SmartCampus: A user-centric testbed for Internet of Things experimentation

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***Abstract*—The Internet of Things (IoT) is not only about improving business processes, but has also the potential to profoundly impact the life of many citizens. Likewise the IoT can provide an useful tool for the longitudinal observation of human behavior and the understanding of behavioral patterns that can inform further IoT technology design. Today experimentation with IoT technologies is predominately carried out in lab based testbeds. There is however an emerging need for increased realism of the experimentation environment, as well as involvement of real end users into the experimentation lifecycle. In this paper we present SmartCampus, a user centric experimental research facility for IoT technologies. The current testbed deployment is focused on Smart Buildings, a key building block for cities of the future. Unlike current lab based testbeds, SmartCampus deeply embeds heterogeneous IoT devices as a programmable experimentation substrate in a real life office environment and makes flexible experimentation with real end users possible. We present the architecture realization of the current facility and underlying considerations that motivated its design. Using several recent experimental use cases, we demonstrate the usefulness of such experimental facilities for user-centric IoT research.**

I. INTRODUCTION

The recent rise of Smarter Cities is fueled by the emergence of Internet of Things (IoT) technologies, which when strategically deployed throughout a city can act as enablers for Smartness in a variety of problem domains. The IoT facilitates the effective integration of the real world with the digital world by providing machines and information systems with increased real world awareness and greater ability to influence real world processes. It will allow a better understanding of the nature of complex interdependent eco-systems of dense urban life and improved (autonomous) decision making capabilities providing the means to optimize and manage urban services in more efficient and effective ways.

An important structural element of Smart Cities are buildings - be it residential or commercial - in which people spend a significant amount of time in their daily lives. Making these buildings smart with IoT technologies will not only improve the quality of life and convenience of citizens in indoor spaces, but also contribute towards more sustainable cities through more efficient utilization of scarce resources such as energy, gas and water.

However building reliable IoT based technology solutions and services that can be deployed at scale requires adequate experimentation environments, in which these technologies can be matured and their effectiveness understood before commercial roll-out. A recent survey on IoT testbeds [1] highlights gaps in existing facilities and identified various desired properties for suitable facilities for IoT experimentation. Among these properties, the *realism of experimentation environment*, *IoT device heterogeneity* and *real end user involvement* in the experimentation life cycle are important dimensions to improve upon existing lab based IoT testbeds, which we tackle in our SmartCampus testbed. Increased *realism* implies matching the experimentation conditions as close as possible to the typically operating conditions that the final solutions are expected to be deployed. This way design flaws or imperfections can be earlier detected and evened out, thus reducing the cost of roll out and maturation time. Increased *heterogeneity* of IoT devices offers experimenters with more experimentation options and resembles more closely how IoT environments are expected to be at more maturer deployment stages. The *involvement of real end users* in the experimentation lifecycle has a particular importance, as the effectiveness of IoT solutions cannot be fully understood without considering the human dimension in experimentation. Despite good technical merits of an IoT solution, it may not be easily accepted by technology users, e.g. due to its intrusiveness. Likewise IoT solutions, although efficient in design, may not have the desired effect in cases where systems cannot rely on autonomous decision making alone and human behavior plays still an important role. Involving users into IoT experimentation allows scientist also to gain a deeper understanding of human behavior, due to the observation capabilities pervasively deployed IoT technologies offer. Some of existing testbeds [2], [3], [4] have already overcome the boundaries of the lab, spanning entire buildings with heterogeneous devices. These testbeds however mainly support communication level oriented experiments. Others are focused on specific applications such as energy monitoring [5], [6], thus becoming very specific and closed to easy reconfiguration and effective inclusion of users.

In this paper we present SmartCampus, a user-centric testbed for experimental IoT research, which is part of the European SmartSantander experimental facility. Deployed in a real world office setting which spans an entire building, SmartCampus overcomes the shortcomings of existing lab based testbeds in the above mentioned dimensions, while offering the same level of control and configuration flexibility. It acts as a microcosm for the study of user behavior in smart building and the effectiveness of IoT technologies and offers advanced tools that overcome the difficulties of experimentation within such complex experimentation environments. By describing experiences from several past experiments that we performed on top of our testbed, we validate the usefulness of it and highlight its potential for the inter-disciplinary IoT research community.

