Modelling mobile health systems: an application of augmented MDA for the extended healthcare enterprise.

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Abstract

Mobile health systems can extend the enterprise computing system of the healthcare provider by bringing services to the patient any time and anywhere. We propose a model-driven design and development methodology for the development of the m-health components in such extended enterprise computing systems. The methodology applies a model-driven design and development approach augmented with formal validation and verification to address quality and correctness and to support model transformation. Recent work on modelling applications from the healthcare domain is reported. One objective of this work is to explore and elaborate the proposed methodology.

At the University of Twente we are developing m-health systems based on Body Area Networks (BANs). One specialization of the generic BAN is the health BAN, which incorporates a set of devices and associated software components to provide some set of health-related services. A patient will have a personalized instance of the health BAN customized to their current set of needs. A health professional interacts with their patients' BANs via a BAN Professional System. The set of deployed BANs are supported by a server. We refer to this distributed system as the BAN System. The BAN system extends the enterprise computing system of the healthcare provider. Development of such systems requires a sound software engineering approach and this is what we explore with the new methodology.

The methodology is illustrated with reference to recent modelling activities targeted at real implementations. In the context of the Awareness project BAN implementations will be trialled in a number of clinical settings including epilepsy management and management of chronic pain.

1. Introduction

Mobile health systems (m-health systems) can extend the enterprise computing system (ECC) of the healthcare provider by bringing services to the patient any time and any place. We present a methodology for design and development of such extended enterprise computing systems. The methodology applies the design and development approach of MDA [1], [2], [3]. The MDA approach is selected as it addresses the complete development life cycle and promises support for portability, cross-platform interoperability, platform independence, and domain specificity. In particular it is selected for investigation as a means to support *genericity* and *evolvability* of a BAN system architecture and to support *domain specific modelling*.

MDA is augmented with formal validation and verification in order to address quality and correctness of both design and implementation, and to support model transformation. The importance of quality and correctness cannot be overemphasized for the sensitive and safety critical application domain of healthcare.

At the University of Twente we are developing m-health systems based on Body Area Networks (BANs). The implementation work began with the European IST project MobiHealth [4], [5], [6], [7], [8], [9] and continues in the Dutch FREEBAND Awareness project [10] and the European eTEN project HealthService24.

In MobiHealth we defined a BAN as a collection of inter-communicating devices (a computer network) which is worn on the body, providing an integrated set of personalised services to the user. One specialization of the generic BAN concept is the *health BAN*, which incorporates a set of devices and associated software components to

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provide some set of health-related services. This mobile healthcare application extends the operation of the health care provider into the community by bringing services to the patient and by feeding back captured data into the healthcare provider's enterprise computing system.

In MobiHealth the prototype BANs and BAN service platform were engineered by conventional methods. We now propose to revisit the design and development process and develop and apply a more rigorous design and development methodology in order to re-engineer the system for genericity, reliability and reuse.

In a previous paper [11] we proposed an extension of the model-driven approach wherein formal methods are used to support the process of modelling and model transformation within an MDA framework. This design and development methodology adds a practical but robust approach to verification and validation of models and of transformations. We described plans to apply this methodology to the development trajectory for BAN systems. In this paper we report on ongoing modelling work in applying the methodology in the applications domain of health Body Area Networks. The models are targeted at real implementations. Prototype BAN implementations will be trialled in a number of clinical settings including epilepsy management and management of chronic pain.

The methodology is summarized in section 2 below and in Section 3 we describe the Body Area Network and supporting system. Example models of BAN components are presented to illustrate the modelling approach used. This modelling exercise represents the first phase in the application of the proposed methodology. Some issues raised are discussed in Section 4 and Section 5 gives some conclusions and plans for future work.

2. The Methodology

Figure 1 gives a simple high level view of the methodology. We propose to follow the model-driven approach of MDA, creating Platform Independent models (PIMS) and transforming them to derive Platform Specific Models (PSMs) and from them implementations. The heavy arrow in Figure 1 marks this transformation trajectory. The innovation of the proposed approach lies in the use of tool based mathematical formalisms to support Validation and Verification (V&V). The light arrows indicate the application of validation and verification techniques. Two main V&V methods are used: application of model checking to models, and formal testing based on automatic test derivation. The tests are derived from the models but applied to the implementations, thus proving some form of formal equivalence between models and corresponding implementations. It is also planned to use formal methods to address the task of model transformation. The approach also relates to previous work on model checking [12], [13], [14], formal testing [15], [16] and transformation [17], [18], [19].

