Wireless energy behaviour monitoring (Wi-be) for office buildings

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Wireless Energy Behaviour monitoring (Wi-be) for office buildings

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Abstract

This paper presents a study on reduction of energy consumption in buildings through behaviour change informed by wireless monitoring systems for energy, environmental conditions and people positions. A key part to the Wi-Be system is the ability to accurately attribute energy usage behaviour to individuals, so they can be targeted with specific feedback tailored to their preferences. The use of wireless technologies for indoor positioning was investigated to ascertain the difficulties in deployment and potential benefits. The research to date has demonstrated the effectiveness of highly disaggregated personal-level data for developing insights into people's energy behaviour and identifying significant energy saving opportunities (up to 77% in specific areas). Behavioural research addressed social issues such as privacy, which could affect the deployment of the system. Radio-frequency research into less intrusive technologies indicates that received-signal-strength-indicator-based systems should be able to detect the presence of a human body, though further work would be needed in both social and engineering areas.

Keywords: building energy management; wireless energy monitoring; people positioning; energy demand reduction

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1 INTRODUCTION

In recent years, there has been increasing development and availability of digital feedback technologies, such as in-home displays, which can provide householders with real-time information about their dwelling's electricity consumption and in some cases individual appliances [1]. The proliferation of feedback technologies is reflected in research that indicates that more detailed and stimulating feedback information can help occupants to reduce energy use through behaviour change [1–3]. Many of these household feedback technologies can be installed easily into homes by utilizing wireless technologies (e.g. ZigBee communications protocols [4]). Similarly, in non-domestic buildings, the increased availability of wireless sensor technologies has allowed energy monitoring systems to be installed relatively simply and at low cost in comparison with wired technologies. These wireless systems provide the opportunity for energy managers to monitor and control the energy use of equipment [5] and deliver feedback to building users.

Although some feedback systems can deliver information disaggregated to particular appliances, they do not provide information about which individuals were responsible for energy use. Post-occupancy evaluation research has shown that collecting occupancy data can improve understanding of how energy is used and highlights an opportunity to enhance energy feedback information by combining energy and occupancy monitoring data [6]. By utilizing wireless technologies to achieve this, there is a real prospect to develop 'wireless energy behaviour information' (Wi-be) systems to deliver personalized feedback to encourage energy saving behaviour.

The move towards smart grids, intelligent transportation systems and smart buildings are a strong driver in the growth of wireless device usage. The increased availability of such wireless technologies, including the growth of smart-phone usage, as well as the proliferation of wireless sensor networks, offers an opportunity for deepening understanding of such technologies particularly in buildings. The role of the body in radio-frequency (RF) positioning is still not fully understood, particularly in the context of indoor positioning systems. Whilst similar in principle to off-body communications, there are unique characteristics for positioning systems that have yet to be fully analysed in body-centric communications. As user location is an important factor in identifying

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behavioural patterns in Wi-Be, experiments were performed to determine the potential usefulness of RF positioning in future Wi-Be implementations. Some aspects of this research are reported in this paper.

The following sections present results from an office building case study that have been exploring the delivery of feedback information for energy management through Wi-be technologies. Results in RF positioning research in this context are presented.

2 ENERGY MONITORING AND MANAGEMENT IN CONTEXT

The built environment professionals face a collective challenge to close the yawning gap between design and in-use performance, which affects a wide range of new and existing technologies for low-carbon retrofit or new build. Gaps of 40–100% are common, and even routine issues like wall insulation are affected by unexpected wasteful energy use in recent construction projects—the substantial heat loss through un-insulated party walls is a well-known example.

Against this background there has been increasing evidence of the major energy saving potential of energy monitoring and management, based on the latest ICT and control technologies, which integrates holistically the optimization of building energy systems, and the engagement of users and facilities management (FM) in the process. Major energy and carbon savings have been repeatedly demonstrated. For example, savings of 27% [7] have been achieved across the retail and office building stock of one of the largest commercial landlords of the UK, based on an energy monitoring and optimization process and through working with building occupiers and FM. Some individual buildings within a given portfolio would achieve even higher reduction rates. Indeed, individual office building case studies have revealed savings of 40% and higher [7, 8] often reflecting better practices in monitoring and action by building users and FM.

