Designing for Connectivity: Rethinking the Interaction with the Built Environment and Wireless Communication Infrastructure

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Abstract. In this article, we present research on the design of buildings that respond to the performance of wireless networks by use of different materials and human-building interfaces. We discuss the way buildings accommodate propagation of wireless signals and different techniques to make this propagation more relevant to the use and experience of space. Early ubiquitous computing research proposed *seamful* design of interfaces and services as a way to promote embodied interaction and agency of the user. Contemporary approach to the design of seams aims to promote legibility of interactions with infrastructures. These interactions include connection, use, and quantification of wireless network performance. We review the work in architectural design that specifically addresses building permeability to electromagnetic radiation. We also examine electrical engineering research that explores the development and possible uses of frequency-selective surfaces in buildings. As a result, we make two proposals for the use of wireless networking infrastructure to promote location aware services and the design of connectivity-selective interiors. These proposals incite the rethinking of design and interaction with the built environment in terms of communication infrastructure that it relies on.

Keywords: Wireless connectivity, Seamful interaction, Full-spectrum design, Indoor positioning, Frequency-selective surface, Design for connectivity

1. Introduction

Computing systems are increasingly embedded in buildings to regulate everything from temperature and lighting to the right of access. This does not imply that buildings are becoming computers for living – computers and buildings have quite different purposes and operate in distinct ways. Computers are universal machines that can perform a large number of unrelated tasks. Buildings, on the other hand, are aimed at producing fixed, immutable environments. While the output of interaction with computers is mostly intangible (something is computed), interaction with buildings is mostly tangible and irreversible.

Before visions of ubiquitous computing manifested themselves as the massive implementation of computing systems throughout the built environment, human-building interaction (HBI) research largely focused on energy efficiency and post-occupancy evaluation scenarios [18,23]. These areas of focus translated from the fields of human-computer interaction (HCI) and building performance research. With the Internet of Things (IoT) entering the scene and the increasing interest from companies and academia in *smart homes* and *smart cities*, it became more compelling to envision the built environment as a connected, sensitive and responsive system. In this light, the design of interaction with buildings followed the trend from tangible: opening a door using a door knob; towards intangible: movement-triggered door sensors, shades that respond to daylight conditions, programmable thermostats, etc. Connectivity gradually became a central requirement in these systems, networking tangible and intangible components with interfaces and people. Yet, designers and architects rarely consider connectivity outside of its functional paradigm.

Offsetting previously mentioned trends that favour intangibility, we observe connectivity both as a resource and a *material* to be designed and interacted with. We present an approach to the design of space, which is sensitive to wireless networking infrastructures. The motivation to include wireless infrastructure in the conception of buildings comes from observations made in the wireless industry [26], as well as in avant-garde architectural. With these in mind, we review existing examples of buildings that address electromagnetic radiation by design. We also look briefly into the artistic practice of rendering wireless communication tangible. We then review a research into wireless friendly and energy efficient buildings, conducted by a multidisciplinary team of researchers at the University of Sheffield, UK and Czech Technical University in Prague. Finally, we present our own experiments with making sense of Wi-Fi and cellular infrastructure use in space. These experiments highlight the relevance of this infrastructure for the experience of space, through a combination of network use and spatial occupancy evaluations. This analysis can bring the thinking about connectivity in space closer to designers and architects.

We make two proposals for the design of and with connectivity at the end of this paper. In the first proposal, we discuss the potential of indoor positioning to play a larger role in conceptualizing building use scenarios. In the second proposal, we discuss connectivity-selective interiors. Building on the occasional efforts in the HCI community to promote a *seamful* approach to design [6,27], these proposals investigate the materiality of radio signals propagation. Through these investigations, we are sketching out the path for architectural and interaction design to systematically engage with wireless communication infrastructures.

2. Interaction with Wireless Communication Networks: Seamless and *Seamful* paradigms

The development and deployment of wireless infrastructure has always been attuned at seamless connectivity across technology and territory. Why do we want seamless so much? For obvious reasons of ease of access while on the move; for letting the users focus on information rather than the availability of connection.

Mainstream interaction design has largely adopted the *disappearing interface* as a principal design challenge, epitomized in the *Age of Context* [29]. Invisibility is the key metaphor for the way technology operates or connects today, from wireless networking to seamless integration of functions in a smartphone. The seamless paradigm embraces easy adoption of technology, reflected in intangible metaphors of the Cyberspace or the Cloud.

As a counterbalance to seamless connectivity, some researchers explored the social and spatial aspects of networking technology. Their interests were driven by a combination of factors, which can be correlated to the availability, adoption rate and social relevance of wireless communication technology. Most notably, they experimented with rendering the *seams* visible – be it through the act of connecting [27], availability of networks [6] their embodiment [11] or interaction with them [2]. Artists and designers too worked on rendering wireless connectivity visible and tangible, especially around the time when the technology was massively deployed [28].

