Sensor and Actuator Networks in Metropolitan Scenarios

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Summary
Sensor and actuator networks promise to revolutionize sensing and control in a wide range of application domains because of their particular characteristics. These networks can sense, compute and actuate into the physical environments creating smart solutions and solving critical problems in a variety of science areas such as industrial automation, environmental monitoring and control and smart environment creation. This paper provides a novel architecture to develop a sensor and actuator network in metropolitan scenarios in order to bring technological development to cities, creating services and solutions for government administration and society as a whole.
Key words:
Sensor Networks, ZigBee, IEEE 802.15.4, Metropolitan Open Access Area Networks

1. Introduction

The improvement in Micro-Electro-Mechanical Systems (MEMs) and wireless communication technology are responsible for Wireless Sensor and Actuator Networks (WSANs) have gained wide popularity in a variety of application scenarios, ranging from monitoring and control applications in industrial automation to more sophisticated solutions in the environmental science [1]. A WSAN consists of large number of sensor and actuator nodes. Sensor nodes are designed to collect information about the environment and transmit the accumulated data using wireless technology to a base station known as sink. The opposite happens with actuator nodes, they receive data from the base station to actuate functions over the environment.

Current and potential applications of WSANs include: industrial and manufacturing automation, military sensing, physical security, traffic surveillance, video surveillance, distributed robotics, environmental monitoring and control, air traffic control, and building and structures monitoring. The sensors and actuators in these applications may be small or large, and the networks may be wired or wireless. However, wireless networks probably offer the most potential of deployment in inaccessible terrains or disaster relief operations once the nodes are able to operate using specific protocols and algorithms where the position of sensor nodes need not be engineered or predetermined [2].

Research in the field of WSANs has come a long way since it began around a decade ago. While there have been numerous small-scale WSAN test bed implementations by the research community, large-scale implementations still unheard of. This paper presents a large-scale architecture to develop sensor and actuator networks in metropolitan scenarios bringing together IEEE 802.15.4/ZigBee and Open Access Metropolitan Area Networks (MANs).

ZigBee is a wireless technology for inexpensive, short range networks, ideal for control of a large number of devices and machine to machine communication over a network. Traditional sensors are not able to obtain particular inputs and reporting data in real time and with high spatial density as sensor networks are able to do [3]. Due to these characteristics mentioned, ZigBee is largely used into field of automatic control, energy monitoring, light control, home security, remote control and smart environments creation. Open Access MANs are communication networks built to allow universal access of city's population to a single digital multimedia communication network. ZigBee and Open Access MANs together offer flexibility in applications, providing reliable services for government and society as a whole.

In this paper, our architecture will be presented, describing possible services that could be applied in metropolitan scenarios. We describe an automatic people-counting and environment monitoring system based on our proposed architecture at a public building in the city of Pedreira, a city localized on Southeast of Brazil. The remaining of the paper is organized as follows: The next section presents related works and successful case studies. Section 3 introduces a background of ZigBee and IEEE 802.15.4 standard. Section 4 shows the characteristics of an Open Access Metropolitan Area Network and services supported by it. Section 5 describes in more detail the proposed architecture. Section 6 presents the implementation of a people-counting and environmental

Manuscript received October 5, 2009
Manuscript revised October 20, 2009

monitoring system as a proof of concept. Finally, the last section presents the conclusions and the future works.

2. Related Works

For metropolitan scenarios, several systems [4], [5] using WSANs have been proposed. In [4] is presented a web service-based infrastructure for traffic monitoring using ZigBee. The goal was to develop a multi-layer architecture so that the infrastructure could be flexible and extensible for multiple applications. For the experimental application, a network of ZigBee devices at each road intersection for monitoring traffic is connected to a central server through access points. The central server hosts a Web Service for users to get congestion information for intersections or for administrators to control traffic lights remotely, if necessary.

