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# Short Papers

# Contextual Location in the Home using Bluetooth Beacons

Charith Perera, Saeed Aghaee, Ramsey Faragher, Robert Harle, and Alan F. Blackwell

***Abstract*—Location sensing is a key enabling technology for Ubicomp to support contextual interaction. However, the laboratories where calibrated testing of location technologies is done are very different to the domestic situations where "context" is a problematic social construct. This study reports measurements of Bluetooth beacons, informed by laboratory studies, but done in diverse domestic settings. The design of these surveys has been motivated by the natural environment implied in the Bluetooth beacon standards relating the technical environment of the beacon to the function of spaces within the home. This research method can be considered as a situated, "ethnographic" technical response to the study of physical infrastructure that arises through social processes. The results offer insights for the future design of "seamful" approaches to indoor location sensing, and to the ways that context might be constructed and interpreted in a seamful manner.**

***Index Terms*—Beacons, Internet of Things (IoT), location, smart homes.**

## I. Introduction

Many Ubicomp services rely on a model of context in order to interpret user actions and needs. However, a classic paper by Dourish [1] challenged the way context models are derived only from sensor and activity data, while failing to recognize the nature of human interaction. Dourish's main contribution was to note the ways that context is jointly established in a kind of conversation, rather than simply being delivered as a technical product feature. In this research, we explore some technical implications of that perspective on context sensing. Location technologies for Ubicomp represent an important and growing element of context. One view of location sensing is that it offers a reference grid—a spatial map on which the user and relevant world features are marked. Outdoor positioning products based on GPS often present their data precisely this way. For some years, developers have been working toward indoor positioning properties that could do the same in relation to a spatial map of a given building. However, it is possible to take an alternative approach to location, for example, as expressed in Chalmers and MacColl [2] proposal of "seamful design" that acknowledges the gaps and inaccuracies in GPS signal coverage, using them as a design resource rather than as a system failing.

In this paper, we apply these perspectives—the human understanding of context, and the strategy of seamful design—to the indoor location technology of low-energy Bluetooth beacons. There have been substantial advances in the calibration of these beacons as a basis for establishing an accurate positioning grid in controlled conditions [3]. However, current commercial applications do not currently emphasize grid position, but simply trigger services based on proximity to the beacon. In a related project, we carried out a design exercise in which the "seamful" approach was applied in a museum context to deal with the ambiguity resulting from the very large numbers of objects in a museum, that are too close together to reliably be resolved by positioning data from a Bluetooth beacon [4].

Our present goal is to study the opportunity for similar approaches in the domestic Ubicomp context. Our specific interest is that, unlike the controlled conditions in which the positioning accuracy of Bluetooth beacons is normally calibrated [3], private houses contain a number of unpredictable elements that are known to introduce challenges for the accuracy and reliability of Bluetooth positioning. These are discussed in more detail later, but include multi-path signal interference, variable surface reflections, attenuation due to human bodies, etc. So many factors affect the accuracy of these location technologies, in fact, that it would be extremely challenging to measure and calibrate them all even for an individual house, let alone to create a generic model that can be transplanted to any house.

Instead, our approach, inspired by Dourish and Chalmers, is to treat the house itself as an "ethnographic" object. We do not mean in the sense that we study people's behavior in their houses (although that will come as a later stage in our research). Rather, we follow the example of ethnographic design theorists such as urban planner Kevin Lynch, who is the author of [5], and architect Christopher Alexander, who is the author of [6], studying the house itself as an ethnographic object that carries the human traces of its occupants. With this ethnographic intent, we have carried out surveys to understand what the near future of location sensing in the home might look like, and the extent to which it is a seamful resource for user interaction. We have drawn on a sample that is rich and diverse, rather than controlled, in order to offer an alternative to existing laboratory study techniques. In particular, we report a user-oriented analysis of Bluetooth location in four very different homes, located in three countries.

## II. Related Work

The use of Wi-Fi and Bluetooth signals for indoor positioning is well established. The received signal strength from a radio transmitter decreases with the distance from the source, but indoor spaces present complicated propagation environments, and so simple ranging models based on free space path loss are known to produce highly variable indoor positioning performance [7]. This was demonstrated as early as 2000 by Microsoft when they compared these two methods [8]. Fingerprinting is now the standard approach employed by indoor location based service providers, but surveying schemes are required to log the locations of the fingerprints initially in order to later provide location-based services. The surveying problem can be solved by

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C. Perera is with the School of Computer Science and Informatics, Cardiff University, Cardiff CF24 3AA, U.K. (e-mail: charith.perera@ieee.org).

