Wireless Sensor Networks for Data Acquisition and Information Fusion: A Case Study

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Abstract - **Data acquisition is one of the most relevant aspects in tele-monitoring systems. Information fusion helps these systems to better unify data collected from different sources. This paper presents a case study that consists of a tele-monitoring system aimed at enhancing remote healthcare for dependent people at their homes. The system deploys a service-oriented architecture over a heterogeneous Wireless Sensor Networks infrastructure to create smart environments. Such architecture can be executed over multiple wireless devices independently of their microcontroller or the programming language they use. Furthermore, the system allows the interconnection of several networks from different wireless technologies, such as ZigBee or Bluetooth. This approach provides the system better flexibility to change its functionalities and components after deployment than other analyzed proposals. The system description, its architecture, and preliminary results of the system prototype implemented in a real environment are presented.**

Keywords: Information Fusion, Distributed architectures, Wireless Sensor Networks, Healthcare, Tele-monitoring.

1 Introduction

Tele-monitoring systems allow a patient's state and vital signs to be supervised by specialized personnel from remote medical centers. Such tele-monitoring systems usually consist of a home monitoring subsystem, a remote monitoring subsystem in the medical center and a network which interconnects both [3]. A tele-monitoring system for healthcare needs to continuously keep track of context information about patients and their environment. The information may consist of many different parameters such as location, the building temperature or vital signs (e.g. heart rhythm or blood pressure). Most of the context information can be collected by distributed sensors throughout the environment and even the patients themselves. To facilitate the deployment of these sensors, it is preferable to use Wireless Sensor Networks (WSNs) [4] instead of wired networks [5–6]. In existing smart environments (i.e. environments that interact with users through sensors and actuators in a pervasive and ubiquitous way) [7], wiring the location is more uncomfortable and difficult than using wireless devices. In the case of the biomedical sensors that monitor the patient's vital signs, it could be quite bothersome for patients to wear a mesh of wires. One solution would be to use a Wireless Body Area Network (WBAN) formed by sensors and wearable computers [8–9].

Whether in home automation, healthcare tele-monitoring systems or hospitals, WSNs are used for collecting information from the users and their environment. WSNs are formed by a set of devices called sensor nodes, each of which is habitually formed by a microcontroller, a radio transceiver and a sensor or actuator mechanism [5]. Some nodes act as routers that can forward data that must be delivered to other nodes. Traditional networks are aimed at providing high QoS (Quality of Service) [10] while WSN protocols must focus primarily on saving power [11]. Examples of wireless technologies for building WSNs are ZigBee/IEEE 802.15.4, Bluetooth and Wi-Fi.

Nonetheless, the development of software for remote tele-monitoring that integrates different subsystems demands the creation of complex and flexible applications. As the complexity of an application increases, it needs to be divided into modules with different functionalities. Since different applications could require similar functionalities, there is a trend towards the reimplementation of such functionalities [12]. Although it implies more development time, it is generally the easiest and safest solution. Nevertheless, reimplementation can lead to duplicated functionalities and more difficult system migration. An alternative to such an approach is the reutilization of resources that can be implemented as part of other systems. This trend is the best solution in the long-term and can be realized using a common platform. However, it is difficult to perform because the systems in which those functionalities are implemented are not always compatible with other systems. An alternative for solving this problem is to use distributed architectures.

This paper presents a context-aware tele-monitoring system aimed at enhancing healthcare for dependent people at their homes. The system utilizes the SYLPH (*Services laYers over Light PHysical devices*) experimental architecture that integrates a SOA (Service-Oriented Architectures) approach with heterogeneous WSNs. The architecture provides the tele-monitoring system with a flexible distribution of resources and facilitates the inclusion of new functionalities in highly dynamic smart environments. Unlike other SOA-WSNs architectures, SYLPH allows both services and services directories to be embedded in nodes with limited computational resources regardless of the radio technology they use.

The next section introduces the problem description and explains why there is a need for defining a new tele-monitoring system. Then, the main functionalities and capabilities of the system and its architecture are described. Finally, the results and conclusions are presented, including future lines of work.

