Pervasive Systems in Health Care

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1 Introduction

An important characteristic of "Ambient Intelligence" (AmI) environments is the merging of physical and digital space (i.e. tangible objects and physical environments are acquiring a digital representation). As the computer disappears in the environments surrounding our activities, the objects therein are transformed to artifacts, that is, they are augmented with Information and Communication Technology (ICT) components (i.e. sensors, actuators, processor, memory, wire-less communication modules) and can receive, store, process and transmit information. Artifacts may be totally new objects or improved versions of existing objects, which by using the ambient technology, allow people to carry out novel or traditional tasks in unobtrusive and effective ways.

In addition to objects, spaces also undergo a change, towards becoming augmented AmI spaces. An AmI space embeds sensing, actuating, processing and networking infrastructure in a physical (usually closed) space and offers a set of services in the digital AmI space. Applications that run on an AmI space use the services offered by the space and the artifacts therein in order to support user tasks.

Everyday habits and activities present an important source of information and may often provide information of medical significance. For example, a person's movement patterns convey important information for the person's status, thus, screening the functional status of patients through an appropriately designed set of set of motion capturing devices is of great importance. Functional activities are fundamental to maintaining independence and mobility. ADLs (activities of daily living) and IADLs (instrumental activities of daily living) are measures of dependency. People who experience a loss in the ability to perform one or more ADL may

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be manifesting the only recognisable sign of an underlying illness, such as cardiac disease.

In section 2 of this chapter, we survey the application of pervasive systems in supporting activities with health significance. A set of important existing healthcare systems is described, in order to clarify how pervasive system architectures have been adopted to meet the requirements of the health care application domain and its subdomains. In section 3, an abstract architecture of pervasive healthcare systems is presented. For each module of the architecture, the services it offers and the technologies it uses are described. Then, as model architecture, we shall describe and analyse in section 4 the HEARTS system, a pervasive system architecture that integrates a number of cutting edge technologies to enable and support patients with congestive heart failure (CHF). The technological framework is designed to be open to many other patient categories and can provide a general-purpose tool for remote monitoring with integrated medical inference and controlled decision making capabilities. The infrastructure is based on state-of-the-art measurement and data acquisition through communities of devices and artifacts, wireless data transfer and communications, data fusion, medical inference and decision making, and automatic planning and execution of advanced response patterns and interaction scenarios. The paper concludes with section 5 where a summary of all the presented architectures will be given as well as brief overview of some more projects and technologies that are related to pervasive healthcare.

2 Overview of Pervasive Healthcare Systems

As a first step we are going to present the architectural approaches adopted by some well known Pervasive Healthcare systems. In our research we focused on nine different systems. In this section we will provide a generic overview of those systems.

2.1 @HOME

Starting with the @Home system [1] which is able remotely to monitor patient's vital parameters, like ECG, blood pressure and oxygen saturation level. The patient is equipped with ambulatory sensors, which acquire this health care data, which is subsequently transmitted to a local PC station at the patient's home via Bluetooth or DECT communication link. The local PC runs special software to analyse the acquired data and produces alerts, according to the parameter threshold table (the doctor is able to remotely set the threshold values of the monitored parameters on the patient's PC). In case of any abnormality the findings and the collected vital data are immediately transmitted to the clinic via GSM for further analysis (Fig. 1):

The whole system works independently without requiring any explicit interaction with the patient. For instance, the patient doesn't connect any ambulatory sensor to

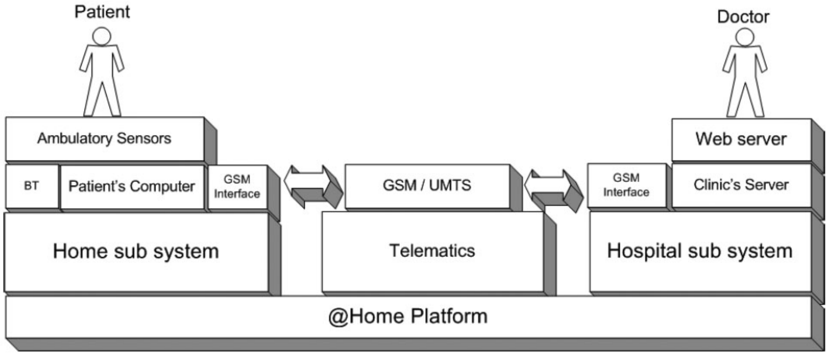

Fig. 1 @ HOME System Architecture

the local PC at the end of the day for uploading the recorded data to the clinic's server. Additionally, the patient's PC is programmed to identify the sensors and to retrieve the readings immediately, when they are accessible. At the clinic, the Monitoring module is responsible for monitoring the patient's progress. It encapsulates the rules for manipulating the @HOME database and the parametric model of the typical patient, for each disease. Then, using rules related to the monitoring of the patient's progress, the system assigns specific values to the parameters of the model, based on the readings of the patient's sensors.

2.2 HEARTFAID

HEARTFAID [2, 3, 4] aims at defining efficient and effective health care delivery organization and management models for the "optimal" management of care in the field of cardiovascular diseases. The system is based on a knowledge based platform of services, able to improve early diagnosis and to make more effective the medical-clinical management of heart diseases within elderly population. The platform provides the following services:

- electronic health record for easy and ubiquitous access to heterogeneous patient data;
- integrated services for healthcare professionals, including patient telemonitoring, signal and image processing, alert and alarm system;
- clinical decision support in the heart failure domain, based on pattern recognition in historical data, knowledge discovery analysis and inferences on patient clinical data.

2.3 ALARM-NET

ALARM-NET [5] is an Assisted-Living and Residential Monitoring Network for pervasive, adaptive healthcare developed at the University of Virginia. It integrates environmental and physiological sensors in a scalable, heterogeneous architecture, which supports real-time collection and processing of sensor data. Communication is secured end-to-end to protect sensitive medical and operational information. The system includes:

- An extensible, heterogeneous network architecture that addresses the challenges of an ad hoc wide-scale deployment, and integrates embedded devices, back-end systems, and user interfaces,
- Context-aware protocols informed by Circadian activity rhythm analysis, which enable smart power management and dynamic alert-driven privacy tailored to the individual's patterns of activity,
- Query protocol for streaming online sensor data to user interfaces, integrated with privacy, security, and power management.
- SecureComm, a hardware-accelerated secure messaging protocol and a TinyOS based module that supports user selectable security modes and multiple keys,
- A system implementation and evaluation using custom and commodity sensors, embedded gateway, and backend database and analysis programs

Fig. 2 shows an example deployment of the system in an assisted-living community with many residents or patients.

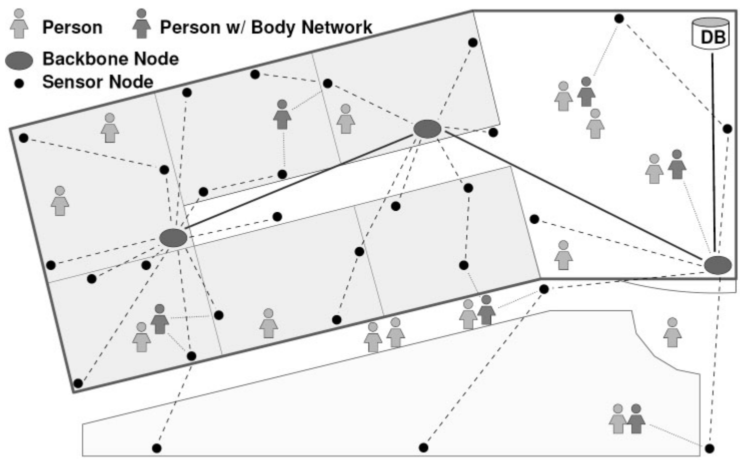

Fig. 2 Assisted-living deployment example, showing connections among sensors, body networks, and backbone nodes

2.4 CAALYX

CAALYX (Complete Ambient Assisted Living Experiment) [6, 7] is a FP6 funded project that aims at increasing older people's autonomy and self-confidence by developing a wearable light device capable of measuring specific vital signs of the elderly, detecting falls, and communicating automatically in real time with his/her care provider in case of an emergency, wherever the elderly person happens to be, at home or outside. Specifically, objectives of CAALYX are:

- To identify which vital signs and patterns are most important in determining probable critical states of an elder's health;
- To develop an electronic device able to measure vital signs and to detect falls of the older person in the domestic environment and outside. This gadget has a geo-location system so that the monitoring system is able to know the elder's position in case of emergency (especially when outdoors);
- To allow for the secure monitoring of individuals organised into groups managed by a caretaker who will decide whether to communicate events identified by the system to the emergency service (112); and
- To create social tele-assistance services that can be easily operated by the users.

