

# A Reference Architecture for Mobile Crowdsensing Platforms

Herbert B. M. Diniz, Emanuel C. G. F. Silva, Thomas C. C. Nogueira and Kiev Gama

*Centro de Informatica, Universidade Federal de Pernambuco (CIn/UFPE), Av. Jorn. Anibal Fernandes, Recife, Brazil*

**Keywords:** Smart Cities, Complex Event Processing, Software Architecture, Crowdsensing.

**Abstract:** Many software solutions today rely on systems that integrate and analyze city data gathered from different sources (sensors and information systems) in real-time. Thanks to smartphones, citizens can act as smart sensors collecting city data in what is being called mobile crowdsensing (MCS). The literature that explores systems in that area, typically present high-level software architectures without much detail about their implementation or feasibility. With the intention of offer a straightforward and easy-to-follow reference architecture, this paper presents an approach that employs off-the-shelves components for the construction of an MCS platform for participatory sensing solutions in Smart Cities. We demonstrate an implementation of that architecture in a specific domain.

## 1 INTRODUCTION

As a consequence of problems resulting from population growth in cities, many technologies are being used for urban monitoring (Odendaal, 2003), influencing the way we are interacting with the urban spaces that are becoming more chaotic, due to the swelling population. Smart Cities (Naphade et al., 2011) is a term that gained traction in academia, business and government to describe cities that, on the one hand, are increasingly composed and monitored by pervasive and ubiquitous computing. Many software systems in that context seek to integrating various sources of information technologies (ICTs), taking into account a holistic view of the city and centralized monitoring and control to aid in supporting decision making (Ganti et al., 2011).

These sources of ICTs form complex structures (Nagel et al., 2014), and generate a large volume of data, which present enormous challenges and opportunities, hindering the possibility to provide programs that integrate sensor information and that capture from the physical space, taking samples of what is happening in real-time. It is necessary to integrate easily data from different sources, and also consider additional sources, such as people providing information in a collaborative way.

The usage of FLOSS (*Freely Licensed Open Source Software*) combined with COTS (*Commercial Off-The-Shelf*) allows the creation of cost-effective solutions with little implementation effort. From a business perspective, Gasperoni (Gasperoni, 2006)

elaborates on the use of FLOSS and COTS offering numerous advantages, such as software quality and speed of evolution.

However, when analyzing the literature on Smart Cities, there is a lack of detailed information on how these types software architectures implemented. Even when looking into particular types of smart cities (sub)systems, such as those focused on Mobile Crowdsensing, there is only shallow evidence on software design and almost absent evidence on the effective usage of FLOSS and COTS components in that context.

Aiming to provide a reference architecture and implementation of Mobile Crowdsensing platforms, in this paper we present an approach using freely available off-the-shelves components. The platform was implemented together with an application in the domain of urban mobility along with some experiments were carried out to prove the feasibility of the proposed approach.

The remainder of this paper organized as follows: Section 2 discusses background and motivation for our work; Section 3, presents an overview of the reference architecture; Section 4 brings details about the architecture implementation in the urban mobility domain; Section 5 presents the tools and methods of the tests in Section 6; Section 7 introduces results and discussions; Section 8, presents related work; and Section 9 brings conclusions and future work.

## 2 BACKGROUND

### 2.1 Smart Cities Software Architectures

It is important to have software architectures that can use as reference models for those who want to put in practice such types of integration scenarios in Smart Cities. The work from Chourabi et al (Chourabi et al., 2012), for instance, provides only a more strategic and high-level perspective on smart cities as a whole. Al-Hader and colleagues (Al-Hader et al., 2009) propose more details about Smart Cities Components Architecture but remain shallow. Even when getting into a more detailed literature survey about software architectures for smart cities, da Silva and colleagues (da Silva et al., 2013) were only capable of extracting general requirements for such architectures. The surveyed articles presented speculative or high-level architecture drafts, with little or no evidence on how such architectures implemented.