2.1. Seamful Design of Systems and Infrastructures

Seamful design is an approach that reveals underlying structures and relationships behind what appears as utilitarian infrastructure [6]. The concept of *seamful* design came out of early ubiquitous computing discourse, drawing upon Mark Weiser's ideas about the integration of digital tools [35]. Weiser insisted that the design of interfaces should preserve the agency of users while technology disappears in the background of attention. Advocating the intentional design of seams which appear at edges of connections and territories, such design encourages user engagement [10] and understanding of the resulting combined space [27].

The most prominent advocate of *seamful* design was Matthew Chalmers with his work on the *Seamful map* and *Seamful game*. The *Seamful game* (see Figure 1) exploited the seams in wireless connectivity as part of the play. Players would have to go into offline spots to pick up virtual bricks. It also allowed users to manipulate the seams, by extending the area of network coverage with their device as a bridge between fixed access points. Finally, it played with tools specific to networking, such as traffic flooding[1], when users would make wrong moves. In sum, these *seamful* experiments explored and promoted user's ability to adopt and adapt to ubiquitous computing tools for their own goals and purposes.

Another line of critique of seamless integration of tools, computers, interfaces and connections came from Paul Dourish in his book on embodied interaction [10] and his subsequent collaboration with Genevieve Bell [5,11]. Central to Dourish's argument about embodied interaction design is the intentional design of *seams*. Embodied interaction design should, thus, encourage user engagement. Just as an invisible pen would be a hard thing to use, interfaces are not supposed to disappear, Dourish insists [9], but have to be designed in such a way that they can be mastered.

[1] Network flooding is a Denial of Service (DoS) attack that can be initiated by sending a large number of packets to random (or all) ports on a remote host. As a result, the host will be forced into responding, eventually making it unreachable by other clients.

Fig. 1 Seamful game play at Ubicomp 2004 in Nottingham, England. *Seamful game* is a GPS and WiFi based game exploring the concept of seamfulness, created by Matthew Chalmers, Marek Bell, Barry Brown, Malcolm Hall, Scott Sherwood and Paul Tennent

More recently, researchers have been addressing the design of invisible technologies in a broader scope of urban surveillance, network sharing, social media feeds and smartphone use. Arguing for the need to take the control of one's visibility in urban space, Martin et al. explored the design of urban camouflage at a DIS12 workshop [24]. In the area of wireless communication, Montes et al. developed BayanihaNets – an implementation of a peer-to-peer network system that renders the act of sharing tangible through cooperative access. Eslami proposed *seamful* design of social media feeds, by exposing the algorithms that curate everyday online content, in the web interface [14]. This work is addressing 10 "folk theories" on automated design, identified by the author [15]. Barkhuus and Polichar have explored how customisation of functionalities of a smartphone enables user empowerment. Dealing with the many features and failures of smartphones in unique ways, users adapt the technology to their needs and this process of adaptation exposes the seams [4].

With new technologies, come new seams. The tendency to cover them up is repeatedly met with propositions to use them productively instead. A productive design of seams gives more power to the user, often subverting mainstream narratives of technical applications in ways that are more relevant to the community they serve.

3. Planning, Designing and Controlling Wireless Connectivity in Buildings

3.1. From Energy Extravagance to Energy Efficiency

More often than not, engineers plan and implement wireless infrastructure after the building design process has been completed. They need to work around all conditions and difficulties inherent in the building design. Contrary to this trend, a recent industry analysis showed that designing wireless infrastructure at the same time as the building would bring both cost and performance benefits [26]. By including plans for cellular connectivity early on in the design stage, additional costs of securing in-building coverage could be defrayed. Distribution and management of wireless networking indoor would be more efficient when its requirements would be taken into account when decisions on interior organization and choice of materials are being made. How could we bring the thinking about connectivity in space closer to designers and architects?

To illustrate this question, it could help to substitute radio waves with visible light. Availability of daylight was a great concern for the indoor organisation of space prior to electrical lighting. Industrial buildings were specifically planned with the constraint of delivering daylight to the workers' operations. Besides limitations set by construction techniques, the width of the buildings and size of the openings were courted to the tasks and lighting required in the inside. Then, around the year 1880, Thomas Edison (US) and Joseph Swan (UK) introduced electrical light bulbs to the market. Artificial lighting industry was born, and it revolutionised the building industry. Another important invention was indoor air conditioning and its widespread distribution throughout the 1930s. These two industries rendered architecture more autonomous from the external environment than it has been ever before.

This autonomy was highly dependent on electrical power, which was perceived as an unlimited resource at the time. Only a hundred years later and several energy crises in, the building industry would begin considering energy efficiency as a design constraint.

Today's trend is to outsource energy efficiency to so called *smart* controls for power consumption, lights, temperature or window blinds. Wireless communication networks enable transmission of wireless sensor data readings, processing this data and sending feedback to the system [1]. The system can then close the blinds if there is too much light; or turn on the heating if temperature is too low.

3.2. Wireless Networks in Building Design: The Negative Approach

In the history of buildings that address electromagnetic (EM) signals, the only response to their propagation was to entirely block them. By constructing Faraday cages (mostly through shielding integrated in the facade), architects have created *EM blind* interiors and entire buildings.