2.5 TeleCARE

Project IST TeleCARE [8, 9, 10] is developing a configurable common infrastructure so that the elderly communities and those responsible for providing care and assistance can get the best out of the technologies developed. The TeleCARE approach integrates the Internet with agent and mobile-agent technologies (Fig. 3).

2.6 CHRONIC

CHRONIC (An Information Capture and Processing Environment for Chronic Patients in the Information Society) project [11] was funded by the European Community in the early years of Pervasive Healthcare research. The main objective of the CHRONIC project was to develop a new European model for the care of targeted chronic patients based on an integrated IT environment. This new model of care was applied to three highly prevalent chronic disorders that are predicted to become the top three causes of mortality in the year 2020 (cardio-vascular, neurologic and respiratory disorders). The model and the role that the use of IT played were evaluated in a series of clinical trials during the life of the project. The CHRONIC System allows the development of integrated services of home care assistance. The complexity of the services depends on the patient's clinical requirements or the supporting organisational structure. Thus, services can range from a simple follow-up

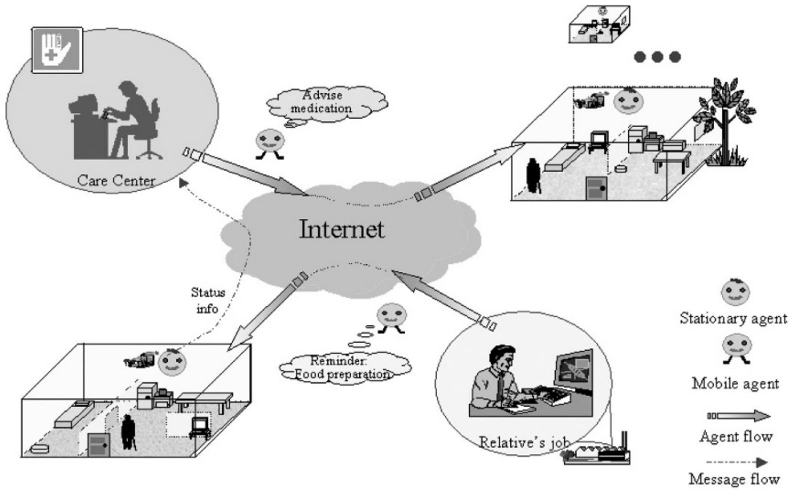

Fig. 3 Plug-and-play approach

call to the acquisition of patient's instrumental clinical data from a distance, which are evaluated at the control centre and dispatched to the networked health care professionals.

2.7 MyHeart

MyHeart [12, 13, 14] is an Integrated Project (IP) funded by the EU in the context of FP6 aiming at developing intelligent systems for the prevention and monitoring of cardiovascular diseases. The project develops smart electronic and textile systems and appropriate services that empower the users to take control of their own health status.

The system uses wearable technology to monitor patient's Vital Body Signs (VBS) and then processes the measured data in order to provide recommendations to the user. As illustrated in Fig. 4, the communication loop can either consist of direct local feedback to the user or of professional help by a physician or nurse. The latter will typically be provided remotely, that is why the MyHeart system also comprises a telemedical element. Data are transmitted to a remote server, where a professional can process it and contact the patient subsequently.

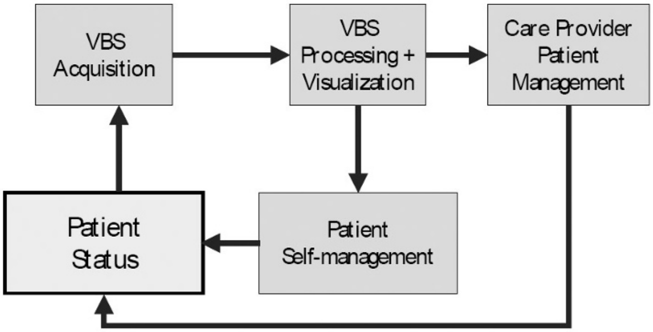

Fig. 4 MyHeart disease management and prevention approach

2.8 OLDES

The OLDES project [15] implements an innovative low-cost technological platform, which provides a wider range of services to elderly people. The goal of the system is to provide both entertainment and communication services. The main actors of the OLDES system are shown in Fig. 5.Different groups connect to the proposed system: thousands of elderly people (clients) and several animators and professionals. In the central system, information about all the users is stored. A direct connection between doctor/social services and elderly people can also take place but, usually, this will happen via the central system on the explicit request by the patient. Moreover, the on-line analysis of the client's behaviour and health status allows health and social operators to give each client specific support if needed through the various communication channels.

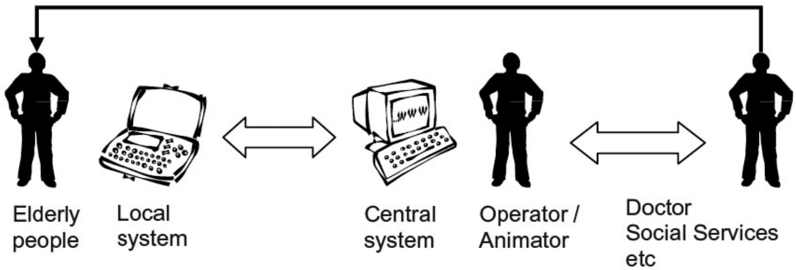

Fig. 5 OLDES Main Actor Groups

2.9 SAPHIRE

In the SAPHIRE project [16, 17] the patient monitoring will be achieved by using agent technology complemented with intelligent decision support systems based on clinical practice guidelines. The observations received from wireless medical sensors together with the patient medical history will be used in the reasoning process. The patient's history stored in medical information systems will be accessed through semantically enriched Web services to tackle the interoperability problem. In order to guarantee long term patient monitoring and successful execution of clinical decision support systems the following services are supported:

- *Accessing vital signs of the patient:* In order to be able to monitor the patient's current condition, the clinical decision support systems need to access the vital signs of the patient measured by wireless medical sensors and body-worn platforms.
- *Accessing Electronic Healthcare Records of the Patient:* The gathered vital signs of the patient can only be assessed correctly when consolidated with the Electronic Healthcare Records (EHRs) of the patient.
- *Accessing the Clinical Workow systems executed at Healthcare Institutes:* While the clinical decision support system is executing the Clinical Guideline Denition, it is needed to interact with several modules of the clinical workow executed at the healthcare institutions.

The SAPHIRE Clinical Decision Support System that is responsible for deploying and executing clinical guidelines in a heterogeneous distributed environment is implemented as a multi-agent system. Its agents communicate in a reactive manner and are instantiated and eliminated dynamically based on the demand.

3 Reference Architecture

In this section we shall present different architectures used in pervasive healthcare systems. One could claim that these systems follow the same high-level architecture and consist of:

- **Input-Output Subsystem:** all these systems use sensory input, albeit of varying data types. This input is provided by sensors attached either to the space or to the user, by wearable devices or by specific healthcare devices that retrieve specific measurements. For each system we are going to analyse the specific input it uses and we are going to provide an overview of the technology used for doing so;
- **Local Subsystem:** the local subsystem locally collects sensory and other information and provides it to the healthcare system. The local subsystem may appear in the form of a single computer or as a small computing device like a PDA. In other cases, it may not be a concrete system but rather a collection of

software agents each one specializing in a different operation. Lastly some systems provide a middleware as a common operating platform so that the devices have a common understanding with the rest of the sensory system. Our purpose is to analyse the specifics of the each subsystem and provide a thorough overview of it;
- **Remote Subsystem:** all pervasive healthcare systems send the data collected to a specific service provider that either does some kind of processing on it, or stores it into health medical records. Usually these subsystems reside on Healthcare service providers, capable of providing scientific monitoring of the data and checking whether the patient is in a critical condition or not in order to provide immediate support.

3.1 Input-Output System

The types of input that pervasive healthcare systems collect depend on the medical variables they monitor or analyze. Sources of input are medical devices, everyday devices and objects, sensors embedded in the user's local space or audiovisual recording devices. In order to achieve closer and seamless monitoring of user's health with the least possible intrusion in the patient's lifestyle, these devices are sometimes adapted as wearable devices or become embedded to specific cloth ware. The most widely monitored medical variables are those related to Cardio Vascular Diseases (CVD); thus, the medical devices that are used are mainly:

- Electrocardiograph (ECG)
- Heart Rate Monitor (HRM)
- Blood Pressure Monitor (BPM)
- Oxygen Saturation Monitor (SpO2)

These devices are in most cases interfaced to a local data collecting station, such a PC or a PDA. In the @HOME system, for example, the wearable sensors transmit continuous information to the patient's computer (Fig. 6). Furthermore, all the sensors are portable, meaning that the patient is able to use them outdoors as well. The sensors are wired through serial ports to a serial communication hub which in its part is interfaced to a Pocket PC or iPAQ that is equipped with a Bluetooth card.