Further remarkable features of this energy monitoring and management approach include the lower costs of its implementation compared with fabric- or HVAC-based building retrofit solution. The cost difference is often an order of magnitude, with the former enjoying rapid payback in many cases, thus greatly increasing the likelihood of its uptake. The two approaches are not mutually exclusive, though it makes a lot of sense to reduce the demand first by improving energy efficiency and minimizing waste, using energy monitoring and management, which may lead to cheaper HVAC and fabric interventions at a later stage.

Building user engagement facilitated by the ICT feedback of the energy monitoring and management system is probably one of its most valuable features as it deals with the source of energy use and waste much more effectively. Active and continuous user participation in identifying and removing the energy waste form an integral part of the energy monitoring and management solution, leading to lasting energy efficiency and durable behaviour change. Many of the faults and problems resulting in the gap between design and in-use performances were identified and resolved this way, which would have been much harder to track down otherwise.

The energy monitoring and management, facilitated by ICT and controls, complements other major industry initiatives. The Soft Landings framework is widely recognized as an important answer to the challenge of the design-operation performance gap, addressing the all-important (early-) design and commissioning/handover/POE stages. The energy monitoring and management complements soft landings by providing a useful tool for the commissioning and performance tuning at these stages. The tool remains valuable and powerful beyond the stages by underpinning the operational energy efficiency and maintenance of facilities through the life of the buildings.

There is further rich interaction with (or influences on) other significant elements/programmes of the construction industry. Smart metres for non-domestic buildings are still evolving and will benefit from the behavioural and people engagement insights gained in the implementation of energy monitoring and management. Many organizations are committed to reducing energy consumption either voluntarily or under the CRC and other mechanisms. The strategies of many organzsations for achieving this objective rely to a significant degree on changing user behaviour, although there are few reliable tools and methods to support the realization of such change. The energy monitoring and management system would help to bridge this gap.

3 OFFICE BUILDING CASE STUDY

Research into energy feedback information has often concentrated on electricity consumption in homes and given much less attention to non-domestic buildings [9]. This reflects the larger gap in research concerning environmental behaviour change in the workplace in comparison with homes [10]. In response, the non-domestic research within the Wi-be project has paid particular attention to the social aspects of Wi-be systems, including people's experiences of using the technologies at work and the social consequences of introducing feedback technologies into the workplace. To explore these issues, the research has adopted a mixed method approach, collecting qualitative and quantitative data. The following subsections provide a summary of the results together with research methods and the technologies used in the study.

3.1 Methods

The first stage of the research involved in-depth interviews with building occupants to explore perceptions of Wi-be systems with a larger sample size and individuals with different responsibilities for energy use in buildings. The sample included energy managers, employees involved in the organization's voluntary environmental initiative and employees with no link to building or environmental issues. The interview questions were designed to investigate occupants' experiences of energy use in the workplace context, their perceptions of Wi-be technologies and preferences for types of feedback information.

For the second stage of the study, four office-based participants used the Wi-be system, which had been installed within their office building on an university campus in the UK. Each participant received feedback information over two separate 1-week monitoring periods; the feedback was based on the energy and occupancy monitoring and designed to support behaviour change. The monitoring data also provided a means to evaluate the effectiveness of the feedback intervention. The use of diaries and regular interviews with the participants allowed deeper insights to be gained about the positive and negative experiences of using the system, the feedback provided and the process of behaviour change. The qualitative data collection was designed to be iterative with the experiences of participants used to improve the system and the feedback provided.

3.2 Occupancy monitoring

The office building case study system utilizes a real-time location-tracking system manufactured by Ekahau, Inc.; this uses of a package of software to exploit a building's Wi-Fi network and locate wearable RF identification (RFID) badges [11]. The installation involves a site survey (with designated software and an RFID badge) to record the signal strength from the available Wi-Fi access points, allowing site locations to be given unique signal signatures that are mapped onto a site plan—this plan is then uploaded to *Ekahau* controller software on a server. Consequently, the signal signature identified by an RFID badge is used to approximate its location (in respect to the site plan) to an accuracy of 1–3 m at optimum installations [11]. The controller software also records the occupancy duration in zones (e.g. rooms) specified on the site plan through a user interface.