Other implementation for traffic monitoring can be found in [5], Street Corners network was deployed on the Kean University campus, which is network architecture to integrate active and passive sensors information gathered from urban environmental sensing networks. For this implementation sensors from Crossbow Technology, Inc. were used, that includes IEEE 802.15.4/ZigBee compliant processors.

Out of the metropolitan scenario, but very interesting application of WSANs, Mainwaring [6] presented system architecture for real-world habitat monitoring, especially to monitor seabird nesting environment and animal behavior in a small island off the coast of Maine called Great Duck Island.

Discussions about design and implementation of Open Access MANs can be found in [7] and [8]. Case studies and successful deployment results of Open Access MANs are presented in [9] and [10].

Examining the related works mentioned above, we can notice a lack of flexibility in to concentrate the data from different locations in a central base station, because there is not such infrastructure to cover a large area. This is the major difference of our model, using all advantages of a short-range communication standard as ZigBee and the scale and capacity of an Open Access MAN. There are benefits and advantages of both technologies together, enabling us to create a WSAN to cover metropolitan scenarios. Another advantage of our architecture is that the Open Access MANs, in most of cases, are public networks which belongs to the government of the city, for this reason monitoring and control on streets, health centers, and public spaces in general there is no cost of connection, and to facilitate the most of these environments are already connected to the MAN taking advantage of other services offered by it.

3. ZigBee and IEEE 802.15.4 Technologies

3.1 ZigBee Standard

ZigBee is a wireless communication standard managed by ZigBee Alliance, a group over 170 companies creating ZigBee related semiconductors, developing tools and products. Solutions adopting the ZigBee standard are embedded in consumer electronics, home and building automations, industrial control, sensor networks and so on.

ZigBee was designed for low power applications and it fits well into embedded system and those markets where reliability and versatility are important but high bandwidth is not. Low power consumption enables to deploy ZigBee devices and sensors in wider areas where power supply is not presented offering extended battery life. ZigBee also offers support of large network size comparing to other technologies, it has the capacity of supporting over 65000 devices within a network, which makes it possible to deploy sensor and actuators at a very high density, which is essential to certain applications such as monitoring and control in a large scale [11].

3.2 ZigBee Protocol Stack

The ZigBee stack architecture is separated in a set of blocks called layers. Each layer performs a specific set of services for the layer above. The IEEE 802.15.4 standard defines the responsibilities of the physical (PHY) layer and medium access control (MAC) sub-layer. IEEE 802.15.4 has two physical layers that operate in two different frequency ranges, 868/915 MHz and 2.4 GHz. The MAC sub-layer controls access to the radio channel using a Carrier Sense Multiple Access/Collision Avoidance (CSMA-CA) mechanism. MAC layer responsibilities may also include transmitting beacon frames, synchronization, and providing a reliable transmission mechanism. The ZigBee specification defines the network (NWK) and application (APL) layers [12] Fig. 1 briefly describes relevant layers and related information.

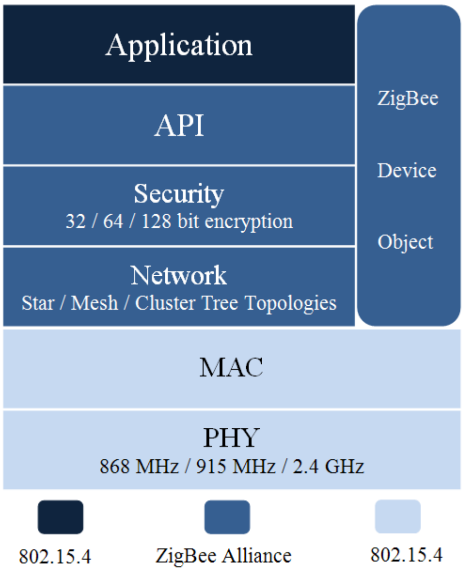

Fig. 1 ZigBee stack architecture.