Many systems being developed including the people as more participatory elements in the system and the city, turning them into crowd sensors. Ganti and colleagues (Ganti et al., 2011), for instance, present only the general functioning of Mobile Crowdsensing (MCS), although their main purpose is not focused on software architecture. However, Guo et al (Guo et al., 2014) propose different layers of architectures such as data collection, transmission, and processing, but do not give details on concrete architectures or how to implement that. Cardone and colleagues (Cardone et al., 2014a) bring one of the MCS architectures that get into more detail, illustrating what component platform to use but without concrete examples on which components to use.

### 2.2 Crowdsensed Data Analysis

As pointed out by Erickson (Erickson, 2010), humans can contribute to deeper qualitative knowledge, analyze vague or incomplete data and act in a way that digital systems are often not capable. Mobile Crowdsensing (MCS) (Ganti et al., 2011), in turn, refers to community sensing (*e.g.* by people) for data collection, in which people act as sensors (*crowd sensors*).

Sherchan (Sherchan et al., 2012) considers two categories of crowdsensing: personal and community sensing. The former refers to the processing of data from a single individual to benefit this same individual with the result of processing of the data which it has issued. In the case of community sensing (Ganti et al., 2011) there are two distinct types of models: opportunistic sensing, which requires minimal user involvement (*e.g.* *automatic geolocation through*

*GPS*), and participatory sensing, which requires the active participation and direct provider of user data.

A major point in collecting that information in real-time is how to generate application-level meaningful events based on the collected data. Many projects combine MCS and EDA (Event-driven Architecture). In Etzion e Niblett (Etzion and Niblett, 2010), EDA is an architectural style in which one or more software components responsive to receiving one or more notification events. Complex Event Processing (*CEP*) (Buchmann and Koldehofe, 2009) is one of the possible strategies for achieving EDA in distributed systems. It helps to build scalable and dynamic systems, allowing to analyze data (*e.g.* *correlation, filtering, aggregation*) in real-time.

### 2.3 Application Domain

One of the widely accepted visions of smart cities, provided by Caragliu (Caragliu et al., 2011), mentions different axes in smart cities (smart economy; smart mobility; a smart environment, smart people, smart living and smart governance). There is an evident relationship between smart living and smart mobility there is a continuous growth of infrastructure, programs and policy interventions to promote bicycling throughout the world (Pucher et al., 2010).

In the context of the work presented here, we are motivated by a mobile application can help cyclists on their daily trips. Although most applications in that context are typically focused on route planning (Gavin et al., 2011), our proposition is focused on reporting users about dangerous spots on their route, while they are moving. These places (*e.g.*, accidents, robbery, intense traffic) are reported collaboratively by the application users.

## 3 REFERENCE ARCHITECTURE

In the face of middleware solutions for smart cities currently most commonly proposed, some characteristics were taken into account in building our architecture, to be treated in the most common form different approaches. As an example, we can mention the sensor connection usage using message queue services for the integration of data sources of the asynchronous and synchronous way using RESTful web services, complex event processing for analysis of streams of data in real-time and using human sensors through Crowdsensing systems. To do this, we organized the platform into components that can be easily found as free off-the-shelves components, aiming to facilitate and to simplify the implementation. The role of each

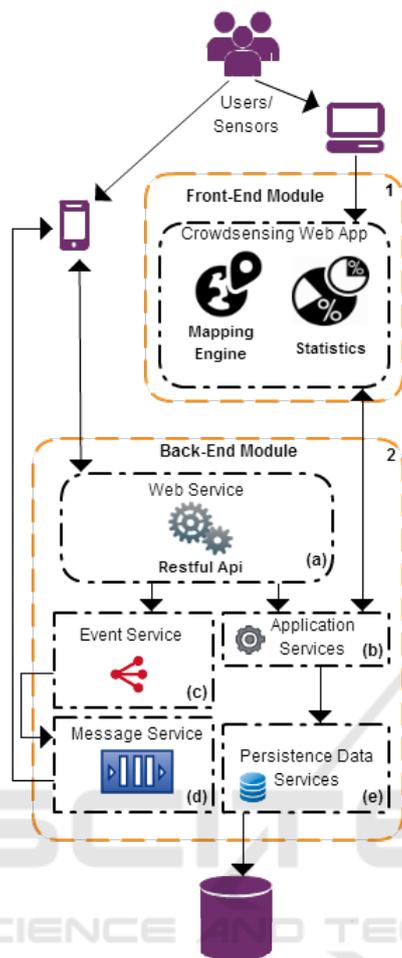


Figure 1: Reference Architecture for Mobile Crowdsensing.

component will be presented later in the description of the platform architecture, which is built based on these characteristics.

