Bridging the Mobile Web and the Web of Things in Urban Environments

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***Abstract*—Embedded sensors are massively deployed around the world, especially in urban areas. The increasing urbanism implies advanced challenges for the citizens. Real-time sensory data is expected to assist in addressing some of these challenges.**

The rise of multi-sensory mobile phones with Internet connectivity and the promising practice of Web-enabling physical devices create the need for a bridging between the Mobile Web and the Web of Things in urban environments.

We believe that location would be the key element that will enable this bridging. Location will facilitate the filtering of large amounts of real-time sensory data, being generated to represent environmental conditions. In this paper, we developed a location-based, mobile application that interacts with Web-enabled sensors that are deployed in the vicinity of the user, by means of online, global sensor directories.

We consider our project as a small contribution towards the vision of a real-time digital city. Our early evaluation efforts indicate the feasibility of our approach.

***Index Terms*—Urban Computing; Web; Mobile Web; Web of Things; Sensors; Real-time data; Location; Context-awareness; Online Sensor Directories; Pachube;**

I. Introduction

Embedded sensors are massively deployed around the world, measuring with high precision environmental conditions such as temperature and humidity or physical events such as pressure and motion. Sensor networks are used in the industry and in modern residences to provide automation solutions.

Urban areas in particular, are equipped with large numbers of digital networked sensors that support the needs of the increasing numbers of inhabitants. It is calculated that urban areas host around 50% of the world's population. It is expected that between 2010 and 2050 the population in the cities will be doubled [22].

New technologies like short-range wireless communications and real-time localization are now becoming largely common, allowing the Internet to penetrate into the real world of physical objects. The introduction of IPv6 and the efforts for porting the IP stack on embedded devices [3] enable the vision of the *Internet of Things* [5], which refers to a network of objects, where all things are uniquely and universally addressable, identified and managed by computers in the same way humans can.

Extending this concept, the *Web of Things* [23] is a notion inspired from the Internet of Things where everyday devices and sensors are connected by fully integrating them to the Web. Based on the success of the Web 2.0, this concept is about reusing well-accepted and understood Web standards to connect constrained devices. Directly embedding Web servers on sensors is a recent development [25].

Sensors are also being integrated in mobile phones, offering advanced capabilities such as measuring proximity, acceleration and location. Sensor enhancement, together with wireless connectivity with the Internet, facilitate the development of rich, context-aware, Internet-based mobile applications [2], [7], [15], making the *Mobile Web*[1] an enticing practice.

A quickly expanding ecosystem of Web-enabled sensors is evolving worldwide. Web technologies began to penetrate in these new generations of embedded devices [8], [10]. However, many issues arise from this new perspective. It becomes extremely challenging to discover these tiny networked devices, locate them and interact with them in uniform ways, notably in urban environments.

The increasing urbanism brings forth new issues that position citizens at the center of their urban environment, encouraged to actively engage with it. The Web of Things can be considered as a real-time platform, for supporting people to shape the city they live in, through their mobile phones.

In this paper, we propose to exploit location, provided as a service from almost all the new mobile phones that appear in the market, to derive only relevant information from all this innumerable available functionality, provided by the vast numbers of Web-based sensors that will surround the citizens in their future cities.

We present a mobile application that discovers, locates and interacts with services, provided by Web-enabled sensors that

[1] http://www.w3.org/Mobile/

are deployed in the vicinity of the user. These services help the mobile user be aware of the local environmental conditions, increasing his overall environmental sensitivity and ensuring his personal health [13].

The remainder of this paper is organized as follows: in Section II we reveal the motivation behind our work and we describe our main idea. Then, in Section III we explain the implementation of our approach and in Section IV we perform a preliminary evaluation of our work. Afterwards, in Section V we describe a possible scenario where our approach might be useful and in Section VI we identify related work. Finally, in Section VII we conclude the paper and mention future work.