The overall design and development steps of the development trajectory are as in MDA:

- Model the PIM
- Derive PSMs from the PIM
- Derive code from the PSMs

The second and third steps are ideally performed by means of model transformation. In parallel the additional verification and validation steps are performed:

- Formulate critical properties (assertions derived from the requirements)
- Model check the PIM against formally expressed properties
- Apply automatic test generation to the PIM
- Apply the test suite thus derived to the implementation.

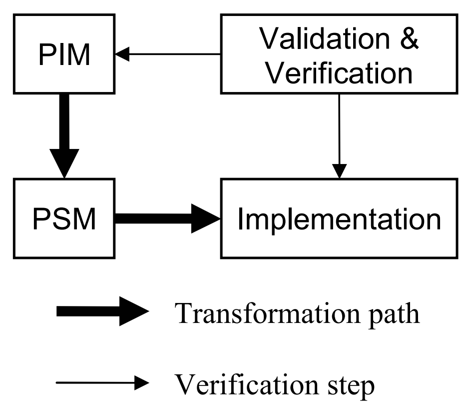

Fig.1. High level view of Methodology: Transformation Path and Verification/Validation steps

Figure 2 gives a more detailed view of one possible way of applying the methodology. As well as showing more detail, in this example we instantiate some of the steps of the general methodology with particular modelling paradigms and notations (UML, Promela, *me too*), particular tools (SPIN model checker, TORX test generator) and aim at a particular target implementation technology (J2ME). Many other choices could be made at all steps.

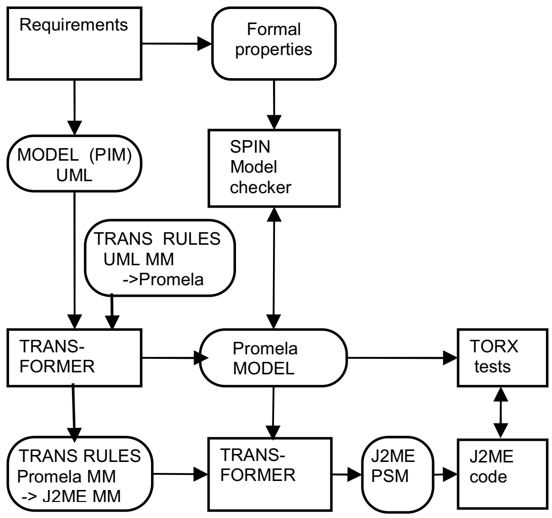

Fig. 2. Example of an application of the methodology

The approach assumes a generic transformation tool which is parameterized to sets of (model) transformation rules. Promela is used in this example as an intermediate notation since it is accepted by the model checking and test generation tools used here. For a more detailed account of the design and development methodology please see [11].

The following sections describe the m-health application and illustrate application of part of the methodology, namely the initial modelling of PIMs. We also discuss some of the PSMs required for this application (BAN-based mobile healthcare services).

3. Modelling an m-health system

First the concept of Body Area Networks is introduced and the space of concepts relating to Body Area Networks is presented.

3.1 Body Area Networks for healthcare

The concept of the Body Area Network originally came from work at MIT and IBM [20]. Historically the concept was first discussed under the topic of PANs (Personal Area Networks) and only later distinguished by the use of a separate term Body Area Network. Zimmerman used the term "Intra-Body Communication" in the context of PANs (Personal Area Networks) to describe data exchange between body worn devices using the body itself as the communication medium. "Electronic devices placed on and near the body modulate an electric field that induces small currents throughout the body. Data connections are established by touch or close proximity (within 2 meters)". One application was to exchange electronic business cards during a handshake.

The concept was developed further by many other researchers, for example at Philips [21], by the MobiHealth team at the University of Twente, and at Fraunhofer [22]. In the Wireless World Research Forum's Book of Visions, we defined a BAN as "a collection of (inter) communicating devices which are worn on the body, providing an integrated set of personalised services to the user" [23]. In the MobiHealth project we defined a BAN not by transmission technology but by physical position and range, as a computer network which is worn on the body and which moves around with the person (that is, it is the unit of roaming). We use this definition in the remainder of this paper.

