Open Urban Computing Testbed

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Abstract. We present a unique urban computing testbed for studying the utilization of ubiquitous computing technology in the public urban space of a city center. The testbed comprises of a wide range of pervasive computing infrastructure and different middleware resources. We demonstrate the applicability and benefits of the testbed in evaluating technology pilots and prototyping new ubiquitous services in real-world urban setting. We conclude with a discussion on the challenges in deploying this kind of a large-scale testbed in a public urban space.

Keywords: urban computing, ubiquitous computing, public private partnership.

1 Introduction

We introduce a unique urban computing testbed in the City of Oulu in northern Finland, just 200 km south of the Arctic Circle. With 140000 citizens Oulu is the sixth largest city in Finland. The Oulu region has strong ICT competence in 14000 ICT jobs and the largest regional R&D expenditure per capita in Finland. In the late 1990's the Wired Magazine ranked Oulu as the number three 'silicon valley' in the world. The long-term goal of our testbed is to provide open horizontal resources for building incremental functional prototypes of a future ubiquitous city. There networked computing devices are seamlessly embedded into the urban space, turning it into a smart space providing different interaction modalities with the physical, virtual and social spaces. The utilization of ubiquitous computing technologies in urban space is studied by the multidisciplinary field of urban computing. It is driven by two important and related trends, urbanization and increasing deployment of pervasive computing infrastructure in the urban areas.

The mainstream research on ubiquitous computing suffers from a distinct lack of longitudinal, real-world case studies of system usage. The vast majority of research consists of studies that typically last a few days or weeks at best. Further, from the viewpoint of urban computing the studies are often executed in artificial settings such as labs and university campuses. While the immense research effort has produced numerous publications laying the theoretical foundation, few visible and lasting contributions to the urban digital fabric have emerged. This lack of coherent progress motivated the 2005 UbiApps workshop at Pervasive 2005, where 25

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researchers were invited based on their position papers. In their workshop summary Sharp and Rehman [10] identified several reasons underlying the crisis in the international ubiquitous computing research. One of them was the well-known fact that the research community values novelty over high-quality implementations and good engineering practices. This leads to ‘reinventing the wheel’ in tiny increments, which may be worth yet another publication, but very little else to the community, as the increments are not shareable due to their poor engineering. The consensus was that the scientific community should reward good engineering and encourage research that constructs open, reusable infrastructure for the wider community’s benefit.

We argue that the lack of visible and lasting results (in terms of applications) in ubiquitous computing is partially due to the lack of open pervasive computing infrastructure in the public spaces. Successful public spaces are mixtures of activities and applications, which purposefully combine physical, virtual and social spaces. They link places and context, consciously avoiding the ‘anything, anytime, anywhere’ paradigm. Doing this in practice requires permanent local infrastructure, which for business reasons is often deployed as closed verticals. Further, dedicated pervasive computing infrastructure would facilitate long-term large-scale real-world studies. Such studies are important because real-world ubiquitous computing systems are culturally situated, which cannot be reliably assessed with lab studies detached from the real-world context. Infrastructure and time are needed to establish the required technical and cultural readiness and the critical mass of users, before a pervasive computing system can be evaluated ‘(un)successful’ [12]. Interestingly, while some research communities have made long-term large-scale investments in shared infrastructure to support joint and transparent research, such as radio telescopes and networking testbeds, no such attempt has been made by the ubiquitous computing research community.

We have set out to deploy a novel city-wide ubiquitous computing testbed, which is provided as an open horizontal resource to the whole community. The infrastructure layer of the testbed comprises of three types of wireless networks (IEEE 802.11 WLAN, Bluetooth, IEEE 802.15.4 WSN), large public displays and various server machines connected via an aerially large layer 2 network. These heterogeneous computing resources constitute a large distributed system which is organized with a middleware layer. It provides various resources for supporting technology experiments, developing ubiquitous computing applications, and managing and monitoring the applications and the testbed. We demonstrate the applicability and benefits of our testbed with several case studies on deploying and evaluating technology pilots and prototype services in authentic urban setting.

To our best knowledge, a similar urban computing testbed with a matching range of computing resources deployed in a city center has not been reported in the literature before. In a historical context the PARCTAB ubiquitous computing experiment at the Xerox Palo Alto Research Center is probably the most similar deployment [15]. Related recent efforts such as the iDisplays at the University of Münster [13] and the e-Campus at the Lancaster University [14] are deployed at university campuses. This is understandable as it is much easier and often more practical to deploy research infrastructure on your own campus than at a city center. However, a campus environment cannot provide the authentic experimental setting pursued in urban computing.