The platform architectural design is described in two service modules: Front-End Module and Back-End Module, as shown in Figure 1. In the Front End Module (Figure 1 (1)), is the crowdsensing system that can either be Web or Mobile. The Back-End module (Figure 1 (2)) contains the RESTful API services (Figure 1 (2.a)). It is responsible for coordinating access to synchronous services of Request/Response and event processing service (Figure 1 (2.c)). That, in turn, accesses the services of the asynchronous messaging service module in the model Publish/Subscribe (Figure 1 (2.d)). Thus providing the transmission of real-time data and signaling the connected clients, which allows establishing and maintaining connections via socket and service interfaces allowing any device to send and receive data to be processed and redistributed. This data is controlled by the Services Manager of the application,

(Figure 1 (2.b)), which accesses through the persistence service, the data persisted in the database (Figure 1 (2.e)).

The platform has two data entry services that can be provided through crowdsensing system on the Front-End module or the Web Service API in Back-End Module.

## 4 IMPLEMENTATION

The system described here details a Crowdsensing approach, which has a Google Maps service, which allows users in the form of human sensors view occurrences of points on the map with bookmarks, graphs with statistics and the table with the detailed list occurrences of data. The proposed platform, the application of crowdsensing is parameterized for various domains offering the opportunity to create custom bookmark this, such as the map described in Figure 2, with urban mobility domain data describing points of traffic accidents involving bicycles.

### 4.1 Front-end Module

The front-end module is comprised of two applications: a Web Application and an Android Mobile Application. The Web Application has a dashboard with charts and statistics showing the total occurrences, a pie chart format showing statistics for each type of occurrence, and the list of events in a tabular format, in addition to being can also report accidents as we can see in Figure 2.

The Android application developed with the intention of consuming platform data and present context-aware information. The application has a cyclist profile with two basic features provided through the Web Services Module data consumption. One such service is the Crowdsensing Alert, where the application sends its current GPS position and receives the information of the distance between the cyclist and the accident points registered by the Crowdsensing system, alerting to the cyclist that he is close to an accident point and the other report problems with cyclists by crowdsensing information with markers on the map. A second profile is the Driver Profile that has a service to the CEP Alert, which in real-time can be identified the nearest user who is using the application in motor-vehicle mode, and be alerted to be more careful, avoiding possible accidents with cyclists. CEP allowed us to employ the concept of geofencing, which is the capability of detecting user proximity to a given geolocation (Cardone et al., 2014b).

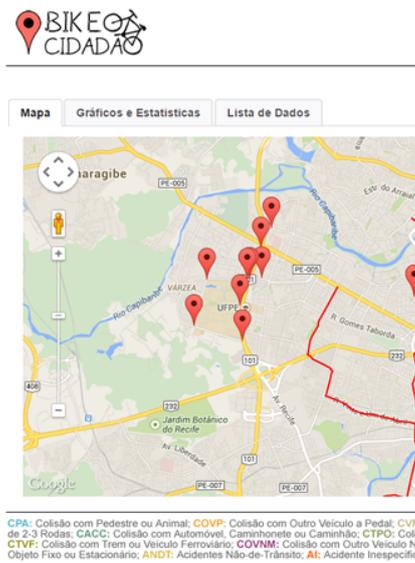


Figure 2: Web view of the example crowdsensing system.

## 4.2 Back-end Module

The Web services model, shown in Figure 3, provides data services in real-time via synchronous and asynchronous requests. Synchronous requests are made through a RESTful web service using the JSON format for data transmission. The requests are made through the client data send requesting services provided by the Web Service via POST/GET that, in turn, requests data persistence layer through configurable functions. For example, there is a location service returning the type of occurrence and the distance between a point latitude and longitude sent from a client and the location of the nearest occurrence, point persisted by the user through the Crowdsensing service.

