Architecture for smart highway real time monitoring

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***Abstract*—When we talk about smart cities, one of the key pillars is a smart management of traffic and transport infrastructure. In this paper, we propose an architecture to support highway monitoring in smart cities. Starting from a project to reduce cost of maintenance tasks in highways, we develop a comprehensive architecture for effectively monitor and manage future highways. Highway's security fence monitoring, environmental pollution, frozen asphalt warning, real-time accident detection, adapting speed limits to weather conditions, are examples of applications of our architecture.**

***Keywords*-Smart Cities, Real Time Monitoring, Smart Highway, Wireless Sensor Network, Intelligent Transport Systems.**

I. Introduction

Currently, the mesh of highways is a key infrastructure of modern societies. All days, we use these highways to transport user/goods enabling our lifestyle. This type of infrastructure, together with new vehicles with capacity of connection with the infrastructure should be a reality for an efficient and safe use of future highway. The introduction of the information technologies in the real-time monitoring of highways will enable to reduce maintain costs and to increase the security as we will see later. Enhancing mobility and transport is one of the key pillars in the smart cities [1].

For example, if we can monitor the temperature every hundred meters of a highway, that fact enable us to prevent frozen asphalt and we could spread salt only where and when it is necessary. With that information we could reduce cost either, reducing the amount of salt to be spread and conserving better the asphalt since this is eroded by salt. Also security can be enhanced reducing the speed limit according to the state of the asphalt by mean dynamic information showed in informative panels.

In this paper we present an architecture for real-time highway monitoring including network topology design, middleware and an example of monitoring tool. We are going to analize how to deploy a Wireless Sensor Network (WSN) in the highway as monitoring infrastructure. Over this WSN we design three software layers which provides a scalable and efficient platform for smart services about traffic control, highway's maintenence tasks , security concerns, etc.

The rest of the paper is structured as follows. Section II describes problem statement and some previous works. Section III introduces the proposed architecture including network topology considerations, sensor type, alternatives, etc. and also describing the software architecture designed. Section IV describes the prototype making emphasis in security wire fence monitoring which is the main motivation of this work. Finally, in Section V, we will draw some conclusions and discuss possible future work.

II. Problem statement and previous works

The current highway's structure is generally composed by two roads with two lanes in each direction, according with European Union law, the roads have to be protected by a security wire fence in both sides of the two asphalt roads to avoid intrusions in the asphalt. Also is common to find informative panels informing to drivers about weather's state, asphalt's state, accidents, traffic conditions,etc.

For security reasons, it is important to keep that wire fence in a good state, for example, if the fence falls and a wild animal invades the asphalt, it could originate an accident. According some European state members law, it is mandatory to check that security wire fence, at least one time every 24 hours. if we can monitor that security fence in automatic and real-time way, we would increase security and, at same time, we would reduce maintenance costs.

This is the main aim of our project, that is, monitor the state of the security fence. However, we are more ambitious and we want to monitor other useful parameters to support more advanced services. According to the domain experts, the most interesting environmental parameters to be monitored are:

- State of the perimeter fence
- Temperature and humidity
- Number and type of traffic
- Pollution monitoring
- Analysis of noise
- Average velocity of traffic

The infrastructure that we are developing is useful for the rest of parameters but we are going to focus this paper in the state of the security fence. As we will see later, we are deploying WSN nodes attached to the fence's posts and to equipped with accelerometeres. Precissely, from networking point of view, this point it is the most restrictive service due to accelerometers' sensibility . As we will show in prototype section, these type of sensors have to be deployed every 85-120 meters in the wire fence to detecting singular events and, to reduce infrastructure costs, we will take advantage of these nodes for also deploy other type of sensors.

In order to allow an incremental deploy, we structure our architecture with the following design principles:

- Each highway is divided into stretches, a stretch of a highway is defined as the portion of the highway between two consecutive exits and the length of a stretch can range from few hundred meters close to cities to ten-twenty kilometers in country areas. Traditionally, several consecutive stretches can be managed by a unique maintenance company but also is usual to have several stretches of a highway managed by different maintenance companies.
- The state of the perimeter fence will be monitored with WSN nodes deployed in fence's posts with accelerometers. The accelerometers mounted on fence's posts to detect frequency disturbances associated with wind, fence fall , impacts, etc.