2 Testbed Resources

Fig. 1 shows the simplified architecture and the building blocks of our urban computing testbed. The key infrastructure installed at downtown Oulu comprises of three different types of wireless networks and large public displays. The server machines are placed in several server farms located both at downtown and at the University of Oulu campus. In terms of network topology these nodes are aggregated into an aerially large VLAN, whose traffic goes via the main switch (corresponds to switch #1 in Fig. 2). The Recorder captures complete packet history with a set of high-speed probes attached to the main switch [2].

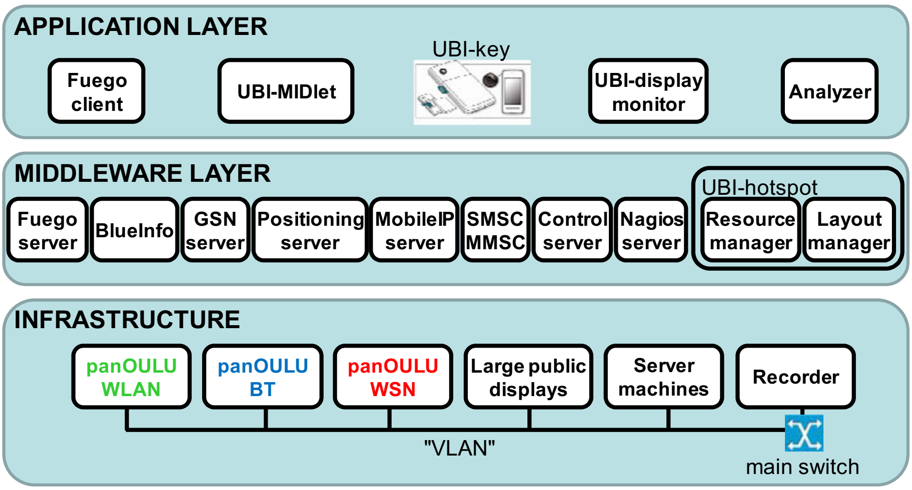

Fig. 1. The building blocks of our urban computing testbed

2.1 Wireless Networks

panOULU WLAN is a large multi-provider wireless network (IEEE 802.11) provided by a public-private partnership [7]. The network comprises of two parts, ‘CITY’ and ‘REGION’, as illustrated in Fig. 2. The ‘CITY’ comprises of two types of WLAN zones, the campus networks of five public organizations (City of Oulu, University of Oulu, Oulu University of Applied Sciences, VTT Technical Research Centre of Finland, and Pulmonary Association Heli) and the panOULU subscriptions sold by four ISPs (DNA, Elisa, LAN&WAN, Netplaza). panOULU subscription is an ISP product, which allows any organization to acquire panOULU WLAN hotspot into its premises to enhance image and customer service. The topology also includes a simple approach for integrating mobile APs (e.g. in buses) into the same IP subnet.

The WLAN zones are aggregated at the central layer 2 switch #1 into a single IP subnet, which effectively simplifies the multi-provider network into a single-provider network. The design comes with a rudimentary built-in session mobility support for the WLAN clients using the network, without any additional client software. The need for session mobility is motivated by the fact that the WLAN zones of different providers overlap in terms of radio coverage, particularly in the city center. If the zones would reside in different IP subnets, a station's roaming from one zone to another would result in the change of IP address which would interrupt ongoing socket connections and application sessions. The session mobility is based on the self- learning property of the layer 2 switches used to connect the APs (access points) into the backbone (not necessarily switches #1 and #2 shown in Fig. 2). When a mobile node roams between APs in two different BSSs (Basic Service Sets), the layer 2 switch connecting the two BSSs will eventually receive a frame from the mobile node, thus automatically learning the new location of the mobile node and updating its forwarding table accordingly.