A BAN incorporates a set of devices which perform some specific functions and which also perform communication, perhaps via a central controlling device which we call a Mobile Base Unit (MBU). Devices may be simple devices such as sensors or actuators, or more complex multimedia devices such as cameras, microphones, audio headsets or media players such as MP3 players. The central controlling device (if there is one) may perform computation, coordination and communication functions. Communication amongst the elements of a BAN is called intra-BAN communication. If the BAN communicates externally, i.e. with other networks (which may themselves be BANs), this communication is seen (from the point of view of the BAN itself) as extra-BAN communication. So far we speak of a generic BAN; this concept can be specialised by application domain, for example a health BAN or an entertainment BAN.

In the MobiHealth project a prototype of a health BAN system was developed, together with several specializations of the health BAN for telemonitoring patient groups including cardiology patients, patient with chronic respiratory disease and pregnant mothers. Further specializations of the health BAN are developed within the Awareness and HealthService24 projects, including telemonitoring BANs for epilepsy and teletreatment BANs for patients with chronic pain. Figure 3 illustrates the MobiHealth/Awareness BAN. Figure 3a shows the architecture and Figure 3b shows the hardware components used in one of the BAN configurations built and trialled during the MobiHealth project.

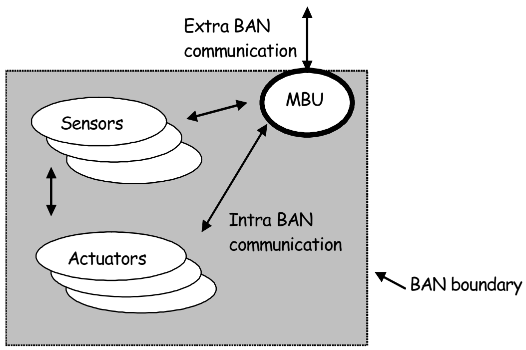

Fig. 3a. Generic architecture of the BAN

Fig. 3b. One BAN configuration: PDA, front-end and sensors

Fig. 3. The MobiHealth Body Area Network

In this case the MBU is implemented by a PDA (an iPAQ). The sensors shown in Figure 3b are electrodes and an activity sensor. They are examples of front end supported sensors systems. The blue box in the lower part of the figure is the sensor front end. This configuration represents one of many different specializations of the generic BAN developed and realized at the University of Twente.

The concept space encompassing generic BANs, health BANS and specializations of health BANs can be modelled as a class hierarchy. Figure 4 shows such a class hierarchy. Figure 4 identifies several levels of increasing specialization of BANs. The top level relates to generic BANs, where class (generic) BAN is seen as a specialization of the more generic class Network.

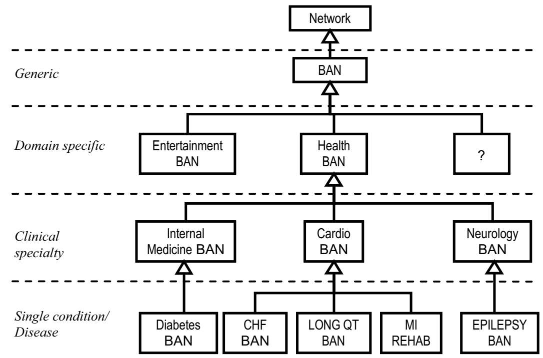

Fig. 4. Position of Health BANs as part of a UML class hierarchy

The generic BAN can be specialized by domain (health BAN, entertainment BAN, and so forth). We choose to distinguish the Health BAN as characterized not by use of medical devices, but rather as including *devices used for medical purposes*. By this means we include generic devices such as cameras or GPS positioning systems in a health BAN on the grounds that they are being used for health-related purposes. Health BANs may be further specialized by clinical specialty (eg. internal medicine or neurology), however this level of specialization may not always be specific enough to begin to talk about services. So we distinguish a further level of specialization: clinical condition. At this level we can begin to identify disease management services and, for each service, an association with a set of devices and an application. Examples of (still rather generic) services would be ECG monitoring, blood pressure monitoring, blood glucose monitoring, alarm services, location services, medication reminders, fall detection, loss of consciousness detection and control signals to implanted devices of various kinds. Within one specialty (eg. cardiology) we can distinguish a different set of services for patients with different conditions. A patient with Long QT syndrome may require ECG monitoring, heart rate monitoring and defibrillation services (hence their BAN devices may include an implanted defibrillator), whereas a patient recovering from myocardial infarction may require heart rate, heart rate variability and ECG monitoring services so their BAN may include electrodes for measuring ECG (from which the other parameters may be derived). Such BANs should be generic for a class of patients, but of course may require tailoring to the needs of individual patients. Later we discuss the issue of customization and personalization of BANs.