Other works deal with security fence monitoring focusing in what type of events can identify from accelerometers information. In [2] the security fence of a building is monitored deploying a WSN node every 3.5m, which is unrealistic in our application target. In this work they deal with security fences in buildings where the deployment of nodes can be more dense. From our point of view, we are only interested in events that can affect to traffic security that is, fence fall, strong wind conditions, jumping attempts, etc but we also focus on extending WSN lifetime.

There are other approaches, for example in [3] proposes an OpenCV based system to build a smart camera which it detects abnormal situations. This type of system could be useful in specific points but can not be used for monitoring environmental parameters and it can not be extended to the whole highway network at a reasonable cost.

Precisely, due to cost reasons, we plan to deploy a WSN infrastructure to support different type of sensors to provide this infrastructure as a service to smart management and control services. In [4], Ghosh and Rao study how deploying sensor in highways from a theoretical point of view, attending to the topography of the highway they estimates the optimal position of the WSN nodes for communication purposes. Other approaches also use a WSN in highways mainly for collecting information from vehicles into a unique database [5] . Another example is [6], where a platform for traffic management is designed, it involves vehicle-to-infrastructure management and again, the nodes in the infrastructure are used only for communication purposes. It could be desirable to have real-time vehicle information and the automotive industry researches on systems for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) is a hot topic. However, we are still far away from a consensus on standards, protocols and technology to be used in such systems.

Figure 1. Example of network topology

As conclusion, we have to take a comprehensive approach covering the full application stack and, from an engineering point of view and by now, without considering to involve automotive industry.

III. Highway real-time monitoring

Our proposed solution has two main parts, firstly we have to analyze the WSN topology considerations in order to study the viability of this type of deployment, then, we design a software architecture for information dissemination and management.

A. Network topology considerations

One of the main risks for project viability is amount of WSN nodes to be deployed and its heterogeneity. A typical deployment is shown in figure 1, nodes with accelerometers are deployed in the highway fence to both sides of the asphalt. Using accelerometers enable us detecting since wind conditions to fence anomalies as impacts. In the picture 3 we can see a node installed in a fence post in one of the test of the architecture.

In the figure 1, the red circles represent nodes with accelerometers meanwhile the blue circle represents a gateway with an interface to a Wide Area Network (in function of the availability, this technology can be ADSL, UMTS, GPRS, etc.). According to our experiments and for the real-time fence monitoring, the distance between nodes can range from 80 to 120 meters according to the type of wire fence, the type of fence posts, type of ground, etc.

Each node can have another sensors as temperature sensor, humidity, pollution, etc. Ideally, the wireless interface of a node is sleeping and, periodically, it wakes up and it sends its data to the gateway which it collects information of all nodes in order to disseminate the information to the rest of architecture as we will see later. We have evaluated also install a wake-up mechanism in WSN each node in order to collect all data one time per day from the maintenance company's car which has to pass periodically for the highway. By contract, it is mandatory to highway maintenance companies to check, at least one time per day, all the stretches of the highways under its supervision. In spite that, from an engineering point of view and according to experts in this domain could be a good solution, we discard this option since it is not a real-time monitoring and limit the type of applications that our architecture could support. Normally, the gateway node is a little more powerful that the sensor nodes and it is attached to an inexhaustible source of energy (power line, solar energy, etc.)

Energy is one of the main issues in this type of deployment, according to currently deployed infrastructure and in opinion of experts, we can assume:

- In stretches of highways close to the cities is normal to have several points where nodes (mainly gateways) can be attached to power line (streetlight, informative panels, etc.). So we can assume that we could deploy several gateways for a unique stretch in order to be fault tolerant and has a direct line of sight with most of the WSN nodes deployed.
- In stretches of highways in the rural areas, we can assume that at least one point of solar powered batteries or connection to a power line can be used.

The heterogeneity of topology and different scenarios made us think that we will have to study each stretch in order to draw up a plan for WSN node deployment and the gateway/s emplacement. Our intention is to work in 802.15.4 868/915 MHz ISM band and avoid multihop scenarios to keep sleeping the nodes most of the time in order to extend the lifetime of the WSN network.

B. Architecture

In figure 2, we can see a global overview of the architecture, according to the requirements we divide the architecture in three layers.