As the requests come in, events are registered in the FLOSS/COTS Esper CEP engine and alerts are triggered for queues in the event processing service the asynchronous model to be consumed by customers. Thus, this model uses the Message Queue service, to capture the CEP alert triggered asynchronously, by capturing events and processing rules, and provides services through the Restlet framework, processing occurrences stored in the data layer.

The Web Services module provides location services that can be parameterized by the functions and customizations of CEP tool of rules, as well as allowing the user to create new rules to be provided through the FLOSS/COTS component RabbitMQ queuing system service, the asynchronous model. A rule of this model (illustrated by Listing 4.2) A rule of this model is parameterized location, that allows trigger alerts with distance, in real-time, the last two loca-

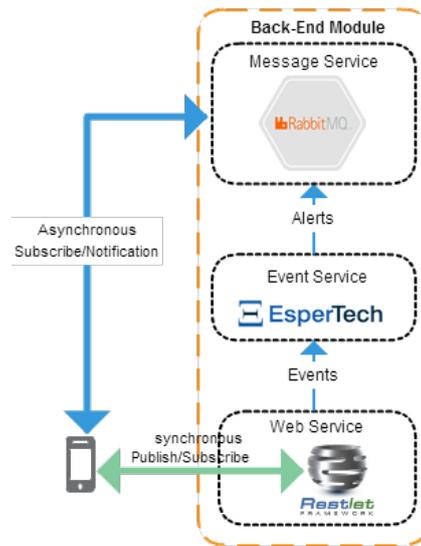


Figure 3: The Service Layer Model.

tion requests latitude and longitude points sent via the REST service and inserted them in the message queue to be consumed by registered users.

```
SELECT 6378137 * Math.sqrt (
  Math.pow ( (Math.toRadians (cast (Vehicle.lat,
double)) - Math.toRadians (cast (
BikePosition.lat, double))), 2) +
  Math.pow ( (Math.toRadians (cast (Vehicle.
lng, double)) - Math.toRadians (cast (
BikePosition.lng, double))), 2))
AS distance, bikePosition.imei,
bikePosition.lat, bikePosition.lng,
Vehicle.imei, Vehicle.lat, Vehicle.lng
FROM BikePosition.win:length(1)
AS bikePosition, Vehicle
ORDER BY distance ASC LIMIT 1
```

## 5 TEST ENVIRONMENT

This section discusses the materials and methods used for proof of concept of the proposed platform. For test running, we used two computers, whose configuration is described in Table 1.

Table 1: Setup of the machines used in the experiment.

-	CPU	Clock	RAM
M.USER	2410M	2,3GHz	DDR3 8GB
M.SERVER	M380	2,53GHz	DDR3 4GB

The computer named M.USER was used to simulate users and send status and requests to the platform. The simulation of the requests was held in M.USER using the performance testing tool JMeter v. 2.9. The computer named M.SERVER was the one who hosted

the platform, received and processed requests from M.USER. Altogether there were two tests. The first test (hereafter referred to as T1) simulated only requests where users were no more points by accident, previously registered by Crowdsensing service. In the second test (hereafter referred to as T2) in all requests, users were in danger route, according to Crowdsensing service, and were in collision zone with another user. Section 6 will describe the result of each test.

We considered the nature of real-time data transferred by the platform and the need to keep up the geographic location of users. In the configuration of virtual users in JMeter the following parameters defined: Threads = 1000, Ramp-up = 2 and LoopCount = forever. So every 2 seconds 1000 virtual users send requests to the platform. In each test in JMeter measure platform performance receiving simultaneous requests from the 1000 virtual users for 15 minutes. The performance monitored for the following metrics: Times Over Time, Transactions per Second, Response Times Percentiles, Time Graph. Requests of virtual users were GET type and configured with the following parameters: Connect Timeout = 10000 (ms), Response Timeout = 10000 (ms). The connection Path for submission of requests follows the following format: /project/rest/trace/[queue id]/[latitude]/[longitude]/, for example: /project/rest/trace/[queue id]/[latitude]/[longitude]/, for example: /project/rest/trace/54321/-8.05529673777147/-34.951613545417786/.