S. Aghaee, R. Faragher, R. Harle, and A. F. Blackwell are with the Department of Computer Science and Technology, University of Cambridge, Cambridge CB3 0FD, U.K. (e-mail: aghaeester@gmail.com; rmf25@cam.ac.uk; robert.harle@cl.cam.ac.uk; alan.blackwell@cl.cam.ac.uk).

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crowdsourcing [9] or by machine-learning methods such as simultaneous localization and mapping [10], [11]. Sadowski and Spachos [12] have ranked the accuracy of Wi-Fi (first), Bluetooth low energy (BLE) (second), and LoRaWAN (third) based on their indoor localization capability.

BLE [13] has been developed in order to provide a method for transmitting very short packets of information over short distances in order to improve the efficiency of the Internet of Things (IoT). BLE beacons can also be used to provide indoor location based services using either proximity detection or fingerprinting. Both BLE and Wi-Fi operate in the same 2.4-GHz radio band, and so both signal types are affected by attenuation and antenna detuning caused by interactions with the human body. The channel bandwidth of BLE is also much smaller than that of Wi-Fi channels, and so the susceptibility of BLE to large signal-strength variations due to multipath interference is much higher than of Wi-Fi [3]. BLE beacons are increasingly used in a wide range of IoT applications [14]. They also come in different form factors and capabilities [14].

## III. Study Design

In the design of this ethnographic study, our goal was to understand the ways in which Bluetooth signal strength could be interpreted in the technologically seamful environment of actual houses, rather than in the controlled and calibrated laboratory environment. This goal led to the following three key decisions with regard to the study design.

1) We wanted to understand context in a way that represented homeowners' conversation with the technical functionality of their houses. As a result, we paid special attention to rooms in the house that had specific technical functions, rather than characteristics defined by spatial layout and infrastructure. In fact, conventional names for rooms in the home already reflect the validity of technical functionality in the semantic interpretation of spatial context—kitchens, bathrooms, and laundries are all marked by their functional context, independent of other location cues.
2) Although one can imagine that future houses might have embedded location-monitoring infrastructure, and indeed many Ubicomp researchers are working to create such infrastructure, we wished to concentrate on the pragmatic and seamful circumstances in which new technologies actually arrive in real houses. Although Bluetooth beacon capabilities may be embedded in a variety of devices, and even distributed around a house by technical enthusiasts wishing to engage in lifelogging or home automation, we decided to explore the more likely near-term scenario that this capability might first be deployed as an additional IoT market feature in a new appliance—for example, a refrigerator, a washing machine, or a shaving station (in the examples of functional spaces already described).
3) Rather than grid-based laboratory survey techniques, we wished to gain insight into the way that signal strength would be experienced by an actual resident in the house, using a commodity mobile device. We, therefore, designed survey routes that represented real walking paths through each home, and carried out the survey by walking along this path, holding the phone in the natural hand position of a standing user during interaction.

Apart from these ethnographic constraints that were chosen to represent seamful and functional context, all other aspects of the survey followed the best practice in signal-strength survey, as derived from our previous laboratory studies—we created an app that sampled signal strength at approximately 10 cm intervals along the path, measured the length of the paths within an accurate floor plan, and repeated each walk several times, in order to assess variability.

## IV. Study Procedure

We used a prototype low-energy Bluetooth beacon made by cambridge silicon radio (CSR). The beacon power setting was configured to transmit a signal capable of covering an open area of around 50 m. We placed the beacon in different locations inside a house/apartment and measured the signal strength at various locations using an Android smartphone, while carrying the phone and walking along pre-defined paths in both directions three times. For each path, we made sure to take the same amount of time to walk both directions. We repeated this procedure in two houses and two studio flats situated in different countries including England, Australia, and Sri Lanka. All the houses and apartments were inhabited at the time of the study and had different characteristics such as layout, ceiling height, and number of stories.

The English house (see Fig. 1) is a two-storey terraced building—a style of housing in which a row of identical houses share side walls. The English studio flat (see Fig. 2, Online Available) is situated at ground level with no upper neighbors. It is technically a part of a detached house—a house that does not share a wall with a neighboring dwelling—and only shares one wall with the main house. The Australian studio flat (see Fig. 3, Online Available) is on the first floor of a three-floor building. There are 15 apartment units with similar layout on each floor. The house in Sri Lanka is a two-storey house (see Fig. 4), but with ceiling height approximately equal to 4 m, in contrast to the English and Australian dwellings, which are approximately equal to 2.4 m.