2 Problem Description

One of the key aspects for the construction of tele-monitoring systems is obtaining information about the patients and their environment through sensor networks. This section presents the strengths and weaknesses of existent tele-monitoring developments and analyzes the feasibility for implementing a distributed architecture for integrating heterogeneous WSNs. This section also discusses some of the most important problems of existent functional architectures for WSNs, including their suitability for constructing intelligent environments.

As a result of extensive research, biomedical sensors have become more inexpensive, accurate and reliable [13]. Moreover, biomedical sensors are now wearable and even implantable [14]. Nevertheless, biomedical sensors (e.g. electrocardiogram, blood pressure, etc.) and automation sensors (e.g. temperature, light, etc.) differ significantly in how they collect data. On the one hand, biomedical sensors obtain continuous information about vital signs that is important and should not be lost [15]. On the other hand, automation sensors obtain information at a lower frequency than biomedical sensors [5] because this information is generally less important than vital signs. In a tele-monitoring scenario, it is necessary to interconnect WSNs from different technologies [8], so having a distributed platform for deploying applications over different networks facilitates the developers' work and the integration of the heterogeneous devices.

There are several tele-monitoring healthcare developments based on WSNs [8, 16–18]. However, they do not take into account their integration with other architectures and are difficult to adapt to new scenarios [19]. This is because such approaches do not allow sensors and actuators to communicate directly with one another, and instead gather data in a centralized way. Excessive centralization of services negatively affects system functionalities, overcharging or limiting their capabilities [20–21]. Figure 1 shows a centralized versus a distributed model for integrating heterogeneous WSNs. A centralized model consists of a central component that gathers all the data forwarded by the nodes connected to it. The main component can be a computer with several wireless hardware interfaces (i.e. wireless network cards). Each of these interfaces is connected to one or more of the WSNs deployed in the system. One of the main problems in this model is that most of the intelligence of the system is centralized. That is, the central component is the responsible for knowing what nodes are in all WSNs.

Thus, it gathers the required data from the nodes and, based on such data, it decides what commands will be sent to the each node. That means that a node belonging to a certain WSN does not know about the existence of another node forming part of a different WSN, although this WSN is also part of the system. This problem can be seen in Figure 1a. In such centralized model, if a certain measurement in a sensor in the WSN #2 has to provoke an action to be performed by an actuator in the WSN #3, the responsible of taking the decisions and invoking the commands in the actuator will be the central nodes. The thinner broken lines between nodes on Figure 1 represent links at each network layer level, whilst thicker lines represent the communication at the application layer level between the nodes implied in the given example. The thinner broken lines around the WSNs represent the knowledge area at the application level. That is, nodes sited inside one of this knowledge area can communicate amongst them directly at the application level. In this centralized model, it is difficult for the system to dynamically adapt its behavior to the changes in the environment, because the decision logic on the central nodes has to be changed every time a new functionality (i.e. sensor or actuator) is added to the system.

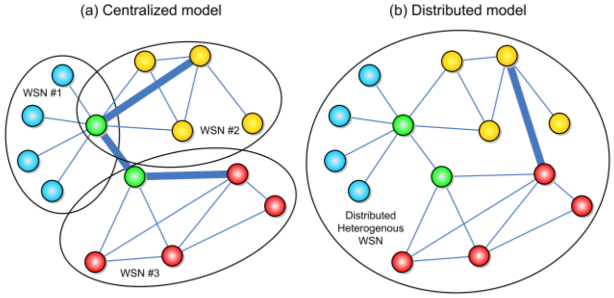

Fig. 1. A centralized versus a distributed approach for integrating heterogeneous WSNs