To meet basic infrastructure requirements, two additional Wi-Fi access points were installed in the case study site; however, the level of accuracy was still found to fluctuate. This was due to a number of factors including: the similarity of the signal signatures in some areas (particularly in the open space area); the stability of the Wi-Fi network; interference to the signal strength from the movement of building occupants, equipment and climatic conditions. In order to improve the accuracy of the system, *Ekahau* location 'beacons' were installed—these are small battery powered infra-red (IR) transmitters that can identify the tags and provide up to sub 1 m accuracy [11]. The beacons were placed in areas of poor accuracy and at participants' workstations to improve the quality of the data. However, this relied on the badges always having a line of sight to the beacons, a situation that often failed to occur due to the badges' IR detectors being obstructed by clothing or participants' alignment whilst working. These issues, along with the factors mentioned previously, could lead to individuals' locations being recorded for periods in the wrong zone (e.g. wrong room). Another problem was that on occasions some participants forgot to charge their tags. Therefore, extensive manual screening was necessary to deliver an appropriate level of accuracy for the provision of the feedback.

3.3 Energy monitoring

The case study focused on electrical appliance-level monitoring with a system produced by *Alertme Ltd*. The system uses a ZigBee wireless communications protocol to transfer power load measurements, from 20 plug-in loggers, to a 'smart hub', which then transfers data to the supplier's server via an Ethernet connection [12]. These data can be downloaded at 1-min time-stamped intervals from the supplier's website as comma separated value files.

Some rudimentary initial tests of the plug-in loggers were undertaken by recording power loads of office printing equipment. Encouragingly, the measurement of 'on' and 'standby' power loads were similar to manufacturers' figures; however, the loggers were unable to detect and record other standby power loads, such as computers and monitors that were in deep hibernation states or switched off but still connected to the mains power supply. Thus, it was evident that the system was subject to a degree of inaccuracy, particularly at low-power loads. Nevertheless, the data provided by the system clearly showed the main patterns of appliance use and were therefore considered to be suitable for the objectives of the case study.

3.4 Data analysis overview

The location and electricity use data were processed by spreadsheet for each case study participant and involved the calculation of electricity consumption values for personal appliances (e.g. computers and monitors) and some communally used equipment. Values were apportioned to 'on' and 'standby' power loads; however, it was often impossible to identify when computers had entered some standby states, because of the range of 'on' power loads at which they can operate. Each minute interval of electricity consumption was allocated to one of the following occupancy categories for each participant: (i) unoccupied (i.e. when not in the office site), (ii) workstation (i.e. when at their workstation) and (iii) office—excluding workstation (i.e. when in the office, but not at their workstation). This allowed the feedback information to link appliance electricity consumption to key patterns of occupancy (Figure 1).

All of the in-depth interviews undertaken for the non-domestic research were semi-structured and conducted face-to-face. These were documented with hand-written notes and a voice recorder. Data have been transcribed verbatim and analysed thematically.

3.5 Results

The findings of the office building case study are presented here.

3.5.1 *Feedback information collected with the Wi-be system*

The study has installed a Wi-be system that can deliver energy feedback information regarding electrical appliance use. Figure 2 shows an example of the type of detailed information that can