ALARM-NET uses a combination of wearable pulse-oxymeter and several ECG sensors, all connected to MicaZ [18] devices. These collect patient vital measurements for Heart rate (HR), heartbeat events, oxygen saturation (SpO2), and electrocardiogram (ECG). The MyHeart system combines input from specific medical devices together with that coming from Body Signal Sensors (BSS) embedded in a specifically designed shirt (Fig. 7). The variables monitored include electrocardiogram (ECG), respiration and motion activity detection.

In addition to the medical devices there is a need of taking measurements of nonmedical variables, which may provide information about the user's current status. These are called Activities of Daily Living (ADL) and are described as "things

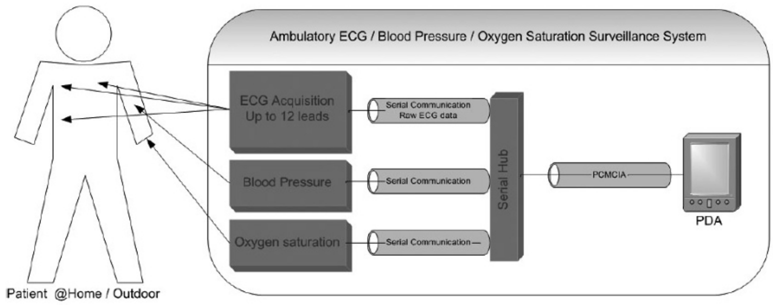

Fig. 6 @HOME Sensors' communication schema

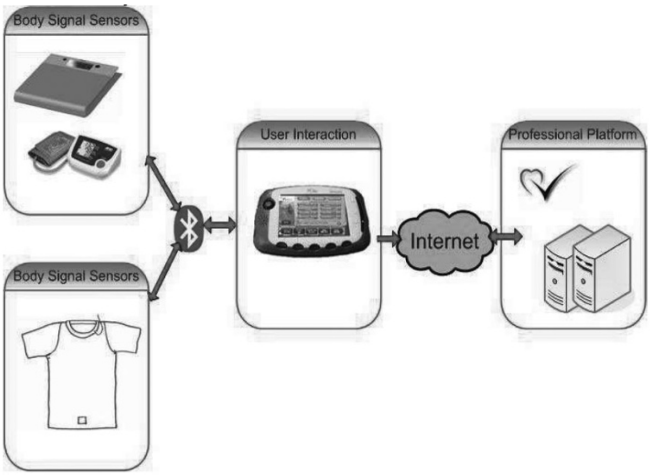

Fig. 7 Architecture of the MyHEART's Take Care System

we normally do in daily living including any daily activity we perform for selfcare (such as feeding ourselves, bathing, dressing, grooming), work, homemaking, and leisure" [19]. Typical ADL measurements contain body weight, movement patterns and sleeping habits. Most of the systems that monitor patients at home take measurements concerning a set of ADL variables. For example, in the ALARMNET system, the monitoring of ADL variables is a highly important task. That is why the system consists of several elements capable of measuring ADL variables, including a motion sensor used to track presence in the house, a body network that records human activities such as walking, eating and stillness and incorporates a GPS to track the outdoor location of the user, indoor temperature and luminosity sensor, and bed sensor(Fig. 8).All these are interfaced to a MicaZ wireless sensor node that processes the sensor data using interrupts and forwards the information through the wireless network.

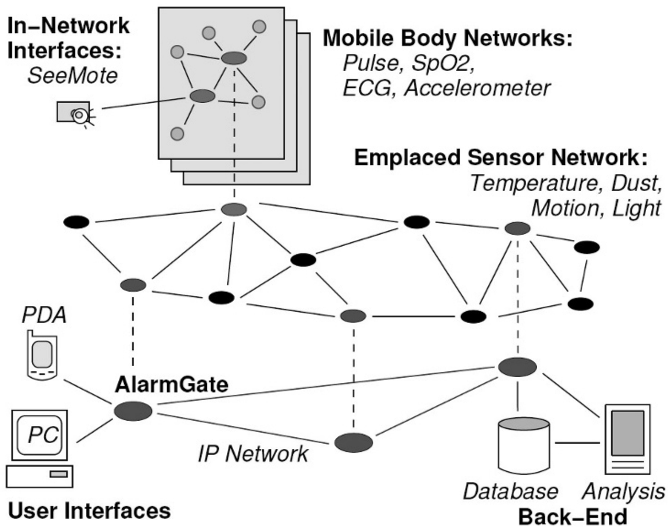

Fig. 8 ALARM-NET architecture components and logical topology

While all systems provide some kind of sensory input some of them provide also output subsystems, for direct communication with the user. For example, at the CHRONIC Integrated Care Platform, the Patient Units (Fig. 9) support video conferencing, telemonitoring, messaging and educational services. The units are to be used in connection with a TV set. The telemonitoring functionality is provided in combination with a set of sensors, which measure oxygen saturation, ECG, spirometry and accelerometer.

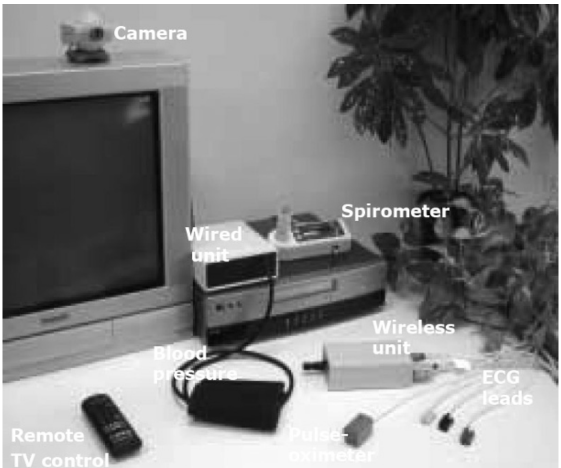

Fig. 9 CHRONIC's Patient Unit (with sensors)

In the majority of the above cases the input-output subsystem is either connected to the local system, or directly to the remote monitoring system, using one or more of the common communication protocols. Commonly used wire technologies are serial connection, X10 or Ethernet. However with the evolution of wireless technologies, which make the monitoring units more portable, a very common practice for Body Area Networks is Bluetooth [20] followed by 802.11b/g [21]. Specific systems however use the logic of sensor networks such as ALARM-NET which uses the MicaZ motes as sensor nodes which communicate with 2.4 GHz IEEE 802.15.4, TinyOS Wireless Measurement System [22].

3.2 Local System

The local subsystem usually is used as a collector for the sensory input that each system provides. It is implemented usually in a PC that resides in the patient's local space and is connected to the Internet so that it can transfer the locally collected data to a remote system. In a much simpler case, the local PC is replaced by a router routing data from the local sensors to the remote system. Such is the case of the @HOME system, which uses a desktop PC or a laptop positioned at some point in the patient's home to provide the user end of the communication link between the clinic and the patient's home. Its functionalities are the following:

- It receives all recordings transmitted from the medical sensors and transmits them to the clinic's Central System Server. The transmission will be realized via wireless infrastructure. The Remote Controller establishes a TCP/IP connection over GSM/GRPS and conveys the data to the Clinic's Central Server (CCS).
- It controls all remote sensors connected to it. It is responsible for the proper functionality and checks the status of each sensor, identifies communicating sensors, downloading the readings, uploading schedules to the sensors.
- Additionally, the Remote Controller enables the patient and his family members to monitor his progress using an appropriate user interface. That interface offers limited functionality compared to the Clinic User Interface.

The same approach is adopted by the CHRONIC Integrated Care Platform where the user station has the responsibility of retrieving the local data and sending them to the Patient Management Module. Similarly, in OLDES system, a PC is used to provide user entertainment (tele-accompany) and care facilities through a series of easy-to-access thematic channels. The PC is integrated with multiple wearable and ambient sensors and devices that gather the information to be sent to a remote Central Node (CN) as is shown in Fig. 10.

