. We would expect, therefore, that they would have the same range of coverage. They have a very different spatial reach and morphology to their coverage, however (Figure 7). Indeed, access point 3, which operates a peer-to-peer network, manages to cover most of the downtown area (over nearly 5 km^2). The operator has his or her own citywide Wi-Fi hotspot! This would suggest that local conditions (building infrastructure, interference, topography, elevation, boundary-layer meteorology) are responsible for significant variation in Wi-Fi signal extent, although empirical validation of this hypothesis is a topic for future investigation.

Looking synoptically, we found the entire central city to be blanketed with Wi-Fi transmissions (Figure 8). Transmissions from individual hotspots bleed together when access points are distributed in proximity to one another, forming an ambient wireless cloud of data transmissions. Private, public, and commercial hotspot providers have accidentally formed impromptu citywide Wi-Fi coverage, without a centralized executive. This has emerged (rather than being coordinated) from the bottom up as a by-product of the popularity of Wi-Fi

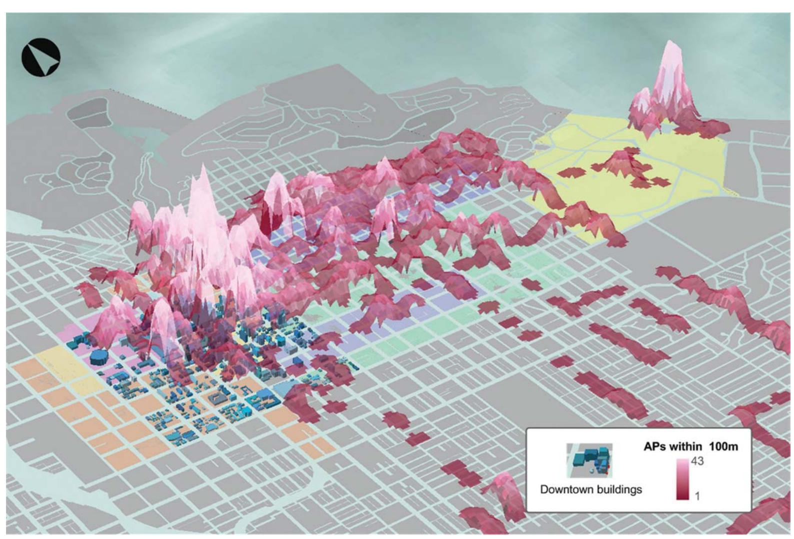


Figure 5. Access point density over the study area (number of access points within 100 m of a given location).