1) Event layer: This layer has the responsibility of guide raw events from sensors to the management architecture, we identify two types of sensors generating events:

- Environmental sensors: with this type of sensors we use, as event management protocol, MQTT-S [7]. MQTT-S is a machine-to-machine (M2M)/"Internet of Things" connectivity protocol. It was designed as an extremely lightweight publish/subscribe messaging transport so covers a key requirement of our architecture, a common framework for getting information from deployed WSN sensors. This event layer is deployed directly in physical WSN nodes with sensors and in the gateways.
- Multimedia sensors (Cameras and Microphones). This type of sensors are devoted to identify anomaly situations by means of analyzing multimedia streaming.

Encapsulated in MQTT-S, we have designed an application protocol which it has a fixed header of 64 bits where the first 8 bits are for version, next 8 bits are for type of event, next 16 bits are for node ID and the last 32 bits are for time-stamp. According to the type of event, the rest of the packet has one information or another. For example, if the event type is accelerometer's information, next to the fixed header, the WSN node inserts X, Y and Z axis variability using 16 bits each. There is a type of event for each type of sensor, together with "alive" messages and configuration messages to notify the type of WSN node and its configuration (sensors available, Node ID, etc.).

This application protocol is designed for 802.15.4 so we deal with its limitations, starting from a maximum physical layer packet size of 127 octets and a maximum frame overhead of 25, the resultant maximum frame size at the media access control layer is 102 octets. So we have 102 octets for MQTT-S header plus application protocol.

MQTT-S uses two bytes as a fixed header and a variable lenght header depending on the type of message. In our case, the *publish* message, the most usual packet, it will have four bytes including the topic name where the information has to be published. As conclusion, the most usual packet, a publish message with accelerometers data has 18 bytes of information including MQTT-S header.

With this size, we have space for additional information, for example, regarding to security concerns. For example, we could use AES-CCM-128 algorithm (21 octets of overhead), which is an authenticated encryption algorithm designed to provide both authentication and confidentiality.

2) Management layer: This layer processes raw data from sensors in making high-level information according to defined algorithms from clients. This layer is based in a object-oriented distributed middleware which to enable us to represent each highway stretch in a distributed object formed by virtual sensors (associated to the physical sensor currently deployed in the highway). The use of the object-oriented distributed middleware give us a set of services very useful for a massive and reliable deployment as, for example, replication, security, AAA services, software deployment, software updates, etc. This layer is deployed since Gateways in each highway stretch to each computer in clients of the platform (public services, companies, etc.).

The wireless sensor network deployed in each stretch will feed a rule based system installed in the gateway that dynamically adapt the information showed in informative panels in that stretch (reducing speed limit, warning to drivers about environmental conditions, etc.). This simple rules extracted from expert knowledge are specific of each stretch according to its conditions and topology. We expect to make autonomous each one of the stretches of the highways.

3) Presentation layer: The presentation layer provides information to final users (Police office, fire station, hospital, companies, etc.) according to their needs and to their permissions. As we will see later, our first prototype of the

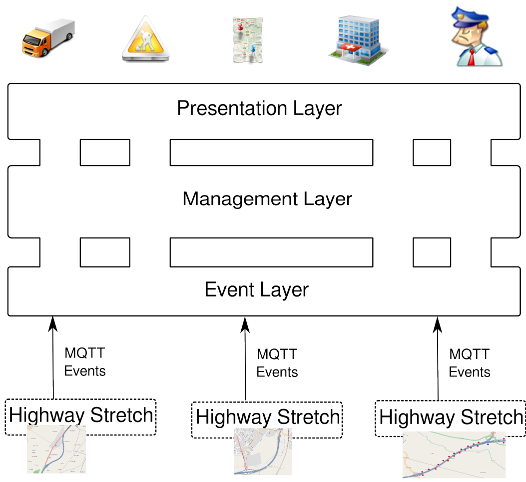

Figure 2. Architecture Overview

presentation layer is an OpenStreetMap project [8] based Geographical Information System (G.I.S) where incidents are reported in real-time.

As design guideline, the distributed objects of presentation layer have to register itself in the management layer, specifically, in distributed objects representing stretches of the highways, in order to receive information updates and events.