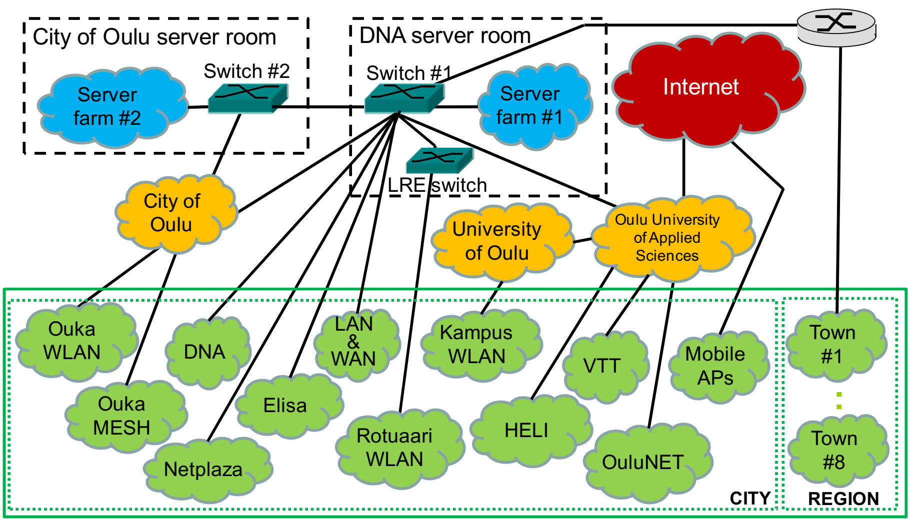

Fig. 2. Simplified topology of the panOULU WLAN network

The 'REGION' subnet comprises of the WLAN zones covering key public locations in eight nearby townships, which are connected to the core via a layer 3 router. The WLAN zones total currently ~1200 access points, of which ~500 reside within a 1 km radius of the city center of Oulu. From the user's point of view the APs appear as one large uniform network with SSID 'panoulu'. The APs provide both indoor and outdoor coverage in places deemed relevant for public access. The city center and its immediate surroundings are blanketed with a WLAN mesh network, but otherwise the coverage is provided in a hotspot manner.

In its coverage area the panOULU network provides open (no authentication or registration) and free (no payment) wireless Internet access to the general public equipped with a WLAN device. Excluding the blocking of outgoing port 25 (SMTP), which is required by the Finnish legislation, there are no limitations or restrictions on the use of the network. Currently, about 20000 WLAN devices use the network every month so that 25-40% of them are visitors and about 30% are WLAN phones.

The large coverage combined with the open and free access make the panOULU WLAN network a valuable R&D resource, as well. The network has been employed by numerous R&D pilots and research projects. Further, the panOULU WLAN network provides backhaul connectivity to some panOULU BT and panOULU WSN AP's, as well. The panOULU WLAN is also used by the municipality for streaming feeds from video surveillance cameras and controlling digital parking guidance signs.

In a historical note, the panOULU WLAN fulfills Weiser's vision on ubiquitous infrastructure from the late 1980's: public access points provide short-range wireless connectivity on license-free spectrum, which allows the user's wireless devices to communicate with the surrounding smart space. A promo video of the panOULU WLAN is available at http://www.strixsystems.com/video/Strix_PanOULU.html.

panOULU BT network is a cluster of Bluetooth APs around downtown Oulu. A BT AP provides open and free connectivity to Bluetooth devices. It effectively establishes a WPAN (Wireless Personal Area Network) hotspot for providing services within the wireless coverage of few tens of meters in range. Since we know the location of the AP, we can also reliably estimate the location of the user to provide context-aware services. We currently have a network of 12 BT AP's co-located with the UBI- displays (see Section 2.2). The APs are equipped with three Bluetooth radios, which can establish their own piconets of seven clients, thus 21 clients can communicate within a single AP simultaneously. We are in the process of expanding the network with additional AP's, which will be using the panOULU WLAN for their backhaul connectivity.

panOULU WSN network will be a cluster of WSN AP's around downtown Oulu. The AP's conform to the IEEE 802.15.4 specification and have dual radios (868 MHz, 2.4 GHz). An AP provides open and free multi-hop half-duplex connectivity with the 6LoWPAN protocol stack, the light-weight version of the IPv6 protocol stack intended for low-power devices. The multi-hop connectivity means that sensors form multi-hop paths, where a sensor can forward the packets of other sensors towards an AP. The half-duplex connectivity means that we can also send packets to individual sensors if needed. The upcoming installation on the 868 MHz band in spring 2010 was preceded with a small trial on the 2.4 GHz band in 2009. However, given the large amount of interference on the 2.4 GHz band and the much better range and penetration of the sub GHz band the APs will only use the 868 Mhz radios.