Moreover, in M.SERVER a setting has been made to deal with the large number of requests from virtual users and reduce the cost for opening connections. Through the library C3PO of Hibernate was set up a pool of 1000 connections.

## 6 TEST RESULTS

In this section the results of the two tests are consolidated. As presented before, the T1 test has simulated a total of 1000 users sending their status to the server and waiting for an answer on the status of the current route. In this test, 100% of the users were in a secure route, i.e., they did not have the Crowd-Sensing service notifications. Therefore, no event was triggered by the CEP service, and no message was added to the user's message queue in RabbitMQ. On the other hand, the T2 test 100% of users were on a route that had any notification by CrowdSensing service. Thus, each request, a CEP event was triggered, and a message was added to the user's message queue with the description of the accident just ahead.

Thus, the T1 test has synchronous feature exclusively. In this test through a RESTful web service provided by the platform the user sends your geographic coordinates and only expects a JSON document with the distance and characteristics of your nearest accident. In fact, no users in this test were in danger route. The T2 test, in turn, has synchronous and asynchronous features. In the synchronous connection test T1, T2 test calculates the distance of the rider about the closest vehicle. In the case both are below a tolerable distance the event service fired alerts in the messages queues of the cyclist and automobile. Thus, both kept an asynchronous connection to the platform to be notified of the proximity of another user.

### 6.1 Response Time

The aim of this metric was to check the average time to respond to a request delay to get to the virtual user. That is the time that starts when the request is sent to the server and ended when the response is completely received by the client. In JMeter is represented by the metric Times Over Time and Time Graph. As expected, the overall response time T2 is greater than time T1. As illustrated in Figure 4, the average response time for T1 was 3708,58 ms and 4660,02 ms for T2. Indeed, having 30 random samples of size 100, with the replacement of the measured response times, and considering a level of 95% confidence level, has an average range of 3604.47ms the 3840.0ms response to the T1 test and 4509.861ms 4627.493ms for the T2 test.

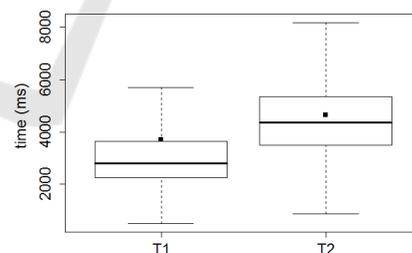


Figure 4: Distribution of response times. Given the variation presented in measurements of time, their representation was better detailed in a chart in the box. The black line, by default, represents the median and the black square represents the average.

In contrast to T1, in T2 for the time dedicated the execution of complex event processing module and notifications in asynchronous connections with RabbitMQ. Through the medium listed above, we can calculate the time spent on these tasks is an average of 951,44 ms. That is, this is the average time the platform takes to receive a stream of geographic coordinates, to calculate the distance from that for the

points of accidents, to verify whether this point is in a danger zone, and finally trigger notifications in messaging queue of RabbitMQ. To better understand the response time, Figure 5 shows the percentile of response times of each test. It can be seen that the average response time T1 is in the 79,0% percentile. That is, 79,0% of the requests have a time less than or equal to the average. Likewise, the average response time T2 is on the 68,8% percentile (Figure 5), given by the metric Response Times Percentiles.

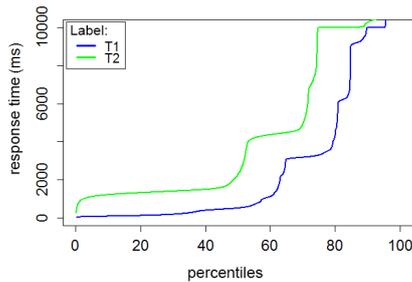


Figure 5: Percentile response time. The percentile values increasingly ordering the sample in 100 parties. Thus, the n-th percentile is the first n% of the sample values.