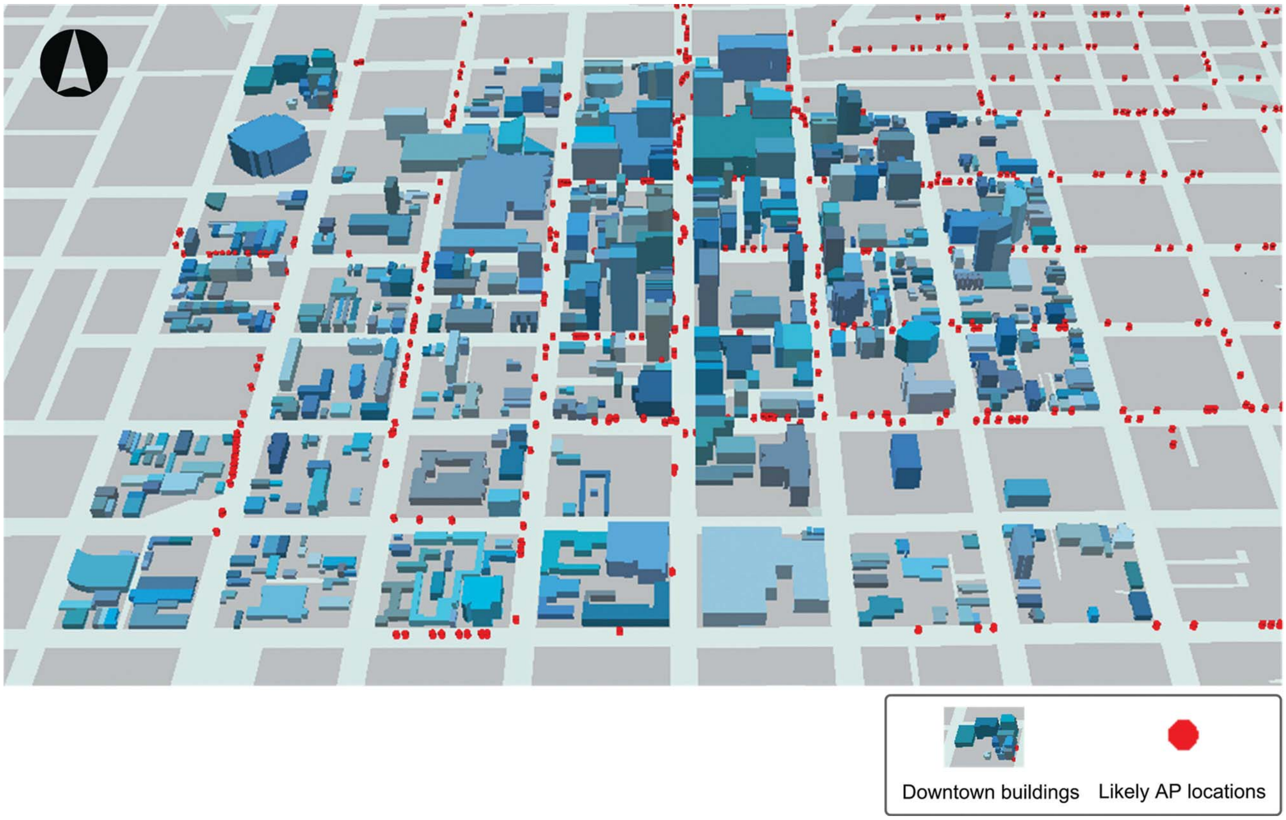


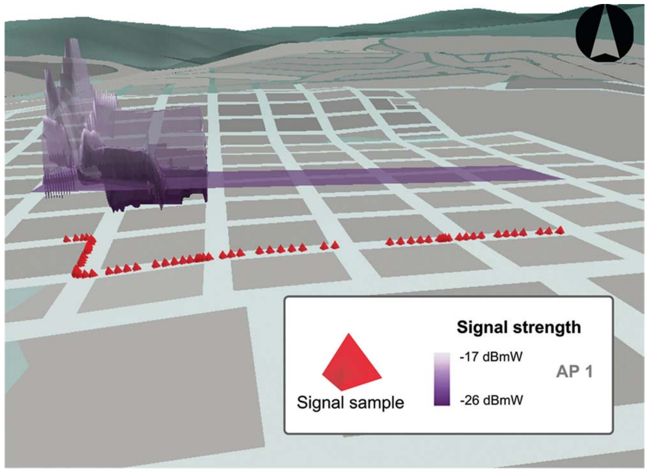
Figure 6. Likely location of access points in downtown Salt Lake City. AP = access point.

in the city and the tendency for individual hotspots to hemorrhage signals into the surrounding environment. Users of Wi-Fi-enabled mobile devices could, potentially, draw network connectivity from any point in the city. Indeed, in many parts of the city they have access to multiple signal sources.

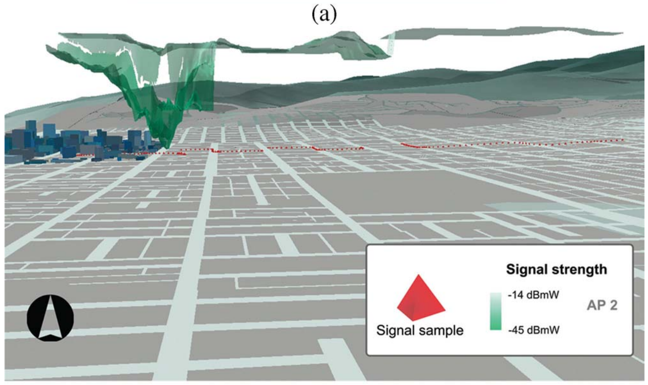
Signal strength within the cloud was found to have a distinct spatial structure, with spatially and statistically significant concentrations of signal strength in parts of the city and weakness in other areas (Figure 9). High signal strength is associated with higher throughput of wireless communications and higher quality network connectivity. The city's Wi-Fi transmission demonstrates neutral global spatial autocorrelation (the Moran's I statistic yielded a value of 0.015 with a significance of 0.001$p = 0.001$ against 999 random perturbations). However, locally, the spatial autocorrelation demonstrates a statistically significant spatial structure of localized hummocks of high signal strength and craters of lower strength. The commercial and office section of the downtown core plays host to significant signal peaks, despite housing

Table 2. Characteristics of individual access point (AP) devices and their hotspots

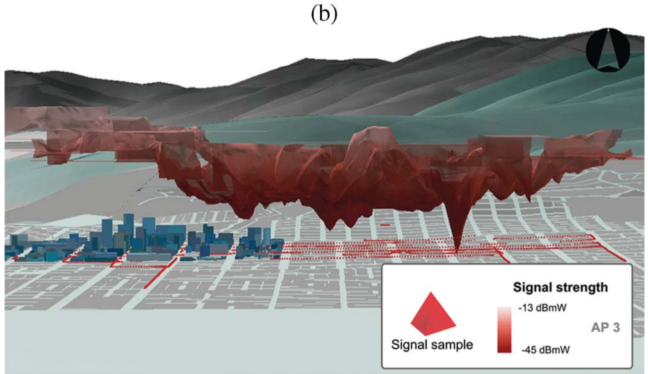
	Access point		
	AP 1	AP 2	AP 3
Manufacturer	Apple	Senao	Unknown
Encrypted?	Yes	No	No
Protocol	802.11b	802.11b	802.11b
Channel (frequency)	3 (2.422 GHz)	11 (2.462 GHz)	4 (2.427 GHz)
Data rate	11 Mbs^{-1}	11 Mbs^{-1}	11 Mbs^{-1}
Signal high	−17 dBmW	−14 dBmW	−13 dBmW
Range	0.07 km^2	0.75 km^2	4.52 km^2