2.2 Large Public Displays

We are deploying two different types of large public displays, UBI-displays and UBI-projectors. They provide large visual capacity for representing information and realizing visual interfaces to the ubiquitous city. Thus, they play a very important role in creating visible artifacts of the new pervasive infrastructure – 'seeing is believing'. The UBI-displays are large interactive public displays (Fig. 3) installed on street level. The first phase installation deployed in summer 2009 comprises of six indoor displays in public buildings and six outdoor displays in the city center. The indoor displays are movable and have one 57" Full HD LCD panel in landscape orientation. The outdoor displays are installed permanently on streets and they have two adjacent LCD panels. The displays are equipped with various accessories such as Internet connection, quad core control PC, 500 MB RAID1 disk, two overhead video cameras, NFC/RFID reader, and loudspeakers. They also contain panOULU WLAN, BT and WSN access points. The UBI-projectors are implemented with data projectors on large surfaces. First two UBI-projectors will be deployed at the City Theatre in spring 2010.

Fig. 3. (a) Outdoor UBI-display at downtown Oulu; (b) Components of an indoor UBI-display

2.3 Middleware Layer

The middleware layer comprises of a number of components that provide various services to the application layer. We have aimed at a cost efficient implementation, utilizing ready-made open source and commercial components when available. We provide just a brief description of each component, while the details can be found in related original publications when applicable.

Fuego server. Open source Fuego architecture provides distributed event-based communication overlay based on the publish-subscribe paradigm. A process publishes an event, which is routed based on its content to those processes that have subscribed to that type of events. This corresponds to so-called degenerative communication, where communicating processes are temporally and referentially uncoupled. This is very practical in a large distributed system, where processes can join and leave dynamically, particularly those executing in mobile clients. A process who wishes to publish and/or subscribe to Fuego events has to execute the Fuego client process. [11]

BlueInfo is an in-house architecture for deploying web services in the panOULU BT WPAN hotspots for cost-free context-aware mobile access. A BlueInfo hotspot either pushes subscribed services at desired intervals to registered devices (BlueInfo Push) or alternatively the user invokes a particular service by sending a simple keyword query to the hotspot (BlueInfo Pull). The BlueInfo hotspot requests the service from the origin server in the Internet and relays the response to the mobile device, possibly after adaptation for mobile viewing. [3]

GSN server. The deployment of WSN applications is supported by the open source GSN (Global Sensor Network) architecture. It comprises of several parts: a data acquisition module, a database module, a web-based query module and an external web services module. [9]

Positioning server keeps track of the current location of mobile nodes. The location is updated when a node establishes a connection with a panOULU WLAN AP or a turned-on Bluetooth radio bypasses a panOULU BT AP.

MobileIP server. A commercial MobileIPv4 solution is provided with a limited number of client licenses. This allows utilizing MobileIP in the management of vertical handovers between different access networks.

SMSC/MMSC. Message (SMS, MMS) delivery to mobile clients is supported by access to commercial SMSC/MMSC hosted by an ISP.

Control server is an in-house component that is responsible for runtime service discovery, user authentication and hosting of application metadata.

Nagios server. Nagios is a popular open source computer and network monitoring software. It allows remote monitoring of multiple computers simultaneously, reporting important metrics such as CPU load, memory usage, and network services. It can be extended to monitor custom metrics from various components. It supports also automatic notifications of service or host problems.

Resource manager is an in-house component that controls temporal access to the resources placed under its administrative domain (the UBI-hotspot) according to predefined policies. Temporal access is enforced with different types of leases, ranging from open multi-user leases to private single-user leases. Users are also able to place leases in queue, thus allowing future reservation of a resource that is currently unavailable or busy. [1]

Layout manager is another in-house component that controls the spatial access to the screen real estate of an UBI-display included in an UBI-hotspot. The Layout manager provides a SOAP interface for triggering state changes and assigning virtual screens with URL's of arbitrary web applications. [16]

2.4 Application Layer

We provide some general purpose resources for application development and for monitoring the testbed and the applications executed atop it.

UBI-MIDlet is a lightweight J2ME software layer (aka stub) that provides native service support for mobile applications by inheriting them from the standard J2ME MIDlet application framework. The UBI-MIDlet implements session control, authentication and transparent integration with the Resource manager.

UBI-key is effectively an RFID tag that serves as the electronic identity of an 'ubiquitous ouluensis'. By showing his/her UBI-key to the RFID reader of an UBI-hotspot, a user can obtain control of the hotspot for further interaction.

UBI-display monitor is provided for monitoring the visual state of the UBI-displays for maintenance purposes. The tool periodically fetches the screenshots from each UBI-display and renders them as a collage on a web page.