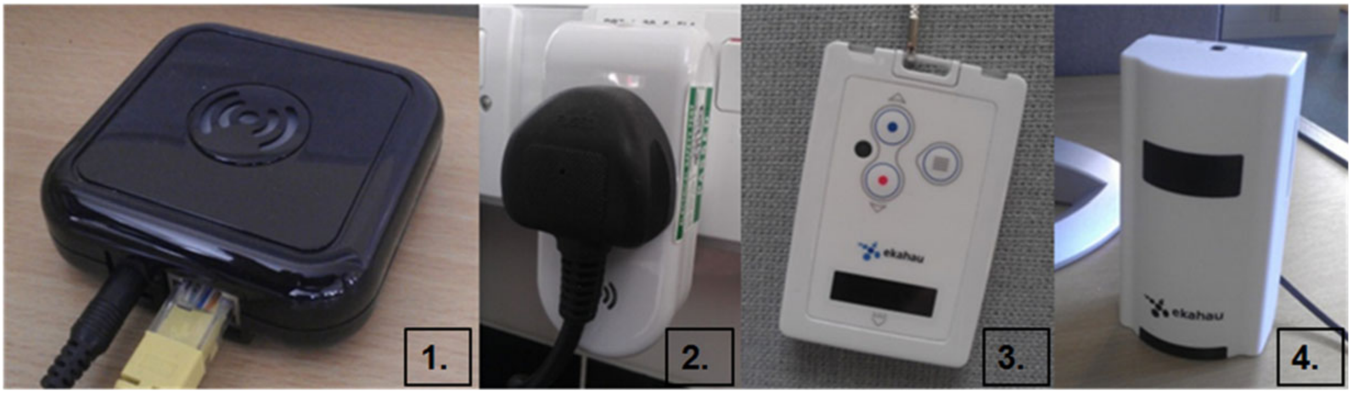

Figure 1. *Energy monitoring and occupancy tracking equipment: (1) AlertMe SmartHub, (2) AlertMe SmartPlug, (3) Ekahau Wi-Fi Badge Tag and (4) Ekahau Location Beacon.*

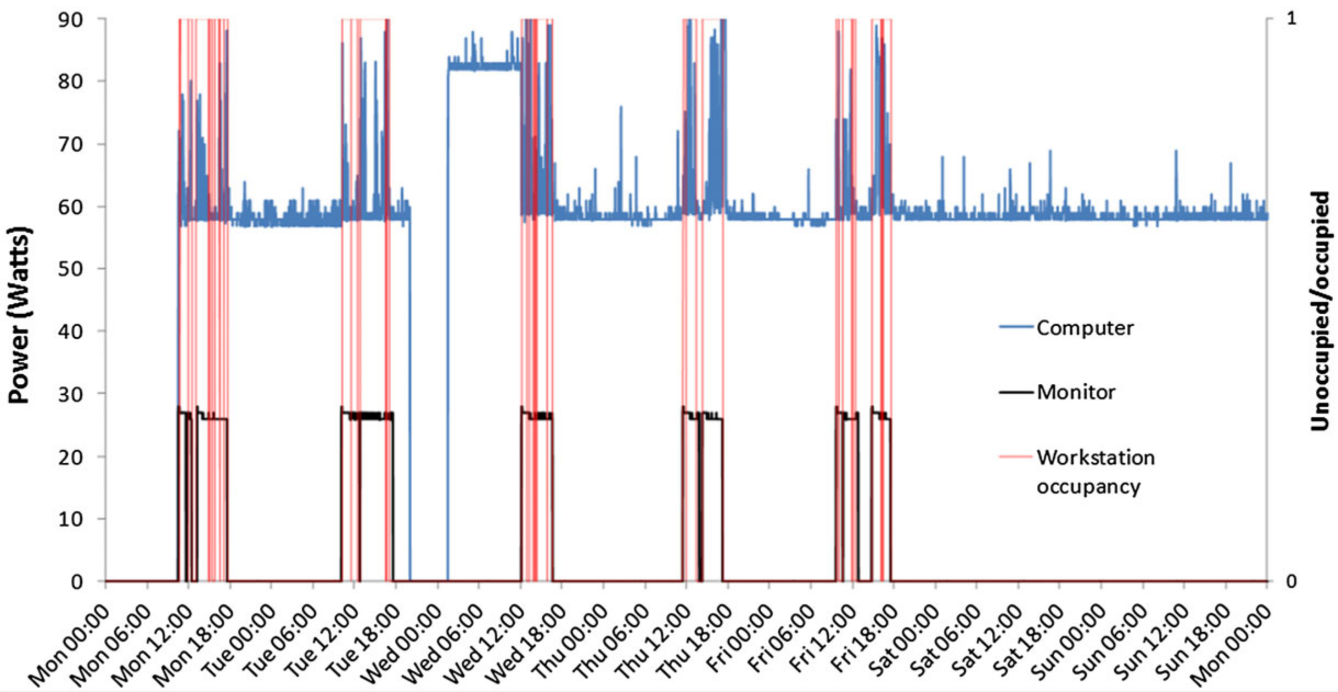

Figure 2. *'Power load profile' feedback chart for Participant 1 showing computer and monitor power loads with workstation occupancy for a week.*

be collected and fed back to building occupants; for this first participant (who worked in the office 5 days), a computer was continuously left in an active state, prior to receiving feedback; however, he regularly turned off his monitor. In the first week of monitoring, this pattern of behaviour led to ~77% (7.7 kWh) of this participant's workstation electricity consumption occurring when he was away from his desk and presented an opportunity to reduce energy consumption significantly.