Fig. 2: Signal Box Auf dem Wolf by Herzog & de Meuron Basel, Switzerland (1989) Realization 1991-1994

Constructed between 1991 and 1994 by Swiss architects Herzog & de Meuron, Signal Box is one of such *EM blind* buildings. It features a Faraday cage as facade design, shielding the control equipment from external events.

These external events come from the surrounding electrical infrastructure used by the railway system. The horizontal copper strips wrapped around the concrete building shell isolate and protect the electrical equipment inside the building from low frequency EM impulses (60Hz). Following the principle of a Faraday cage, the spacing between metal strips is determined by the wavelength of the signal.

The NSA Headquarters in Fort Meade, Maryland is designed to keep sensitive information secured in the interior of the building. Not much is known about what goes on in the inside. What one sees is really what it does – a slick opaque facade reflecting light off the dark glass panels. Rumour says its facade doubles as a Faraday cage, shielding from eavesdropping by diverse active and passive wireless spying techniques. The technique of wirelessly spying on information systems, also known as TEMPEST, has been widely explored in radio wave communication, notably through devices such as Leon Theremin's Thing[2], which enabled remote listening of conversations in the USA ambassador's residency in Moscow.

[2] The Thing bug comprised a capacitive membrane and an antenna. The bug was hidden in the Great Seal which hung at the US ambassador's Moscow residential study and was activated from the outside by "illuminatig" the antenna with a radio signal of the correct frequency It was used between 1945 and 1952.

Fig. 3: NSA Headquarters Eggers and Higgins (RMJM Hillier) Fort Meade, MD, USA completed 1986

Such wireless intrusions are getting even more common today, with more than 9 Petabytes of data was transferred over US wireless carriers in 2015 alone[3], all this data potentially subject to analysis. To ensure the traditional secrecy of the the Papal Conclave in 2013 – both in direct and in telecommunications, the Sistine Chapel was secured with GSM jammers and Faraday[4]. These measures were supposed to prevent communication with the outside world as well as eavesdropping – through hidden microphones picking up the discussions or similar tricks. Although this intervention was not visually substantial, it shows the discrepancy between architecture as a shelter from weather and from electromagnetic radiation.

3.3. Wireless Networks in Interactive Installation Art and Design: Designing with *Wirelessness*:

Wirelessness is a term introduced by Adrian Mackenzie [22] to discuss empiricism in the context of wireless networking: the experience of connectivity in the realm of chipsets and communication signals. Intuitions about this experience lead Anthony Dunne and Fiona Raby to work on, what they termed *Hertzian space* [12], and subsequently the influential *Design Noir* [13]. Designers and artists working with

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[3] This number is based on the CTIA Anual Wireless Industry Survey, http://www.ctia.org/industry-data/ctia-annual-wireless-industry-survey

[4] Not much has been written about this aspect of the event, besides short news articles which can be found here : http://www.nytimes.com/2013/03/12/world/europe/in-conclave-ritual-and-secrecy-in-election-of-pope.html or here: https://www.theguardian.com/world/2013/mar/13/pope-elected-but-still-unnamed

digital media used the terms *wirelessness* and *hertzian space* to refer to the vague terrain of wireless communications, electromagnetic radiations and their spatial, social, cultural and political representations.

In our previous work, we explored some of these works in terms of wireless network tangibility [28]. We looked into the language these artworks developed as well as types of interaction they enabled. Between 2006 and 2008, an artist trio (Usman Haque, Bengt Sjölén, Adam Somlai-Fischer) developed the *WiFi Camera*, which uses waves in a way similar to the photographic camera's use of light, and "reveals the invisible electromagnetic space" [30]. Activity within different wireless network channels (laptops, Wi-Fi hotspots, smartphones and microwave ovens) is represented by the intensity of points in the image. Another team of designers and artists use the light painting technique applied to Wi-Fi, visualising the presence of wireless network signals in space. In 2011 Timo Arnall, Jørn Knutsen, Einar Sneve Martinussen performed walks around the Oslo School of Architecture campus and created a series of long-exposure photographs of Wi-Fi signal strength. *Immaterials: Wi-Fi Light Painting* created a set of "cross sections" of network signal strength in space [3].

3.4. Wireless Networks Interacting with Frequency-selective Surfaces

Research in Wireless Friendly and Energy Efficient Buildings (WiFEEB), conducted jointly at the University of Sheffield, UK and Czech Technical University in Prague, proposed engineering of *intelligent walls* that would respond to changing needs in use patterns of the wireless infrastructure.

Through a set of different use-scenarios in a fictional office building, researchers developed a system which relies on cognitive management of infrastructure and a layout of intelligent walls which can reconfigure their properties to achieve the best system performance [33].