Analyzer summarizes the packet data collected by the Recorder with various visual presentations representing different entities, for example individual events, identities, flows between identities, or causal relationships of flows. The available of complete packet data and the visualizations facilitate visual drilling down from high-level visual abstractions to the level of individual packets and back. This in turn allows high-level visual analysis of complicated events without tedious and time consuming detailed study of large amounts of packet data. [2]

3 Usage Examples

We demonstrate the practical applicability of our testbed with six case studies representing two different types of R&D, technology pilots and service prototypes. Details of the case studies can be found in the related publications, when available.

3.1 Technology Pilots

Three technology pilots illustrate the utilization of the testbed and especially the panOULU WLAN in the deployment and empirical assessment of a particular technology in real-world setting

UMA pilot. Nokia's first public UMA (Unlicensed Mobile Access) pilot was conducted atop our testbed in June-September 2006 in collaboration with DNA (local ISP) and the City of Oulu [6]. An UMA-enabled dual-mode handset is configured to access GSM core services over unlicensed wireless network (panOULU WLAN in our case) if it is available, otherwise licensed cellular network is used. The purpose of the pilot was to evaluate the functionality of the UMA technology in authentic setting. About 60 UMA-phones were distributed to the City of Oulu personnel, who used the phones for three months, totaling 1.03 million online seconds in the panOULU WLAN.

Mobile IP technology pilot. Mobile IP is a mobility management protocol standardized by the IETF. A Mobile IP pilot was conducted atop our testbed by the City of Oulu, Fujitsu Services and Secgo Software (later acquired by Birdstep). The City's mobile workers were equipped with laptops that provided transparent and seamless connectivity in a multi-access network. The laptops were furnished with various network interfaces and Mobile IPv4 client for mobility management. The successful pilot started in September 2006 and eventually led to the purchase of a production system a year later.

HIP technology pilot. HIP (Host Identity Protocol) is a security and mobility protocol standardized by the IETF. HIP-based distributed user authentication architecture was empirically evaluated in the panOULU WLAN network by the WISEciti project in 2008. A HIP proxy was installed in the network for establishing connections with HIP mobile clients. The proxy authenticated clients, provided terminal mobility and encryption of user data over unprotected wireless links. [5]

3.2 Service Prototypes

The following three cases demonstrate the exploitation of the testbed in deploying a novel service prototype to the general public. The usage of the service is then monitored, providing feedback on the usefulness and user experience of the service.

UBI-hotspot provides rich interaction between the physical, virtual and social spaces. The first version of the UBI-hotspot is effectively an UBI-display embedded with other co-located computing resources such as panOULU WLAN, WSN and BT APs. UBI-hotspot offers a wide range of services via different interaction modalities including mobile. In the current interaction model the UBI-hotspot alternates between a passive broadcast mode and an interactive mode. The transition to the interactive mode is triggered when a user touches the touch screen or presents an UBI-key to the RFID reader, or a face is detected from the video feed of the two overhead cameras. In the broadcast mode the whole screen is allocated to a digital signage service called UBI-channel. In the transition to the interactive mode the UBI-channel is smoothly squeezed into the upper left hand part of the screen and two additional virtual screens are created, one assigned for a touch screen portal called UBI-portal and another assigned for mobile services. The UBI-portal is effectively a web portal of various information and leisure services (web pages), which can reside on any web server in the public Internet. The default view of the UBI-portal can be configured on per hotspot basis. A video illustrating the services of the UBI-hotspot version 1.0 is available at http://www.ubioulu.fi/node/133. We have deployed a network of 12 UBI- hotspots in pivotal indoor and outdoor locations around downtown Oulu. The UBI- hotspots have been in everyday use by the general public since June 2009, attracting on average about 50 interactive sessions per panel each day. [8]

UBI-AMI prototype for advanced metering demonstrates the capabilities of the panOULU WSN network. The UBI-AMI socket sensors measure the power consumption of the devices attached to it together with temperature and illumination in that location. The UBI-AMI mains sensor measures the power consumption from the main electricity meter. The sensors packetize the measurement data and transmit the packets to a panOULU WSN AP. It forwards the packets to the UBI-AMI server (based on the GSN server), which filters and stores the data. The user can explore the data via a web interface, for example study how expensive is the electricity consumption of particular devices. Further, the user can configure to receive a SMS or email alert if a particular device (e.g. a freezer) is accidentally turned off. Thanks to the half-duplex connectivity provided by the 6LoWPAN protocol stack, the user can also remotely turn off the devices (e.g. a coffee machine) connected to a particular sensor. An UBI-AMI pilot with ten households as test users commenced in January 2010.