3.2 Modelling the Health BAN (PIM level)

The objective of the modelling activity is not only to encompass all the existing specializations of the MobiHealth BAN but also to be generic enough to cover the current BAN developments conducted in the Awareness and HealthService24 projects as well as many future possible instantiations of BANs, including those based on future ambient intelligence technologies and smart sensor networks.

First we model the BAN system. There are two main categories of users of the BAN system: the patient users and the professional users. A patient wearing a BAN has a set of services available to him, varying with his current set of needs and his clinical conditions(s). Some of the services may be transparent to the patient and fully automatic (eg. telemonitoring, automatic alarms) others may be patient driven (eg. patient initiated alarms).

The professional users are the consumers of BAN captured data such as biosignals and alarms. They may be health professionals or other professional care providers. The (health) professional or (health) care provider interacts with their patients' BANs via a BAN Professional System. This system provides BAN specific services, but may interface to the healthcare provider's ECC such as a GP practice administrative system and/or clinical information system (CIS) or a Hospital Information System (HIS), possibly interfacing directly to the EMR (Electronic Medical Record). The professional system may itself run on a mobile system (eg a laptop or PDA.). Services for professionals include access operations (eg retrieving and viewing biosignals) and also control operations such as remotely activating a BAN, or a BAN device, or altering sampling frequencies of sensors. Both patient and professional systems will have many different specializations incorporating different functionality sets, hardware and applications.

3.2.1 The BAN system model. A great many individual patient BANs and professional BAN systems may be in operation out in the field at any one time. These components are supported by a server which knows about management of BANs and BAN applications and which mediates between the patients and the professional users. We refer to this server as the BAN Back End System *BESys*. Together these components: BANs, Professional Systems and BESys comprise a distributed system which we refer to as the BAN system. Communication between the components is effected via communications channels. At the most abstract level we do not distinguish further (eg. into wired/wireless channels). Figure 3 illustrates a logical view of these components. The components to the right hand side of the dotted line are in the domain of the healthcare provider and are outside the scope of the BAN system, apart from the interface components.

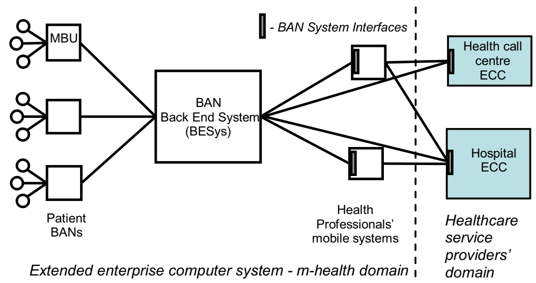

Fig. 5. Components of the BAN System and its interface to the healthcare provider domain.

The BeSYS provides, amongst others, the BAN access functions to the healthcare providers' enterprise computer systems and to health professionals' mobile systems.

Our model identifies the classes of objects involved in a BAN System as seen in Figure 2, provides a mathematical representation of the object class BANSystem and identifies the services it offers, eg. ECG monitoring. These services will be further specified at a lower level of abstraction, depending on the clinical requirements. ECG monitoring may be specified as 3-lead or 12-lead, for example. At time of instantiation further attributes such as sampling frequency and required mode and quality of presentation can be specified. The model shows that a BAN System consists of one Back End System, a number of BANs, a number of BAN Professional Systems and a set of channels linking these systems.

BANSystem =
tuple(BESys, set(BAN), set(BANProfSystem), set(Channel))

This is a type specification taken from a *me too* model. If using the *me too* language for modeling, the first step is identification of objects, operations and their relationships. This gives a mathematical description of the concept space and plays a role in the elaboration of the domain ontology. In further modelling steps the signatures and formal definitions of operations are given. Constraints which can be used for model checking can be expressed as predicates. A full explanation of the *me too* notation can be found in [24].

The BAN system provides services to different classes of user (patients, health professionals) and also provides system services. BAN services offered to health professionals include:

- Request subscription
- Start BAN
- Stop BAN
- Show BANs
- Show BAN
- Show BAN Devices
- View BAN Data
- Call Patient
- Change Sampling frequency
- Add Application

The *me too* model will include these as operations, specified by signature and by formal definition.

BAN services offered to patients might include: ECG monitoring, blood pressure monitoring, blood glucose monitoring, patient initiated alarm, automatic alarm, location services, medication reminders, activity monitoring, fall detection, loss of consciousness detection, epileptic seizure detection, epileptic seizure prediction.