3.3 ZigBee Topologies

In the ZigBee network, the devices can be classified as full-function device (FFD) and reduced-function device (RFD). The FFD implements all the ZigBee functionalities while RFD only implements partial functionalities of the protocol stack in order to reduce the power consumption. FFD is able to communicate with FFD and RFD, however, RFD only can communicate with FFD. The ZigBee network supports the star, tree and mesh topologies [11]. There are three type nodes used in a network, they are the coordinator, the router and the end device. Only FFD can be worked as the coordinator and router, while, the FFD or RFD can be used as the end device. Fig. 2 shows an example of the three topologies.

It can be seen that at least there must be a coordinator in a network. The coordinator is responsible for initiating the network and setting the network parameters. For example, in a star topology, the coordinator communicates with all other devices (end devices) directly, which means that the communication between end devices have to go through the coordinator. Besides, in the tree topology, the coordinator, routers and end devices act as the root, branch nodes and the leaves, respectively. In general, the routers transmit data and control messages through the network using a hierarchical routing strategy. Moreover, the mesh topology is more complicate than the other two topologies. There are more links among coordinator and routers. The links form the network like a mesh. In the mesh topology, there are multi-routes between two nodes. Therefore, it provides the ability to establish the communication by selecting an alternative route when some nodes in the previous selected route are malfunction. This feature makes the network more robust at the price of increasing the implementation complexity and its power consumption. The strategy of topology selection depends on the application requirements and the hybrid application is selected in the most cases.

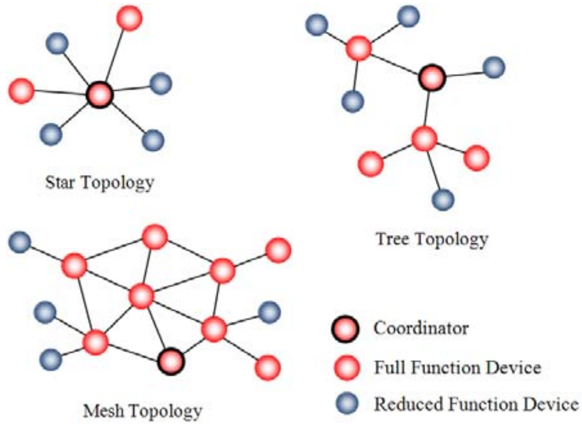

Fig. 2 ZigBee topologies.

4. Open Access MAN

Since the end of 19th century, with the first electrical systems, communications has contributed to provoke periodic radical changes in the *modus operandi* of modern society. After the development of digital technology, the frequency of occurrence of such changes has increased enormously. Thus society, nowadays, is maintained in a perennial state of technological revolution.

Perhaps the most recent of these changes, which is daring to sparkle another revolution, is happening with the convergence between high speed (optical and wireless) networks, offering virtually unlimited bandwidth, with the concept of network multimedia data transmission through TCP/IP. This convergence takes us to the construction of an intelligent communications network allowing the offering of huge amount of services and applications to attend the needs and under the control (at least partial) of final users. In particular, the recent development of Digital Cities and Open Access Metropolitan Area Networks, and their convergence, are an interesting occurrence that may trigger the creation of a new paradigm in communications.
An Open Access MAN can be defined as a convergent multimedia network offering universal access for the whole population of a city [13]. Many network solutions may fall in the category of this broad definition. However, the state of the art development of TCP/IP networks

powered by optical and wireless Ethernet solutions (Gigabit Ethernet, 10G Ethernet, IEEE 802.11x, IEEE 802.16x, and others) offer a single generic environment that may be considered the best candidate to become the solution of choice for a single and universal convergent network. Thus, new services and applications such as videoconference, virtual schools, e-Gov platforms, TV distribution service, telephony, monitoring and control as our model, and many other solutions may be developed and deployed easily upon such networks.

4.1 Open Access MAN Physical Architecture

On the physical point of view, we can describe the Open Access MAN as divided into three layers: Access Layer, Distribution Layer, and Network Core. Fig. 3 below presents the conceptual physical architecture of the network.