Put simply, these walls and access points control network capacity by switching between transmission and reflection modes and dedicating more bandwidth to certain access points when only parts of the building are used. Intelligent walls are dynamic

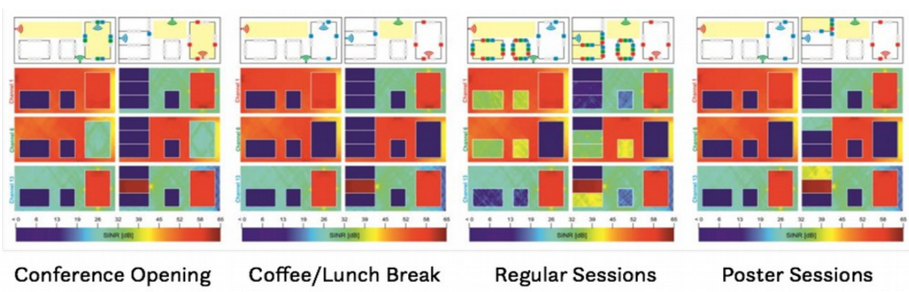

Fig. 4. Scenario simulations for four difference distributions: a) Conference Opening, b) Coffee/Lunch Break, c) Regular Sessions, d) Poster Sessions

elements of architecture, reconfigurable to EM propagation needs and scenarios. They are a new method of controlling coverage and interference inside an indoor scenario.

In the light of different scenarios, researchers identify two kinds of control that the system could enable [32,33]. On one hand, cognitive management of infrastructure would imply gathering data on building occupancy – identification of the number of connected devices through the infrastructure itself – and determining the strength of signal needed to serve these needs. Cognitively managed access points could switch on or off depending on occupancy. On the other hand, settings for different use scenarios can be instructed by human users: conference opening, coffee/lunch break, regular sessions, poster sessions (see Figure 10). We believe such a system could also address more general needs such as public gatherings (conferences, symposia) normal working hours, activities requiring special levels of privacy (such as sensitive, closed meetings).

4. Understanding Network Use and Spatial Occupancy through Traffic Counting and Indoor Positioning

From September 2014 to August 2015, we worked on an indoor localization tool that couples usually unrelated quantities: the amount of data or traffic load and the device's position. The tool is essentially an on/off switch for transmission of information about network traffic. It logs usage of data, cell towers, SMSs and location estimation based on *Wi-Fi fingerprints*.

4.1. Gathering Data: Wi-Fi fingerprinting

Wi-Fi fingerprints are impressions or traces of radio signal broadcast by Wi-Fi access points. A fingerprint consists of a measured intensity of the received signal (RSSI) at a particular point in space, together with parameters such as the MAC address of the AP, and a timestamp. By collecting *fingerprints* at different positions in space, the system is able to estimate position based on similarity of the current measurement to an existing one in its database. The database is organised around readings of individual access point RSSI measurements, which are related to a timestamp and thus belong to a single Wi-Fi fingerprint. A Wi-Fi fingerprint obtained with our tool contains data as shown in Table 1. Using this technique, we were able to gather and visualise network traffic load in space.

Table 1: One reading of the positioning system: measurementId 668, at 23:23:36 CEST, October 14th 2016 (BSSID and ESSID redacted for privacy)

wifiReadingId	BSSID	ESSID	RSSI
49752	bc:ee:7b:##:##:##	doub*******	-60
49753	00:26:42:##:##:##	bby-*****	-44
49754	70:5a:0f:##:##:##	DIRE***************8710	-59
49755	c0:25:06:##:##:##	FRIT*********	-66

49756	bc:ee:7b:##:##:##	laza***	-56
49757	c0:25:06:##:##:##	FRIT************	-51
49758	c0:25:06:##:##:##	FRIT***********7390	-83
49759	80:c6:ab:##:##:##	SebI**	-71
49760	c0:25:06:##:##:##	FRIT************7390	-90
49761	cc:03:fa:##:##:##	odib******	-79
49762	d0:05:2a:##:##:##	vcs-*****	-83
49763	00:26:42:##:##:##	mlb-*****	-78

4.2. Indoor Positioning: Iterative System Development

Indoor positioning is based on triangulation[5]: estimating the position of a device according to known positions of wireless devices it is able to identify. For this purpose, we used two types of devices: Estimote™ Bluetooth-light-energy (BLE) beacons and Wi-Fi access points. The beacons are certified Apple iBeacon™ compatible with both iOS and Android powered devices. They could be easy implemented into our measuring system with the software development kit (SDK). Each beacon sends out a continuous signal in a predefined range (range is based on signal strength, it can be set in the application and it ranges from 1.5m to 7m). It contains a UUID, a major and a minor number unique for the beacon[6]. The variance in range determines the precision a space is marked up with – the shorter the range, the more precisely one can associate device's position with the nearby beacon. Conversely, the longer the range, the more overlap between different beacons signals will occur. Unlike the beacons, Wi-Fi access points we used in the positioning experiments were part of the existing infrastructure. They did not require physical setup or redistribution but were introduced into the system through measurements.