Although these are patient care services in most cases they are transparent to the patient and the only active use is by the health professional who is also a user of these services.

BAN system services include: BAN/MBU discovery, BAN/MBU release, BAN service discovery, BAN service registration, add service to BAN, remove service from BAN and push sensor data.

We can view a BAN system as a network, where the nodes are BANs, professional systems and the Back End System. In terms of network topology it could be modelled as a graph. We now turn to the BAN itself.

3.2.2 The BAN model. Now we look at the internal components of the BAN. The MBU or Mobile Base Unit is an (abstract) device which combines the functions of communications gateway and a computation platform. In the MobiHealth and Awareness projects the MBU functions have been implemented on PDA and smart phone platforms but in future the functionality could be implemented on a specialized chip, which could perhaps be implanted. In the network view a BAN is a kind of network where the nodes are the MBU and the other BAN devices and the channels are the (wired or wireless) links between the devices. Since the nodes may themselves be complex components or subnetworks we refer to them as BAN Connected Device Systems (BCDSs) or BAN devices for short. From a network point of view the BAN can be specified thus:

BAN = tuple(MBU, set(BCDS), set(Channel))

Here we identify three subclasses of BCDS: sensors (devices which perform some measurement), actuators (devices which cause some mechanical action) and multimedia devices (such as cameras, microphones, display devices and headsets). Many more devices, such as pumps, pacemakers and defibrillators, are possible candidates. We specify this at a high level as:

BCDS = Sensor | Actuator | MM_device | ...

We may extend the model to include the concept of services offered by the BAN:

BAN = tuple(MBU, set(Service), set(BCDS), set(App), set(Channel))

where each service implies a set of hardware components (BAN devices) and an application (a set of software components).

In order to support reuse, the high level mathematical representation (at the level of the PIM) needs to cover not only devices used in the past and current projects, but should also accommodate all kinds of BAN devices that we can envisage in the future.

Constraints on permitted connectivity and attributes of nodes and channels need to be modelled at a later stage. Care should be taken to introduce constraints at the appropriate levels of abstraction and at the appropriate levels of specialization.

A channel links two network nodes and has some associated attributes. Attributes will include, which (wired or wireless) technology is used (eg. Bluetooth, Zigbee, WLAN, WIFI) and characteristics of the communications channels including dynamic properties such as available bandwidth. It may also represent information about data flows and synchronization.

From the possible range of devices which may be connected to a BAN, we focus now on sensors. Individual sensors may be connected directly to a

BAN. Another case is where a collection of sensors which is managed by its own front end device may be connected; we refer to this subsystem as a *Front End Supported* sensor system (FESSS).

Sensor = SimpleSensor | FESSS

A front end supported sensor system may take care of several different sensing functions each with their own group of sensors (known as a sensor set). The front end performs tasks such as powering sensors, synchronizing the sensor sets according to a built in clock and performing some signal processing on raw sensor output. It will also mediate control signals originating externally.

FESSS = tuple(FrontEnd, set(Sensorset), set(Channel))

Figure 6 shows the arrangement of components in a front end supported sensor system. The front end device receives raw signals from one or more sensor sets and performs some processing on the signals before outputting the processed signals to a consumer component. The front end handles synchronization of signals and may be able to handle different sampling frequencies for different sensors.

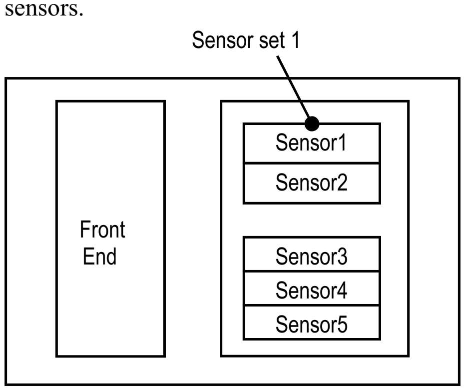

Fig. 6. Front End Supported Sensor System (FESSS)

We have noted that the BAN system is a network, some of whose nodes (BANs) are themselves networks. Within the BAN we also see networks of devices, such as sensor systems comprising a set of sensors, a clock and a sensor front end. An FESSS (especially from the topological perspective) may in turn be modelled as a graph. We represent this concept of nested networks in a UML diagram in Figure 7.