The remaining paper is structured as follows. In section II we present the architecture and realization of our testbed and important considerations that motivated its design. Section III presents several experiments that we conducted as use cases examples while concluding remarks are provided in section IV.

II. THE SMARTCAMPUS FACILITY

This section provides an overview of the SmartCampus testbed, introducing its key design considerations and the testbed architecture.

A. Design considerations

As identified in the introduction, our main objective was to build an experimental facility that allows advanced user centric experimentation with heterogeneous IoT technologies deployed in a real-world setting, where real-world data and feedback can be obtained from users and their environment under realistic experimental conditions. While our final ambition is to cover both indoor and outdoor environments on our University campus (as the name suggests), our starting point has been the deployment of a smart building testbed, SmartCCSR, which is further discussed in this paper. Work on advanced outdoor experimentation platforms is ongoing [13] and an outdoor deployment encompassing other parts of the campus are envisioned by 2013, taking into consideration valuable experiences that have been meanwhile obtained from the outdoor deployment in Santander of the SmartSantander experimental facility.

A further key consideration was that the testbed infrastructure should support rapid prototyping and experimentation cycles for the different envisioned IoT techniques and smart building solutions and allow for the evaluation of those in an interdisciplinary context. Consequently we chose to implement the facility as a living lab in our research centre, where each employee can become part of the experiment during his or her daily activities.

In order to increase the flexibility of the testbed to cater for demands of diverse experiments, we deployed in each room a mix of heterogeneous IoT devices, implementing a wide range of sensing modalities and common communication interfaces. This fixed infrastructure is complemented with mobile experimentation nodes that can be carried around by end users and fixed interaction displays in the infrastructure providing additional means for end user interactions.

B. Architecture overview

Figure 1 provides an overview of the network architecture of our testbed. Three tiers can be identified: i) a Server tier that hosts all the back-end functionalities of the testbed and provides the entry point for an experimenter to access the testbed, ii) an embedded Gateway (GW) tier which forms the testbed infrastructure and allows the iii) IoT tier to be connected and reachable to a backbone network through WiFi or Ethernet. Although all the tiers can be involved in each experimentation phase, the IoT tier represents the user-centric component of our testbed, merging embedded IoT nodes with sensing capabilities together with more higher-end user-centric devices such as Smartphones and Smart Displays. Each IoT node provides two forms of connectivity: i) wireless communication capabilities (IEEE 802.15.4, and through the GW devices WiFi and Bluetooth) that can be exploited during an experiment in order to form different kinds of networks, ii) a wired USB connections to a dedicated GW for management purposes. Differently, Smartphones and Smart Displays are connected only through wireless links (Bluetooth or WiFi) either through GWs or directly to the backbone network.

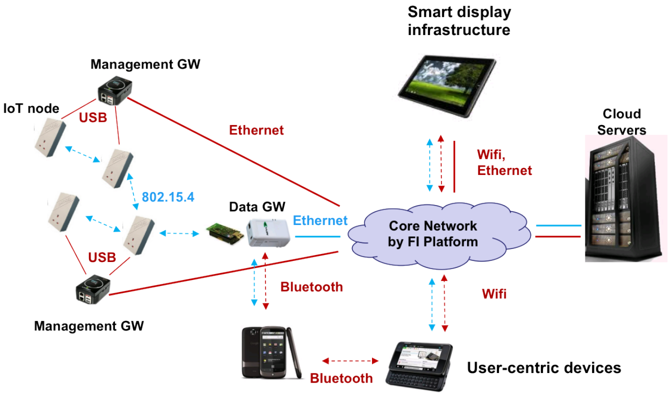


Fig. 1: Network architecture of Smart Building testbed.