### 6.2 Success and Fail Rate

The aim of this metric was to demonstrate the success of behavior and failure in requests in T1 and T2 test. As mentioned in Section 5, the JMeter requests were configured with parameters Connect Timeout = 10000 (ms) e Response Timeout = 10000 (ms). That is, if a connection delay more than ten seconds to open or if the delayed request more than ten seconds to be answered, this request was considered failure. In JMeter is represented by the metric Transactions per Second.

Looking at Figure 6, it can be noted that T1 for the test there was an average of 313,31 requests per second successfully processed and 21.02 requests per second failure. As for the T2 test, there was an average of 189.14 requests per second completed successfully and 32.53 requests per second failure. Indeed, as in Section 6, having 30 samples of size 100 of the measured response times and considering a 95% confidence level, has an average range of 306,78 to 317,32 successful requests per second in the T1 test and 186,93 to 191,29 to test T2. As for the failures, the confidence intervals are 19.77 to 21:34 failures requests at test T1 and 31.22 to 33.28 for T2's failures.

In the T2 test, for each request successfully answered, two messages were sent to RabbitMQ, one for the message queue of the cyclist and the other on automobile message queue the RabbitMQ control panel and monitor in real-time the activities of the Message Queue service was accessed through the

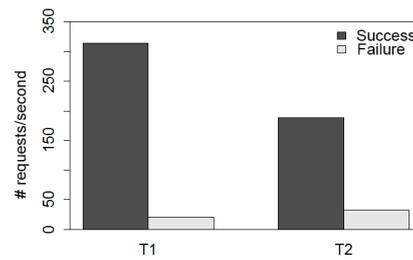


Figure 6: Success rate and failure in requests. The dark bars represent the successful conclusion requests. The light bars represent the failures requests.

server address localhost:15672/#/, you can find. In all they sent 350,307 messages to the RabbitMQ, corresponding to an average of 389.23 messages per second (see Figure 7). In fact, this rate is almost double the amount of completed requests in T2.



Figure 7: Rate messages published in RabbitMQ queue per second. The period illustrated corresponds to the last ten minutes of test.

## 7 RESULTS AND DISCUSSIONS

As illustrated in Section 6, considering a total of 1000 simultaneous requests the platform had an average time of 3708,58 ms response for the safe route (test T1) and an average of 4660,02 ms for proximity notification with other users (test T2). Since, for T1, 79% of the requests have a time less than or equal to T2 and the average, 68,9%. An average of 334.33 requests per second to T1, only 6,28% of them were not completed, and for an average of 221.67 requests per second in T2, 14,67% were failures requests.

On a comparison of results obtained with real demand requests, the BikePE project (BikePE, 2015), from Recife, Brazil, was used as a parameter. In this bike sharing initiative, 800 bikes are available for rent at 80 stations around the metropolitan area of Recife. According to that source, from Monday through Friday there is an average demand of 1100 trips. That is, although different contexts of applicability, and considering the performance data provided by the platform, it can be seen that using only a computer with domestic settings would be enough to meet such demand using the solution proposed in this paper. Moreover, in case there are a greater demand requests, the platform may be instantiated on different machines, then offering the possibility of horizontal scale. So,

to meet an ever increasing demand, it is not necessary to improve the machine's hardware hosting platform. Indeed, platform instances can be replicated on multiple machines with traditional settings and thus obtain a higher scale at a lower cost.

As threats to validity, a 3G data network for communication between virtual users and the platform has been the fact of not having been used. However, as the tests had the purpose of proving the possibility of development platform, it was not necessary to network latency test, for example. Thus, he preferred to opt for simulation in a local wireless network.

## 8 RELATED WORK

This section presents a non-exhaustive list of platforms employing similar approaches to ours and a brief comparison with our proposal.

SOFIA (Filipponi et al., 2010) is a semantic interoperability platform between a selected set of applications and an ecosystem of interactive objects such as sensors, actuators, and other embedded systems. Their goal is to provide features for the building of intelligent environments. The project addresses three application areas representing different types of space in terms of scale, applications and services: intelligent personal spaces (e.g. cars), smart indoor spaces (e.g. home and office), and intelligent city spaces (e.g. expanded infrastructure and facilities such as a subway station, shopping and the like).