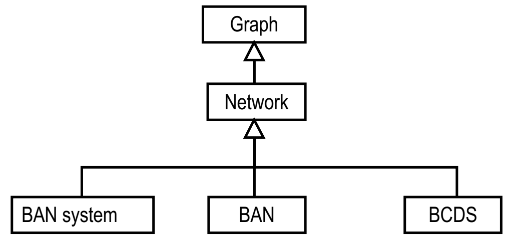

Fig. 7. Nested networks

The recursive relationship between networks and nodes may be modelled at a meta-level in UML as shown in Figure 8.

We exploit this concept of nested network models to give both genericity and leverage to our models at appropriate levels of abstraction.

In this section we have endeavoured to give an outline of the concepts involved in the m-health application and to give some illustrative example of the modelling activities whereby these concepts are being formalised. This gives a flavour of part of the PIM modelling step of the methodology. In this case we have used UML diagrams for graphical representation and me too for textual representation.

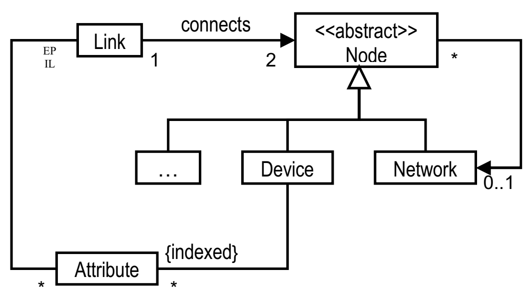

Fig. 8. UML metamodel: nested networks

3.3 Technologies and platforms for the Health BAN (PSM level)

In this section we describe some of the technologies and platforms which may be used to realize subsystems of the BAN system model. For each of these we will require a PSM. Many kinds of PSMs will be required, addressing different aspects of the implementation, for example, modelling the target middleware technologies, programming languages and operating systems and of course the hardware components of the BAN.

For each of these PSMs many choices of platform can be made for a given PIM. The models of hardware components such as commercially available sensor systems can be regarded as PSMs in the sense that they refer to a particular hardware platform for implementation of a given (abstract) function. For example a location service may be implemented using a particular commercially available GPS positioning device. Elaboration of the method of deriving PSMs from PIMs and the validation and verification trajectory; are for future work; here we proceed directly to some outline examples of some of the components for which PSMs will be required.

3.3.1 The Back End System. The Back End System was realized in MobiHealth as a proxy server using Jini technology to realize the BAN system services. The Back End System also implements other functions including a BAN Data Repository (BDR) for storing BAN captured data. For more details please refer to [25]. At the PSM level then we will need models and metamodels of the Jini architecture, the BDR and the other components of the Back End System. Access to BAN data is mediated by the proxy server. In future the interfaces in the healthcare providers' Enterprise computing systems and the health professional mobile systems may be implemented by Web Services technology.

3.3.2 Sensor systems. For implementing location services we select a particular positioning device, such as the GPS device from EMTAC. We define a specialization of class Sensor to be the class EMTAC GPS system, and specify as an attribute the service it offers (location service). This is a simple sensor so it can be connected directly to the MBU.

If ECG monitoring services are needed, we may choose to implement this service using a particular front end supported sensor system, the Mobi from Twente Medical Systems International. The Mobi receives signals via wired connections from a number of signal sources and transmits the processed signals to a consumer over a wireless (Bluetooth) connection. We refer to the Mobi and attached sensors as a Mobi sensor system. This is an instantiation of an FESSS. The technical specification of this version of the Mobi includes the property that all sensor sets attached to the Mobi are synchronized with each other. All sensors within a sensor set are not only synchronized with each other, further they all operate at the same sampling frequency. This and other constraints and definitions can be expressed in the PSM and will be part of the specification which constrains the application model for BANs and BAN applications using this version of the Mobi. Below we show the part of the PSM for (this version of) the Mobi which expresses these properties. The model fragment shown below is read not as a requirements specification but as a specification formalising fixed properties of this device which need to be taken into account in the design and implementation of BANs which integrate instances of this device.

MOBISensorSystem

OBJECTS

MobiSensorSystem
Mobi
SetofSensorset
Sensorset

MobiSensorSystem = pair(Mobi, SetofSensorset)
SetofSensorset = set(Sensorset)
Sensorset = set(Sensor)

CONSTRAINTS

$\forall$*mss : MobiSensorSystem .*
$\forall$*ss1, ss2 : 2(mss) . synch(ss1,ss2)*

$\forall$*s1,s2 : Sensorset .*
synch(s1,s2) ^
samplefreq(s1) = samplefreq(s2)

This model fragment identifies the objects concerned and shows their representations and relationships (eg a MobiSensorSystem can be represented as a pair; the first element of the pair is the Mobi and the second is a set of sensor sets). The first constraint expresses the sychronisation property and the second the constraint on sampling frequencies as explained above.