II. The Mobile Web meets the Web of Things

We believe that location-based services are the key to integrate the Mobile Web and the Web of Things, at least in urban areas, where large numbers of Web-enabled sensors are being deployed. Location is the dimension that will facilitate the filtering of enormous amounts of data, collected by embedded sensors that will flood the cities of the future.

In the next subsections we describe the new perspectives that emerge from Web-enabling physical devices and we illustrate our approach for exploiting this potential through the Mobile Web.

A. A Global Web of Physical Objects

Web-enabling physical devices and services has been gaining increasing popularity. Web-based sensors proliferate around the world, especially in urban areas where the large majority of humans lives. The Web is preferred because it is ubiquitous and scales particularly well. Web practices guarantee simplicity and interoperability.

The Web-enabling process can be performed in two ways. Either through embedding Web servers directly on physical devices or by employing gateways, which perform protocol translation, from the TCP/IP protocol to the dedicated protocol used by the physical device (e.g. Bluetooth, ZigBee).

REST [4] is mainly suggested for Web-based interaction with embedded devices because it is a lightweight protocol that defines how to use HTTP as an application protocol. It models services and data as *resources*, which can only be manipulated by the methods specified in the HTTP standard (e.g. GET, POST, PUT, DELETE), under a uniform interface. REST guarantees loose-coupling and a smooth transition from the Web to the embedded environment of physical devices.

Even though the Web seems to be a promising approach, a need remains for a real-time search engine for the Web of Things. Just as current search engines are used for discovering Web sites, social networking sites are used for discovering people and sharing data, also scalable and efficient methods are needed for discovering real-world entities, with certain properties.

Although, until today, standardized Web protocols for real-time sensor discovery are inexistent, efforts are made towards this direction. Dyser [17] is a real-time search engine that enables finding real-world entities such as sensor devices. Microformats[2] and RDFa[3] are believed to be the main drivers in these efforts as they are a set of simple, open data formats built upon existing standards, for better structured Web content publishing.

This absence of standardized discovery methods for Web-enabled physical devices led to the development of online, global sensor directories. The most well-known directories available today are SenseWeb [20] and Pachube [9].

These infrastructures act as data brokerage platforms, managing millions of data points per day from thousands of individuals and companies around the world. They enable people to share, discover and monitor in real-time sensor, energy and environmental data from objects, sensors and buildings that are connected to the Internet, around the world. These platforms promote the Web-enablement of sensors and allow the propagation of sensory readings to interested third parties. Sensors are presented inside satellite maps, in the absolute position where they are located. These sensors can be fixed or even mobile, provided that they are able to inform their hosting platform in frequent intervals about their location.

A key future of these online directories is that they provide open Web APIs that urge the development of smart applications from third parties.

The drawback of these infrastructures is that they are centralized, with a single point of failure. Decentralized approaches have also been proposed, such as IrisNet [6], which uses a hierarchical architecture for a worldwide sensor Web. More advanced, G-Sense [18] is a peer-to-peer system for global sensing and monitoring. These approaches, although more robust and scalable, have not been largely adopted yet by the public. Furthermore, sensor discovery in these cases is still a challenging issue.

B. Location-based Discovery of Web-enabled Sensors

Online sensor directories offer a great opportunity for automatically discovering Web-enabled sensors. Our core idea is to interact with such a directory, through its Web API, and locate sensors that are deployed in the region of the mobile user. Since sensors are registered to these directories with the absolute position where they are located, it is easy to identify and select them based on their proximity from the absolute position of the user. The user's location is easy to be found, as almost all new mobile phones integrate GPS modules and offer location-based services, with highly accurate location results.

Mobile phones that do not yet possess GPS functionality, can leverage other modern localization techniques such as Wi-Fi positioning [1] or localization based on GSM Cell ID [16].

Wi-Fi positioning harnesses the rapid growth of access points in urban areas. It offers 10-20 meter accuracy and operates well, also indoors. However, this approach has restricted coverage and does not scale in dynamic urban changes.