Some systems use a middleware layer, which manages the data exchange between the various system modules. In addition, this level ensures that all the incoming, outgoing and exchanged information, as well as all the communications taking place among the internal modules of the platform and between the platform and the

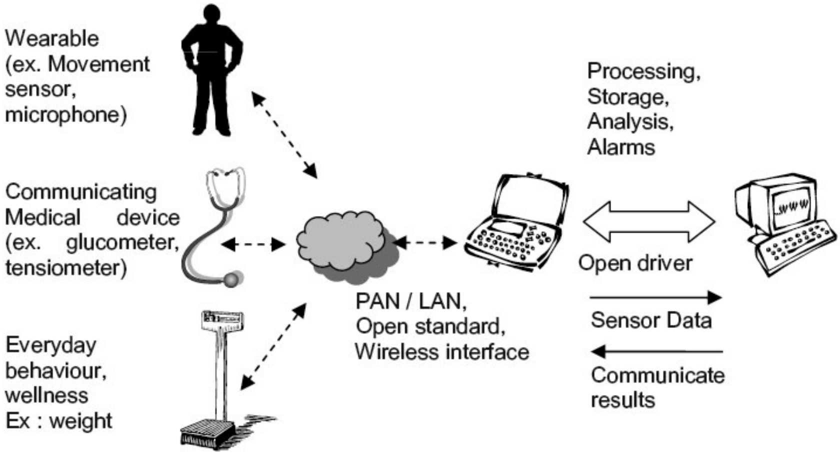

Fig. 10 OLDES' System architecture

external applications are compliant with the standards for clinical data representation and communication.

In the case of the HEARTFAID system, all biomedical devices interact with the middleware level. The TeleCARE platform consists mainly of a set of agents, whose purpose is to discover local services, offered either by existing medical devices or by ubiquitous computing devices and sensors. The Device abstraction layer of the TeleCARE platform provides the necessary interfaces to the sensors, monitoring devices and other hardware (home appliances, environment controllers, etc.). In the TeleCARE environment each service can be implemented as a set of distributed stationary and mobile agents. For instance, a monitoring service might involve a stationary agent in the care center (interacting with the care worker), a number of stationary agents in the elderly home (agents in charge of monitoring local sensors, e.g. temperature sensor, presence sensor), and a mobile agent sent from the care center to the elderly home (Fig. 11). This mobile agent might carry a mission to collect information from different sensors and report back to the care centre.

A different approach is used in the SAPHIRE architecture.

The bottom layer represents the actual sensor hardware. Above that, the networking layer is comprised of a Bluetooth stack and a TCP/IP stacks. The sensor driver layer implements the communication protocol that determines the sensor's data structure and how it is transmitted through the network layer. If a new sensor is introduced to the system, the Data Point Abstraction layer ensures that only the proprietary sensor driver needs to be adapted. A Virtual Device, as it can be seen in the layer above the Datapoint Abstraction can - but does not necessarily have to - correspond to a physical device. A Virtual Device can also receive its data from an algorithm that derives data from other (possibly also virtual) devices (Fig. 12).

The sensor data coming from wireless sensors to the gateway computer are exposed as Web services (Fig. 13). These Web Services have been published to the

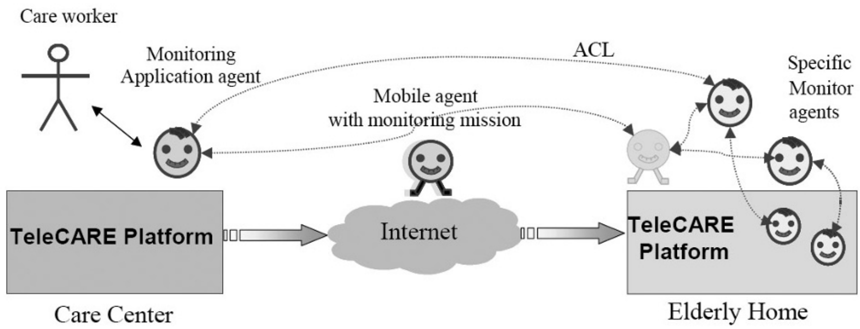

Fig. 11 Example of a service implementation

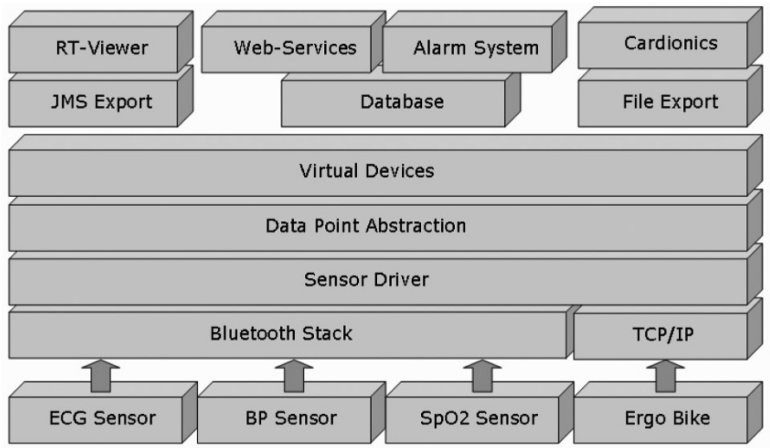

Fig. 12 Sensors and Data Point Abstraction

UDDI Registry together with their functionality semantics, which are based on the IEEE 11073-10101 standard. The bottom layer represents the actual sensor hardware. Above that, the networking layer is comprised of a Bluetooth stack and a TCP/IP stack.

In other cases there is no concrete local system, in the form of a single unit. For example in the case of the ALARM-NET the infrastructure of the local system consists of a sensor network. Data from the body network and the sensors is transmitted to user interfaces or back-end programs. These devices form a multi-hop wireless network to the nearest AlarmGate application. AlarmGate applications run on embedded platforms, managing system operations and serving as application level gateways between the wireless sensor and IP networks. These nodes allow user interfaces to connect, authenticate, and interact with the system. There are also systems that don't support any kind of local subsystem, such as CAALYX, where

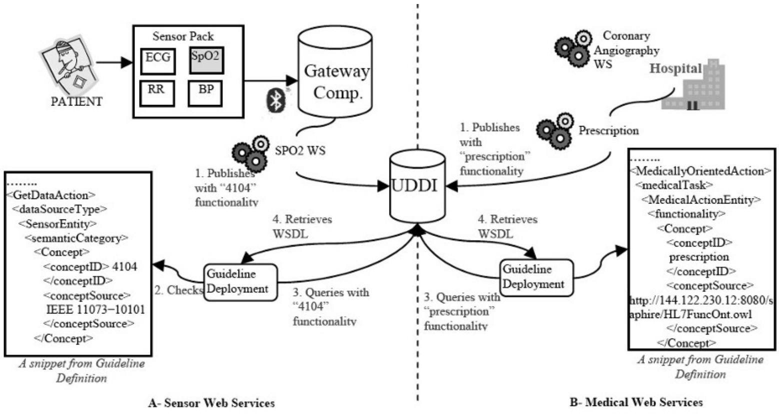

Fig. 13 Sensor and Medical Web Services Architecture

both roaming and home monitoring devices are connected directly to the Internet in order to provide their data to Healthcare systems (Fig. 14)

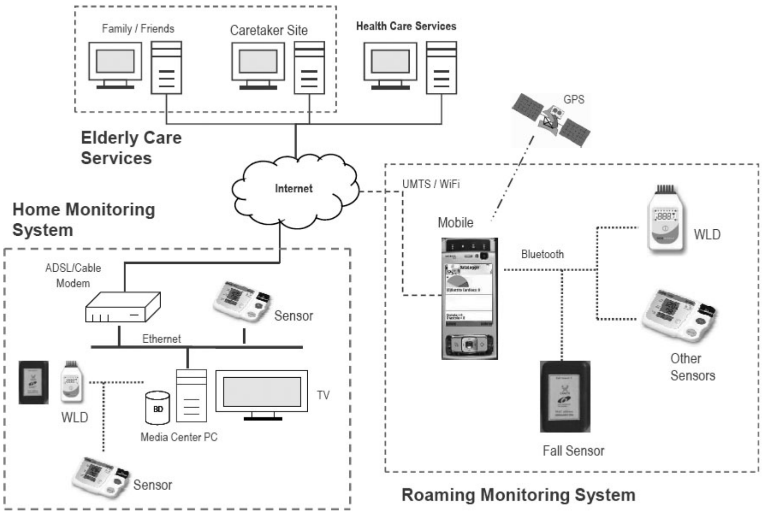

Fig. 14 CAALYX system diagram

3.3 Remote Subsystem

Data collected from the local subsystems is usually sent to a remote system. The remote systems are mostly sophisticated systems that run special algorithms for further data extraction. They combine both medical and ADL data in order to provide a holistic view of the patient's current medical status. Furthermore they may keep thorough patient health records in order to have a complete overview of the patients fact file. A typical remote system, as the one supported by the @HOME system, consists of:

- Clinic's Central Server (CCS), is responsible for monitoring the patient's progress based on a parametric model of the typical patient;
- Health record system / Database, which enables the system to keep in a uniform way the records of each patient;
- Clinic user interface (CUI), which provides access to each member of staff in the clinic.