In our first experiments we used low-grain positioning based on Estimote beacons. Figures 5 shows one day in the experiment, visualising data and space occupancy based on measurements acquired by the system we developed. Red circles mark the position of Estimote beacons. Thin circles in different colours represent the amount of traffic occurring in the proximity of a beacon, each colour tied to a single user (anonymised). Circle circumference size is scaled to fit the image best, varying between 11 and 140.8MB, most frequent value of about 24 bytes.

We then coupled Bluetooth beacons with Wi-Fi fingerprints to compare the two technologies and improve the positioning precision. First the space needs to be set up – marked up with Wi-Fi fingerprints. We performed a series of in the attempt to correctly estimate devices position according to existing Wi-Fi fingerprints. At first the estimation based on wireless infrastructure does not show very good results. After two training sessions, Wi-Fi fingerprinting is correct 61.5%, while Estimotes estimate

[5] Dictionary.com definiton of triangulation: http://www.dictionary.com/browse/triangulation
[6] Technical details about Estimote beacons and their use: http://developer.estimote.com/

correct location only 27% of the time (calculation based on duration the device was correctly localized). In Figure 6, we show the difference and the training progress. The importance of this finding is in emphasizing the potential of existing infrastructure to serve an additional purpose. It also makes the case for a spatially relevant performance of wireless infrastructure.

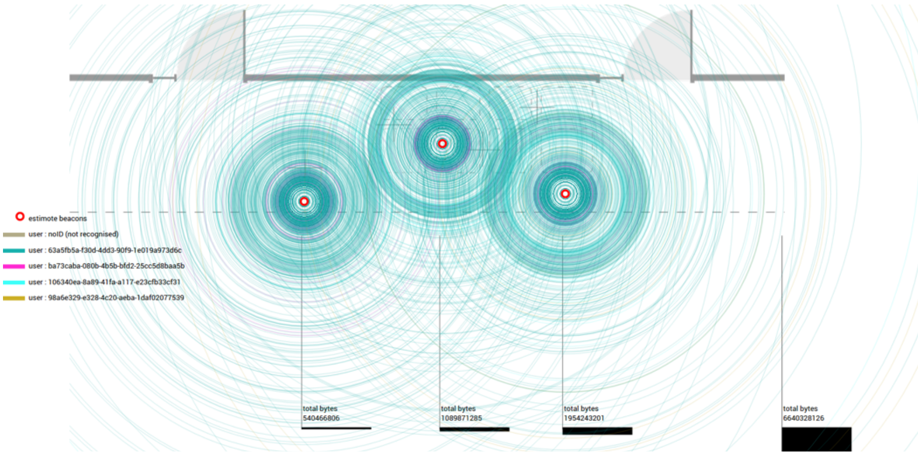

Figure 5: Visualisation of data/space occupancy. Lisbon, IST, Pavilhao Civil 17.09.2014, from 10:11 - 17:17 (roughly 7 hours). Estimotes marked with red circles, data packets in thin-lined circles of five different colours. The size of a data-packet circle is determined by the amoiunt of data (circle circumference scaled to best fit the image)

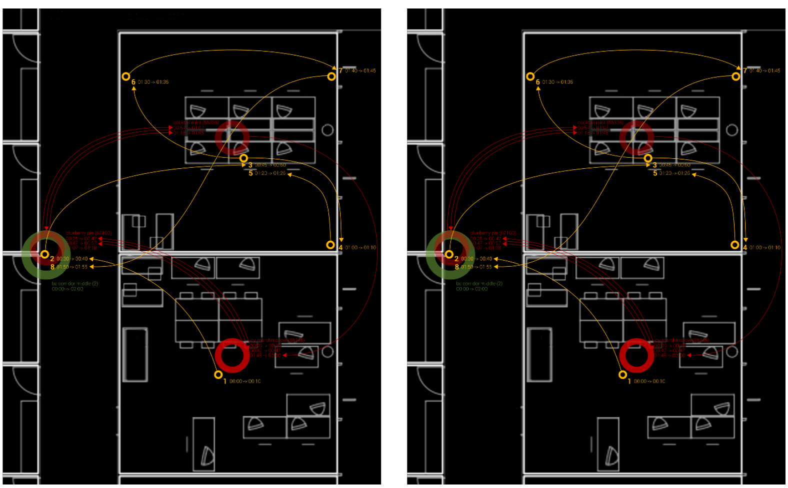

Figure 6: Comparison of the two positioning systems: Bluetooth (red) and Wi-Fi (green). Actual position is marked by a small yellow circle. Measurements taken in December 2014 (left) and in August 2015 (right).