(a)



(b)



(c)

Figure 7. The geography of individual access point (AP) hotspots shows varying ranges and morphologies, despite having identical hardware specifications. (A) Access point 1 (0.07 km^2), (B) access point 2 (0.75 km^2), (C) access point 3 (4.52 km^2). (Further details are provided in Table 2.)

a concentration of the city's tallest buildings. The residential sections of the city, as well as a portion of the University of Utah campus, sit in a signal trough. This is indicative of systematic place-based degradation of network performance in those areas.

There are some important implications of ubiquitous signal coverage. The 1,739 access points detected in our study are clearly sufficient to deliver signal coverage citywide. Selectively placed access points, wired to broadband wired Internets, could deliver network connectivity across the entire city relatively easily and cheaply. Wi-Fi, and metropolitan-scale Wi-Fi in particular, is often touted as a bridge for the digital divide and a solution to the last-mile problem, with the ability to provide widespread, low-cost access to wired Internet. The cloud of Wi-Fi transmissions hanging over Salt Lake City covers the urban area completely, irrespective of social and economic divisions.

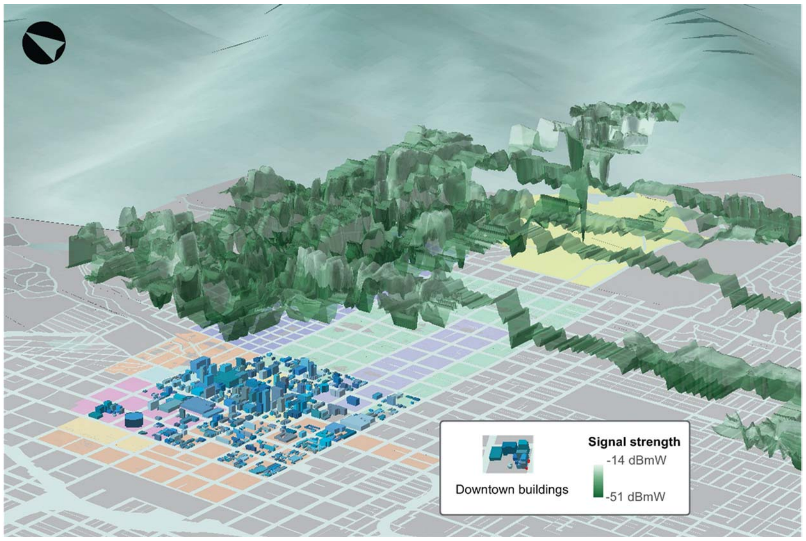


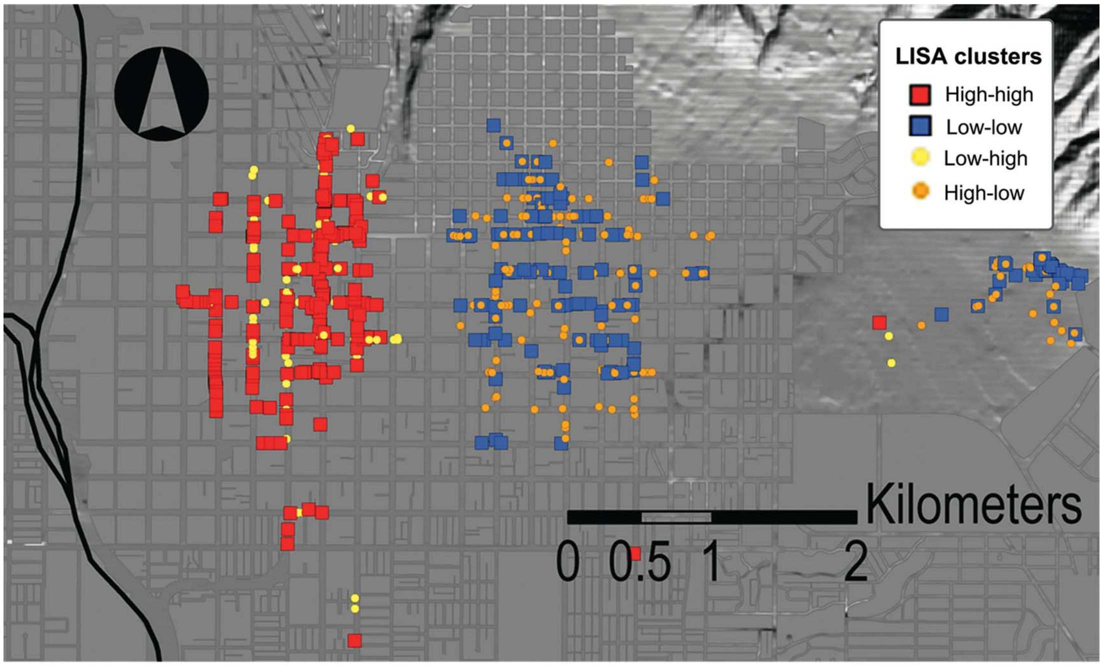
Figure 8. Wi-Fi coverage blankets all of central Salt Lake City, but with varying signal strength. (Coloring of city blocks matches the study areas from Figure 3.)