In direct contrast, a second participant (who worked in the office 2 days) frequently turned all his workstation equipment off when not at his desk. As a result, he used ~1 kWh during his first week of monitoring, prior to feedback, and only 14% of this occurred when he was away from his desk.

3.5.2 *Interviews with building occupants*

As mentioned previously, the first phase of research used in-depth interviews to explore perceptions of Wi-be systems with a larger sample of building occupants. The interviews provide some support for the idea of providing personalized energy feedback, which was largely perceived as useful for raising awareness and informing an individual's efforts to reduce energy consumption. However, the responses also highlight issues that must be managed in non-domestic Wi-be installations.

First, the potential for the feedback to elicit behaviour change may be restricted by occupants' perceived level of control, which was often believed to be limited to workstation equipment. Communal energy end-uses (e.g. space and water heating, communal lighting, communally used electrical appliances) were often perceived to be out of people's control due to building automation and group behaviour. As a result, the expansion of personal-level feedback may be problematic, because providing feedback about energy that cannot be controlled could be frustrating and potentially counterproductive (e.g. people may disengage with other energy saving efforts). Furthermore, the data suggest that the small amounts of energy associated with personal electrical appliances could also be viewed as insignificant, if not presented as part of collective behaviour. However, there was evidence that additional feedback to energy managers may increase occupants' ability to indirectly control energy use by providing a mechanism to report energy wastage (e.g. from poor heating or lighting automation).

The interviews also suggest that supporting feedback content with additional information (e.g. regarding energy units and practices) is required to improve employees' ability and willingness to make appropriate behaviour change. Unlike the domestic sector, presenting personalized feedback in cost terms may be less appropriate in the workplace due to employees not paying energy bills and, as seen above, the small financial cost associated with some personal energy use. However, some responses suggest that linking the financial cost of energy to job security—i.e. through the financial viability of the organization—may encourage some employees to adopt energy saving behaviours. Thus, identifying mechanisms for motivating employees to respond to personalized feedback is important, and it was suggested by some interviewees that increased support from senior managers could be an example of such a driver.

Importantly, some of the key concerns to arise from the interviews related to confidentiality, the implications of surveillance and the potential misuse of energy and tracking data for the assessment of work performance. Responses suggest that if overlooked these issues could undermine employees' motivation to use Wi-be systems and attempts to adopt energy saving behaviours.

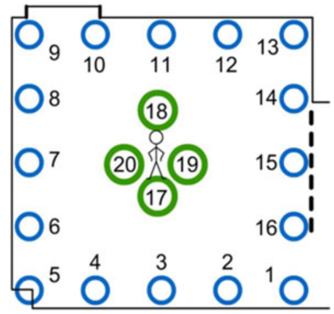

Figure 3. *Topology for the initial experiment. Blue circles denote fixed wireless nodes; the green circles mobile wearable nodes. The dashed black line represents a temporary partition. A master node (not shown) was positioned out of the monitored zone.*

Figure 4. *The test subject wearing the wireless modules.*

4 WIRELESS POSITIONING

People positioning is central to determine the energy behaviour of building users and the privacy issues highlighted in the case study point to a need for less intrusive technologies. The follow sections describe research activities within the Wi-be project in this particular direction.

4.1 Experimental design and objectives

Most on-body wireless communications research has been conducted at 2.45 GHz [13]. This includes antenna performance and channel propagation characteristics. This experiment used the IEEE 802.15.4 communication standard at 2.45 GHz. This was selected as it is the technology underpinning ZigBee, one of the main standards used in smart buildings. The concept behind the experiment was to use the received signal strength indicator (RSSI) parameter as means of determining path loss (for a fixed transmit power), with changes in path loss mapped to separation between fixed and body-worn nodes.

The aims of this experiment were as follows:

- to investigate the capability of a positioning system based on RSSI;
- to investigate how multipath effects and shadowing from the body affect the performance of the positioning system.

