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A Modular Platform for Wireless Body Area Network Research and Real-life Experiments

The ASE-BAN Testbed

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***Abstract* – The paper presents ASE-BAN, a wireless Body Area Network (BAN) developed at Aarhus University School of Engineering (ASE). ASE-BAN is a modular platform enabling research in the healthcare area and allowing real-life experiments with real users. The paper presents requirements, architecture and implementation of a hardware platform consisting of different modules, the current progress of research with development of sensor nodes for this ASE-BAN and the corresponding software. The concept of a body gateway is presented alongside with the preliminary results obtained with our current wireless BAN prototype.**

Keywords-low power; wireless sensor network; WBAN; Body area network; BAN; healthcare; Body gateway; testbed; IEEE 802.15.4; 6LoWPAN.

I. INTRODUCTION

There is an increasing need for personal home healthcare due to a growing population of elderly people [1]-[3]. To support the health problems of the elderly population wireless sensor technologies have enabled new types of applications for monitoring and controlling people's physiological parameters.

The first generation of e-healthcare solutions were more or less replacement of a wire with a wireless communication channel, i.e., another set of protocols on top of a new physical communication media. In the second generation, the devices communicated wirelessly with a local system host, which relayed alarms and possible also data to remote sites. In the third generation the healthcare sensors and actuators are wirelessly connected to a mobile body area network.

Miniaturization and cost reduction of modern electronics facilitate the assembly of tiny and affordable wearable devices for real-time monitoring systems of personal medical data. There is an increase in the demand for such devices, partly due to the demand for highly person-centric and prevention-based health-related services and partly because of the relative increase in number of elders in the developed countries.

A wireless network system can be set up, where network devices communicate accurate personal medical data to a host for storage or post-processing. The data may also be sent to medical practitioners such as caregivers and physicians for examination and diagnostic purposes. This enables greater mobility; reduces hospitalization, and results in better welfare at reduced costs for the society. The system provides ease in information-flow from the user to the central server or the doctors and caretakers, in a convenient and secure way.

A system for wireless real-time monitoring of physiological data from a body can be organized in a wireless BAN [4], as illustrated in Figure 1. The BAN consists of a number of different sensor and actuator nodes interconnected by using wireless communication with a body gateway. Sensors can be devices for picking up physiological signals from the body, e.g., electro-cardiogram (ECG) sensor used to monitor cardiovascular activity, an oximeter sensor used to monitor pulse and blood oxygen levels etc. Another example is an actuator node that can be used to stimulate muscle activity.

The body gateway communicates wirelessly with a local or a remote host application at a home base station or a

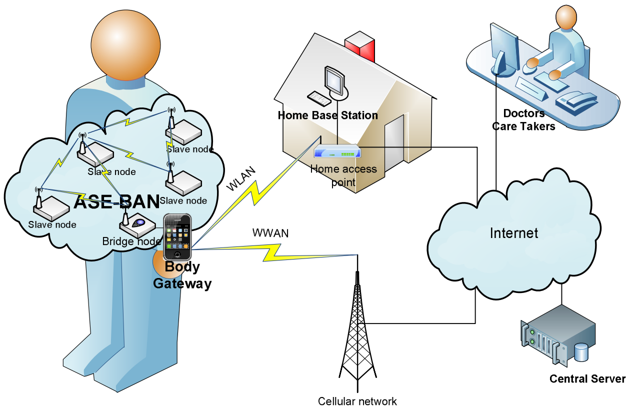

Figure 1. A wireless body area network system.

remote central server as shown in Figure 1. Some types of sensor nodes may acquire large quantities of medical information in real-time. Subsequently, data must be sent to the host for storage or post-processing from time to time.

Since wireless transmission is relatively energy costly, the gateway should only transmit context relevant data when needed, to minimize energy consumption. This is one of many requirements for a well-designed BAN.

As described above the concept of a BAN has over the last decade been researched intensely. This research involves investigating different themes raging from wireless propagation models locally around the body to how to design a feasible physical wearable low-power small scale network. The work described herein is an extension and an elaboration of our recent publications [1][5]. The target has from the beginning been to design a modular, wireless BAN testbed based on state-of-the-art wireless communication technology that can connect different wearable biomedical sensor nodes as integrated system components. To achieve this it was decided to make proprietary hardware that, over time can be re-designed and enhanced according to different design parameters like power consumption, physical size, price etc.

Figure 2 shows a picture of the hardware modules that can be mounted on top of each fitting in a small "box". The use of an open source software platform with a high degree of flexibility was subsequently chosen.