The omnipresence of accessible Wi-Fi signals in the city is useful for ubiquitous computing (Weiser 1991), offering networking for mobile devices and with 802.11 and IP packet-switching protocols that support a multitude of devices and services. Ubiquitous computing has a symbiotic relationship with geography, as it relies on geographical context, location, place, setting, proximity, and so forth. Clearly, understanding the geography of wireless communications is central to planning the future of ubiquitous computing. Our results show that Salt Lake City already supports a large wireless network on an unplanned basis. If we consider that each access point likely supports several wireless devices, many of which will be capable of performing large volumes of computation, it becomes clear that ubiquitous computing is already with us in unplanned form.

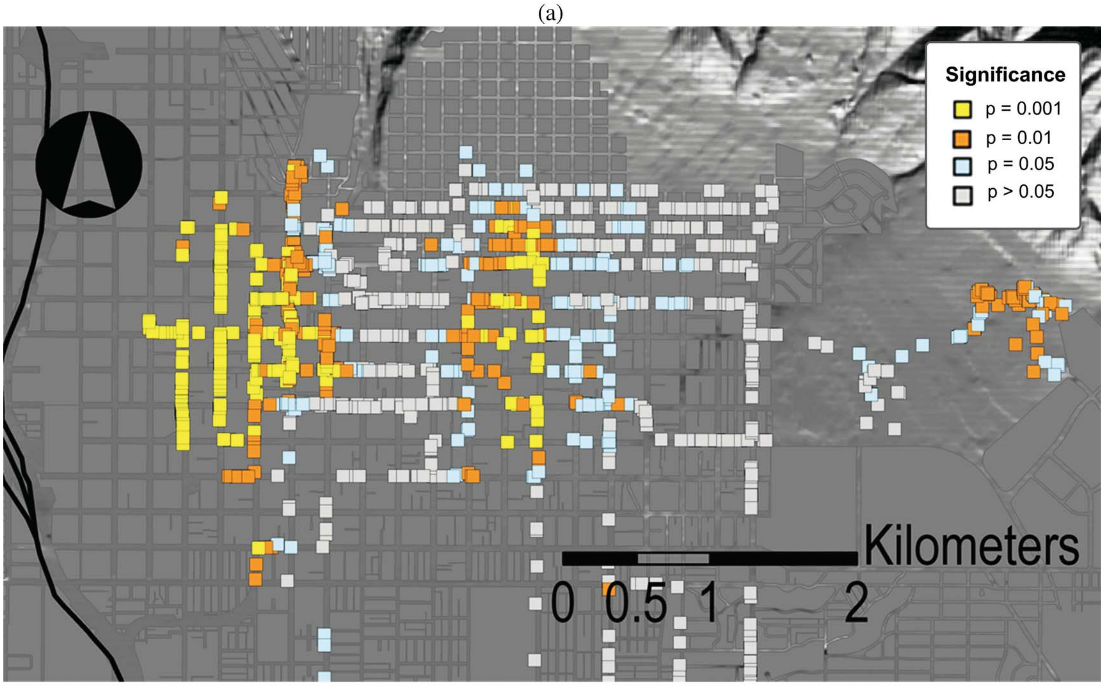
This also bodes well for location-based services. Such services are already provided over cell-phone networks and devices. However, given that Wi-Fi modems are usually wired to a computer (a laptop, palmtop, or a handheld device), there exist greater opportunities for providing a broad range of services, from computation of proximal opportunities and query-specific services to mobile gaming. Provision of robust location-based services requires large networks of access points and devices. Our findings clearly demonstrate that such networks already exist.

Although the radio waves from access point broadcasts comingle in the airwaves to produce a contiguous cloud of coverage, the cloud manifests as a continuum of overlapping lilypads from the perspective of the user and the user must log off and reauthenticate to gain connectivity on each distinct lilypad of coverage as he or she moves from one hotspot to the next. Control of those network resources rests heterogeneously with the individual owners of the access points and their ISPs that provide the hard-wired link to the Internet. Negotiating access to the cloud citywide would be multiplicative in nature and would likely go against the spirit of the business model for the providers, who might be less than enthusiastic about households sharing the network resources offered by an ISP with their neighbors and passers-by with no compensation for the provider. Indeed, sharing of Wi-Fi networks in this way is often prohibited as part of the user agreement for many ISPs. The experience contrasts with that of cellular networks, whereby cell towers and base stations collaborate to hand over users' network connections as they roam between cells, thus providing a seamless link across cells. Of course, cell-phone users pay for this convenience.