Some other remote systems, as the one of the ALARM-NET, provide online analysis of sensor data and long-term storage of system configuration, user information, privacy policies, and audit records. Note that, as wireless sensor networks grow stronger in their capability to collect, process, and store data, privacy and the protection of personal information become rising concerns. Systems must include a framework to protect privacy and still support the need to provide timely assistance to patients in critical health conditions.

In the CAALYX system all data and alerts produced by both the Roaming and Home Monitoring systems are sent to the Central Care Service and Monitoring System. The caretaker will evaluate whether received alerts need to be communicated to the emergency service, in which case the geographic position and data about the likely type of emergency (fall, stroke, etc.) will be provided to the emergency service, so that a suitably equipped emergency team may be dispatched in a timely manner to the patient's location. Besides this service, video-communication with the home environment will be provided to attend to the older person's demands.

In the CHRONIC system, the Chronic Care Management Centre (CCMC) is the core of the whole system and is composed of two main modules: the Call-Centre and the Patient Management Module. This centre can be placed inside a hospital or another healthcare structure, or it can be part of a service centre from which requests and/or clinical data can be transmitted to the clinical reference centre of the patient.

The HEARTFAID system uses an ontology-based decision support mechanism. The knowledge level integrates symbolic knowledge and computational reasoning models. The decision support subsystem implements data processing algorithms and provides guidelines to using medical protocols and accessing the knowledge base, as well as alarms and diagnostic suggestions in case of critical situations. The architecture of the CDSS subsystem is typical of an ontology-based system, comprising the following components (Fig. 15):

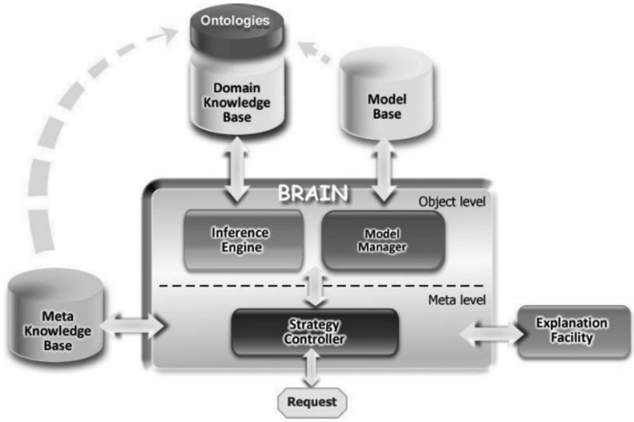

Fig. 15 The general view of the HEARTFAID CDSS architecture - dashed arrows correspond to reference to the ontologies, while the others denote a direct communication

- *Domain Knowledge Base*, consisting of the domain knowledge, formalized from the European guidelines for the diagnosis and treatment of chronic HF, and the clinicians' know-how;
- *Model Base*, containing the computational decision models, as well as signals and images;
- *Processing methods and pattern searching procedures*;
- *Meta Knowledge Base*, composed by the strategy knowledge about the organization of CDSS tasks;
- *Brain*, the system component endowed with the reasoning capability;
- *Explanation Facility*, providing means to explain conclusions taken.

As one can see, the knowledge in the system is partitioned into different modules, something that makes knowledge maintenance easier. Specifically, the Domain Knowledge Base uses a hierarchy of core and upper level ontologies combined with rules as knowledge representation formalism; this facilitates easy re-use and sharing of knowledge. In the agent based architecture adopted in the TeleCARE platform, the main purpose of the Care Center is to produce specific task agents to be sent to the local system in order to collect and report back information from different sensors. The Core MAS Platform (Fig. 16) is the main component of the basic platform. It supports the creation, launching, reception (authentication and rights verification), and execution of stationary and mobile agents as well as their interactions.

The SAPHIRE system architecture combines multi-agent systems with ontologies. The Clinical Decision Support System is implemented as a multi-agent system, so as to cope with the heterogeneity and dynamic nature of the distributed clinical environment. Agents are autonomous components that communicate with each other in a reactive manner; some of these components can be instantiated and eliminated dynamically. Various roles are assigned to the system agents, as can be seen in

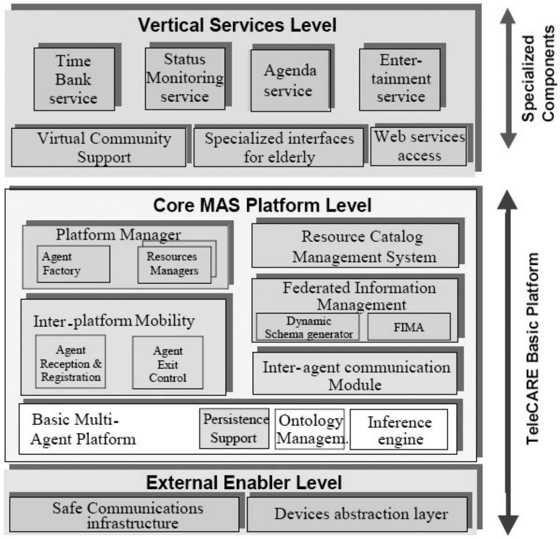

Fig. 16 The TeleCARE platform architecture

Fig. 17. Among these, the Ontology agent resolves the semantic heterogeneity that appears when the medical Web services, the sensor data, and the EHR documents use different reference information models and clinical terminologies.

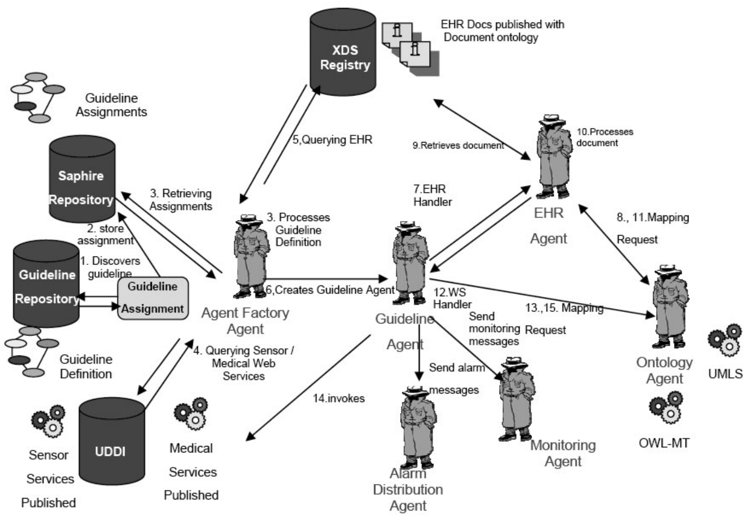

Fig. 17 The SAPHIRE Multi Agent System

4 The HEARTS System

The HEARTS system [23] aims at assisting in the rehabilitation and remote monitoring of people with cardio-vascular diseases by using an ambient monitoring environment installed in the user's own space. The system adds services in user's space, which help the patient in taking the necessary measurements himself, in his own local space. At the same time, it supports remote monitoring of user activities, as they could provide more information about the user's daily status. The HEARTS system gathers information using devices and sensors in the user's local space, filters this information in the local subsystem and forwards the formatted information to the specialized remote system that can take decisions about the patient's status. The above tasks are carried out without intruding in the patient's daily activities.

The functionality of the system transcends simple monitoring and plain comparison of measurements to predefined values that could lead to alarms. When potentially negative trends are identified in the monitored health variables, the system issues effective pre-alarms or alarms, involving the automatic creation and execution of in-situ responses (such as audible and/or visible feedback through appropriately adapted familiar common devices) and external responses (engaging health service providers and other formal and informal health structures). Interaction scenarios with the user are integrated into the system's operation either as part of a medical data acquisition schedule or as an automatically created system response.