Nonetheless, this model can be improved using a common platform where all the nodes in the system can know about the existence of any other node in the same system no matter the technology they use. This is achieved by adding a middleware logical layer over the existing application layers on the nodes. Figure 1b shows a distributed model for integrating heterogeneous WSNs. It can be seen how only one knowledge area now covers all the WSNs. That is, following the previous example, the sensor node in the WSN #2 knows about the existence of the actuator node in the WSN #3, so the sensor node can send a command to the actuator node directly at the application layer level. A service-oriented approach is adequate for being implemented in wireless sensor nodes due to it allows distributing the functionalities of the system into small modules. Such small modules are ideal for being executed by devices with limited computational resources as wireless sensor nodes. This platform covers aspects relative to services such as registration, discovering and addressing. The code executing in a certain node can invoke functionalities (i.e. services) offered by any other node in the system, regardless the latter node is in the same WSN or not. This way, the central component now only has to act as a gateway amongst the distinct WSNs connected to it. Thus, it has not to keep track of either the nodes in the system or the functionalities they offer. Some nodes in the system can integrate services directories for distributing the registration and discovering of services. A node can know about the existence of other nodes and services offered by them. Thus, it can directly communicate with other nodes in order to execute commands or gather data. Moreover, a node belonging to the system can react to a certain change in the environment with no need of having into account all the factors involved on the system. In addition, the node registration is done in the corresponding WSN and the service registration is maintained by the service directories. Thus, the process of connecting a new node offering additional functionalities to the system is performed in a dynamical way.

In classic functional architectures their modularity and structure are oriented to the systems themselves. However, modern functional architectures such as SOA allow functionalities to be created outside the system, as external services linked to it. Thus, distributed architectures look for the interoperability amongst different systems, the distribution of resources and the independency of programming languages [22]. SOA proposes a model based on a collection of services and a communication way between them. The communication can involve a simple interchange of data, two or more services coordinating a certain activity, etc. A service can be defined as a function that must be well-defined, self-contained, and non-dependent of the context or the state of other services [22]. Services are integrated through communication protocols that have to be used by applications to share resources in the network [20]. The compatibility and management of messages that the services generate to provide their functionalities are important and complex elements in any of these approaches. Some developments try to reach integration between devices by implementing some kind of middleware, which can be implemented as reduced versions of virtual machines [23], middleware [24] or multi-agent approaches [25]. However, these developments require devices whose microcontrollers have large memory and high computational power, thus increasing costs and physical size. These drawbacks are very important regarding WSNs, as it is desirable to deploy applications with reduced resources and low infrastructural impact, especially in healthcare tele-monitoring scenarios.

There are different technologies for implementing WSNs, such as ZigBee or Bluetooth. The ZigBee standard allows operating in the ISM (Industrial, Scientific and Medical) band, which includes 2.4GHz almost all over the world [26]. The underlying IEEE 802.15.4 standard is designed to work with low-power and limited resources nodes [27]. ZigBee incorporates additional network, application and security layers over IEEE 802.15.4 and allows more than 65,000 nodes to be connected in a mesh topology network [28]. Another common standard to deploy WSNs is Bluetooth. Bluetooth allows multiple WPAN (Wireless Personal Area Network) or WBAN (Wireless Body Area Network) applications for interconnecting mobile devices or biomedical sensors. Bluetooth also operates in the 2.4GHz band and allows creating star topology networks of up to 8 devices, one acting as master and the rest as slaves, but it is possible to create more extensive networks through devices that belong simultaneously to several networks [29]. However, it is not easy to integrate devices from different technologies into a single network [30–32]. The lack of a common architecture may lead to additional costs due to the necessity of deploying non-transparent interconnection elements amongst different networks. Moreover, the developed elements are dependent on the application to which they belong, complicating their reutilization.

The architecture for the tele-monitoring system presented in this paper tackles some of these issues by enabling an extensive integration of WSNs and providing a greater simplicity of deployment, optimizing the reutilization of the available resources in such networks. The architecture integrates a SOA approach for facilitating the distribution and management of resources (i.e. services). A distributed architecture provides more flexible ways to move functions to where actions are needed, thus obtaining better responses, autonomy, services continuity, and superior levels of flexibility and scalability than centralized architectures [22, 33]. Unfortunately, the difficulty in developing a distributed architecture is higher [34]. It is also necessary to have a more complex system analysis and design, implying more time to reach the implementation stage. There are several developments to integrate WSNs and a SOA approach [30, 35]. However, those developments do not consider the necessity of minimizing the overload of the services architecture on the devices. In contrast, our solution allows the services to be directly embedded in the WSN nodes and invoked from other nodes either in the same network or another network connected to the former. It also specifically focuses on using devices with small resources to save CPU time, memory size and energy consumption, which is very useful to design and construct smart environments. Furthermore, as previously mentioned, the system contemplates the possibility of connecting WSNs based on different technologies.