Similar functionality is beginning to feature in Wi-Fi networks, through so-called mesh networking. Mesh networking relies heavily on geography; Wi-Fi lilypads are essentially coupled spatially, with rules for trading authentication details seamlessly at the boundaries of the lilypad. Commercial cell-phone providers that also operate Wi-Fi hotspots have announced plans to release phones and services that can use their commercial Wi-Fi hotspot service for voice telephony (Richtel 2006).



(a)



(b)

Figure 9. (a) Spatial clustering of signal values and (b) their statistical significance (against 999 random perturbations).

The Geography of Wi-Fi Use

The vast majority of the ambient cloud of Wi-Fi transmissions is deployed for private purposes. Only a small volume of the cloud is given over to commercial Wi-Fi hotspots operating on a pay-per-use basis. We found three major pay-per-use providers in Salt Lake City; taken together the footprint of pay-per-use coverage carpets a large portion of the urban area (Figure 10). The downtown core and the tourist areas in particular are not well covered by commercial hotspots. Hotspots open to the public were less expansive in coverage, focusing mostly around the city's library, which serves as a civic hub in the city and is situated adjacent to a prominent local ISP. Other isolated public hotspots centered on various coffee shops in the city.

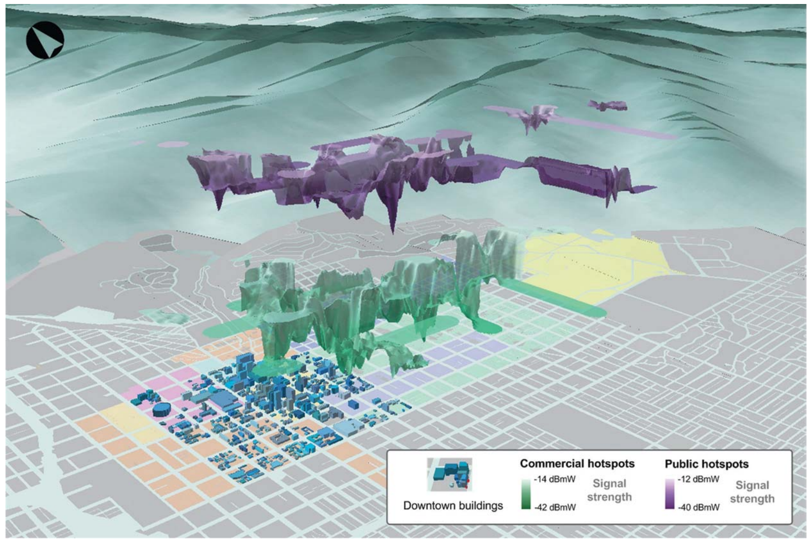


Figure 10. Commercial hotspots cover a large part of the city, but miss much of the downtown and tourist core (central and northwestern sections of the area shown as comprising downtown buildings). Public hotspots are focused on civic space and around the city's library.

The Network Capacity of Ambient Airwaves

The network capacity of ambient airwaves for Wi-Fi communications was found to vary geographically, as evidenced by the technical benchmarks of our sampled frames (signal noise, signal power, and supported data rates). Wi-Fi communication is well supported over the city. This is surprising; the density of access points and omnipresent overlap of transmissions is a recipe for widespread problems in network throughput.

Signal strength as measured in units of noise is high across the city, suffering a distinct dip only on the outskirts of the city's commercial core and on sections of the University of Utah campus (Figure 8). Signal power is also consistently high across the study area and spikes in the commercial core, the University of Utah campus, and the residential Avenues district (Figure 11). As mentioned, signs of systematic place-based signal loss were discovered in residential areas and this is indicative of problems with signal propagation in those areas. No technical explanation in the network traffic over those areas was found, leaving us to assume that the lows are a function of physical factors.

Information exchange over Wi-Fi is supported at very high data rates citywide (Figure 12). Two access points supported communication at a rate of 55 Mbs^{-1}; 579 (33 percent) supported 54 Mbs^{-1}; 69 (4 percent) supported 22 Mbs^{-1}; 1,071 (62 percent) supported 11 Mbs^{-1}; and

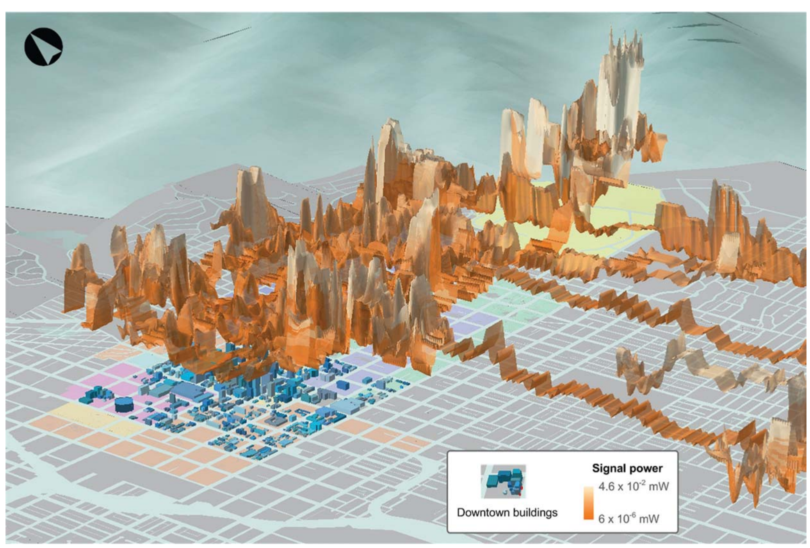


Figure 11. Signal power over the study area.