From a logical point of view, two planes can be distinguished in our architecture: an experiment data plane (cyan lines) and a control and management plane (red lines). The *data plane* allows for the actual information flow within the IoT network, which can be caused by the information exchange of distributed learning, reasoning and control mechanisms, real world data collection and persuasive user interactions. The observation of the data plane will provide a means to evaluate different use cases for IoT experimentation scenarios, either aiming at assessing the efficiency and effectiveness of an experimenter designed solution or to collect relevant user-centric data. The *control and management* plane in contrast is used for the configuration, monitoring and control of experiments on the testbed. It allows remote reprogramming of the hardware under test with suitable software stacks for the IoT nodes and the data Gateways (GWs). It also includes the possibility for out-of-band collection of debugging information and experimental results and statistics related to the data plane exchange and nodes performance. Such out-of-band capabilities not only simplify the rapid prototyping of new solutions, but also allows the assessment of the solution without interfering with the data plane of the experiment.

C. Hardware components

The main hardware components of our testbed are described in the following.

1) IoT nodes: Figure 2 (left) shows the main elements composing an IoT node. The main design principle of such device was to provide vast set of sensing modalities for smart

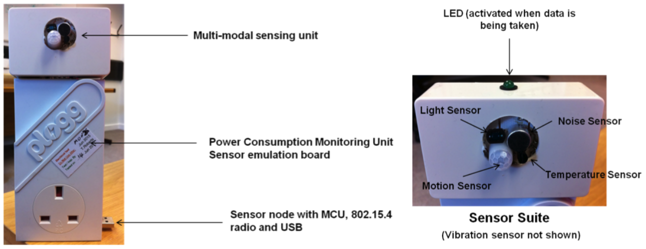


Fig. 2: IoT node:Energy Meter (left) and Sensing Unit (right)

building environment. To this purpose, a TelosB [8] mote has been interfaced with an off-the-shelf energy meter (Plogg) allowing the monitoring of energy use of user-related appliances in their work environment and basic on/off actuation. A custom designed multi-modal sensor board is connected to top of the IoT node casing. The board provides additional sensing modalities in the form of relative amount of light, relative noise level, temperature and motion within the range of the IoT node through a PIR sensor. A vibration sensor has also been included to determine tampering with the device, while an LED provides feedback to the user about the device state. 200 of such IoT nodes have been deployed at each work desk in the SmartCCSR building, connecting utilized user appliances (desktop computer, LCD screen, lamp, fan, charger, laptop) via a multi-socket.

2) Embedded GWs: The GWs tier wires the IoT nodes to the testbed and guarantees the realization of a reliable management plane. It consists of 100 embedded Linux GWs deployed across all rooms of the building. The selected platform is a GuruPlug providing a 1.2GHz Marvell Embedded CPU, coupled with 512MB of RAM and 512MB of storage space available for deploying user software. While allowing wired USB connectivity of external devices, Ethernet, WiFi and Bluetooth technologies are also available for network connectivity. The ratio of GW nodes to IoT nodes is between 1:1 to 1:4, depending on the number of IoT nodes that are deployed in a room and availability of Ethernet ports in the office space for the connection of GWs to the backbone network.

In order to reduce the costs of such embedded GWs, while allowing energy efficient implementation of the two testbed planes for self-sustainable outdoor operation a new embedded testbed observer called SmartEye [13] has been designed and manufactured. By allowing the observation of different type of IoT nodes, embedding advanced monitoring capabilities such as energy profiling of the connected device, SmartEye will form the basis for our outdoor deployment.

3) Smartphones: Smartphones play an important role in an IoT, providing both user centric sensing and user interaction capabilities. The testbed encompasses 30 Android4 based Smartphones (5 Sony Xperia S with NFC and 25 HTC One S) that can be used for experiments involving end users. The phones can interact directly via Bluetooth or WiFi with the embedded GWs or using WiFi and 3G connectivity with the application server tier of our testbed. The phones can be instrumented with experimentation code and are distributed for students and staff in our building for the duration of an experiment.

4) Smart Displays: The testbed provides also a public display infrastructure offering enhanced user interaction capabilities inside of a Smart Building. Our testbed relies on 10 Android tablets (Samsung 10.1) that are deployed at strategic locations of the building as part of a permanent installation. These 'Smart Displays' are linked through WiFi to the testbed infrastructure and provide Bluetooth for localized device interactions. Example use cases that utilized these displays are indoor guidance systems for visitors and for emergency evacuation. They can be freely configured with experimentation code for other user centric experiments.