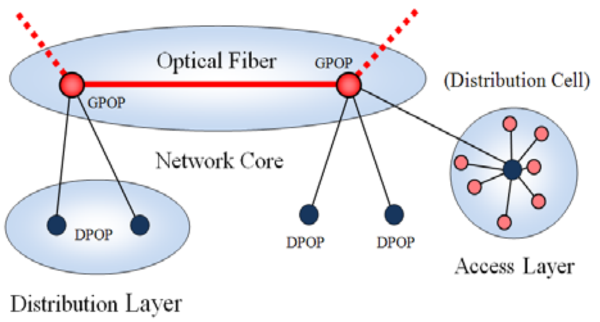

Fig. 3 Physical Description of an Open Access MAN.

The network core, normally built using an optical fiber backbone, forms the central part of the network. Being capable to transport hundreds of gigabits per second of information, the core is what guarantees that the Open Access MAN will support the full traffic demand of the city. Most of projects, the network core is built to attend large bit rates generators of the city. These normally are the private and public data centers, universities and schools, hospitals and health centers, and other information relation enterprises of private and public origin. The must also take care of the Open Access MANs' interconnection with public service networks, like the Internet, public telephony, and TV distribution enterprises. Finally, the core must also offer the points for the interconnection of the distribution layer network. All these connections link themselves to the core through specific points called POPs (points of presence). Because of the high speed nature of the network core, we shall call these POPs as GPOPs (from Gigabit POPs).

The Distribution Layer is responsible to centralize the flow of data in and out of the access points. This layer is composed of several distribution centers connected directly to the network core through a GPOP. Because of its function, the distribution center must be capable of handling from tenths of megabits per second up to a gigabit per second of data flow. A point of connection in this layer is called a DPOP. The DPOP can be constructed using several different technologies, from wireless technology to twisted pairs or even fiber links.

Finally, the Access Layer is responsible for handling the generic point of presence of the Open MANs. These points are aimed at connecting homes and small businesses. They derive from the DPOP forming distribution cells. The technology used must follow that adopted for the DPOP to which the distribution cell is connected.

5. Architecture Design

Interfacing to the physical world involves exchanging energy between embedded devices and their environments. Usually, each device is either a sensor node or an actuator node. Sensor nodes translate a particular form of energy or a phenomenon (light, heat, vibration) into information. Actuator nodes convert information into action over the environment around them [14].

As stated earlier, the architecture design provides a sensor and actuator network to operate in metropolitan areas in order to monitor environments such as hospitals, schools, health centers, government buildings, streets and other public spaces. The model allows an interaction between physical characteristics from real cities with computational tools, resulting in a system where information from real places can be accessed and manipulated by specific communities, administrators from government, and also to be used to create intelligent environments.

The architecture lowest level consists of sensor and actuator nodes that interact directly to the environment based on their physical characteristics. Nodes may be deployed around the environment in large number, either sensor and actuator nodes communicate among them using the ZigBee wireless network. The sensor nodes collect information about the environment and transmit the accumulated data using ZigBee to the gateway. The gateway is responsible to manage the connection between ZigBee wireless technology and the Open Access MAN. The base stations can stay in any point of the city, close to the place being monitored or on the other side of the city. The same happens with the actuator nodes, however in an opposite way, data is transmitted to them, which respond the request with specific actions over the environment. The architecture is presented in Fig. 4, where it shows the lowest level (sensor and actuators), how it connects to the Open Access MAN and the base stations using a software application.

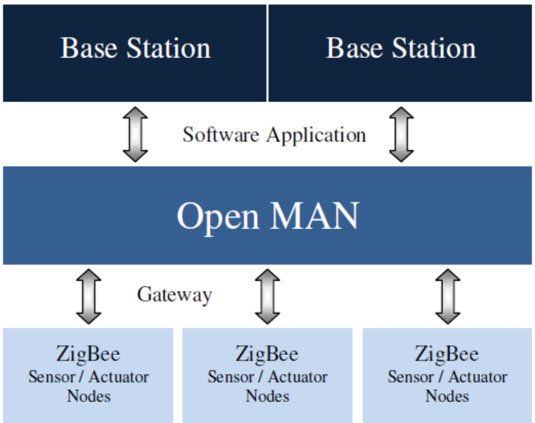

Fig. 4 Architecture design.