3 Tele-monitoring System Description

This section describes the main features of a tele-monitoring system designed and developed with the aim at improving healthcare of dependent people at their homes. Figure 2 shows the basic schema of the tele-monitoring system. The system utilizes WSNs for obtaining context information about users (i.e. patients) and their environment in an automatic and ubiquitous way.

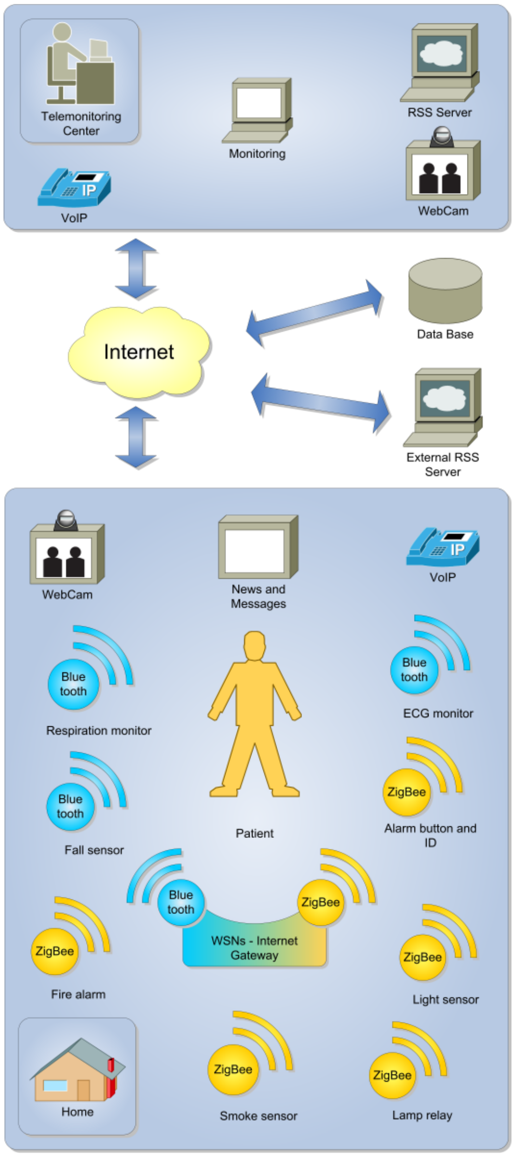

Fig. 2. Schema of the tele-monitoring system

The system uses a network of ZigBee devices placed throughout the home of each patient to be monitored. The patient carries a remote control (a small ZigBee device embedded in a wristband) that includes an alarm button which can be pressed in case of emergency or the need for remote assistance. There is a set of ZigBee sensors that obtain information about the environment (e.g. light, smoke, temperature, etc.) and react to changes (e.g. light dimmers and fire alarms). Each ZigBee node includes a C8051F121 microcontroller with only 8KB of RAM and 128KB of Flash memory and a CC2420 transceiver, consuming only a few μA in sleep mode. There are also several Bluetooth biomedical sensors placed over the patient's body. Biomedical sensors allow data about the patient's vital signs to be acquired continuously. Each patient carries an Electrocardiogram (ECG) monitor, an air pressure sensor acting as respiration monitor, and a triaxial accelerometer for detecting falls. These Bluetooth devices use a BlueCore4-Ext chip with a RISC microcontroller with 48KB of RAM. All ZigBee and Bluetooth devices can offer and invoke services (i.e. functionalities) within the network. There is also a computer connected to a remote healthcare center via Internet for forwarding possible alerts to caregivers and allowing them to communicate with patients. This computer acts as a ZigBee coordinator and is also the master of a Bluetooth network formed by the biomedical sensors as slaves. Thus, the computer works as a gateway interconnecting both WSNs. If the size of the patient' home were be too large, it could be possible to add more gateways for allowing Bluetooth sensors to not lose their connection with the system and to transmit continuously the patient's biomedical data to it.