5) Servers: A server cloud hosts the testbed management servers and allows the on-demand creation of other application servers and data management tools. It consists of 10 High End Servers (12 Xeon Cores, 24GB RAM each) with 8TB of storage and a VMware Cloud Computing Platform.

D. Software components

Figure 3 shows a high level overview of the software architecture and components supporting IoT experimentation on our testbed [9]. The SmartCampus testbed relies on the SmartSantander [10] management framework, developed on top of the WISEBED APIs [11] for the common management plane tasks, such as IoT nodes reservation, reprogramming and collection of out-of-band statistics. It further extends these by providing more advanced functionalities to assist the user across the overall experimentation life-cycle [1] and to improve its experimentation experience.

One of the most critical task is the experimentation scenario design and the selection of appropriate testbed resources for the envisioned experiment. The latter is particularly challenging for large scale IoT testbeds such as the emerging SmartSantander facility [10] as the experimental user is confronted with hundreds or more heterogeneous experimentation resources with different capabilities and specific connectivity characteristics, which are constrained by their deployment environment. This is further complicated by that fact that experimentation resources may fail or become temporarily unavailable for experimentation due to connectivity failure or other ongoing experimentation tasks. Furthermore time-varying interference levels at wireless experimentation resources due to ongoing experimentation at neighboring nodes or external sources may have an influence on the suitability of a particular experimentation resource.

As can be seen from the figure, the framework functions and support tools are exposed through a JAVA graphical user interface called *TMON* towards the experimental users of the testbed. *TMON* allows user friendly access to a variety of different testbed services, which are able to support experimenters during all experimentation stages. This includes access to functions that assist the user during experiment specification and resource configuration phases but also during experiment execution and experimentation data analysis.

The framework provides two dedicated functional component for the support of the resource selection phase: the *resource explorer* and the *topology explorer*. They assist the user with an exploration of available testbed resources and their static and dynamic properties and topological interdependencies. In our framework testbed resources and the

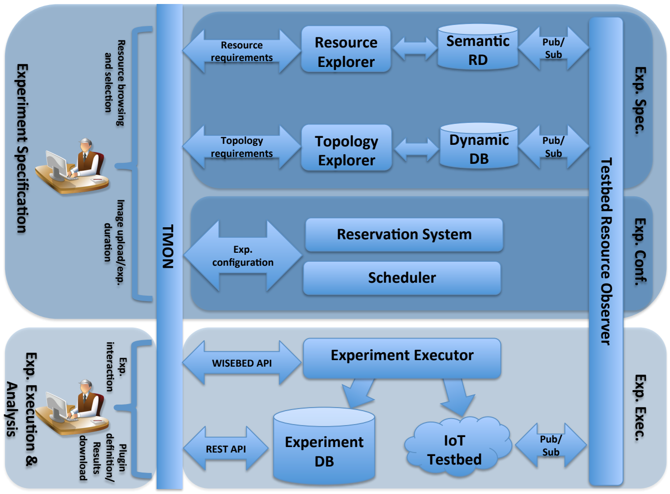
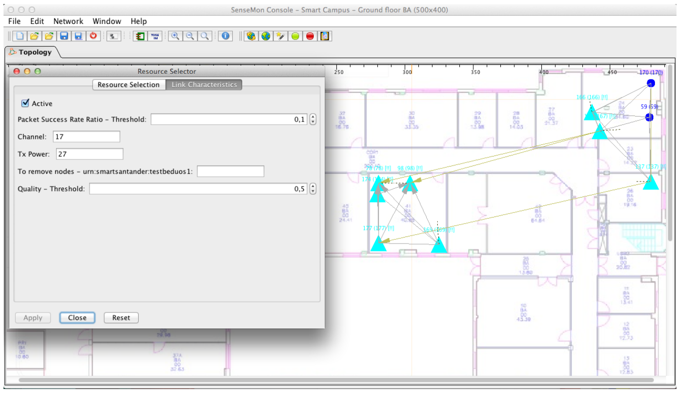


Fig. 3: SW components overview



☑ Active

Packet Success Rate Ratio – Threshold: 0,1

Channel: 17

Tx Power: 27

To remove nodes – urn:smartsantander:testbeduos1:

Quality – Threshold: 0,5

Fig. 4: Resource and Topology explorer

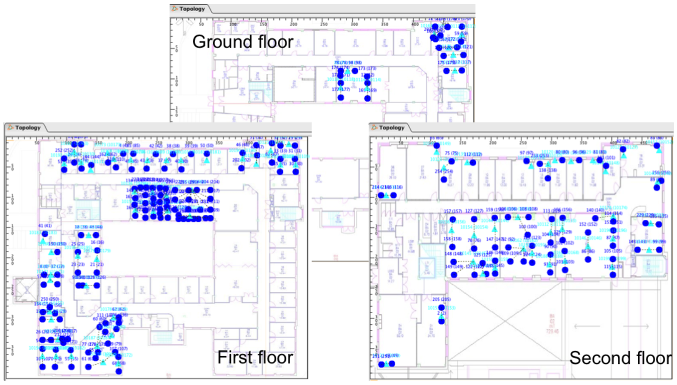


Fig. 5: SmartCCSR IoT nodes and GWs deployment

preliminary static capabilities they provide are described by semantic resource descriptions (RD), which are stored in a RDF database (*Semantic RD*). [9] provides more detail about the developed semantic model.

Through *TMON* (see Figure 4) a user can visually formulate queries for specific resource properties that satisfy the requirements for a particular experimentation scenario, that are then translated into SPARQL queries for the Sesame Semantic RD . The resource explorer evaluates these queries and performs a semantic matching against RDs, in order to provide the user with a selection of testbed resources fulfilling the desired properties. Once an initial subset of resources has been selected, the *topology explorer* allows a user to explore the topological relationships and characteristics of the links between static nodes (Figure 4) and the presence of source of interference affecting particular nodes (triangle-shaped nodes). As this information is quite dynamic and may change in particular for wireless links, it is updated regularly by the testbed management framework and kept in a separate database (*Dynamic DB*). This database also includes other dynamic properties such as the interference levels experienced in different wireless channels. *Testbed resource observers* that are attached to each testbed resource through the GWs infrastructure are able to detect the availability of new testbed resources, as well as corresponding status and topology information and ensure that the information available to the proposed testbed framework functions are always up-to-date. The preliminary event based communication is realized through a publish/subscribe messaging bus implemented inside our framework using MQTT for its suitability to operate in constrained and embedded GWs.

Once a user has selected a suitable set of experimentation resources, the experimentation specification is completed through *TMON* by provisioning of images for experimentation and by specifying experimentation timing requirements. The experimentation configurations are passed to the reservation system and scheduler for execution of the experiment. An *Experiment Executor* controls the execution of experiments and allows testbed users to interact with the experiments, by sending command and receiving answer from the selected resources. During the experimentation phase, results and traces are collected to a MySQL *Experiment DB* that stores standard trace format and expose them for further analysis through a well-defined REST interface. Additionally *TMON* provides the user with different views to the experimentation data, allowing quick visual inspection of the behavior of an experiment during execution or a detailed analysis after experimentation, the complete logic of which can be easily defined and integrated by the user creating *TMON* plug-ins that exploit well-defined API for experiment interaction, Experiment DB access and objects visualization. [12] shows a live record of an experiment involving wireless packets exchange between IoT nodes visualized in real time through *TMON*.

E. *Deployment overview*

While the Smartphones represent the mobile or semi-mobile portion of the testbed and for which a precise location cannot be provided and can change over time depending on the number of devices employed in each experimentation phase, differently the position of static IoT nodes and GWs is well-known and reported in Figures 5.

Each employer desk in the three floors of the Centre for Communication Systems Research building (CCSR) at University of Surrey is monitored through a testbed infrastructure made of 200 IoT nodes (circle) and 100 GWs (triangle). While a wireless data plane can connect all the IoT nodes, therefore for management purpose a wired USB link (dotted lines) exists between each GW and a subset of IoT nodes as shown in Figures. Smart Displays (not showed here) are located in correspondence of every corridors and other access points of the building (such as external entrances, staircase, meeting room entrances).

III. CASE STUDIES

In the following we present several case studies in order to show the potential of the SmartCampus testbed and to exemplify the nature of user-centric IoT experimentation that can be carried out on top of it. The experiments made use of heterogeneous IoT infrastructure available in our testbed and involved real end users during their daily life activities.