We placed the beacon in functional locations such as kitchen, laundry room (if available), bathroom, bedroom, and living room. As discussed, the beacon was either placed on an electronic appliance such as refrigerator, washing machine, or television, or attached to the ceiling with an adhesive. The beacon antenna direction faced outward when on appliances (see Fig. 1). In ceiling locations, separate measurements were made with the antenna facing each of the four directions. Data were collected using a commodity smartphone: a Nexus 4 running Android "KitKat" 4.4.4. We implemented a mobile app that collected all messages transmitted by the beacons and recorded their signal strengths for the entire duration of walking in the pre-defined paths. All survey measurements were made by the same person, walking at a steady natural speed, while holding the smart phone in a natural position. In the results reported below, the position of each signal-strength reading is determined by linear interpolation along the path, based on timestamps of the beacon messages.

## V. Results

Typical results from the four different dwellings are explained with reference to Fig. 1, which shows the floor plan of the English house. The observations reported below reflect the qualitative finding from all four properties.

In Fig. 1, the signal-strength variations observed along each path are shown as a color map. For each survey path, we collected data during six walks along the path three times in each direction to show both the variability in signals, and also the degree to which the natural walking pace results in consistency of time-interpolated positions.

The first observation is that there is a considerable variation in the pattern of signal-strength variation, depending on the direction in which the user walks. This is due to the attenuation of the signal by the user's body, when facing away from the beacon. In Fig. 1(c), the signal level in the next room when walking away from the beacon is the same as that three rooms away when walking toward it. This effect is occasionally reversed in the same room where the beacon is placed, apparently as a result of reflection from an opposite wall.

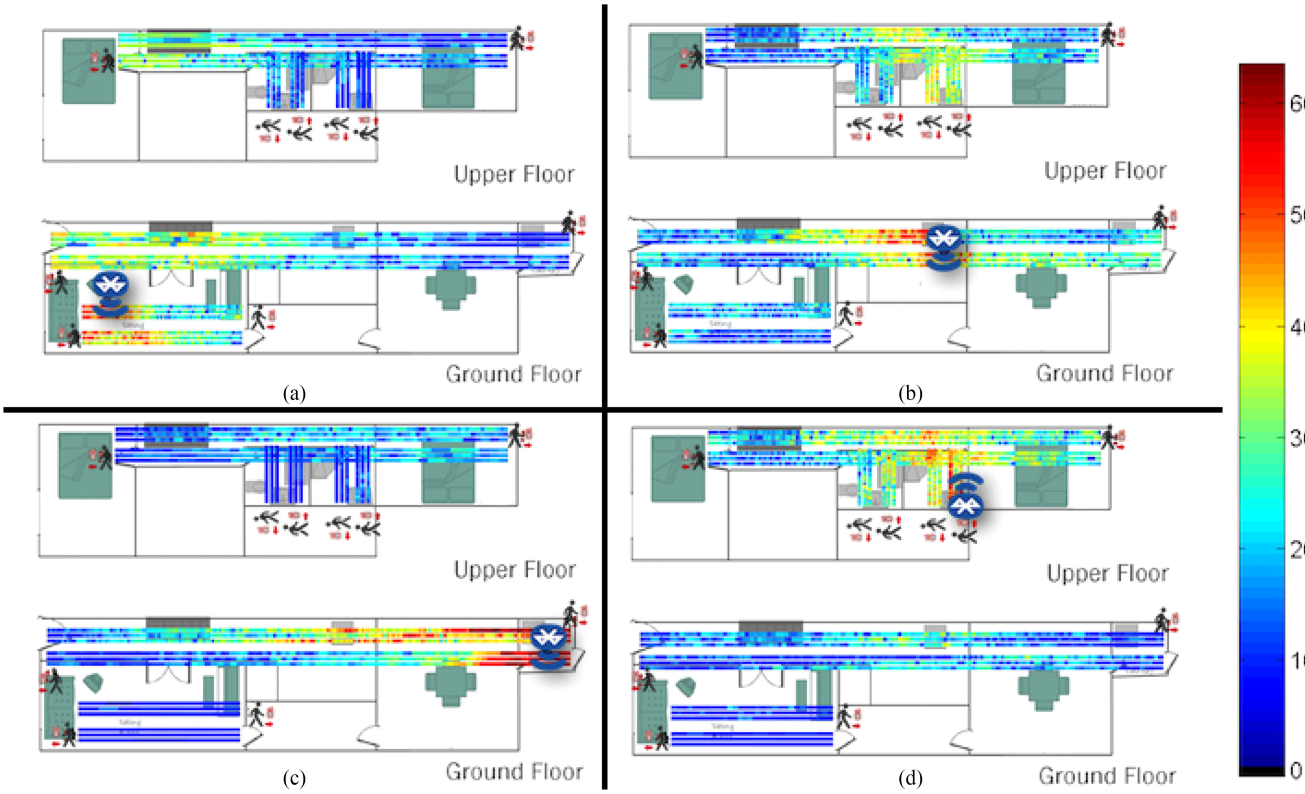


Fig. 1. Signal strengths recorded in a two-storey terraced English house. The beacon was placed in four different locations: (a) living room, (b) kitchen, (c) laundry room, and (d) bathroom. The colored lines indicate the walking paths and different colors represent different signal strengths (red highest and blue lowest). The direction of the beacon antenna is depicted using the direction of the waves in the Bluetooth icon. It is ideal for red color (stronger signals) to be spread within limited area. Such localized signals allow us to deploy multiple beacons without creating ambiguous signal overlaps. However, weak walls (e.g., wood) and openings (e.g., door) allow signals to penetrate across multiple rooms/sections and make localization much difficult (ambiguous).