Figure 3 shows an example of the system operation. In this case, a smoke sensor detects a higher smoke level than a previously specified threshold (1). Then, it invokes a service offered by the node which handles the fire alarm, making it to ring (2). At the same time, it also invokes a service offered by the computer that acts as both ZigBee master node and Internet gateway (3). Such gateway sends an alert through the Internet towards the remote healthcare tele-monitoring center (4). At the remote center, the alert is received by a monitoring server (5), which subsequently queries a database in order to obtain the information relative to the patient (6) (i.e. home address and clinical history). Then, the monitoring server shows the generated alert and the patient's information to the caregivers (7), which can establish a communication over VoIP (Voice over Internet Protocol) or by means of a webcam with the patient's home in order to check the incidence. The patient can also ask for assistance by pressing its manual alert button (using the personal remote control) or making a call through the VoIP terminal. In the example in Figure 3, the caregiver decides to request the monitoring server to start a voice and video communication with the patient's home (8). The monitoring server starts such communication through VoIP (10). As the gateway in the patient's home accepts it automatically (11), now the caregiver can see the patient and talk with him (12). Several webcams can be deployed through the patient's home to assure the chance of establishing the communication with the patient. If the patient is conscious, he can also talk with caregivers and explain the situation (13). If necessary, caregivers will call the fire department, send an emergency ambulance to the patient's home and give the patient instruction about how he should act.

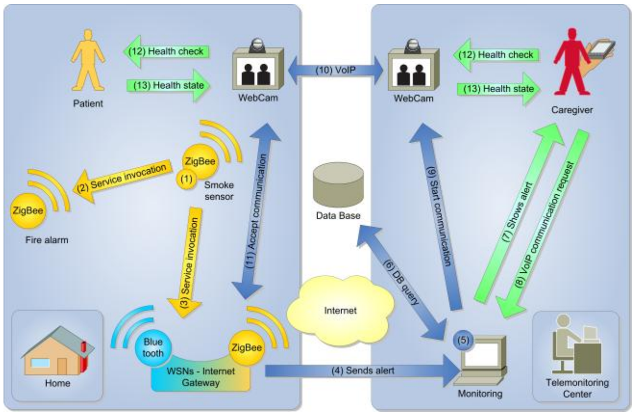

Fig. 3. Example of the system operation

Although the system is mainly focused on monitoring tasks, it also provides useful features to patients and caregivers. For example, the remote center can consult RSS (Really Simple Syndication) sources to obtain weather reports or entertainment options for patients and inform them of their scheduled medical staff visits. This information is shown on a graphical user interface on a display connected to the computer at home. Moreover, the system is not only restricted to tele-assistance but also performs home automation tasks, so that a light sensor can dim a lamp by invoking a service stored in the dimmer actuator node connected to the lamp. Furthermore, patients are not only monitored at their home, but also at the medical center when they arrive for an appointment with the doctor. The ZigBee remote control carried by each patient has a unique identifying electronic label. There are ZigBee and Bluetooth networks throughout the medical center so that the ZigBee identification label and its Bluetooth biomedical sensors can automatically connect to the corresponding patient. Moreover, the same wireless devices are useful for patients checked into the medical center because the system receives all the data gathered by the Bluetooth sensors located on the patient's body, and the caregivers will be warned if a patient is at risk. Furthermore, medical personnel as doctors and caregivers also carry ZigBee devices with identifying electronic labels, so the system keeps track of their location and movements. This allows obtaining information relevant to optimize the number of personnel necessary for taking care of each area in the center.

As previously mentioned, the system implements a distributed architecture specially designed for integrating heterogeneous WSNs. This distributed architecture is called SYLPH (*Service laYers over Light PHysical devices*) [36]. It integrates a SOA approach over WSNs. The main objective of this proposal is to distribute resources over multiple WSNs by modeling the functionalities as independent services.