Figure 3 gives a simplified representation of the initial lay-out for the experiments.

The nodes used were the commercially available Telos-B wireless sensor-board [14], which is based around a low-power microcontroller and an IEEE-802.15.4-compatible radio transceiver, the CC2420 [15]. This sensor-board is shown in Figure 4. It can be powered by two AA-batteries or via USB. It has a printed IFA integrated into the design, but the design allows an alternative to be used by attaching an SMA connector.

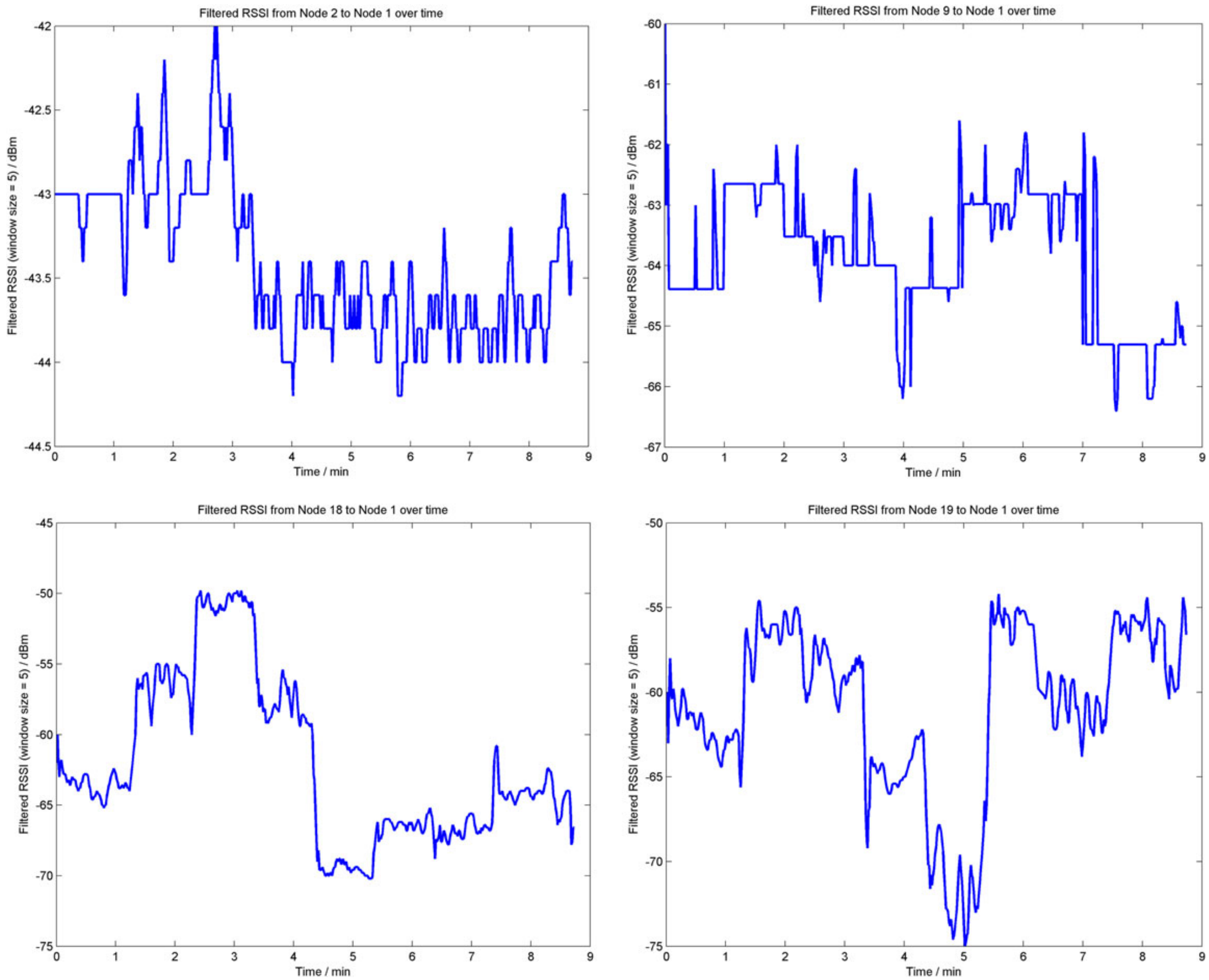

Figure 5. *Representative RSSI time-series plots. All links are from the identified nodes to fixed node 1.*