GSM cell tower triangulation provides generalized location results with only 150-1000 meter accuracy. It serves only as a

[2] http://microformats.org/

[3] http://rdfa.info/

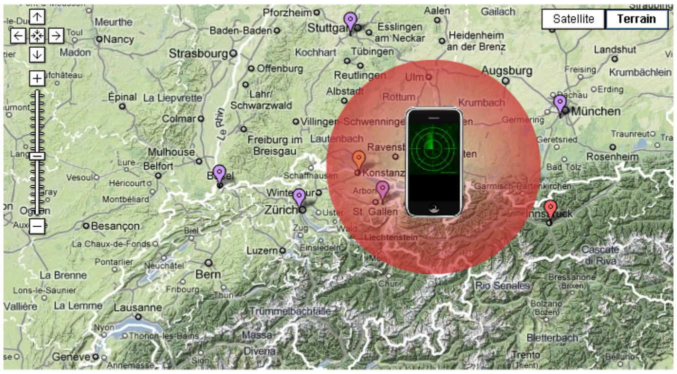

Fig. 1. Web-based Discovery of nearby Sensor Devices.

coverage fallback. Its main advantage is its energy-efficient operation since integrated GPS receivers and Wi-Fi radios suffer from excessive power consumption.

We define proximity as a circle with the user's exact location at the center of this circle. The radius of the circle is user-defined, ranging from some meters to hundreds of kilometers. In highly dense areas such as big cities, a radius of some meters can be enough while in rural areas this radius can cover a number of kilometers.

In Figure 1, a graphical representation of this concept is shown. The mobile phone indicates the user's position and the red circle defines the area of interest, in which the user wants to be informed about any sensory measurements. According to the figure, there exist two sensors in this covered area, with which the user can interact.

While the mobile user can be wandering inside his city, he can be informed in real-time about the local environmental conditions, for example the outside temperature, the levels of humidity, the pollution of the air etc. The localization technique on his mobile phone will continuously update his absolute position and new information will appear on his phone based on the capabilities of the sensors that are deployed in the nearby area.

An important requirement for the smooth operation of our application is ubiquitous wireless Internet connectivity. We believe that this is not a big issue because in the near future, technological advancements in mobile telecommunications such as 3G and WiMAX are expected to pervade our daily lives.

C. Urban Mashups

Online sensor directories offer open Web APIs that permit the development of Web mashups[4] from third-party application developers. Web mashups, when they exploit real-world services offered by Web-based physical devices, are characterized as *Physical Mashups* [8], and they combine sensor functionality using the same tools and techniques of classic Web mashups.

We further extend physical mashups into *Urban Mashups*, to deal with the highly dynamic and mobile urban landscape. We define urban mashups as opportunistic physical mashups that are validated only when the local environmental conditions support the sensor-based Web services, which are defined by these mashups. Urban mashups follow a service-centric approach, taking into account the high probability of sensors' presense in the nearby environment.

Uniform, RESTful interfaces allow the interaction with heterogeneous sensor devices in an interoperable way, making the development of urban mashups a feasible task.

As an example, we may want to be informed about today's traffic in our nearby area. We develop an urban mashup by combining CO2, movement/traffic and even sound services, offered by any sensors placed in the local area. This mashup will be validated opportunistically, only in case these sensors appear in the vicinity of the mobile user.

III. Implementation

We defined GPS as our localization technique because high accuracy is required in dense urban settings with rich populations of Web-enabled embedded devices.

We implemented our application in Java Platform, Micro Edition (J2ME), which is a Java platform designed for mobile devices and embedded systems. We selected J2ME to make our application portable across many mobile phones.

Mobile phones must support the Location API for J2ME (JSR 179), which is a generic API that produces information about the device's present physical location. By means of JSR 179, the application can communicate with the onboard GPS sensor to get real-time positioning data. Since GPS service is energy-demanding, we set the GPS sampling frequency to be user-defined. The default is one sample every 60 seconds.