As described by [1], "A SOA-based system is a network of independent services, machines, the people who operate, affect, use, and govern those services as well as the suppliers of equipment and personnel to these people and services". The term *service* can be defined as a mechanism that facilitates the access to one or more functionalities (e.g. functions, network capabilities, etc.). Services are linked by means of standard communication protocols that must be used by applications in order to share resources in the services network. A SOA approach has been chosen because such architectures are asynchronous and non-dependent on context (i.e. previous states of the system) [2]. Thus, devices working on them do not take up continuously processing time and are freer to do other tasks or consume less energy. SYLPH is based on a SOA approach, but modifying this model to fit our requirements and designing goals.

SYLPH covers aspects relative to services such as registration, discovering and addressing. Some nodes in the system can integrate services directories for distributing registration and discovering services. SYLPH allows the interconnection of several networks from different wireless technologies, such as ZigBee or Bluetooth. In this case, the WSNs are interconnected through a set of intermediate gateways connected to several wireless interfaces simultaneously. Such gateways are called *SYLPH Gateways*. SYLPH implements an organization based on a stack of layers. Each layer in one node communicates with its peer in another node through an established protocol. In addition, each layer offers specific functionalities to the immediately upper layer in the stack. These functionalities are usually called i*nterlayer services*. The SYLPH layers are added over the existent application layer of each WSN stack, allowing the platform to be reutilized over different technologies.

The *SYLPH Message Layer* (SML) offers the upper layers the possibility of sending asynchronous messages between two nodes through *the SYLPH Services Protocol* (SSP), the internetworking protocol of the SYLPH platform. That is, it allows sending packets of data from one node to another node regardless of the WSN to which each one belongs. The *SYLPH Application Layer* (SAL) allows different nodes to directly communicate with each other using SSDL (*SYLPH Services Definition Language*) requests and responses that will be delivered in encapsulated SML messages following the SSP. The SSDL is the IDL (*Interface Definition Language*) used by SYLPH. SSDL has been specifically designed to work with limited computational resources nodes [36]. Furthermore, there are other *interlayer services* offered by the SAL for registering services or finding services offered by other nodes. In fact, these *interlayer services* call other interlayer services offered by the SYLPH

Services Directory Sub-layer (SSDS). The SSDS creates dynamical services tables to locate and register services in the network. Any node that stores and maintains services tables is called *SYLPH Directory Node* (SDN).

As mentioned above, in SYLPH, a node in a specific type of WSN (e.g. ZigBee) can directly communicate with a node in another type of WSN (e.g. Bluetooth). Therefore, several heterogeneous WSNs can be interconnected through a SYLPH Gateway. A SYLPH Gateway is a device with several hardware network interfaces, each of which is connected to a distinct WSN. The SYLPH Gateway stores routing tables to forward SSP packets amongst the different WSNs with which it is interconnected. The information transported in the SSP header is enough to route the packets to the corresponding WSN. If several WSNs belong to the SYLPH network, there is no difference between invoking a service stored in a node in the same WSN or in a node from a different WSN.

3.1 Experiments and Results

Two experiments were realized to evaluate the overall performance of a tele-monitoring system prototype. The system's functionalities were compared with a previous system in a healthcare institution in Salamanca (Spain). The name of this institution is omitted in this paper due to confidentiality. The previous system consisted of a VoIP infrastructure connected between the remote center and the patients' homes. Patients were 20 elderly people with a relative risk of having a fall or home accident due to their limited mobility capabilities. With this system, each patient carried a bracelet with an alarm button that could be pressed to initiate a VoIP conversation between the home and the remote center. The panic button transmitted the alarm via Bluetooth to a USB dongle connected to a mini barebone (i.e. a personal computer) which forwarded the alert to the center through the Internet. This system was substituted by the tele-monitoring system prototype described in this paper. With the new system each patient carried the three biomedical sensors previously described (id and fall detector, ECG and breath monitors). It is important to mention that the high update rate of biomedical sensors can be a problem for small autonomous devices, especially related to power consumption and network traffic.