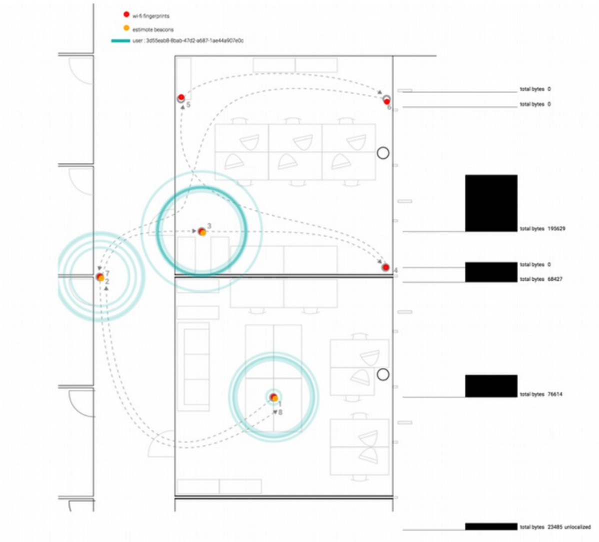

Fig. 7. Visualisation of data/space occupancy. Training phase. Lausanne, EPFL, BC building (offices 117 and 121). 17 August 2015 from 12:55 - 12:57 (2 minutes).

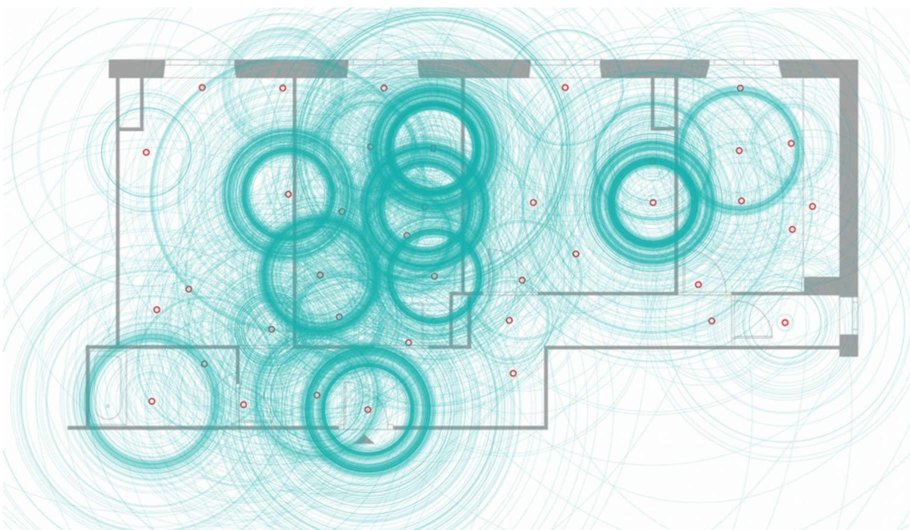

Figure. 8: Visualisation of data/space occupancy. Lausanne, Av. de France apartment building, 2nd floor. 16.10.2016 from 00:30 to 17.10.2016. 23:55 (2 days). Red circles mark pre-configured Wi-Fy fingerprings. Blue circles denote the amount of trafic recorded at a specific position. Their size is scaled to fit the image best, varying between 3 and 10.8MB, with most frequently appearing values of about 65 bytes.

In Figure 7 we show plotted results of data/space occupancy observation during the training phase: red dots are Wi-Fi fingerprints we made to mark up the space, and blue circles show the amount of data traffic that the system “caught” at each location. Red circles mark positions of pre-configured Wi-Fi fingerprints; yellow circles mark positions of Estimote beacons. Blue circles denote the amount of trafic recorded at specific position. Their size is scaled to fit the image best, varying between 65 and 4174 bytes.

Finally, we conducted a longer observation of data traffic load in space over the course of two days. This observation is shown in Figure 8. It confirms basic assumptions about daily network activity in an apartment – such as that the most of the time is spent and the most of the data is transferd while the device is in the living room. It also shows that there is a standard packet size which appears most often. This is most probably due to the repetivite type of machine-to-machine communication, devices acknowledging their presence through beaacon frames.

5. Designing for Connectivity

One of the main problems in designing space for EM signal propagation is that we cannot see it. Unlike light, the only way we can envision signal propagation is through hardware and software tools that are able to measure and represent signal values in a tangible way. There is a large number of smartphone applications that are able to measure and display signal strength on the screen. Professional signal monitoring tools (Ekahau[7], AirMagnet[8], etc.) can produce heat-maps and represent complex situations on multiple levels. Signal, however, is in constant flux and a visualisation is only able to capture one single moment - even if representative – of propagation behaviour.

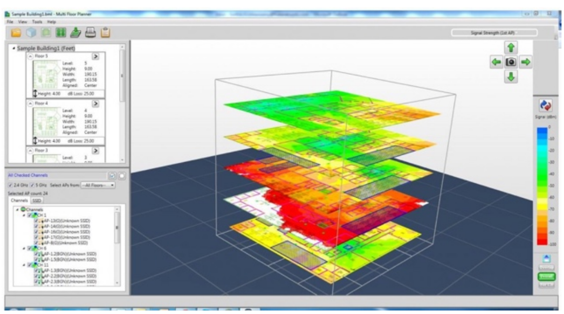

Fig. 9: Commercial tools for network planning and evaluation: signal strength values mapped onto floors of an office building using AirMagnet Planner software

[7] Ekahau site survey software, http://www.ekahau.com/wifidesign/ekahau-site-survey
[8] AirMagnet Planner software, http://airmagnet.netscout.com/

Two proposals we make in this article illustrate our ideas on paths to take when designing for connectivity. We already identified efforts in the academia and in architectural practice which address these scenarios. The first proposal discusses our own work on localising network traffic in space, based on the user. We approach indoor positioning as a way to render the presence and qualities of wireless communication signals relevant to the experience of space. The second proposal concerns application of carefully selected or engineered materials that promote networking adapted to difference use-scenarios.