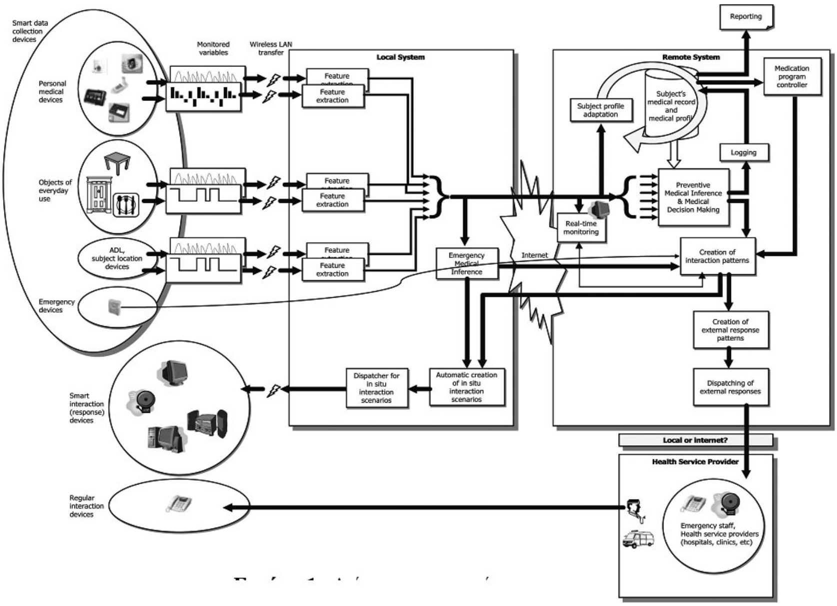

Fig. 18 HEARTS System Architecture

The HEARTS architecture is composed of the following subsystems (Fig. 18):

- **Local Devices/Services:** contains all the devices and services that are deployed in the user's local space. These are not used just for sensory input but they also provide actuation (such as warning messages and guidelines for the device usage);
- **Local Subsystem Manager (LSM):** this is the gateway for the local services, where initially processed data are gathered, packaged and sent to the remote system;
- **HEARTS Middleware:** the purpose of the HEARTS middleware platform is
  - to provide a common interface between the devices and LSM, in order to maintain a rich communication, and
  - to provide a common interface among the devices themselves, in order to form artifact communities
- **Remote Subsystem:** the purpose of the remote subsystem (that resides in a health care service provider) is to collect the data for each patient from each local subsystem and to run sophisticated algorithms, which may derive pre-alarm or alarm states. In such cases the system either notifies its administrator to contact the patient or sends back to the LSM the appropriate notification messages in order to be presented to the user using his local devices

A simple usage scenario of the system goes as follows: The system notifies the patient to take a measurement (i.e. using ECG). The measurement data is sent to LSM through the middleware communication protocol. LSM packages the data into a secure XML envelope and sends it to the remote subsystem. The remote subsystem combines the data with past measurements (e.g. taken during the past month) and tries to analyse the patient's current status by running the appropriate algorithms. The system decides that there is a possibility of heart failure in the next days. It sends a message back to the local system for a pre-alarm warning and communicates with the local administrator. When LSM receives the pre-alarm message, it sends it to a vocal notification device which warns the user to communicate with his doctor because his readings aren't too good.

4.1 Local Devices/Services

The HEARTS system aims to provide the user-patient with a set of services that will enable him to take any measurement that may be needed in order to have a secure overview of his heart condition, while minimizing intrusion in his living environment. They are classified in the following categories:

- **Medical Devices:** All the devices used for taking the necessary measurements of medical variables. These include:

  - Electrocardiograph (ECG): An ECG device that is able to analyse the patients heart state
  - Oxymeter: The oxymeter measures the amount of oxygen (SPO2) in the user's blood
  - Blood Pressure Monitor: The BPM device is used to get regularly reading of the user's blood pressure
  - Thermometer: A simple temperature reading device that record patient's temperature

- **ADL Devices:**A set of devices and artifacts that monitor ADL variables. Currently, two devices are used::

  - Weight Scale: The measure of every day weight is considered important since most people with CVD problems tend to have abnormal weight changes
  - Bed: A specifically designed bed with embedded sensors able to monitor the time that the user stays at bed. Abnormal sleeping patterns of a patient may indicate problems that may be connected with imminent cardiac arrest

- **Sensors:**A set of sensors attached to the home enables the system to record the current state of the patient's local space. These sensors include temperature, light, location indication.
- **Actuators:** Artifacts (such specially designed lamps) that are able to provide the end user with health related information from the system are deployed in the local system. These can be used to provide warning messages to the user (e.g. a lamp that flashes may indicate to the user that he has a pre-alarm state) or to provide an easy living ambient environment in conjunction with the sensors of the system (i.e. a lamp to light if the light sensors of the system sense low ambient luminosity)
  All the above devices/services are adapted to the system with the help of the HEARTS-OS middleware that is going to be analysed in the next paragraph.

4.2 HEARTS-OS

The HEARTS-OS kernel is the fundamental component of the HEARTS system architecture (Fig. 19).

It is the smallest set of components and functionalities needed so that any device can become an artifact and interact with the HEARTS system. The kernel itself(Fig. 20) is divided in four distinct parts: the Communication Module, the Process Manager,the Memory Manager and the State Variable Manager.

The *Communication Module* is responsible for handling communication between different artifact nodes and the local server. This module implements algorithms and protocols for wireless, connectionless communication (using the 802.11b/g protocol) as well as mechanisms for internal diffusion of information exchanged. The

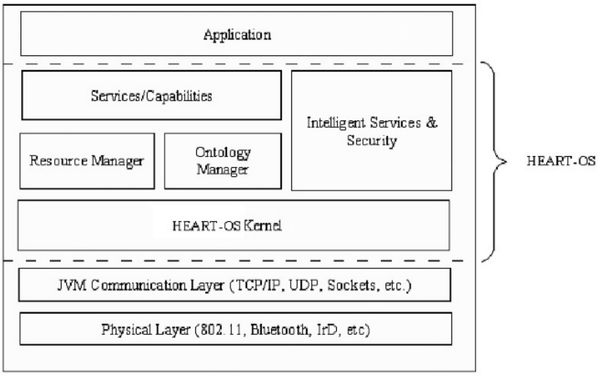

Fig. 19 HEARTS-OS Architecture

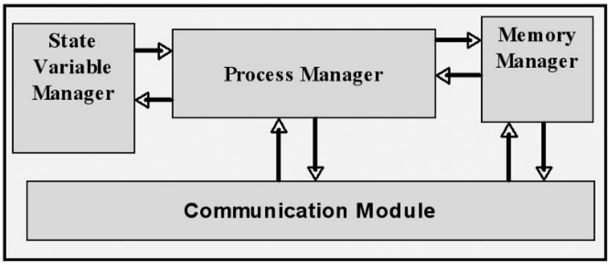

Fig. 20 HEARTS-OS Kernel

Process Manager is the coordinator module of HEARTS-OS. Some of its most important tasks are to manage the processing policies of the HEARTS-OS, to accept and serve various tasks set by the other modules of the kernel and to implement the artifact collaboration protocol. The *State Variable Manager* is a repository of the hardware environment (sensors/actuators) inside HEARTS-OS reflecting at each particular moment the state of the hardware. Finally the *Memory Manager* is a local storage module for various storage operations, like communication paths, current connections available etc The communication between artifacts or artifacts and local server is perceived as peer-to-peer. Communication between two peers is accomplished with asynchronous XML messages. In order to provide stability as well as abstraction to the communication interface we have divided the communication system into three layers.

- **Peer**: A peer is any networked device that implements one or more communication protocols. Each peer operates independently and asynchronously from all other peers and is uniquely identified by a Peer ID. Peers allow for other components higher in the hierarchy, like the Process Manager, to register themselves as event listeners, in order to receive notifications for incoming data. Peers are also responsible for the implementation of communication protocols, such as discovery protocol, message exchanging protocols, routing protocol etc.

- **Pipe**: Each peer owns two pipes: an Input pipe waiting for incoming messages and an Output pipe that sends either unicast or multicast messages to the network. Pipes are an asynchronous and unidirectional message transfer mechanism used for service communication. Pipes are indiscriminate; they support the transfer of any object, including binary code, data strings, and Java technology-based objects. However, as HEARTS-OS is a platform and language independent system, only XML messages are transferred through pipes
- **Endpoint**: Each pipe is bound to one or two Endpoints, which are considered as the fundamental networking units of the Communication Module. The Endpoint may be associated to specific network resources such as a TCP port and associated IP address. An input pipe owns two Endpoints, one for listening multicast messages and one for listening TCP p2p messages. An output pipe owns one Endpoint which is configured dynamically to send either multicast messages to a default multicast group, or p2p TCP messages.