The second observation is that in this (brick) two-storey house, the wooden floor between stories is rather permeable to the signal. As a result, in Fig. 1(a), the signal from a beacon on the TV set is stronger in the hallway upstairs than it is at the other end of the room where the TV is located. This effect was also noted in the house in Sri Lanka. Of course, this is not a problem in the two single-floor apartments, although other effects (reflections and doorways) became more salient in those smaller dwellings. In general, larger houses provided better support for separation of functional locations.

Partition walls allow Bluetooth signals to pass easily, with less attenuation than those presented by the user's body. This was a major factor in the small apartments, and can be seen between the two upstairs bathrooms in Fig. 1(d). This could present a significant obstacle to the type of conversational context setting that we had envisioned; in that the apparent context of a functional space may be completely different in the room next door.

A further seamful consequence observed in signal propagation is that signal strength is relatively high when passing by the open doorway of a room containing a beacon, especially when there is a line-of-sight to the beacon location. This is seen in Fig. 1(a), and especially markedly in Fig. 1(d), where walking along the hall presents the same signal strength as that in the room containing a beacon. It would be difficult for a user to diagnose this cause immediately in Fig. 1(a), because the apparent signal path comes from a beacon location that is not visible through the door apparently having been reflected through the door from a metal fireplace screen on the far wall.

## VI. Implications for Design

We have presented a brief summary of signal-strength measurements in a naturalistic situation, in order to show the ways in which location technologies do not (yet) support the functional conversations that are essential to contextual interaction in Ubicomp.

Existing applications of Bluetooth beacons typically expect that the user is standing in close proximity facing the beacon, in order to avoid the ambiguity that results from multiple paths and body attenuation. In our previous work, we have explored seamful experiences designed around the observation that, although we might not know where the user is, yet we are reasonably confident that he/she is not near the beacon [4].

We have described our observational approach as ethnographic, in order to contrast it with the calibrated laboratory measurements of signal-strength based location sensing that we have carried out in the past. However, even in the course of this study, it was clear that the expert usage of the signal-strength measurement device (a conventional mobile phone) was essential for obtaining reliable results. Our earliest surveys resulted in contradictory and inconsistent readings far beyond those shown in Fig. 1. As our project continued, more consistent results represent a kind of taming of the measurements intended to be made in the wild. This can be compared to the well-known finding from laboratory studies, that replicability of experimental results depends on the social context in which the work is done [15]. It is interesting to speculate how far this kind of calibration work might be necessary in order for householders to work with context in domestic settings. In the first dwelling we surveyed (the studio flat in Australia), we compared ceiling-mounted beacons to beacons embedded in appliances. This scenario more closely resembles the current market expectation for location beacons, which are often sold in a stick-on package so that they can be deployed as location infrastructure. However, despite apparently unambiguous positioning (the center of a ceiling in a small room), these free-standing beacons were even more ambiguous than opportunistic placement in appliances, because they allowed for a greater range of reflections, signal paths through doors, etc. This appears to be an important piece of design guidance for determining functional context, given that so many functional appliances (e.g., refrigerators) are explicitly linked to the functional rooms in which they are found.

## VII. Conclusion

Location sensing is a key enabling technology in order for Ubicomp to support contextually informed interaction. Most calibrated testing of location-sensing devices takes place in the controlled environment of laboratories. However, laboratories are very different to the domestic situations in which "context" has been identified as a problematic social construct. In this study, we have taken a systematic but contextually informed approach to the use of Bluetooth signal strength as a location-sensing technique. We have made systematic measurement surveys, informed by laboratory studies, but in a diverse range of domestic settings. The detailed design of these surveys has been motivated by the natural environment implied in the Bluetooth beacon standards—relating the technical situation of the beacon to the functional semantics of different spaces within the home. This research method can be considered as a situated, ethnographic response to the study of the physical infrastructure in houses, as opposed to their occupants, whose lives are reflected by that infrastructure. The results offer insights into the future design of "seamful" approaches to indoor location sensing, and to the ways that context might be constructed and interpreted in a seamful manner.

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