3.3.3 The MBU. Any number of Platform Specific Models (PSMs) of the MBU can follow from the PIM of the MBU. The PIM specifies that the MBU is the BAN's communication gateway taking care of Intra-BAN and Extra-BAN communications, and the computation platform providing BAN processing (generic BAN functions plus specific BAN services) and local storage functions.

MBU services may be realized in one device, for example a UMTS enabled PDA or a smart phone, or they may be distributed over different devices, for example a UMTS phone (for communications services) and a PDA (for storage and processing services).

The following platforms have been or are being targetted in the BAN development work at the University of Twente.

- HP iPAQ 6340
- QTEK 2020 with Wifi card
- HP iPAQ 5550 / 4150 with Mobile Phone
- T-mobile MDA III
- Nokia 9500

In addition to a set of PSMs for the selected MBU device(s), we need PSMs for the software implementation technology, eg. J2ME or C++.

3.3.4 A PSM of a condition-specific BAN. A condition-specific BAN provides a set of services associated with a particular disease or condition (see Figure 9). Each service implies a set of devices and associated application components to be configured on the MBU. Applications may in fact be distributed across the BAN and BeSys, even migrating dynamically between them.

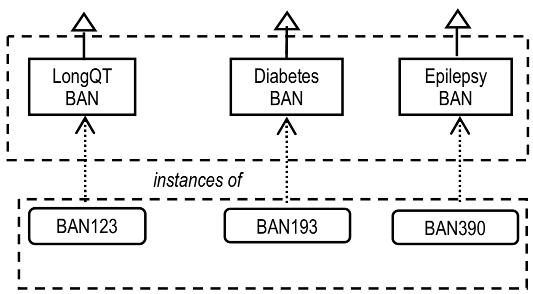

Fig. 9. Condition specific BANs

A BAN for Long QT syndrome patients might include ECG monitors and an implanted defibrillator. A BAN for diabetes management might include a blood glucose monitor and an implanted insulin pump.

The purpose of the Epilepsy BAN developed in the Awareness project is to detect (and perhaps even predict) epileptic seizures. The services required are ECG monitoring, motion detection and location detection. Onset of seizure is detected by means of analysis of ECG signals including patterns of heart rate and heart rate variability (parameters derived from the ECG signals). The ECG information is analysed in the context of the patient's movements as detected by the motion sensor. The analysis software forms part of the accompanying condition specific application, which may also include disease management functions such as medication reminders and alarms. The location service gives positioning information so that the patient's geographical location can be pinpointed and assistance can be sent if necessary.

The PSM supports implementation of condition specific BANs by realization with particular hardware components and associated software components. In realizing instances of the Epilepsy BAN for example the actual hardware components might be

- HP iPAQ (for MBU functions storage and processing and communications gateway)
- EMTAC GPS device (a simple sensor) for location service
- TMSI Mobi and 12-lead ECG (a front end supported sensor system)
- Xsens MT9 Motion sensor

The PSMs corresponding to each selected device form part of the Epilepsy BAN PSM.

4. Creation of a personalized BAN

The model of a condition specific BAN represents a class of BANs which address the core needs of a group of patients with a certain condition. However every instantiation of the BAN may need to be customized for an individual patient. By customization we mean providing the set of services required by the particular needs of an individual patient at a certain time. By personalization we mean adjusting to the preferences of patient and treating health professional(s).

Customization may involve fine tuning service parameters, or adding additional services and devices. Many patients suffer from multiple conditions (co-morbidities) and therefore may need some combination of two or more condition-specific BANs. The methodology should support creation of personalized BANs. One approach would be by composition of condition-specific BANs as shown in Figure 10. Figure 10 refers to the BAN needed by our hypothetical patient, Vic. He suffers from a life threatening cardiac arrhythmia know as Long QT syndrome. He is also an insulin dependent diabetic and suffers from epilepsy. Figure 10 shows that the BAN needed by Vic is some combination of the generic LongQT, Diabetes and Epilepsy BANs. In Figure 10 we introduce some graphical conventions by using a cross hatched oval to represent composition of BANs and a cross hatched bar to represent personalization. The figure should be read thus: Vic's BAN is derived from the generic LongQT, Diabetes and Epilepsy BANs by a process of composition followed by personalization.