IV. Prototype

First prototype is being developed in one of the stretches of highway managed by the company AUDECA. We are monitoring the security fence, together with temperature and environmental pollution. We can show here preliminary results related with monitoring the security fence. We deployed several IRIS nodes from Crossbow [9] attached to fence's post as we can see in figure 3 (red point) in order to see which type of events can identify. The IRIS node is equipped with the MTS310 sensor board including:

- Dual-Axis Accelerometers: the propagation of impacts and the sensibility of this sensor establishes the distance between nodes. Meanwhile the rest of sensors can be deployed in two or three nodes by each highway stretch, the key requirement of monitor the highway fence obligate us to deploy a WSN node every 80-120 meters as we will see later.
- Temperature sensor: In order to monitor when the temperature low of zero degrees to determine the risk of freeze asphalt and to take an appropriate decision, for example, to reduce speed limit, to spread salt in the asphalt, etc.
- Acoustic sensors: we will investigate the viability of making audio streaming to get cognitive events from that audio streaming analysis. Some events we thought we would identify could be amount and type of vehicles, the sound produced by an accident, etc.

Figure 3. Node deployed in the security fence

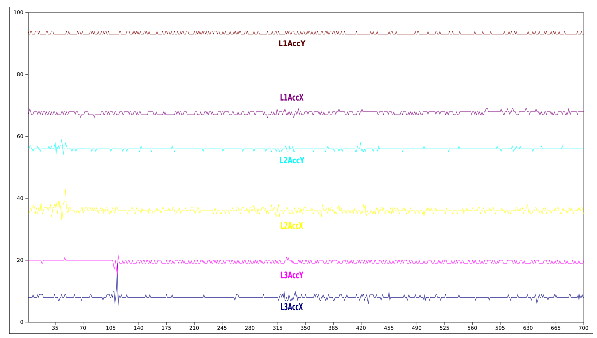

Figure 4. Wind vibration detected by accelerometers

In sensor layer we have implemented an MQTT-S module for TinyOS [10] operating system in order to collect all information from sensors to the gateways. As far as we know, this is the first implementation and application of MQTT-S protocol in this operating system. Using this MQTT-S module, we get information periodically from accelerometers, temperature sensors, etc. One of our aim of this prototype is to identifies the sensibility of the accelerometers according to the type of highway fence.

In figure 4 we can see the wind vibration detected by three WSN nodes deployed in different fence posts (X-Y coordinates from its accelerometeres), as we can see, we easily can identify this wind vibration from impacts in the fence (showed in figure 5). Also wind information can be used in traffic management in order to reduce speed limits when the velocity of wind is higher than in a specific threshold.

In figure 5 we can see the experiment devoted to identify the required distance between nodes according to accelerometers' sensibility, we deploy a single sensor in a fence post and we produce two impacts in each fence stretch. In picture 3 we can see (left of red circle) the WSN node installed in the fence's post. We were moving away from sensor node emplacement reproducing the impact two times