This paper is organized as follows. In Section II state-of-the-art for wireless BANs is described. Section III provides details about for requirements for the design of a BAN. Section IV describes the architecture and design of ASE-BAN. Section V goes into details about the current implementation status of ASE-BAN including the specific sensors integrated into the system. Especially, the fluid balance sensor and the ECG sensor node are described. Section VI presents the demonstrator and the preliminary results made so far. The paper concludes with a discussion of future research directions in Section VII.

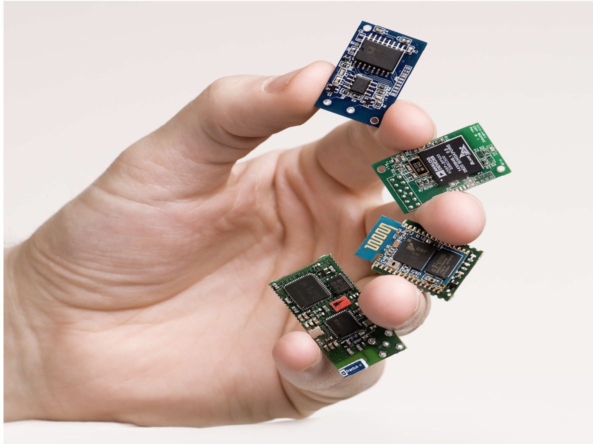

Figure 2. Four hardware modules of the ASE-BAN testbed.

II. STATE-OF-THE-ART FOR WIRELESS BANS

The wireless BAN has been a topic for research and development during the last ten years and several surveys on wireless BAN and their application in mobile health and telemedicine have been published in the literature [6]-[16]. The growing interest in building large-scale BANs across a public healthcare system such as a hospital have fueled a large number of research and development projects such as OpenCare [2], MobiHealth [6], MIMOSA [17], CodeBlue [18], SMART [19], AID-N [20], CareNet [21], ASNET [22], MITHril [23], WiMoCa [24] to mention a few. Whilst there are many similarities among the different approaches taken by research groups, the research domain suffers from a large fragmentation.

1) BAN sensor nodes

Essentially, wireless BANs are used to transmit physiological data such as vital signs by using radio wave communication. Most body sensors are utilized in an event-driven fashion, but BANs also need to support data streams for real-time monitoring [25]. Analysis of sensor data streams in BANs involves identifying and extracting the set of attributes or characteristics from each multi-dimensional time series that correspond to different performance goals of health monitoring applications.

To better monitor a human's vital signals, behavior, and the surrounding environment, a wide range of commercially available sensors can be deployed, such as accelerometer and gyroscope, as well as traditional medical sensors including electroencephalography (EEG), electromyography (EMG), electrocardiogram (ECG), blood pressure, pulse oximetry (SpO_2), respiratory inductive plethysmography (RIP), carbon dioxide (CO_2), and so on. Accelerometer sensors, along with visual and biosignal sensors, are utilized to characterize movement and to detect falls of the user [26]. Finally, ambient sensors measure environmental phenomena, such as humidity, light, sound pressure level, and temperature.

Recent technological developments have enabled sensor miniaturization, power-efficient design and improved biocompatibility. Issues related to systems integration, low-power sensor interface, and optimization of wireless communication channels are active research fields. With advances in MicroElectroMechanical systems (MEMS), sensor devices are getting even tinier in size. These are changing the traditional way of measuring human physiological parameters.

2) Radio communication

A wireless BAN is a radio frequency-based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on, or around a human body. As such the topic has fueled research in the area of a body-centric wireless communication channel [27]. Antennas and propagation for telemedicine systems can be considered in two parts, those for systems outside the body and those that communicate with internal implanted sensors and devices. The increased interest in wireless channels on the body has led to a review of the types of propagation mode that may occur on the body. Use of the Medical Implant Communication System (MICS) at 402 MHz to

405 MHz, allows bands of 300 kHz to be achieved. However, due to the high availability of components for wireless body sensor networks both the industrial, scientific, and medical ISM bands between 400 MHz and 2.45 GHz, and the ultra-wideband (UWB) frequency allocation between 3.1 GHz and 10.6 GHz are frequently seen in actual implementations [27][28]. More recently there is an interest in investigating the performance of BANs operating at millimeter wavelengths and in particular at 60 GHz [29][30]. Looking at BANs, a more generally attractive alternative by using the radio channels for communication between sensors is to have bio-channels serving as a unique secured means of communication, where the human body is used to transmit either exogenous or endogenous information [31].