HEARTS-OS Communication Module defines a series of XML message formats, and protocols, for communication between artifacts, which use these protocols to discover each other, advertise and discover network resources, and communicate and route messages. There are four basic and two complementary communication protocols:

- **Gadget Discovery Protocol (GDP)**. This protocol is used to discover artifact in the local space using resources as criteria. Resources are represented as advertisements, and usually contain information about a remote artifact (i.e. ID, Services, Relay, etc.). This information can then be used to establish a p2p communication. An artifact creates a discovery message that is sent to all listening artifacts through a Multicast Endpoint. There are two kinds of discovery messages, the simple ones, where a specific ID is requested and the complex ones, where either a specific service from an unknown artifact is requested.
- **Gadget Advertisement Protocol (GAP)**. This protocol is used to advertise one or more attributes of an artifact. An advertisement message is usually a response to a discovery message, thus formed according to the requested information.
- **Gadget Information Protocol (GIP)**. This protocol is used for exchange of data between artifacts. It uses a single unicast pipe to send the information to a specific peer. Each data message is folded inside an envelope that contains the recipient's identification.
- **Message Acknowledging Protocol (MAP)**. This underlying protocol is responsible for the robustness of the communication system. Its main task is to provide acknowledgements (ACK) for each arrived message to the sender and NACK receipts for each lost message. Furthermore if a message is lost the MAP protocol is responsible for resending the message to the target artifact.

Apart from this basic protocol scheme there exist two complementary protocols that may optimize the network performance and increase the capabilities of HEARTS system.

- **Service - Resource Discovery (SRDP)**. This protocol is used to discover specific services and resources that specific artifacts may have throughout the network. The services or resources may vary from low level resources like CPU, memory, etc. to high level like light, display, sound capabilities etc.
- **Routing Protocol (RP)**. This protocol deals with the problem of what should an artifact do when it cannot reach a synapse-peer directly. A solution is to apply the relay technique.

While communication module handles all the message transaction between two artifacts (or artifacts and server) there is an important virtual communication level that takes part in the process manager, the Plug - Synapse communication model (Fig. 21)

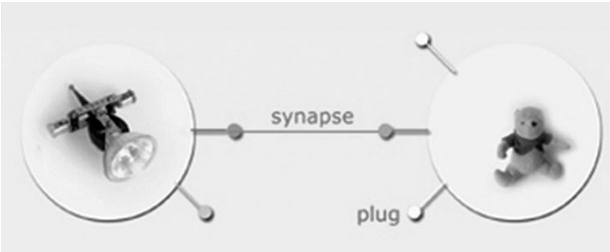

Fig. 21 The Plug-Synapse Communication Model

- **Plugs**. A plug belongs to an artifact and is an abstraction of its properties and abilities. It is the only way other artifacts can use an artifacts's services and have access to the artifact's properties, and is accessible to other artifacts modules via HEARTS-OS only. Each artifact has several S-Plugs and one T-Plug.
  - **S-Plugs**. An S-Plug is the plug that describes services and there is one S-Plug per service.
  - **T-Plug**. Each artifact has a T-Plug that contains its physical properties as well as a list of its S-Plugs. A T-Plug comprises the HEARTS identity of a component as it gathers all the HEARTS specific information in one object.
- **Synapses**. A synapse is a connection between two S-Plugs.

By collaborating with the Communication Module and the State Variable Manager, the Process Manager sets up an event based internal messaging system that combines input from sensors and actuators with input received via synapses from other artifacts. The Plug-Synapse model envelops a set of services that can initiate a virtual path, send data through this path and break it if necessary. The communication is done through well define XML messages. These services are:

- **Synapse Request:** One of the artifacts sends a Connection request message to another artifact. The message contains information concerning the local and remote plug.

- **Synapse Response:** When the target artifact receives the message, it checks the plug compatibility of the remote and local plugs. If plug compatibility test is passed, an instance of the remote plug is created and a positive response is sent to the artifact that initiated the synapse. The instance of the remote plug is notified for changes by its remote counterpart plug and in fact serves as an intermediary communication level. In case of a negative plug compatibility test, a negative response message is sent to the remote plug, while no instance of the remote plug is created. When the initial artifact receives a positive response, it also creates an instance of the remote plug, for the same reason as before, and the connection is established.
- **Synapse Activation:** After connection established, the two plugs are capable of exchanging data. Output plugs use specific objects, called shared objects (SO), to encapsulate the plug data to send, while input plugs use specific event-based mechanisms, called shared object listeners (SOL), to become aware of incoming plug data. When the value of the shared object of the output plug is changed the instance of the remote plug is notified and a synapse activation message is sent to the other artifacts. The remote artifact receives the message and changes the shared object of the instance of the remote plug. This, in turn, notifies the target local plug, which reacts as specified.
- **Synapse Disconnection:**Finally, if one of the two connected plugs breaks the synapse, a synapse disconnection message is sent to the remote plug in order to also terminate his end of the synapse.

The communication scheme described above supports artifact-to-artifact communication. The logical communication channel used between the artifacts and Local Server is provided by the HEARTS-OS middleware. Local Server and artifacts exchange information through a specific Synapse between a specially designed Plug, the Monitoring Plug, or MPlug. The MPlug inherits its basic properties from the Plug class, therefore, has all the abilities of a single Plug. However, its functionality is enhanced in the following ways:

- **Monitoring of the low-level context of the host artifact**. When created, the MPlug is connected to the State Variable Manager in order to retrieve the low level data of the host artifact. From this point on, any change on those data is reflected to the MPlug through an event based mechanism
- **Monitoring of high level state**. The MPlug may receive high level monitoring data, provided by the inference engine, representing higher level states of the artifact. These variables are processed in the same manner as the state variables.
- **Monitoring the variables of a remote artifact**. The MPlug can receive the variables of a remote artifact (via a synapse), and monitor the data they represent

The MPlug has a dual role. On one hand, it monitors the parameters of a local artifact and on the other hand, it records changes in the synapse for visualization purposes. Two connected MPlugs are completely synchronized and any change made on one is also sent to the other (Fig. 22).

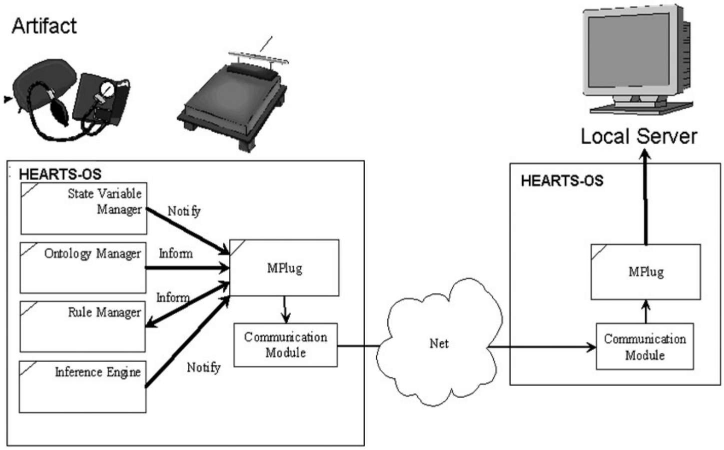

Fig. 22 MPlug Communication Mechanism

4.3 HEARTS Local Subsystem Manager (LSM)

The HEARTS Local Server contains a series of end user tools that support the creation of pervasive computing applications that collect measurements. These tools interact with the artifacts in the HEARTS-OS level in order to create/break connections and monitor data through the conceptual model of HEARTS-OS. Furthermore the Local Server is responsible to forward the information to a remote system where specific algorithms run in order to make a decision about the patient's current health state. Lastly an important task for the Local Server is to provide informative messages to the user from the remote system, such as an imminent warning about his condition.

The Local Server's tools aim to (i) create the appropriate tests so that the Local Server can gather the appropriate measurements (ii) create home based applications between artifacts and (iii) trace back specific data in order to provide to the end user history data about a medical variable.

The Scenario Creation Tool (Fig. 23) aims to discover the local devices, and provide to the user with an appropriate mechanism to create scenarios of Device usage. It is actually an interface where the user can add specific tests needed to be done after a certain amount of time (e.g take ECG measurements every 6 hours). The tool provides a series of steps where the user can add the interactions needed to be done between the system and the patient in order to take the appropriate measurement. After the execution of a scenario, the system can decide if the scenario was executed correctly and collect the appropriate measurements, or may notify the user to repeat the scenario.