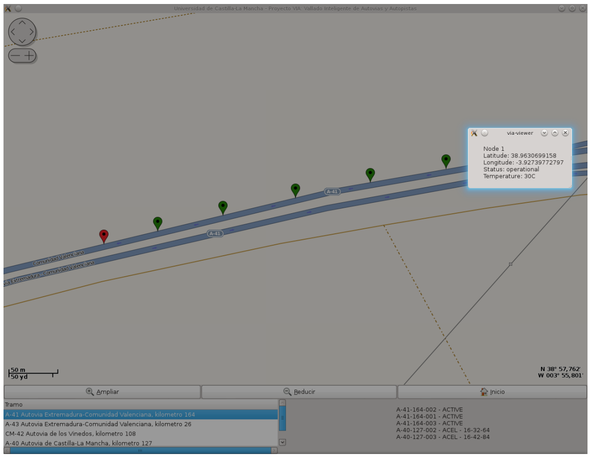

Figure 6. Via Tool: Monitoring a specific sensor values

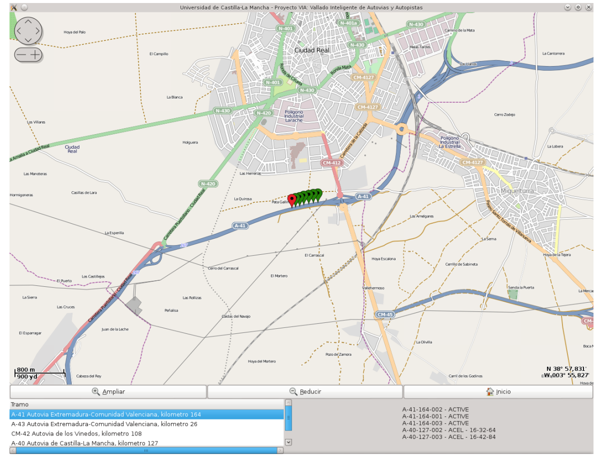

Figure 7. Via Tool: Global overview of highway stretch

in each stretch of the fence, as we can see the impacts are detected and can be easily distinguishable of wind vibration as far as nine stretches of the wire fence. Assuming five meters as standard length of each stretch of a wire fence in a highway, we can determine that we need to deploy around a node with accelerometers every 80-120 meters.

In both figures (5 and 4), the x-axis is a time-mark meanwhile the y-axis represents accelerometers variation value.

The middleware selected for our prototype is ZeroC ICE [11]. This middleware is an object-oriented middleware platform suitable for use in heterogeneous environments that enable us to build scalable and efficient distributed applications.

As example of monitoring control tool we are developing a real-time Geographical Information System (G.I.S.) where we can connect to different areas where a monitoring infrastructure has been developed.

In figures 6 and 7 we can see screenshots of the monitoring console prototype. We are taking as base platform the OpenStreetMap project. Depending of the geographical information contained in the configuration message (position of the nodes, the area covered by the sensors, etc.). we can establish a correspondence with the WSN node ID and display the status of each node as managed information.

The format selected for geographical information is the Mobile Location Protocol [12](MLP) defined by the Open Mobile Alliance that enable us to define GPS coordinates, polygonal areas, etc.

In each moment, we can monitor the last information collected from the gateways through management layer. In this tool, access to information from a sensor means to access to the management layer in the gateway of the stretch of highway (red node in figure 6) where a distributed object represents the whole stretch of the highway. This information is collected periodically in case of sensors related with environmental variables and when a high variation is detected in the accelerometers. As we mention before, in both cases the protocol used is MQTT-S.

Due to the possibility of existence of a great number of clients, together with energy limitations of WSN nodes, we discard the possibility that clients directly access to WSN nodes in order to get information directly from the sensors. In the same way, the gateway only communicates the information of its stretch of highway directly on-demand of clients. The mechanism enabled to provide such information is a subscription mechanism implemented in order to provide a reference to the gateway of a distributed object. The gateway will invoke a procedure in that distributed object according to the method of subscription (changes in the value of a sensor, periodically, under specific conditions,etc.)

Our current efforts are focused on identifying if this type of information dissemination covers the requirements of all models of services that they could be interested in use our platform.

V. Conclusion and future work

The smart management of transport infrastructures is a key point in future smart cities. In this paper, we analyzed and presented a solution for real-time monitoring of highway. According to domain experts, we designed the deployment of a wireless sensor network to gather together information and distribute among clients.

The proposed architecture is based in a object-oriented distributed middleware and it uses MQTT to collect information from sensors. This combination enables us to design specific solutions according to the characteristics of the highway to be monitored and applications to be developed. Our prototype helps us to design the network topology (an estimation of number of WSN nodes per security fence kilometer) and also to study the propagation of signal through the fence, to identify wind events, to study gateway emplacements, etc.