The nodes ran custom programmes written for the experiment, using the TinyOS embedded operating system [16]. Each fixed and mobile node listened to the transmissions from the other nodes and recorded the RSSI value for that packet. When it was allocated a transmission slot, a given node broadcast a custom packet containing the most recent RSSI values for all other nodes, together with the associated node IDs. The master node was connected to a PC and listened to all packets transmitted by the fixed and mobile nodes, allowing RSSI data to be recorded in real time. Each node transmitted approximately once per second.

As a control, the signals between the fixed nodes, with the room empty, were monitored for ~30 min (to allow for the removal of uncontrollable effects from outside the monitored zone). For the main experiment, the test subject stood in the centre of the zone. The subject was asked to rotate clockwise 45° after every minute, such that a complete rotation was achieved after 8 min. The subject thus faced node 3 for 1 min at both the beginning and end of the measurement.

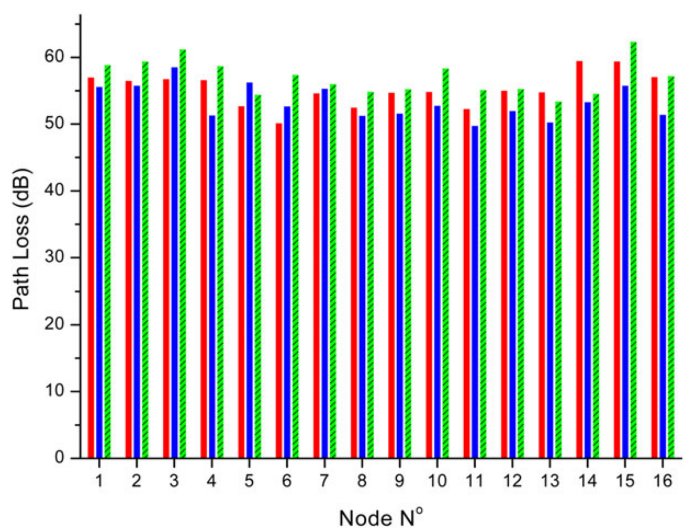

Figure 6. *Mean path loss between mobile and fixed nodes. Red—front (node 17), blue—back (18), green—left waist (19).*