Remote base stations may receive information from different locations of the city depending on the specific area of monitoring or control, for example, information about health centers should be concentrated in a base station which is responsible to administrate these environments and so on. It is important to highlight that the architecture combines ZigBee technology and an Open Access MAN, even the MAN offering a diversity of other services mentioned previously, it make part of an entire metropolitan sensor and actuator network, not just a backbone to connect small WSANs, and in specific solutions where ZigBee networks do not attend the needs, sensor and actuator nodes can be mounted directly on the MAN infrastructure. The TCP/IP protocol is used to transmit data through the Open Access MAN.

5.1 Services

A wide range of services can be developed using the proposed model, and most of them can be used for government administration proposal. Depending on the cities needs, new environmental monitoring and control solutions can be developed, improvements in existing infrastructures can be made to achieve a high spatial resolution, artificial intelligence can be applied in some cases creating smart environments with a certain level of autonomy. Another solution offered by our model is the concentration of variety of services already implemented using other technologies.

6. Case study: People-Counting and Environment Monitoring

During the last two years we have developed specifications for several cities willing to deploy such MANs. Also, we have a cooperation agreement with the city of Pedreira - SP, a city localized in Southeast of Brazil, where we have implanted a MAN. This consists in hybrid optical wireless network, where the main infrastructure is composed by an optical backbone Gigabit Ethernet complemented by wireless access cells. The radios are a dual band system that provides access point and bridging services through either 5.7 GHz or 2.4 GHz radio interfaces. In Pedreira we are using the frequency of 5.7 GHz (IEEE 802.11a) to connect the points and 2.4 GHz (IEEE 802.11g) to provide services of access point. The infrastructure and the map describing the city are presented below in Fig. 5.

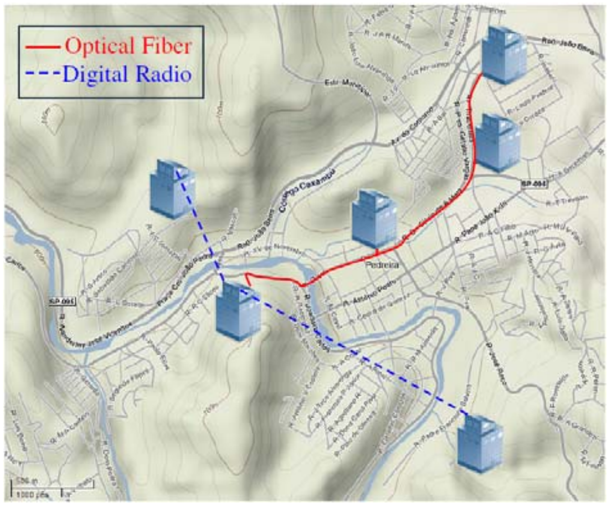

Fig. 5 Open Access MAN of Pedreira – Brazil.

Pedreira created a network that attends both, public sector buildings and universal access to people and businesses. The goal of the city government, besides developing public sectors own network, was also to offer free access to e-Gov solutions, being sensor network one of them, and access to the Internet to the whole population.

In our case study, we developed a large-scale sensor and actuator network taking advantage of Pedreira's MAN infrastructure. A people-counting and environmental monitoring and control system was implemented as proof of concept, which implementation is composed by XBee OEM RF Modules from Digi International, Inc., photo-beam sensors, and specific hardwares to mount the XBee modules. Also to bring more flexibility to the administration of the application a Virtual Local Area

Network (VLAN) was defined over the Open Access MAN to separate the monitoring and control architecture from the other services already implemented in Pedreira's MAN. Security is very important in this kind of environments, especially to be a network opened for the whole population, another function of the VLAN is to bring protection for data and connection from users that are not allowed to have access to information.