The Artifact Editor is a complementary tool that can be used to create associations among artifacts used to monitor ADL (Fig. 24). The tool provides an overview of the artifacts that exist in the area and their services. It also supports the estab-

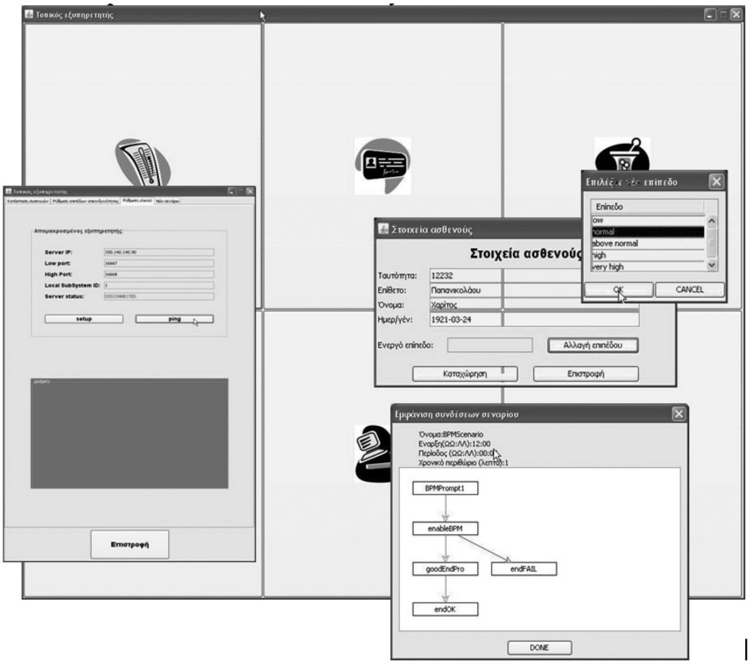

Fig. 23 Local Subsystem Manager - Scenario Creation tool

lishment of Synapses between the artifact Plugs, so as to facilitate data exchange. For example one can connect an artifact chair with a desk lamp so that the lamp is switched on whenever the user is sitting on his chair. This kind of applications, created by the end-user himself, aim to ensure the user's easy living.

4.4 Remote Monitoring

In the HEARTS system, the data that are collected locally is sent to a remote server for further processing. The remote server is designed is such way that it can monitor multiple local environments, and includes decision making mechanisms in order to extract information about the current state of the patient and to deduce if the patient is on an imminent alarm of a heart stroke (Fig. 25).

The communication protocol is based on a simple XML mechanism. However, because personal data concerning a patient's health state are sensitive, security and privacy algorithms are applied in the whole process. Any message that is sent to the Remote Server and contains sensitive data is packed within two different envelopes: *the Privacy envelope*, which ensures that the data is coded with a user's specific key so that it can be used only by the specific user, and *the Security envelope*, which ensures that the information will be point-to-point encrypted.

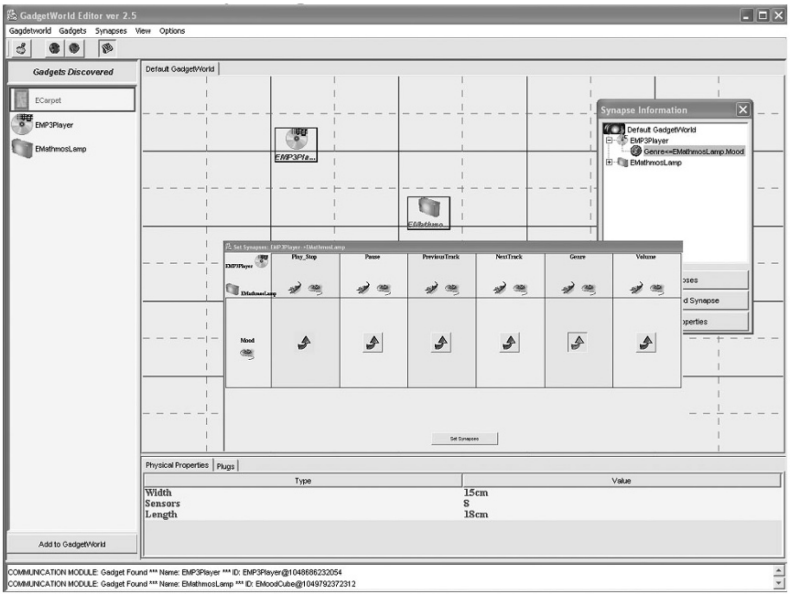

Fig. 24 Artifact Editor

Fig. 25 Remote subsystem communication module and risk detection

The Remote Server also provides a set of tools for monitoring a patient's medical data over a period of time so that a doctor can be aware of the current health state of the patient. Data is encrypted in the remote system so that only the attendant doctor can have access to a patient's medical history. However an alert that results from the decision making algorithms becomes known to anyone who is in the interest set of the user (family, doctor, health service provider).

5 Conclusions

In this chapter, we surveyed a few pervasive systems, which provide holistic pervasive healthcare support and can be regarded as representing different architectural approaches. Three subsystems are commonly found in these systems: the input/output subsystem, the local processing subsystem and the remote subsystem. The first is used as source of health-related data (these are a combination of medical variables and ADLs), as well as communication channels between the system and the user. The local processing subsystem may simply transmit the data to the remote system, or it may apply complex processing on it, before sending it. The remote subsystem stores and processes the data and creates alerts when the patient's condition becomes critical.

While all the systems presented in this chapter fall into the same architectural style each of them presents a different set of novelties, such as:

- Wearable body electronics that are seamlessly added on the patients clothing (or as a part of the clothing like shirts), which enable medical and ADL measurements to be recorded (*@Home, CAALYX, ALARM-NET, MyHEART*)
- Middleware components specifically tailored for medical systems in such way that the whole system won't lose any critical data (*HEARTFAID, HEARTS*)
- Agents based systems that are able to pickup the appropriate devices for specific critical medical tasks (*TeleCARE, SAPHIRE*)
- Development of medical ontologies for providing better decision support systems (*TeleCARE, HEARTFAID, SAPHIRE*)
- Sophisticated algorithms for decision support that are able to provide a-priori knowledge of heart failure conditions (*HEARTS*)

The list of pervasive healthcare systems grown constantly.

MobiHEALTH [25, 26]. The system provides new mobile health services, based on the on-line, continuous monitoring of vital signs, via GPRS and UMTS technologies. These services are supported by the MobiHealth Body Area Network (BAN), a wireless system that allows the simple connection of different vital signal sensors; **SAPHE** [27] which develops a new generation of telecare networks with miniaturised wireless sensors worn on the body and integrated homes (and ultimately offices, hospitals, etc.) to allow for intelligent, unobtrusive continuous healthcare monitoring; **WASP Project** [28] (Wirelessly Accessible Sensor Populations), which has made a case study on the deployment of sensors network specifically aimed for elderly care monitoring. **SOPRANO** [29] (Service-oriented Programmable Smart Environments for Older Europeans) is an Integrated Project in the European Commission's 6th Framework Programme and aims is to enable older Europeans to lead a more independent life in their chosen environment. Research within SOPRANO focuses on three pillars.

- To design the next generation of systems for ambient assisted living in Europe, including innovative contextaware, smart home environment services with natural and comfortable interfaces for older people at affordable cost.
- To set up large-scale, visible demonstrations of innovative Ambient Assisted Living systems showing their viability in European markets.
- To adapt and extend state-of-the art Experience and Application Research methods, integrating design-for-all components and providing innovative tools to create a new, consistently user-centred design methodology.

Finally **M-POWER** [30] is an IST project whose aim is to develop a middleware platform that enables rapid development of novel smart house systems in a SOA environment. The platform in particular supports: (a) Integration of SMART HOUSE and sensor technology; (b) Interoperability between profession and institution specific systems (e.g. Hospital Information System); (c) Secure and safe information management, including both social and medical information; and (d) Mobile users which often change context and tools.

As a general conclusion there is a lot of work done and going on that is focused on pervasive health care environments. Most of the work focuses on patients either on Cardio Vascular Diseases, Alzheimer or Dementia. The purpose of all systems is to provide people with an easy living and safe monitoring environment in such a way that they will continue to carry on with their daily activities while under the system's "care".

6 Acknowledgement

This paper describes research done in various Pervasive Healthcare projects. Pictures describing architectures of those systems are owned by the respective project consortia. Furthermore the work presented for the HEARTS plarform describes research carried within the HEARTS project funded by GSRT. The authors wish to thank their fellow researchers in the HEARTS consortium.

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