5.1. Proposal I: Using Wireless Networking Infrastructure to Promote Location-aware Services

Repeated measurements of signal strength can give us a better idea of wireless networks signal fluctuations. They also reveal the degree of stability in this environment which can be used to extrapolate interesting information. Indoor position tracking is one such extrapolation. By measuring and collecting signal strength values in space, it is possible to triangulate the position of a device based on *Wi-Fi fingerprints*. Position tracking based on received signal strength (RSSI) of Wi-Fi access points renders its radio signals relevant to organization and experience of space. Information on RSSI is used by networked devices to determine which access point to connect to. When used in Wi-Fi positioning, RSSI becomes significant for locating a device in space and consequently for what the user gets to experience based on their location.

Different kinds of actions can be taken when the position of a device is evaluated through wireless networking infrastructure [17]. The most prominent use of such technology today is serving contextual information, such as contextualized marketing in shopping malls or assistance in parking garages [21]. Location-aware services are also relevant in smart-home scenarios, providing adaptive personal services based on the user's presence and preference [19]. These services can be equally provided by demarkating space with beacons and with Wi-Fi fingerprints. We believe that the Wi-Fi based approach provides more flexibility, because it does not require any additional physical intervention (e.g. bringing beacons in, distributing them in space, changing their location to fit changing use scenarios).

The tool we developed can report on portable, networked devices position and traffic use. The focus on devices is driven by the fact that the majority of network bandwidth is used by smartphones, tablets and laptops and that these can be used to acquire a realistic image of a landscape of connectivity. We use position tracking as a way to point at an alternative use of wireless communication infrastructure installed in buildings. The performance of Wi-Fi access points becomes relevant to the use and experience of space when it is used to determine one's location. This overlap is only a starting point in articulation of a language of Wi-Fi informed design.

5.2. Proposal II: Connectivity-selective Buildings

Architectural design can be used to optimised the presence and distribution of wireless networks in buildings. Architects can account for the use of materials and disposition of routers in a more instrumental manner, resulting in better signal propagation. This requires in-depth studies of network propagation similar to the ones currently done with building performance metrics. Building performance studies focus on energy use, daylight performance, thermal, visual or aesthetic comfort, but their interest could be extended to wireless connectivity.

The research in Wireless Friendly and Energy Efficient Buildings, discussed above, provides a detailed study of electrical properties of standard building materials such as plaster walls, bricks, glass and insulation materials [31]. It also presents a detailed study of wireless system's performance in a real-world building [34]. These coincide with research done by electrical engineers in the area of meta-materials and frequency selective surfaces[9]. Meta-materials can be engineered to reflect electromagnetic radiation using the faraday cage principle, but also to actively change states between complete permeability and obscurity to the propagation of radio waves of certain frequencies.

People are sometimes concerned with the amount of radiation from wireless networking equipment. The maximum amount of power that a Wi-Fi device can transmit is limited by local regulations. Even though they differ across countries, these regulations prescribe a level which is significantly lower than what is considered harmful. Nevertheless, switching the phones off at night or putting them in the airplane mode is a standard practice. If the living environment is to adapt to these habits, in the most basic case, one might want to isolate a sleeping room from signals while providing uninterrupted reception in the office or living room. This can be done by isolating the space with a faraday cage in the first, while using a thin and transparent enclosure in the other. Accounting for signal propagation would require rethinking the use and qualities of existing materials in order to design connectivity according to the use of space.

Such an approach should not be limited to an inflexible, hard-coded materialization described above. Coating one's room as a faraday cage would require significant intervention once the function of the room would change (which is often the case in residential, as well as in office architecture). It is, thus, even more important to work on developing meta-materials whose properties can be adapted to current needs in a flexible way. Switching between permeability and isolation is a much more realistic scenario than hard-coding a faraday-cage into one's bedroom. In this scenario, *seamful* design of such a switch can contribute to readability and feelings of agency with the human user, as opposed to having the house or office adapt to some predefined, automated rules.

5.3. Synthesis: Towards Full-Spectrum Design

Although we previously stated that there is little interest amongst architects for wireless communication technologies, there are a few interesting proposals that

[9] A metamaterial is a material engineered to have a property that derives not from base materials, but from their newly designed structures. Frequency-selective surfaces are a kind of metamaterials, made of metallic grids deposited on a polymer substrate. The spacing of the grid determines material's opacity to specific EM frequencies.

advocate for the design of *full-spectrum* architecture – a design approach that takes into account not only the visible portion of the electromagnetic spectrum but also radio waves.