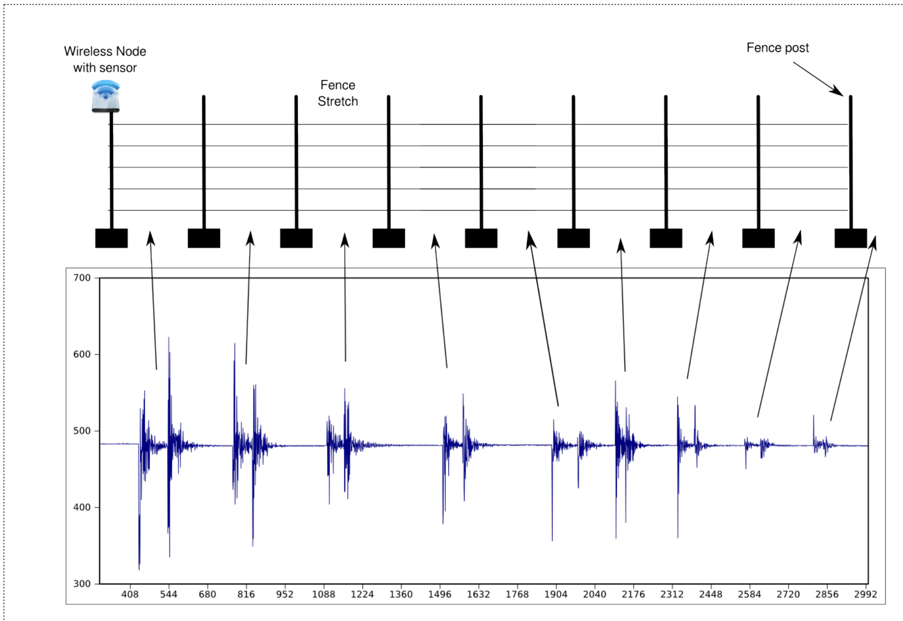

Figure 5. Vibration received by a node due to impact in different fence stretches

In a near future we will focus in new forms of getting information. For example and as we mention before, we will study noise analysis as possible source of information in order to detect traffic type, collisions, etc. In this point, we study to use the Xinergy board [13] with an FPGA integrated as a gateway of specific stretches where this audio analysis can really enhances the information about the highway state. We will continue testing network topology and analyze the expected time of live of WSN nodes to study the economical viability of the proposed solution.

The proposed platform described in this paper, is going to be an excellent platform for testing new smart services and designing new ways of manage future transport infrastructures.

ACKNOWLEDGMENT

This research was supported by AUDECA S.L.U and DEIMOS SPACE under the project VIA and by the Spanish Ministry of Economy and Competitiveness under the project DREAMS (TEC2011-28666-C04-03)

REFERENCES

[1] E. Commission, "Smart cities and communities- european innovation partnership," EU, Tech. Rep., 2012.

[2] G. Wittenburg, K. Terfloth, F. Villafuerte, T. Naumowicz, H. Ritter, and J. Schiller, "Fence monitoring experimental evaluation of a use case for wireless sensor networks," in *Wireless Sensor Networks*, ser. LNCS. Springer Berlin Heidelberg, 2007, vol. 4373, pp. 163–178.

[3] Z. Wafi, R. Ahmad, and M. Paulraj, "Highways traffic surveillance system using opencv," in *Control and System Graduate Research Colloquium (ICSGRC). IEEE*, 2010, pp. 44 –48.

[4] S. Ghosh, S. Rao, and B. Venkiteswaran, "Sensor network design for smart highways," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 42, no. 5, pp. 1291 –1300, sept. 2012.

[5] B. Chowdhry, K. Shardha, U. Naeem, and A. Rajput, "Development of wireless sensor networks for smart civil structures and highway safety," in *Signal Processing and Communications, 2007. ICSPC 2007. IEEE International Conference on*, nov. 2007, pp. 420 –423.

[6] J. Santa and A. Gomez-Skarmeta, "Sharing context-aware road and safety information," *Pervasive Computing, IEEE*, vol. 8, no. 3, pp. 58 –65, july-sept. 2009.

[7] U. Hunkeler, A. Stanford-Clark, and H. L. Truong, "Mqtt-s: A publish/subscribe protocol for wireless sensor networks," in *Proceedings of the 2nd Workshop on Information Assurance for Middleware Communications*, 2008.

[8] B. Ciepluch, P. Mooney, R. Jacob, P. Corcoran, and A. Winstanley, "Using a fully open source approach to working with openstreetmap," 2010, open Source GIS 2010 Nottingham.

[9] Crossbow, "Iris datasheet," Crossbow S.L., Tech. Rep., 2008.

[10] P. Levis, S. Madden, J. Polastre, R. Szewczyk, K. Whitehouse, A. Woo, D. Gay, J. Hill, M. Welsh, E. Brewer, and D. Culler, "TinyOS: an operating system for sensor networks," in *Ambient Intelligence*. Springer-Verlag, pp. 115–148.

[11] M. Henning, "A new approach to object-oriented middleware," *IEEE Internet Computing*, no. 1, pp. 66–75, 2004.

[12] O. M. Alliance, "Oma mobile location protocol version 3," Open Mobile Alliance, Tech. Rep., 2011.

[13] Silica, "Xynergy board flyer," Silica, Tech. Rep., 2011. [Online]. Available: http://www.silica.com/