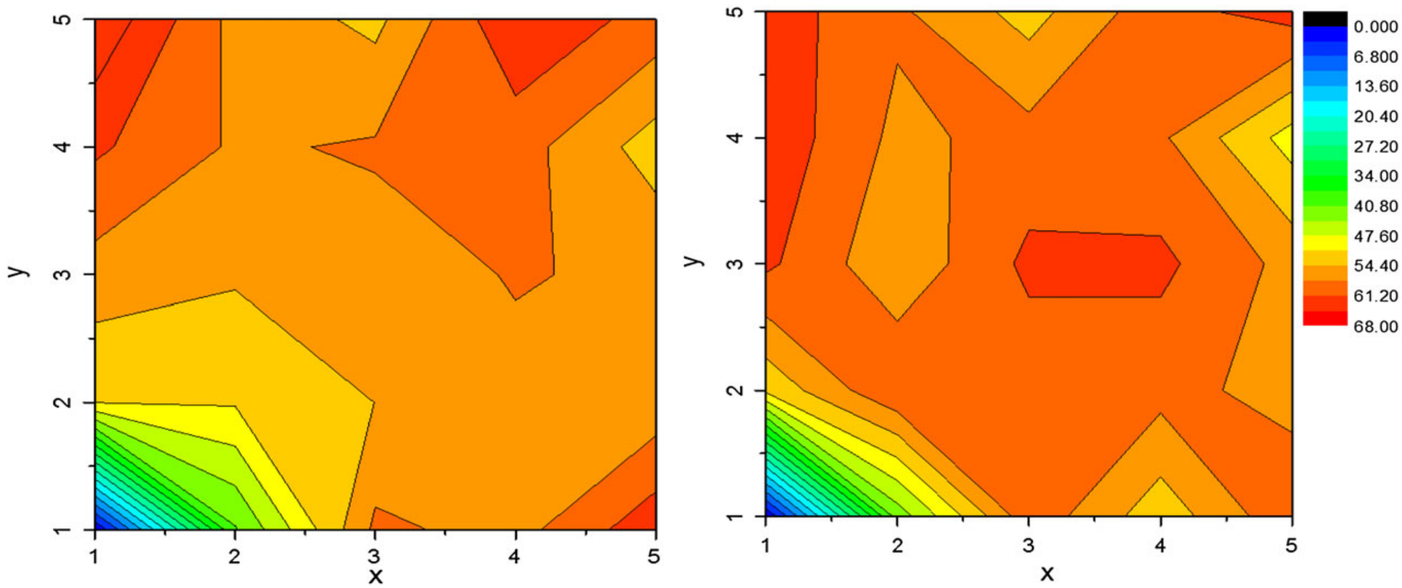

Figure 7. *Path loss distribution for empty (left) and occupied (right) rooms, with reference to node 1 (bottom left corner). Colour-bar in dB.*

During this experiment, the test subject wore wireless nodes on the abdomen, lower back and both sides of the waist (see Figure 4). The waist locations were chosen to mimic the carrying of an RF device in a waist pocket; the abdomen reflects the likely position of a device worn on a lanyard. The back was included to complete the analysis of the effect of the lower torso on RF positioning sing wearable RF devices.

4.2 Results

Representative time-series plots of the wireless communication links are shown in Figure 5.

Figure 6 shows the mean path loss for the links between on-body nodes and fixed nodes, when the on-body nodes are transmitting. The right waist results are omitted for brevity. Figure 7 shows path loss distributions for the empty and occupied room scenarios, using node 1 as the reference point. These distributions were computed using the fixed links only (data from nodes 17–20 were ignored).

4.3 Discussion

The effect of the rotation of the test subject on the wireless links is clear for the on-body nodes. The local variation in mean power in a given 1-min period increases for those periods where the worn node is hidden from the reference fixed node by the body. A maximum variation due to rotation of between 15 and 20 dB is observed. This can introduce a significant error in any RF indoor positioning system, if unaccounted for.

The line-of-sight node (node 2) is essentially unaffected by the presence of the test subject, as expected, but the obscured node (node 10) shows a greater variation (caused by multipath reflections) and lower local mean received power, due to the increased separation and additional absorption from the body. It is possible to discern the effect of the rotation on the obscured link, but it is far less obvious than with the on-body nodes, due to the other multipath contributions from the environment.

The variation in overall mean path loss is related to the separation between nodes but also includes multipath effects and body shadowing. However, the distribution of the means is reasonably flat, between 50 and 60 dB; this is as expected, as the main component of the separation between test subject and fixed nodes remained almost constant. Our ongoing work in this area is examining the explicit inclusion of body effects into the path loss model used to determine separation from received power measurements.

The computed path loss distributions of Figure 7 demonstrate that, in principle, RSSI data can enable object detection and positioning for people not wearing RF devices; this can be important in emergency scenarios, for example. This is evident from the additional shadow in the right-hand plot, which is approximately in the centre of the zone.

5 CONCLUSIONS

The research to date has demonstrated that, technically, Wi-be systems can be installed into buildings to provide detailed energy feedback information. The highly disaggregated data about personal-level and device-level energy consumption have been shown to be effective for developing greater and meaningful understanding of people's energy behaviour, which could lead to effective interventions. The small number of case studies has shown that significant energy saving (up to 77% in specific areas) can be achieved using the technology, but the rebound effect is also observed. The Wi-be technology provides an alternative or complementary method to the traditional behaviour evaluation, allowing behaviour patterns and insights to be obtained through more objective data collection. However, social factors such as levels of control and ethical and privacy issues could undermine its deployment and would require more comprehensive study.

People positioning is central to determine the energy behaviour of building users, and the privacy issues highlighted in the case study point to a need for less intrusive technologies. This work investigated the RSSI technology for this purpose and results showed that RSSI-based systems is capable of detecting the presence of a human body without identifying of the person. However, the body is likely to introduce a bias into the position estimation, which need to be better understood in future studies.

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