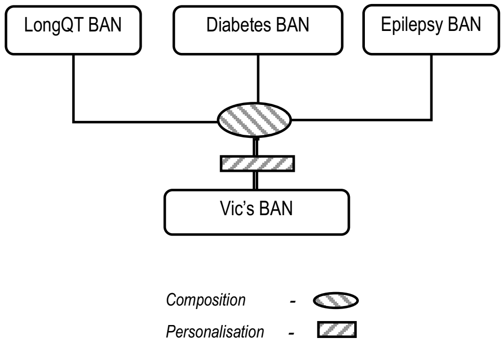

Fig. 10. Composition of condition-specific BANs

This procedure to create a BAN for Vic by composition of condition specific BANs could be modelled at a high level as:

personalize(compose(LongQTBAN, DiabetesBAN, EpilepsyBAN))

Exploration of the issues involved in BAN composition is a question for future research.

4. Discussion

The formulation of BAN models given here needs to be further generalized to permit possible future BAN configurations where the MBU as a device may disappear completely, for example if future smart sensor networks can delegate processing, communications and storage functionality to each node in a wireless sensor network.

The construction of customized BANs by composition is not straightforward, for a number of reasons. Firstly, the mapping between devices and conditions is many-to-many. In the examples shown above the Epilepsy BAN and the Long QT BAN both provide ECG monitoring services. However in such cases the parameters may vary (such as sampling frequency and number of leads/electrodes). Perhaps even more complex is the question of composition of application components. Combining components (hardware and/or software) may lead to unpredicted conflicts, inconsistencies, performance degradation and perverse behaviour. Composition should be handled in such a way that correct behaviour, reliability, performance and safety of the resulting composed functionality can be assured. Where should the composition be expressed? At implementation time? At the model stage? Should each individual customized instance of a BAN have its own PSM? The question of composition strategies is raised here as a research issue and is an example of a general research problem in software (and systems) engineering. We will investigate the composition problem by means of a number of approaches. One approach is to consider not composition of BANs but composition of services. The problem then can be expressed as one of service composition and orchestration. Many interesting research questions arise relating to how to combine MDA and object orientation concepts with a service oriented approach. Several orthogonal hierarchies are evident in the models, raising the question of formulating an explicit approach to views and facets in the methodology.

Another point of discussion is the added value of the MDA approach to this specific domain. Developments in wearable devices proceed at a rapid pace, implying an urgent need for a methodology that supports platform shifts and offers flexibility. A possible disadvantage of MDA is the need for platform models driving the PIM-to-PSM transformation: who will provide them? (This, in fact, points to a weak point of the MDA methodology in general.)

Finally, we wish to stress that we are aiming towards a formal model. Given the highly sensitive and safety critical nature of the domain, we view formal verification as an absolute requirement. In the context of MDA, this exposes the need for further research since the issue of correctness preservation across transformations is a wide open question.

5. Conclusions and Future work

BAN based applications are among the many potential new applications for the extended enterprise systems of the health sector enabled by wireless technologies. Healthcare systems for use by patients require high levels of safety, reliability, performance and ease of use and must be based on sound design and development paradigms. High standards are enforced by certification procedures.

We have described a design and development methodology based on a model driven approach and illustrated it with respect to an m-health application. The methodology is intended to provide a robust method for designing and developing m-health applications. At this early stage the methodology seems promising and we plan to continue to develop and apply it. Here we have described some initial modelling work at PIM and PSM levels, and much work remains to be done to arrive at a first complete application of the methodology. The transformation and V&V steps remain to be worked out in detail. Existing tools which support some degree of automatic code generation (such as CodeGenie, and Arcstyler with its 'cartridge' approach to code generation) will also be investigated.

In the future we plan to complete the modelling work for this application and address the other parts of the trajectory, namely transformation based on formal metamodels and verification and validation steps based on model checking and formal testing. Formal methods can also be brought to bear on the question of how to perform safe composition of services and components.

Amongst the major implications of implementation of BAN-based m-health services are the scaling issues, both technical and (health) service oriented. Rollout of BAN services across the population would require automated analysis of BAN data since health services could not dedicate staff to observe BAN data from large numbers of patients around the clock. Different BAN applications would involve different levels of sophistication in the algorithms and inferencing procedures needed to analyse (multiple) biosignal streams and other BAN data. For many conditions automated analysis would require development and quality assurance of very sophisticated analysis software. This further reinforces the need for the development and application of sound formally based software engineering methods in order to reach the high levels of confidence in the quality and robustness of designs and of the implementations derived from them.

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