3) Networks and standards

Emerging and existing standards for wireless BANs and Wireless Personal Area Networks (WPANs) include Bluetooth Low-Energy, UWB, and ZigBee. However, proprietary and open technologies like Z-Wave [32], ANT [33], RuBee (IEEE 1902.1) [34] and RFID [35] have been utilized as well. Z-Wave is a proprietary mesh networking technologies for home automation. It works in the 900 MHz band. ANT is another proprietary sensor networking technology, featuring a simpler protocol stack and lower power consumption [36]. It implements a light-weighted protocol stack, ultra-low power consumption, and a data rate of 1 Mb/s. ANT has been embedded in some Nike shoes to collect workout data and it is able to talk to iPod products. RuBee and RFID are both used for logistics applications.

There have been many academic research projects utilizing IEEE 802.15.4 for transmitting health-related data [37][38]. These are based on IEEE 802.15.4 chips such as the CC2420 and the CC2430 from Texas Instruments. Implementations do seldomly use the higher-layer ZigBee protocol stack because either networking capability is not a must, or researchers are interested in devising more appropriate protocols.

Body area networking, i.e., networking among devices in, on, and around the body poses unique challenges for resource allocation, sensor fusion, hierarchical cooperation, quality of service (QoS), as well as security and privacy. Hierarchical aggregation, topology control, star and star-mesh hybrid topologies, coordination, multi-hopping multi-hop data forwarding [39]. In terms of research and development mesh networking and energy-efficient routing in BANs are still open issues. On the one hand, minimalistic networking schemes increase system run-time and reduce obtrusiveness. However, this could jeopardize QoS or privacy, which is unacceptable for life-critical or sensitive medical applications. Other topics related to the practical applications of body sensor networks such as multi-sensor data fusion, decision support, and technological scaling are also important.

Technologies for inter-BAN communication are mature, and include: WLAN, Bluetooth, Zigbee, cellular (GPRS), and 3G/UMTS etc. The more communication technologies that a personal server supports the easier it is for a BAN to be integrated with other applications.

On-going work within the IEEE 802.15.6 Task Group 6 aims at supporting applications with various data rates, where quality of service guarantees are crucial in case of life-threatening conditions [40]. An emerging BAN standard, IEEE 802.15.6 will likely employ UWB.

4) MAC layer

At the MAC layer, there is a tradeoff between reliability, latency and energy consumption that needs to be resolved. Normally, an asynchronous MAC mechanism, such as carrier sense multiple access with collision avoidance (CSMA/CA), is used with IEEE 802.15.4 to deal with collisions. To increase the lifespan of these sensors, energy-efficient MAC protocols will play an important role. Corroy and Baldus present in [41] a comparison between different low-power MAC layers. S-MAC [42], T-MAC [43], and TRAMA [17] use their transmission schedule and listening periods for synchronization and to maximize throughput, while reducing energy by turning off radios during much larger sleeping periods. On the other hand, low-power listening (LPL) approaches such as WiseMAC [44] and B-MAC [45] use channel polling to check if a node needs to wake up for data transmitting or receiving. Hereby the necessity of idle listening is reduced. Several other power-efficient MAC protocols have been developed and investigated. MAC protocols have been surveyed in [46]. It has been shown that many MAC protocols offer better performance in terms of the end-to-end packet delay and energy saving compared to the IEEE 802.15.4 MAC.

5) 6LoWPAN

The Internet Engineering Task Force (IETF) has led the specification of 6LoWPAN or Internet Protocol (IP) version 6 over low-power wireless personal area networks [47]. The approach has been to define modifications to IPv6 that allow it to be used over the IEEE 802.15.4 MAC/PHY layers. By using IP for the higher networking layers, the sensor network is interoperable with other IP networks including the Internet. This has the potential of making gateway devices simpler. The use of IEEE 802.15.4 allows the requirements of wireless BAN for low power and long lifetimes to be met. In addition, IPv6 has an addressing space adequate for all conceivable sensor networks. It also has the advantage that it is an established technology with an extensive set of support tools for development, design, control and reconfiguration. 6LoWPAN allows existing standards to be leveraged, rather than fostering a need to build standards from the beginning.

6) Software frameworks, middleware and OS

Many BAN projects use the open source operating system TinyOS [48] designed for small wireless devices. Another emerging operating system for wireless sensor networks in general is Contiki [49], designed for the Internet of Things.

Waluyo *et al.* presents in [50] a lightweight middleware for personal wireless body area networks designed to reside in personal mobile devices. A middleware taxonomy together with examples of current middleware projects grouped according to the taxonomy.

To support communication between the central located server computers and the body gateway, frameworks can be built to support the IEEE 11073 standard implementing a composite IEEE 11073 agent consisting of the body area network sensors communication with an IEEE 11073 manager on the central server [51]. On the sensor side, one project [52] has recently implemented the IEEE 1451 smart transducer standard in a BAN context [53].