We selected Pachube as our online sensor directory because it is a global platform with increasing popularity. It is a platform that guarantees high performance, scalability and advanced security. Its Web API is fully RESTful, conforming perfectly with the notion of the Web of Things. Pachube also offers detailed documentation and a large variety of libraries, tutorials and examples. In particular, we exploited the Geolocations API, offered by Pachube for supporting requests that involve location information. This API is still under experimentation from Pachube developers.

Sensor data in Pachube is represented as feeds, in RSS[5] and Atom[6] syndication protocols. Content delivery is available in Extended Environments Markup Language (EEML[7]), CSV and JSON[8] data formats. EEML is an XML schema for formatting data streams from sensors and embedded devices. We requested data in EEML in our application, because it contains the most complete representation. To parse EEML-based feeds, we used the kXML[9] pull parser.

As soon as a mobile user performs a *Search* through our application, every nearby sensor inside the user-defined circle

[4]http://www.programmableweb.com/

[5]http://cyber.law.harvard.edu/rss/rss.html

[6]http://tools.ietf.org/html/rfc4287

[7]http://www.eeml.org/

[8]http://www.json.org/

[9]http://kxml.sourceforge.net/

Fig. 2. Sensor Motes Deployment at the area of the University of Cyprus.

is displayed, along with basic information about its type and its exact distance from the user's current position. If the user requests more details about a specific sensor, then all the related information of that particular sensor is presented. This information includes the latest value measured, a timestamp of the last measurement, minimum and maximum values sensed, the absolute position of the sensor, description of its services, units in which the measurements are made (e.g. Celsius degrees for temperature) as well as some other relevant information such as whether the sensor is indoor/outdoor, fixed/mobile etc. The user has also the option of viewing historical sensory measurements of the last few days on graphs, instead of only the latest value in plain text.

Since, in urban areas a large number of sensors may exists, we included a keyword-based search, only for services of interest. For example, the mobile user may only be interested for specific physical aspects of the local external environment, such as magnetic fields or detection of poisonous gases.

Security is an important issue at the Web and Pachube accepts only authenticated requests from Web clients. Users need to insert their unique API key (received from Pachube during online registration), the first time they use our application.

We have already registered our application with Pachube, under the name *PachuRadar*[10]. It is freely available for download in Pachube.apps repository[11]. Feedback from real users is expected to help us eliminate any bugs that may exist in the first official release of our software.

IV. Preliminary Evaluation

We uploaded our application on a Nokia N95 8GB mobile phone, which employs a Texas Instruments GPS chip launched in 2006, to test our system in real-life conditions.

We placed three Telosb sensor motes in the area of the University of Cyprus. These sensors could sense the temperature, humidity and illumination of the local environment. We exposed their sensing capabilities as RESTful Web services, transforming the sensor motes into embedded Web servers, which could be addressed using standard HTTP calls. Our implementation was based on Blip[12], which ports the 6LoWPAN stack on TinyOS 2.x[13]. We connected the sensor motes to Pachube, which proved to be a very simple process of a few clicks. Each sensor transmitted new measurements to Pachube every one minute. Our testing infrastructure is depicted in Figure 2.

TABLE I
Preliminary Evaluation Results.

Ref. Point	Accuracy	Sensor1	Sensor2	Sensor3
1 (0.1 km)	4 m	4 m	4 m	3 m
2 (0.5 km)	5 m	3 m	3 m	3 m
3 (1.5 km)	3 m	3 m	2 m	3 m
4 (4.5 km)	4 m	6 m	6 m	7 m
5 (10 km)	3 m	9 m	12 m	11 m

We set a number of reference points near the university area, with well-known coordinates and different distances from the sensors. We measured the location estimates for each reference point and the distances from each point to the three sensor motes, using the phone's onboard GPS sensor. We compared these estimates with the true coordinates and distances, in order to calculate the accuracy of our application and its overall effectiveness. During the experiments, we used a default radius of 10 km. At each reference point, we performed 10 measurements and we took the average to derive our results.

The final results are listed in Table I. The first column presents each reference point and its average distance from the three sensors. The second column shows the absolute location estimation error in meters, while the next three columns display the distance estimation errors in meters, from each reference point to all the three sensors.