Traffic Info (Farkas et al., 2014) is an application based on crowdsensing that views public transport information of the city in a map in real-time. It is built using publish/subscribe model to communicate passenger who subscribed in the Traffic Info, according to their interest, for the traffic information channels dedicated to different public transport lines or stops. They are informed live about the situation of public transport, such as the actual position of the vehicles. When passengers gather the real-time data, information is updated in a map to reflect the traffic situation.

CrowdOut (Aubry et al., 2014) is also a mobile crowd sensing service for smart cities, which allows users to report road safety problems that they experience in their urban environment (speeding, illegally parked cars, traffic signs and symbols, quality roads and traffic levels) and share this information with your community. A user can specify the type of crime, take a picture with your smartphone and add it to the report to present it; it can also add a short comment to describe the infraction more precisely. The service also registers the GPS coordinates of the users, to indicate the precise location of the offense occurred on

the road so they can be shown on a map in real-time.

Choi & Kang (Choi and Kang, 2014) propose a platform on top of a mobile application developed in HTML5, with location-based services (LBS) making use of GPS, to find points of interest. As a result, we present a case of a mobile tool to aid foreigners and Koreans in a complicated process of registration purchase and alienation of real estate in South Korea.

By analyzing these solutions, our solution differs from SOFIA platform because it has a narrower scope, aiming to offer the crowdsensing services. In contrast, SOFIA addresses presented by the various areas of applications. Nevertheless, we propose the domain configuration, contrasting this aspect with TrackInfo platforms and the proposal presented by Choi & Kang. The CrowdOut platform contrasts to ours not having information resource alerts triggered by complex event processing.

## 9 CONCLUSION

This paper presents the proposal and validation of a architecture for a mobile crowdsensing platform that takes advantage of free software and off-the-shelves components. It meets and implements an effective and simplified way a middleware platform for Smart Cities solution. Among its features include: configurable for multiple domains, Complex Event Processing use for analysis of real-time data streams, integration of data using RESTful services, message queue and the utilization of human sensors (crowd sensors).

From the analysis results, we can conclude that the platform behaved satisfactorily in the tests since supported a load of similar requests the real demands, considering the machine that hosted the platform had the typical configuration a home computer. Finally, this study proves the concept that you can build a middleware platform for smart cities, based on location, using complex event processing, configurable for multiple domains and capable of processing rules developed by the users.

Currently, a similar architecture to the one that is described in this paper is being developed, using Storm as the main component, which is a distributed computing system in real-time. We intend to make experiments using the same conditions already carried out in this paper so that in future work we can make comparisons between the results obtained with the two architectural approaches.

## ACKNOWLEDGEMENTS

This work was partially funded by the National Counsel of Technological and Scientific Development (CNPq Universal grant #485420/2013), the National Institute of Science and Technology for Software Engineering (INES - CNPq grant #573964/2008-4) and the Foundation for Science and Technology of Pernambuco (FACEPE).