XBee OEM RF Module was engineered to meet IEEE 802.15.4 standards and support low cost, low power and wireless communication. The module operates within the ISM 2.4 GHz frequency band. It can operate in different topologies either point to multipoint or ZigBee/Mesh topologies, which definition depends on the firmware configuration of the module and for what application is destined [15].

The gateway was developed using the module described above and an USB interface board which is one of the specific hardware mentioned and presented in Fig. 6. This gateway takes all accumulated data collected from the nodes deployed on the environment and transmits to the base station. Being an USB gateway, a Java application was developed to manage the communication between the ZigBee network through the USB gateway and the Open Access MAN.

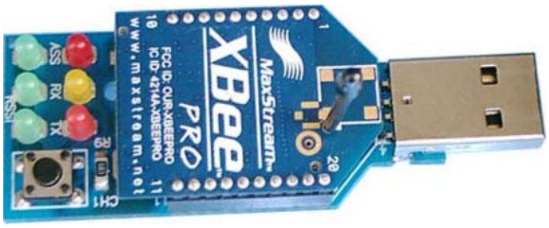

Fig. 6 USB Interface board.

The nodes embedded around the environment use the same module used by the gateway. The module is mounted in a multi task board presented in Fig. 7 which can support different sensor specifications and it is able to trigger at least two devices using relays mounted on the board. The multi task board also enables to collect information from other instruments through serial interfaces as RS232, TTL 5V and TTL 3.3V, where data gathered is transmitted via ZigBee network to the gateway as well.

Besides the ZigBee radio modules and boards the implementation is composed by photo-beam sensors which are the main responsible to count the number of incoming and outgoing people in a building administered by the government of the city of Pedreira. The sensors are mounted on the multi task board. Every time the sensors capture events the information is sent to the gateway which transmits the data to the base station.

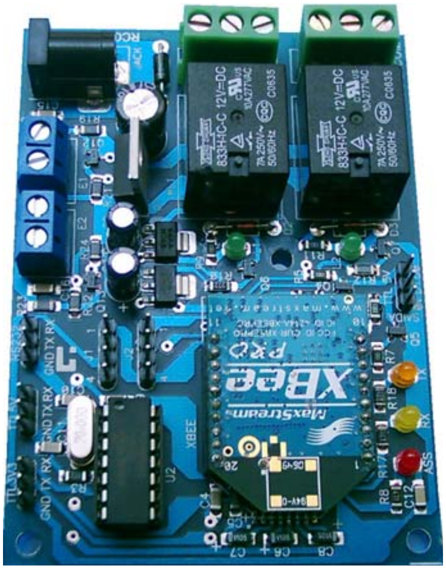

Fig. 7 Multi task board.

The objective of our proposal is to develop e-Gov solutions using the presented architecture, and the government of Pedreira allows us to implement our case study in two of its buildings. The environment being monitored is a public building where people responsible for maintenance of the Open Access MAN work and the base station is the city hall, a building localized on the other side of the city. Fig. 8 shows the log of our people-counting system during a short period of monitoring on September 29.

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7E0007010150010007C003000000000000000 27/09/2009 00:21:15.46
7E00078150012C004510AC0000000000000000 29/09/2009 11:48:37.453
7E00078150012F004500B9000000000000000 29/09/2009 11:48:37.515
7E00078150012F004510A9000000000000000 29/09/2009 11:48:37.828
7E00078150012F004500B9000000000000000 29/09/2009 11:48:37.890
7E00078150013200 4510A6000000000000000 29/09/2009 11:50:14.560
7E000781500137004500B1000000000000000 29/09/2009 11:50:14.919
7E00078150013600 4510A2000000000000000 29/09/2009 11:51:05.556
7E000781500130004500B8000000000000000 29/09/2009 11:51:10.681
7E0003890100757E00078150012C005200AF 29/09/2009 11:51:12.603
7E00078150012F004510A950012C005200AF 29/09/2009 11:51:16.118
7E00078150012F004500B950012C005200AF 29/09/2009 11:51:16.977
7E000781500130004510A850012C005200AF 29/09/2009 11:51:21.149
7E00078150012D004500BB50012C005200AF 29/09/2009 11:51:24.242
7E0003890100757E00078150012F005701A6 29/09/2009 11:51:28.664
7E0003890100757E00078150012F005700A7 29/09/2009 11:51:29.976
7E0003890100757E00078150012E005702A6 29/09/2009 11:51:31.70
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Fig. 8 Implementation log.