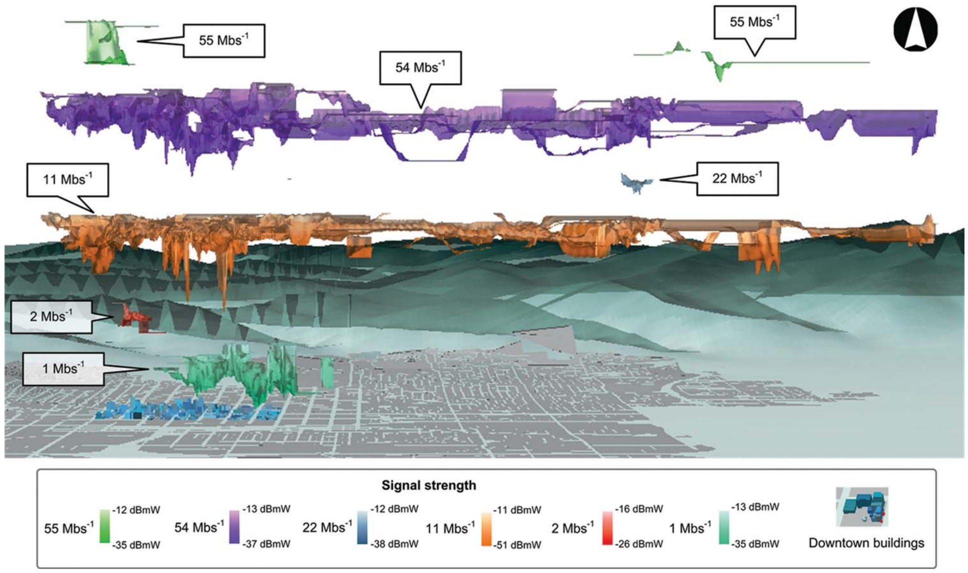


Figure 12. Observed data rates in the study area.

a handful communicated at rates of 2 Mbs^{-1} and 1 Mbs^{-1}. Considering the number of access points discovered in the city, and the rate at which they can communicate, this is representative of support for a massive volume of data transmission over the airwaves. If each device were to broadcast at full capacity, the network of access points that we detected could communicate collectively at a rate of 44,680 Mbs^{-1}, capable of exchanging 5.45 GB of data every second. If this kept up, it could handle 460.19 terabytes per day, 3.15 petabytes per week, and 164.14 petabytes per year. This is equivalent to transmission of the storage capacity of more than 271 million compact discs a year, in just one part of a city.

Only a small portion of the study area exhibited signs of problems in Wi-Fi data exchange. Data rates below 11 Mbs^{-1} are the tell-tale sign of data congestion over the airwaves. When Wi-Fi transmissions suffer difficulty in stretching between an access point and a receiver, the access point automatically scales back the data rate to essentially reshape the form of the transmission so that it can push through a congested part of the spectrum. This feature is clearly operating in sections of the city where local clustering of high signal strength (measured in units of noise) was highest, where there was a spike in the power of Wi-Fi transmission, and where access point density was the highest (Figures 9, 10, and 12). These are the areas where low data rates ($\leq$2 Mbs^{-1}) were detected. This is indicative of problems with the technical ability of the airwaves to support networking in these areas.

Our analysis of spectrum geography found traffic to be concentrated around channels 1 (2.412 GHz), 6 (2.437 GHz), and 11 (2.462 GHz; Figure 13). Broadcasting on one of these three frequencies ensures maximum separation between channels, and it is generally advised that access points be set to those channels to avoid spectrum congestion. This is because the space to either side of the Wi-Fi channels is very narrow ($\pm$25 MHz) and transmissions might drift around the central frequency in each band, causing interference. We did, however, find a significant volume of traffic on intervening channels between 1, 6, and 11 and a notable concentration of traffic in bands around channel 11, with associated risks of channel collisions. We also found almost continuous spatial overlap of channel traffic across all bands (Figure 13). The potential for channel collision is clearly prevalent across the city.