panOULU Luotsi was a location-based information mash-up for the users of the panOULU WLAN. XML content in various forms, such as RSS/ATOM feeds from several content providers were automatically merged into the Luotsi database using a flexible XML aggregator. It allowed mapping different heterogeneous information feeds into the Luotsi database without any changes to the application source code. The location of the user was provided by the Positioning server, estimated by identifying the WLAN AP to which the user's wireless device was connected. The information relevant to the user's current location is imposed on a map for a location-based browsing. [4]

4 Discussion

This type of large-scale testbed deployment comes with many challenges, first and foremost financial and technological viability and sustainability. The public sector has made a considerable capital investment in our testbed, thus we wish to offer it as open horizontal resource to the whole community. Many (academic) infrastructure deployments have fallen apart, because they did not have any long-term financial basis for covering operational and renewal expenses. The panOULU WLAN has survived seven years with its PPP model, where the owners of the WLAN zones are responsible for all the expenses incurred by their zones, and the City of Oulu sponsors the core services outsourced to subcontractors. In 2010 the City of Oulu uses about 75000 € to the panOULU WLAN, which corresponds to 0.04 € per citizen in a month – a very smart investment in an open and free public service used by 20000 people every month. The panOULU WLAN is due a major renewal of APs in a few years, if a city-wide WLAN network is still deemed a worthwhile resource amidst improving mobile data networks. To cover the operational expenses of the UBI-hotspots we are selling a portion of their capacity for commercial use. However, as of now we do not have such business model for the panOULU BT and panOULU WSN networks.

Shared urban spaces can be very dynamic, diverse and dense with complex ownership and decision making mechanisms. While you may have full control and command of your own research lab, the public city space falls under the authority of the city administration. We are very fortunate to have the unwavering support of the City of Oulu's administration, which is mandatory for the implementation and sustainability of this kind of testbed deployment. At the same time you have to comply with the municipal decision making procedure, which can introduce delays at times. For example, the installation of the panOULU WLAN APs and UBI-hotspots was subject to the formal urban planning process of the city. Further, you may need favorable cooperation with private parties such as property management companies and housing cooperatives, for example to acquire cost-free sites for APs.

Another major challenge is the operational execution of maintenance, where research organizations are typically not good at. Outsourcing maintenance or allocating designated maintenance personnel is highly recommended, if you can afford it. If researchers have to take care of maintenance, then you need to specify clear roles to avoid confrontations between research and maintenance tasks. Further, maintenance expenses and the availability of the testbed can be greatly optimized by automating maintenance.

Research on a real-world testbed in a city center differs from lab research in few important aspects. First is the demand for high quality engineering. For example, the engineering of the UBI-hotspots the user community expects to be available 24/7 is a totally different ball game than presenting a one-shot demo to your sponsors in your own lab. Second, you have to comply with the many ramifications of the real-world setting. A research prototype may depend on particular infrastructure which will not be available in the real-world in the foreseeable future. No matter how fascinating a novel mobile application developed for a particular exotic mobile device may be, it is rather pointless to bring the application to the real-world setting, if the market penetration of the mobile device is negligible. Further, while most lab studies happily ignore value networks, business models and economic sustainability, we are trying to build a sustainable ecosystem around our infrastructure, for example by selling a portion of the capacity of the UBI-hotspots for commercial use to cover their operational expenses. This commercial dimension limits the research use of the UBI- hotspots, which may be difficult for researchers to accept. Another important difference is the public scrutiny in the real-world setting. While nobody cares about the mistakes you do in your own lab, a deployment in a city center is subject to daily scrutiny by the general public and media, which in our case has been rather ill-tempered at times. Finally, while usability evaluation has established itself as the de facto yardstick in lab studies, there is no such universally accepted methodology for evaluating real-world deployments. This is probably one of the reasons why the mainstream research community values lab studies over real-world studies.

We have a number of ongoing activities to make our testbed available to the whole community and to stimulate open innovation. For example, students build new services to the UBI-hotspots as their course works. We currently have a public tender for businesses to purchase rights to offer commercial services in the UBI-hotspots. We are executing a national 'UBI-challenge' where both individuals and businesses are challenged to innovate and implement novel services to the UBI-hotspots so that best proposals are supported with grants. An international 'UBI-challenge' prepared with a number of leading international researchers will be launched in 2010, inviting the international research community to show what they are able to do atop our urban computing testbed.

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