The control over some devices and equipments embedded around the environment is also proposed in this paper, and the case study was implemented enabling this functionality. From the remote base station the user can trigger a device making use of the relays mounted on the multi task board. The user interface was also implemented in Java language and it enables the user to have access to the log and manipulate devices remotely. Fig. 9 shows the frequency of people's incoming and outgoing during 07:00 to 17:00 during the three first days of our implementation.

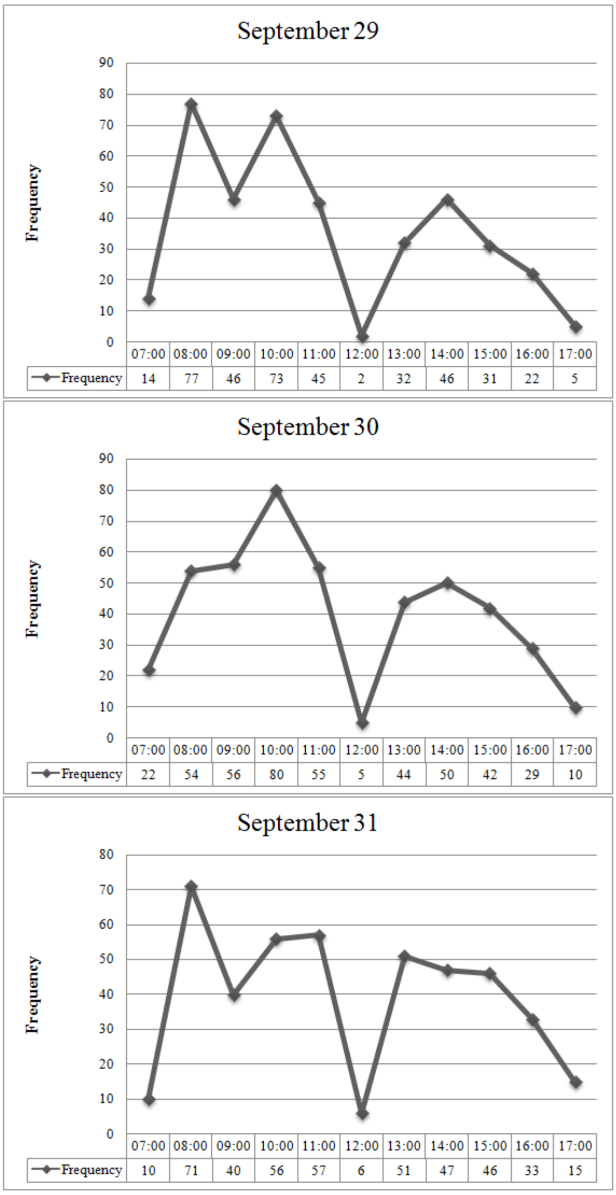

Fig. 9 Results of the monitoring.

6. Conclusion and Future Works

Monitoring and control in metropolitan scenarios represents an important class of municipal services and an interesting application of sensor and actuator networks in municipal environments. Our proposal differs from other works specially for offering control over the environment instead of just monitoring. Another benefit is the large scale infrastructure provided to cover city areas and the diversity of services that can be integrated in municipal scenarios.

Our People-Counting and environment monitoring system is the first implementation for monitoring and control in such infrastructure. However, future works are expected which includes the design and implementation of new applications, development of new hardwares for specific tasks, creation of a platform to group data from related environments in order to organize the base station and the types of monitoring and control. Pervasive computing also is being studied to be applied in some future implementation to achieve a certain level of intelligence in metropolitan environments.

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