## REFERENCES

- Al-Hader, M., Rodzi, A., Sharif, A. R., and Ahmad, N. (2009). Smart city components architecture. In *Computational Intelligence, Modelling and Simulation, 2009. CSSim'09. International Conference on*, pages 93–97. IEEE.
- Aubry, E., Silverston, T., Lahmadi, A., and Festor, O. (2014). Crowdout: A mobile crowdsourcing service for road safety in digital cities. In *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2014 IEEE International Conference on*, pages 86–91. IEEE.
- BikePE (2015). Bikepe. <http://www.bikepe.com/>. Accessed in 2015-10-01.
- Buchmann, A. and Koldehofe, B. (2009). Complex event processing. *it-Information Technology Methoden und innovative Anwendungen der Informatik und Informationstechnik*, 51(5):241–242.
- Caragliu, A., Del Bo, C., and Nijkamp, P. (2011). Smart cities in europe. *Journal of urban technology*, 18(2):65–82.
- Cardone, G., Cirri, A., Corradi, A., and Foschini, L. (2014a). The participact mobile crowd sensing living lab: The testbed for smart cities. *Communications Magazine, IEEE*, 52(10):78–85.
- Cardone, G., Cirri, A., Corradi, A., Foschini, L., Ianniello, R., and Montanari, R. (2014b). Crowdsensing in urban areas for city-scale mass gathering management: Geofencing and activity recognition. *Sensors Journal, IEEE*, 14(12):4185–4195.
- Choi, M. and Kang, B.-T. (2014). Html5 platform independent mobile application using location-based service. *Life Science Journal*, 11(7).
- Hourabi, H., Nam, T., Walker, S., Gil-Garcia, J. R., Mellouli, S., Nahon, K., Pardo, T., Scholl, H. J., et al. (2012). Understanding smart cities: An integrative framework. In *System Science (HICSS), 2012 45th Hawaii International Conference on*, pages 2289–2297. IEEE.
- da Silva, W. M., Alvaro, A., Tomas, G. H., Afonso, R. A., Dias, K. L., and Garcia, V. C. (2013). Smart cities software architectures: a survey. In *Proceedings of the 28th Annual ACM Symposium on Applied Computing*, pages 1722–1727. ACM.
- Erickson, T. (2010). Geocentric crowdsourcing and smarter cities: Enabling urban intelligence in cities and regions. In *1st Ubiquitous Crowdsourcing Workshop at UbiComp*.
- Etzion, O. and Niblett, P. (2010). *Event Processing in Action*. Manning Publications Co., Greenwich, CT, USA, 1st edition.
- Farkas, K., Nagy, A. Z., Tomás, T., and Szabo, R. (2014). Participatory sensing based real-time public transport information service. In *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2014 IEEE International Conference on*, pages 141–144. IEEE.
- Filipponi, L., Vitaletti, A., Landi, G., Memeo, V., Laura, G., and Pucci, P. (2010). Smart city: An event driven architecture for monitoring public spaces with heterogeneous sensors. In *Sensor Technologies and Applications (SENSORCOMM), 2010 Fourth International Conference on*, pages 281–286. IEEE.
- Ganti, R. K., Ye, F., and Lei, H. (2011). Mobile crowdsensing: current state and future challenges. *Communications Magazine, IEEE*, 49(11):32–39.
- Gasperoni, F. (2006). Floss, cots, and safety: A business perspective. *3rd European Congress ERTS – Embedded Real Time Software*.
- Gavin, M., Ghosh, B., Pakrashi, V., Barton, J., O’Flynn, B., and Lawson, A. (2011). A cycle route planner mobile-app for dublin city. In *Irish Transportation Research Network Conference (ITRN2011), 31 Aug-1 Sep 2011, University College Cork, Cork, Ireland*. Irish Transportation Research Network.
- Guo, B., Yu, Z., Zhou, X., and Zhang, D. (2014). From participatory sensing to mobile crowd sensing. In *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2014 IEEE International Conference on*, pages 593–598. IEEE.
- Nagel, T., Maitan, M., Duval, E., Moere, A. V., Klerkx, J., Kloeckl, K., and Ratti, C. (2014). Touching transport—a case study on visualizing metropolitan public transit on interactive tabletops. In *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces*, pages 281–288. ACM.
- Naphade, M., Banavar, G., Harrison, C., Paraszczak, J., and Morris, R. (2011). Smarter cities and their innovation challenges. *Computer*, 44(6):32–39.
- Odendaal, N. (2003). Information and communication technology and local governance: understanding the difference between cities in developed and emerging economies. *Computers, Environment and Urban Systems*, 27(6):585–607.
- Pucher, J., Dill, J., and Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: an international review. *Preventive medicine*, 50:S106–S125.
- Sherchan, W., Jayaraman, P. P., Krishnaswamy, S., Zaslavsky, A., Loke, S., and Sinha, A. (2012). Using on-the-move mining for mobile crowdsensing. In *Mobile Data Management (MDM), 2012 IEEE 13th International Conference on*, pages 115–124. IEEE.