Security of Wi-Fi infrastructure and transmission is particularly important to the network performance of wireless communications. Access points that are tethered to wide area networks, local area networks, or computing devices might be vulnerable to intrusion (with potential theft of user credentials, passwords, credit card details exchanged between client and server machines, and so on), misuse, and hijacking if not properly configured. Wi-Fi transmissions are vulnerable to theft if they are not encrypted when broadcast. This is particularly problematic when access points are configured with default settings for encryption and SSID, an issue that is not easily resolved. Wi-Fi technology is reasonably easy

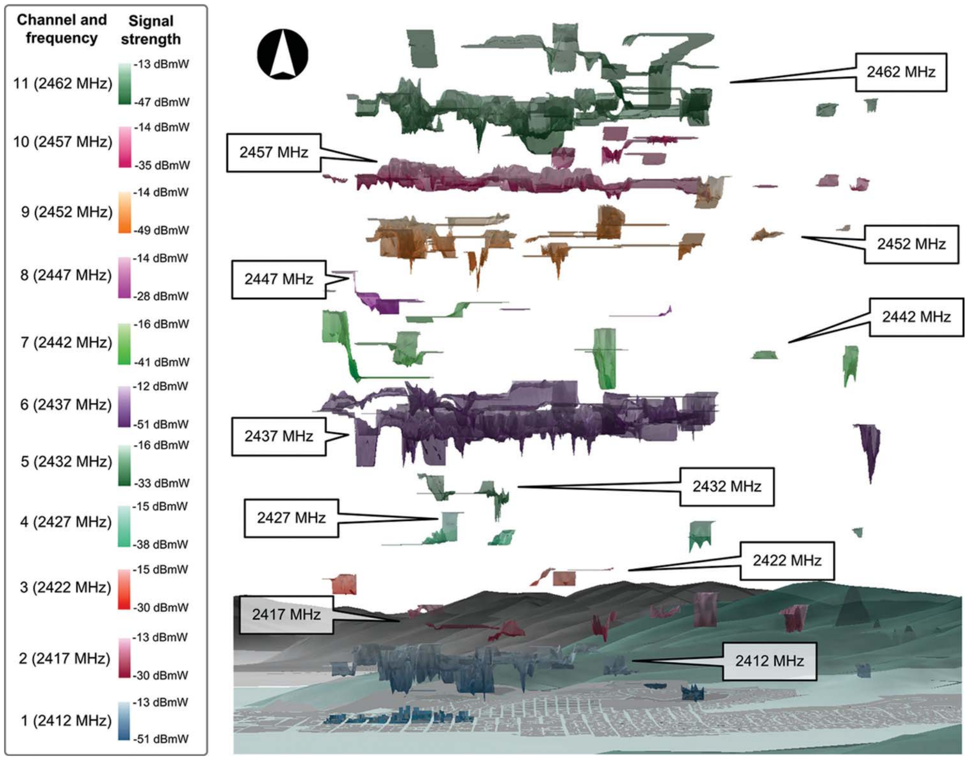


Figure 13. The position of Wi-Fi transmissions in the radio spectrum, by channel.

to use, but quite difficult to configure, as it requires users to develop encryption keys and protect SSIDs. As a result, the devices often ship with open configurations.

Our analysis showed widespread evidence of unsecured access points and unencrypted transmissions across the city. Of the detected access point, 1,333 (70 percent) were actively transmitting data without encryption. A total of 470 (27 percent) of the access points had been powered on with the default SSID (which implies default passwords and other settings). Moreover, 401 (23 percent) of the access points were wide open with default SSID and no encryption. Geographically, these security problems persist citywide (Figure 14). Clearly, the majority of Wi-Fi transmissions in the city are susceptible to theft and the infrastructure supporting it is wide open to vulnerability and accessible from almost any vantage point. Indeed, the only contiguously secure area is the section of central city around student accommodation near the University of Utah, on the far east of the study site.

These lapses in security are indicative of the problems of impromptu Wi-Fi hotspots: they are often configured in an amateur fashion. Our findings regarding security are similar to those noted in other cities. Data from worldwidewardrive.org, a group that tests for access point security in San Diego, California, every year reported similar statistics in their last test (2004): 61.6 percent of access points broadcast without Wireless Encryption Protocol (WEP), 31.4 percent had a default SSID, and 27.5 percent had a default SSID and lacked WEP.

Conclusions and Epilogue

Wi-Fi technology and wireless data traffic are of growing importance. However, there are significant difficulties in determining the geographical significance of what is an emerging phenomenon, despite the relevance of understanding wireless spaces.

We have set out, with this work, to map the hidden geography of Wi-Fi in Salt Lake City. Using a broad methodology involving fieldwork with various hardware and software to probe the airwaves for wireless transmissions and pick apart communications exchanged within clouds of data broadcasts, and spatial analyses to analyze its properties, we have also investigated the underlying infrastructure responsible for feeding the airwaves with wireless data, the geography of Wi-Fi transmissions across scales, and the technical functionality of ambient airwaves to support wireless networking, the uses to