A. *Energy efficiency in buildings*

One key application of IoT technologies in smart buildings is to improve the energy efficiency of a building, which provides a basis for increased sustainability and reduced energy costs. To this purpose solutions that embed semi-autonomous forms of smart interventions that involve humans in the decision cycle are gaining attention. In our study we proposed and examined different technology enablers that contribute to an increased awareness of energy use in office spaces and user side energy demand management.

1) Energy awareness: In 2012, we conducted an interdisciplinary study using the IoT nodes deployed at the work desks of employees. Overall 102 office workers participated in the study which lasted over a period of 22 weeks. The experimental trial comprised pre- and post-intervention surveys, measurement of energy and consumption context and provision of feedback for 18 weeks post-baseline, and two participants focus groups. During the study participants where able to explore current daily or historic energy use (past week, past month) and energy efficiency at their work desk. The information was accessible through a gadget at the desktop which provided feedback on current trend as well as a personalized web-site showing a detailed breakdown on the energy use and efficiency. The user was able to track his progress over time and compare himself anonymously to other users and provided suggestions of how energy efficiency can be achieved. Figure 6 provides an overview of the developed feedback tools, developed by periodically pulling data from the Experiment DB. The study highlighted noticeable energy savings given an engagement with the participants can be maintained.

2) Interactive mobile feedback: Our initial study on energy awareness highlighted the need for more continuous involvement of end users in the feedback process in order to sustain the energy efficient behavior. Consequently we experimented with new solutions allowing real time intervention with the user for a more dynamic management of user side energy demand. Using the IoT nodes deployed at the desk our algorithms determine in real time situations of energy inefficiency and notify the user mobile phone of their occurrence (Figure 7a) through a Pub/Sub Broker deployed on the testbed servers. The user is furthermore provided with ability to turn of remotely devices that are wasting energy in her/his work environment. A user can also pro-actively turn on new devices before reaching his work.

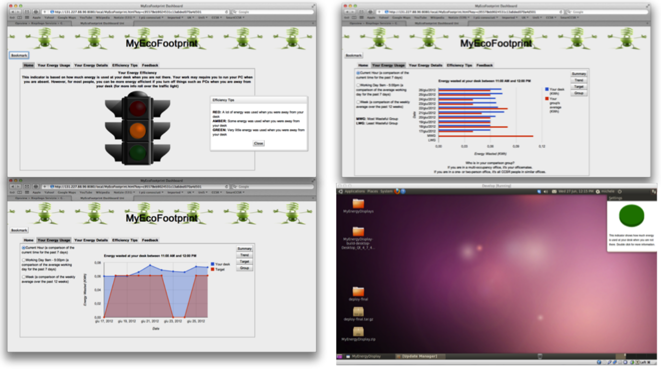
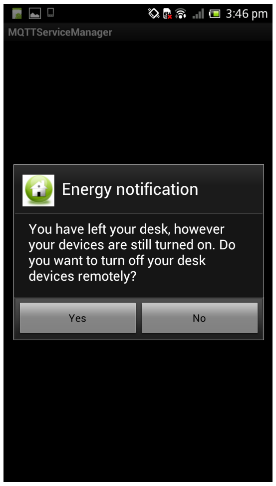


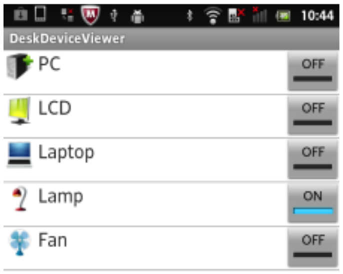
Fig. 6: MyEcoFootprint (MEF) GUI and Gadget



Energy notification

You have left your desk, however your devices are still turned on. Do you want to turn off your desk devices remotely?