The patients selected had similar home characteristics (i.e. 5 rooms, including bathroom and kitchen). In each home, 5 smoke sensors, 5 light sensors, 5 light dimmers and 1 fire alarm were installed. Both systems were subjected to observation during a period of four weeks in order to gather information and make comparisons. The data tracked were relative to the alerts registered by the system from the patients' homes. These alerts could come not only from the alarm button but also from any of the other sensors that constituted the new tele-monitoring system. As a result, more risks sources, including the fall detector, the fire alarm or the heart pulse, were taken into account in the new system data. The precise measured variables were: average response time to incidents; average assisted incidents per day; average number of false positives per day; and the time employed by the medical staff to attend to an alert.

Table 1 illustrates how the new tele-monitoring system reduced the average response time to incidents. However, it was unable to reduce the false positives, increasing them instead, because the number of sensors is greater than in the former system and, consequently, the number of alarm sources. These results demonstrate that the prototype still needs more development in this aspect. It is important to mention that the new system does not reduce the time employed by the medical staff to attend to an alert, but does allow patients to be attended to earlier. Moreover, the new system allowed caregivers to detect some situations that the older system could not have. For instance, one diabetic patient tracked with the new system fainted due to a hypoglycemia situation, and was unable to press her alert button. However, the new system detected the risk with the fall detector, prompting caregivers to assist her at home, since they could not contact her through VoIP. Furthermore, the SYLPH architecture allowed the new system to merge biomedical and automation sensors from different radio technologies and at a low deployment cost.

Table 1. Comparison between both tele-monitoring systems

Factor	New tele-monitoring system	Previous tele-monitoring system
Average response time to incidents (minutes)	10	14
Average assisted incidents per day	5.7	3.1
Average number of false positives per day	3.3	1.6
Time employed by the medical staff to attend to an alert (minutes)	75	75

4 Conclusion and Future Work

The system presented in this paper allows wireless devices from different technologies to work together in a distributed way in smart environments. Because such devices do not require large memory chips or fast microprocessors to exploit their functionalities, it is possible to create a more flexible system and reduce the implementation costs in terms of development and infrastructure support compared to other analyzed tele-monitoring approaches [8, 16]. The distributed approach of this system makes it possible to add new components in execution time. In this respect, this model goes a step further in designing dynamic systems in wireless communications scenarios (e.g. E-healthcare). In addition, the system includes features that make it easy an adaptation amongst heterogeneous networks and technologies through SYLPH.

Future work includes the addition of new automation and biomedical sensors to the system to obtain additional context information. The suggestions and the necessities of patients and caregivers have been taken into account. Plans are being made to include new automation sensors to measure ambient humidity and gas detectors in order to improve patient comfort and avoid accidents. Regarding biomedical sensors, we are expecting to add electro-dermal sensors to track the cognitive activity in patients with certain brain pathologies. Other planned biomedical sensors include peripheral body temperature to detect fevers, and surface Electromyography (sEMG) sensors to monitor muscle activity. Thus, both the comfort of home automation and the vital signs gathered from patients will increase.

In addition, some improvements are under development to enhance the overall system operation. An indoor Real-Time Location System is intended to be implemented both in patient homes and medical centers. Patients will continue to carry the ZigBee wristbands as identification tags, and more ZigBee presence detectors will be present both in center and homes. Thus, if a patient suffers an accident at home, the system will warn caregivers about what room the patient is in, and activate a corresponding webcam. At the medical center, the system will keep track of the location of each patient, alerting the medical personnel if anyone leaves the center or accesses to a restricted area.

Future work on SYLPH includes an improved SYLPH Gateways performance and support for other WSN technologies as Wi-Fi. These changes will facilitate the interconnection of more WSNs technologies and in a more efficient way. To reduce design and implementation times, it is in progress the development of a tool for generating code skeletons from the human-readable SSDL language, so that the building and delivering of SSDL frames will be coded directly from the services definitions. Nevertheless, the main efforts on improving SYLPH are aimed at increasing the service registration, SDN query, service invocation and service response success ratios to nearly achieve the 100%. This is very important for the use of SYLPH in healthcare applications as such applications work with critical data and the actions performed on them can have serious consequences.

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