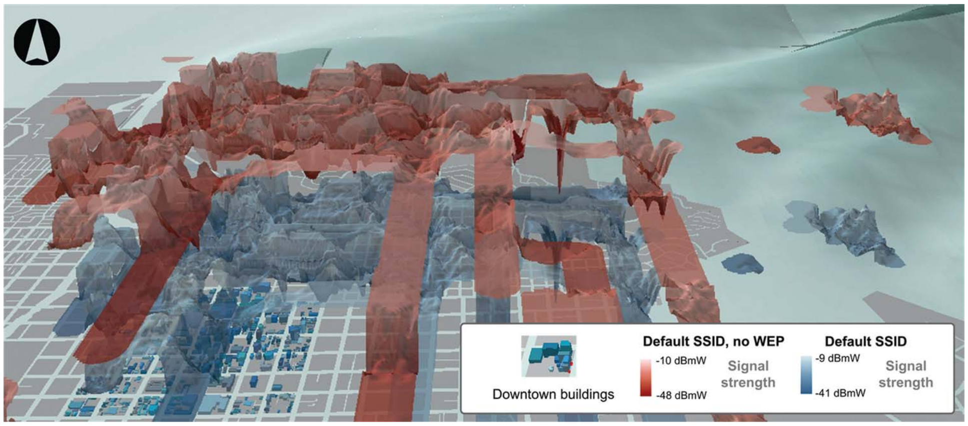


Figure 14. Wi-Fi security: Signals broadcast with default service set identifier (SSID) and without the Wireless Encryption Protocol (WEP).

which Wi-Fi technology is put, and the activities that it supports.

Our findings paint a picture of a massive cloud of overlapping and intermingling Wi-Fi transmissions blanketing the city, with ubiquitous coverage under its shadow. This cloud of broadcast data is supported by a relatively small number of access points distributed evenly over the city. The technical functionality of Wi-Fi clouds is geographically heterogeneous. Signs of emerging technical limitations and potential adverse physical effects on signal propagation were discovered, but the network of wireless transmissions in Salt Lake City was found to be surprisingly robust and resilient to problems.

Wi-Fi is clearly important in most U.S. cities, and growing increasingly so. There is every indication that this is a situation reflected in other cities around the world. Wi-Fi is capable of taking wired broadband to new places with relatively little additional infrastructure. The popularity of digital devices designed to operate wirelessly in cities, using the same mechanisms and frequencies as Wi-Fi, is gaining ground, with the potential for a disruptive influence on the business model for wireless telecommunications and society. Salt Lake City is no exception to the trend. An impromptu wireless network carpets the city, wiping out last-mile problems in a city that has struggled with the politics and economics of access to broadband networking resources (Wallace 2004). There is no digital divide for users with hardware and rights to access Wi-Fi in the city.

Nevertheless, there are early indications that Wi-Fi in the city is beginning to fall prey to its own success. There is adverse crowding of infrastructure in parts of the city and signs of saturation in the radio spectrum. This is understandable given the relatively moderate costs and ease of installing and operating Wi-Fi infrastructure. The spectrum space for Wi-Fi is somewhat of a free-for-all, relatively unregulated and with low barriers of entry. This has led Wi-Fi developers to next-generation technologies based on spread-spectrum pulsing broadcasts (so-called Ultra-Wideband, or UWB) that can eke out the few remaining paths in a crowded radio space (Sharma and Nakamura 2003). The problem has also led to discussions in several countries about extending the unlicensed spectrum for Wi-Fi or licensing the spectrum commercially. Commercial interests have already begun to license spectrum for Wi-Fi communications in airplanes.

In obvious defiance of claims that ICTs would herald the death of distance and the end of geography (Cairncross 1997), place, space, proximity, and location are clearly essential to consideration of Wi-Fi communications. Wi-Fi infrastructure and transmissions have already begun to influence the urban geography of Salt Lake City, reinforcing the dominance of its dense central commercial core with hubs of wireless infrastructure and signals. Nevertheless, the technology is available citywide, bucking classic trends by carpeting interstitial sites and outlying areas with coverage.

Wi-Fi also has the potential to usher in entirely new geographies. A new chorography of location-based services and ubiquitous context-aware computing is emerging. Cities are fast becoming cyberplaces and computable spaces. The codes, protocols, and software that govern access and authenticity in such spaces (Thrift and French 2002; Dodge and Kitchin 2005) are capable of redefining urban geography. There is evidence of this in our findings for Salt Lake City: public hotspots in the city encapsulate civic areas and reinforce their utility as public spaces.

There are, however, foreboding implications to Wi-Fi prevalence and popularity. Wireless networking has become ambient and omnipresent, bathing citizens in connectivity to a growing array of computers and databases. The air around cities hosts a burgeoning urban data cloud, connecting urban citizens and commercial entities in new ways. Indeed, our digital devices—cell phones, pagers, laptops, gaming devices, handheld computers, and even the tags on retail goods and the credit cards that we use to purchase them—serve as beacons amid this cloud, broadcasting our presence in space and time with an increasing level of precision and depth of associated information. Our activities are trailed by expanding data shadows (Westin 1968) as we move, act, and interact in urban space.

Note

Parts of the technology reported in this article are patent-pending with the U.S. Patent and Trademark Office. Please contact the author for details.

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