(a) Notification



DeskDeviceViewer

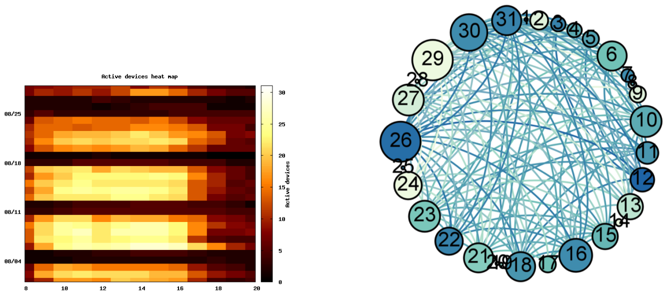
PC	OFF
LCD	OFF
Laptop	OFF
Lamp	ON
Fan	OFF

(b) Load

3) Load disaggregation: An important dimension of reducing energy use in office spaces is the ability to understand what devices are operating in an office environment. As intrusive monitoring of individual appliances is a costly task, non-intrusive load monitoring approaches provide a more cost effective alternative as the operation of aggregate devices behind a circuit or floor can be discerned with the use of machine learning techniques. We performed experiments with several such techniques that overcome the challenges associated with overlapping signatures of low power devices and multiple operational states. Using an approach based on Factorial Hidden Markov Models [14] our algorithm was able to correctly recognize the power state of different low power devices based on an analysis of device signatures computed from energy meter readings from the work desks of participants. The information is accessible to users via their mobile devices (Figure 7b), in order to understand what devices have been left operating at their desk.

B. *Human dynamics in office spaces*

The user-centric nature of the SmartCampus testbed has been successfully exploited for other studies that actively engaged with the users not only as consumer of the generated data but also as source of them. An understanding of movement and co-presence patterns of workers in an office environment is not only interesting for gaining insights into the social nature



(a) Activity Heatmap

(b) Social Graph

Fig. 7: Human dynamics in office spaces.

of the relationships that take place in such context. It can also be exploited for improving the design of Smart Building infrastructures, where the transmission of information flow can not only rely on a fixed infrastructure, but also benefit from opportunistic contacts between mobile elements, i.e., user carried mobile phones, and static infrastructures.

In order to shed more light on the potential of such opportunistic communication solutions in smart building environments, we performed an experiment in August 2012 for a period of three weeks involving 30 real users. Focus of the experiment was to collect information about all the possible contacts that can happen among people sharing the same work space and among people and infrastructure devices. The volunteer participants users were provided with a smartphones and a mobile IoT node based on TelosB, which they were asked to carry around during their time at office. Both of the devices were instrumented with experimentation code that generated and collect the results of a scanning phase through Bluetooth discovery (mobile smartphone) and IEEE 802.15.4 beaconing messages exchange, respectively. This allowed the detection of mobile-to-mobile contacts. The experiment also involved the utilization of GW devices across the building for the detection of mobile-to-infrastructure contacts. A simple data collection application was installed on the GW devices, which exploited different radio interfaces such as the built-in Bluetooth and IEEE 802.15.4 of an attached static IoT node.

By means of the static infrastructure and the inclusion of the mobile devices into it either through WiFi connectivity for the mobile phone and through IEEE 802.15.4 enabled GWs for the mobile IoT nodes, it was also possible to establish a control management plane that allowed the mobile devices to periodically report the results of such contact directly to the back-end Experiment DB server. While providing quick feedback on the ongoing experiment, loss of information due to storage limitations on the mobile IoT nodes could be avoided.

The following examples show the effectiveness of user participation to the experiment and of the collection infrastructure built exploiting the testbed. Figure 7a shows the number of Bluetooth enabled devices active during the overall experiment duration over time. As expected the numbers tend to reach the maximum during the peak hours, i.e., 10am to 5pm, and are lower during early morning hours/ night time or week ends and bank holidays. Similarly, Figure 7b shows the social graph for a particular day of observation thus allowing nearly real-time identification of the device/user with highest centrality during the day, obtained by simply adding query capability to the Experiment DB.

IV. CONCLUSION

This paper presented SmartCampus, a testbed for user-centric IoT experimentation. Its infrastructure provides increased realism and end user involvement into IoT experimentation as it is deeply embedded in a real life office environment, while providing the convenience and flexibility of lab based testbeds for experimentation. Our initial experiences have proven the usefulness and maturity of our facility, which we plan to open to the public summer 2013, hoping that it will inspire exciting ideas for user-centric IoT research.

ACKNOWLEDGMENT

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