Examining the results, we believe that the overall accuracy is satisfactory. Few meters inaccuracy is an inevitable issue, due to the default positioning inaccuracy of the current GPS modules. These small inaccuracies are mostly responsible for the errors in distance estimations, for distances less than two km. For greater distances, we can see that the error is slightly increased. This is mainly because we did not take into account that the earth is slightly flattened around the equator. We will fix this issue in the next release of our software.

A small disadvantage of the system is the quite long time to first fix for each measurement location. We observed a strong dependency between the signal strength and the time it takes to acquire the GPS signals. This implies that in locations with weak signals one can expect high values for time to first fix. For cold starts (when no initial information about satellite constellations is available) the average time to first fix was between 60 seconds and three minutes.

In general, the communication interval with the Pachube server is very low, certainly dependent on the wireless Internet connectivity at each reference point. Our efforts showed that the Web API of Pachube operates perfectly. Data is consistent with the real-time measurements from our Telosb sensors.

[10] http://apps.pachube.com/pachuRadar/

[11] http://apps.pachube.com/

[12] http://docs.tinyos.net/index.php/BLIP_Tutorial

[13] http://www.tinyos.net/

We also tested the application in distances greater than the default radius and we did not receive any results, as expected. Any attempts to perform indoor positioning failed, since GPS is a technology mostly for outdoors. Recent studies show that *"using state-of-the-art receivers, GPS availability is good in many buildings with standard material walls and roofs"* [11]. However, such receivers are not expected to be integrated soon in mobile phones.

Our experimental methodology denotes the simplicity in designing advanced sensory systems in cities. Designers only need to Web-enable their sensors and register them through a sensor directory. Citizens can then exploit their functionality, just by moving near them. It is a plug and play, elegant approach to inspire people to engage with their public spaces, promoting the idea of community-based sensors sharing.

V. Example Scenario

Large cities, due to the increasing numbers of citizens, become densely populated. Many urban areas are uncomfortably dirty and large numbers of pathogens may be hosted there. These infectious agents cause diseases to people and these urban environments face many health issues.

A possible countermeasure would be the utilization of pathogen sensors, which can be distributed to the city citizens, who can place them near their houses, both indoors and outdoors to monitor their nearby environment for possible contaminations. Citizens could then share their sensory measurements with the city community and especially with people that pass near their houses. This way, people would be informed in real-time about the possible existence of pathogens in the neighborhood, which they would then be able to avoid. In addition, health services would easily identify these areas and eliminate any pathogenic microorganisms.

Short-range communication technologies are not appropriate to be used in such a scenario, as pathogens are effective in infecting humans from large distances. Besides, some sensors could be placed indoors, inside residential houses or even in sewers. Our approach seems appropriate in this case. Citizens need just to enable these sensors to the Web and register them to some online sensor directory. They can then use a mobile application such as PachuRadar in order to be informed about possible infections in their local environment, in a range specified by them, according to their sensitivity.

VI. Related Work

Our approach spans in three research domains: location-based services, participatory sensing and urban computing, all three in relation to sensor systems.

Location-based services make use of geographical positioning services, provided by mobile devices to perform some advanced tasks such as smart navigation, travel assistance etc. Positioning sources may be the Global Positioning System (GPS) or local network services (e.g. GSM Cell ID [16], Wi-Fi fingerprinting [1], DHCPs GeoConf [19]).

In a relevant study, Trifa et al. [21] have built a location-aware infrastructure for embedded devices using hierarchically structured, Web-enabled gateways. However, this approach is not flexible in case of mobile users in urban spaces.

Participatory sensing involves the tasking of everyday mobile devices to form interactive, participatory sensing systems that enable individuals in the general public to gather, analyze and share local knowledge. The MetroSense project [2] aims at transforming the mobile device into a social sensing platform. Goldman et al. [7] show the significance of participatory sensing for our daily lives, namely its impact on climatic change. GPS-equipped mobile phones are used to photograph diesel trucks, in order to understand community exposure to air pollution. In the NoiseTube project [15], mobile phones are used as noise sensors, to measure the personal exposure to noise of citizens, in their everyday environment.