An interesting example in this respect is Space Caviar's RAM[10] house, a home prototype. The RAM house project proposes to facilitate setting the house in the "Airplane Mode" (The fundamental principle is that of a reconfigurable grid, organised by movable shields which filter, or not, EM radiation in the interior. By sliding the shield in, the ritual of privacy is facilitated similar to switching off the smartphone. It is not a permanent faraday cage but a space of selective EM autonomy. The authors are searching for "a space of domesticity which isn't permeable to observation through sentient appliances". They claim to care also for the degree of privacy this type of signal filtering enables, and which is unachievable though traditional architecture.

Fig. 10: RAM house, Space Caviar; Genoa, Italy 2015

6. Conclusion

We present two strands of research concerned with the design of buildings and interiors for optimal functioning of wireless communication infrastructures. We discuss the use of wireless access points to promote location aware services and make

[10] RAM stands for Radar-absorbent material

the experience of using the networks relevant to the design and use of space. We introduce a second proposal for considering new material properties in function of wireless network performance and the design of connectivity-selective interiors.

We build the argument about novel ways of interaction with wireless networks on an older discussion on *seamful* design and interaction with infrastructures, introduced in the early ubiquitous computing research. The question of seams remains unresolved in this community. Weiser and Chalmers saw the seams in the integration of different tools, devices and services. Chalmers considered spotty network coverage as a manifestation of seams in otherwise seamless wireless network infrastructure [6,8]. Dourish located seams at the edges of connections and territories within infrastructures and interfaces [10]. Rudström, Höök, and Svensson worked with seams they perceived between digital information and the physical or social contexts [27]. The seams of interest for this paper are by-products of connectivity such as access point overpopulation (every room has one of its own) and the planned vs. actual signal propagation indoor. The two proposals discussed in 5.1 and 5.2 are a reaction to this.

We discuss the disconnect between the processes of designing buildings and the process of planning network coverage infrastructures within them. Several notable exceptions exist, namely buildings that block signal propagation for the purpose of equipment preservation (e.g. Signal Box by Hertzog & deMeuron) or information secrecy (e.g. the Maryland NSA Headquarters). These cases serve as historical examples, strong points for the debate on inclusion of connectivity in building design agenda. While we are aware of the attention researchers in the HCI field have given to wireless networking [6–8,27], we have not observed an equivalent interest among architectural practitioners or theoreticians.

Our first proposal addresses the potential of existing wireless infrastructure to serve development of new interfaces and services. A continuous logging of network information (signal strength, SSID) can be rendered into a tool that can localize mobile devices and facilitate contextualized interaction. Visualisations of collected data facilitate observations about the nature of network traffic which normally go unnoticed. With the tool we developed, we were able to understand the traffic load in a spatially relevant manner. By associating network use with the user, we were able to get a unique view of activity within the network infrastructure, a view that was constantly updated.

The second proposal – design of connectivity-selective interiors is linked to this last observation. When we are able to identify specific use-patterns in buildings, we can consider designing the infrastructure in ways that are adapted to these needs. For this purpose, we recounted some outputs of the research on engineering materials and network infrastructures for Wireless Friendly and Energy Efficient Buildings (WiFEEB). Researchers proposed design of intelligent walls which would offer a high degree of flexibility in terms of coverage and bandwidth. They can switch states between permeability and impermeability to wireless network propagation. They can change these properties according to current users needs.

Energy efficiency returns as a relevant metaphor here. Wireless networks are, much like electricity has been since 1920s, an essential infrastructure to functioning buildings, but one that doesn't have a major impact on building design. The way electrical installations are placed around homes does not, per se, affect the performance of the infrastructure – wires transmit power with equal capacity through all types of walls and building forms. Propagation of wireless signals, however, can be reduced by building material. The performance of wireless infrastructure is, thus, affected by building design. To overcome this, additional infrastructure is needed (more routers, switches and cable), which in turn uses more energy.

There is a lot of ongoing work on rendering visible or otherwise readable the amount of energy consumed in both home and office contexts. The idea behind most of this research is to reduce energy consumption. Resources used by Wi-Fi routers are not significant (estimates are between 5 and 15$ per year, in US and Europe) and can easily be afforded in all contexts. But simply because we have no financial incentives, doesn't mean we should not think about more elegant, building-relevant ways to provide connectivity in buildings.

The relationship between architecture and electromagnetic radiation is based on countable phenomena (such as signal strength, number of data packets) and developing tools that lead to more freedom in thinking and designing the electromagnetic landscape. We have seen two examples of buildings that act as permanent shelters from electromagnetic radiation. With the research presented in this paper, we should be able to start thinking beyond shelters from electromagnetic radiation, just as we think of architecture beyond caves. Recent efforts that advocate full-spectrum design (such as the RAM house) are a good lead in this direction.

The proposals to design for connectivity illustrate the way to take electromagnetic radiation in buildings seriously. Beyond energy efficiency or post-occupancy evaluation, design of our interaction with the built environment needs to be rethought in terms of the core infrastructures it relies on.

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