In [13], a case study is performed, involving sensors deployed in public areas, shared by different communities. Users get informed of environmental conditions directly from these sensors. The findings indicate sensitivity to environmental factors from the people involved.

Urban computing is an emerging research area that focuses on the use of technology in public environments such as cities, parks and suburbs and the interaction possibilities between humans and such environments. The Urban Sensing project at CENS[14] seeks to employ mobile sensing to enhance civic life. MobEyes [14] performs urban monitoring by means of a vehicular sensor network, using opportunistic dissemination of road information to neighboring vehicles.

The authors in [12] use a Bluetooth-based infrastructure to identify characteristics of urban environments such as mobility patterns, social and spatial structures etc. Ubiquitous Oulu[15] is a prototype of a future city, in which better services are being offered to the people, by embedding information technology into the urban environment in an invisible way. SmartSantander[16] is a city-scale experimental research facility of more than 20,000 Internet-enabled sensors, in support of a real-life deployment in an urban setting.

Our approach is an alternate form of participatory sensing where local, real-time urban knowledge gathered from sensors, is shared through the Web. In this case, citizens contribute indirectly by Web-enabling sensors and registering them to some online sensor directory. Instead of sensing data directly through mobile phones, we use mobile phones and their GPS services to be informed about local environmental conditions.

The novelty of our work is that we leverage the Web to propose a flexible, large-scale, location-based city monitoring solution that promotes the idea of Web-based sensory sharing among people. It is an effort towards realizing an urban, location-aware Web of Things that contributes in sustaining the well-being of humans.

VII. Conclusions

In this paper, we developed a mobile application that employs location information to identify Web-enabled sensors,

[14]http://research.cens.ucla.edu/projects/2006/Systems/Urban_Sensing/

[15]http://www.ubioulu.fi/en/home

[16]http://www.smartsantander.eu/

placed nearby the mobile user. We utilized real-time sensory measurements, provided by an online sensor database, to inform the user about the environmental conditions in his area. We propose location as the element that would allow the bridging between the Mobile Web and the Web of Things. Our preliminary evaluation efforts indicate that our approach is feasible and it offers acceptable accuracy.

We estimate that future urban areas will be highly crowded, massively equipped with networked sensors. Location-based services will facilitate the filtering of vast amount of sensory data into crucial information that would enhance the quality of life of citizens, while moving within their cities. A culture around making sensors publicly available through the Web, could be used as a pressure method to individuals, factories or even governments to improve possibly poor life conditions.

Our core idea can also be applied in more constrained areas such as factories. For example, inside a power plant, information about the levels of electromagnetism from networked sensors, could contribute in assuring the safety of the workers.

We expect that location will be an important parameter in the future Web, directly integrated into it. Recently, the Locative Web [24] has offered interesting insights towards turning the Web into a location-aware infrastructure.

The Semantic Web[17] promises to shed light into the issue of discovering in real-time services from local Web-enabled sensors. It is highly desirable in the future, to achieve real-time, Web-based service discovery without utilizing online sensor directories [17].

As future work, we plan to increase the functionality of our application, by including automated tasks such as an event-based notification mechanism and a Web-based, urban mashups editor, for defining more complex queries such as "what are the weather conditions in my area", combining temperature, humidity or even anemometer sensors.

In addition, our future plans involve a large-scale deployment of Pachube-enabled chemical sensors near sewers in a major city, to inspect possible contamination of the water supply and inform in real-time the citizens who are passing along the local area, through their mobile phones. Such a project would reveal the real potential of our approach and the effectiveness of using location-aware, mobile services to benefit from the introduction of Web-enabled sensors in our everyday lives.

We consider our efforts as a small contribution towards the vision of a real-time digital city, in which the citizens are at the center of their urban environment, synchronized with it through the Web of Things.

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