III. GENERAL REQUIREMENTS FOR WIRELESS BAN

Requirements in this section are mainly requirements which will have an influence on the system architecture for the BAN. It is thereby not an attempt to define a complete set of application-oriented functional requirements, which normally are defined by the use case technique. More technical requirements are currently being defined by the IEEE 802.15 WPAN Task Group 6 (TG6), which define the requirements for a WPAN [54]. An overview of these requirements, current challenges and wireless technologies for BANs are presented by Patel and Wang [3].

First, the user related requirements are described, followed by a set of more general system requirements. Most of these requirements have an impact on the hardware architecture and partly also on the software architecture. A subset of these requirements is also listed by Shnayder *et al.* [55].

A. User Related Requirements

1) Diverse User Group

Users of the BAN can for example be elderly persons living at home or in a nursing home. It can be physically disabled persons at all ages,; it can be persons suffering from dementia; it can be persons with chronicle diseases at all ages; and it can be athletes. Some of these users have several of these characteristics e.g., an elderly physically disabled person with a chronic disease.

In this way, a very diverse user group, spanning from young to very old, and in some cases people suffering from dementia, can be addressed. These different types of users have very different needs and different skill levels for handling new technology. The user group with dementia and disabled people raise the largest challenge for healthcare developers. This leads to the first challenge:

Challenge 1: Dealing with very diverse types of users, with different application needs and different skill levels.

Requirements: Adjustable technology, user friendly, easy installation and configuration of software and hardware**,** easy to add new functionality, sensors, and actuators.

Development of a BAN system for this diverse user group will benefit from using a user driven innovation and development process.

2) User Communication

The BAN should support different ways of communicating with the user. It could be by messages, LED lamps and sounds; it could be by speech syntheses or speech recognition, by activating normal buttons or soft buttons on a touch screen. Another possibility is communication with hearing-aids or headphones. Some of these devices can be used to give reminders to the user e.g., a reminder to take medicine or to exercise or to measure blood pressure.

Challenge 2: User interface design for a diverse user group.

Requirements: User friendly and easy to use interfaces.

This could be obtained by conducting usability studies with different user groups and different types of interfaces supported by incorporating industrial designers in the design team and process.

3) Calling for Help

The BAN should support a “call for help” device so a user can call for help at any time. This functionality could be supplemented with a voice-channel so the caretakers can communicate with the user.

Challenge 3: To offer safety and security to users.

Requirements: Physical design of a reliable call-device and a reliable system for transferring this event, as this could be an emergency call.

4) GPS Outdoor Positioning

The BAN should allow the connection of a GPS-device for locating people in case of an accident. It could for example be demented people who left the nursing home without supervision or a user getting a heart attack outside the home. As a GPS-receiver is a power demanding device, the receiver should be controlled by the BAN and the connected system so it only works on demand and therefore only use power in a short time frame.

Challenge 4: To locate a user in case of an accident.

Requirement: Outdoor navigation using GPS.

Ideally, indoor positioning is also relevant. However, this is currently much more challenging and not part of our current research scope.

5) Fall Detection

The BAN should support a fall detection device node with the purpose of sending an automatic call for help. It could be in situations where the user is unconscious after a fall or it could be a person with dementia, who could not operate a call button or a call device.

Challenge 5: Reliable detection of a fall.

Requirement: Physical design of a tiny and reliable fall detection node integrated on the person e.g., in the cloth or in a belt or as a decorative, personalized object.

6) Mobility

The user should be allowed to move freely around. For example a heart ECG monitoring should take place indoors in a private home or at work as well as outdoors and in public places.

Challenge 6: To be anytime and anywhere connected.

Requirement: Seamless connectivity over heterogeneous networks with automatic roaming supporting indoor as well as outdoor communication over Wireless Local Area Network (WLAN) and Wireless Wide Area Network (WWAN).

7) Physical Constraints for BAN Components

All the BAN components are connected with wireless technology and should be integrated in the person’s daily life. This raises specific requirements for the physical design, i.e., it should have a small form factor, be light-weighted, and have a smart design. Some of the devices requires skin contact and could be integrated in a plaster; some could be integrated in the cloth as an intelligent textile and some should be visible e.g., a device with user interaction for example integrated in the body gateway.

Challenge 7: Obtaining user acceptance of healthcare technology devices and wearing.

Requirements: Low form factor, low weight and easy installation, wearing and a nice-looking design.

8) Power Consumption

With the diverse user group in mind it is difficult for these users to handle battery exchange and charging of a number of sensor nodes. For general convenience the devices should be developed as low-powered devices with either long battery life or by utilizing some kind of energy harvesting technique. This leads to the architectural design with essentially only a single power demanding unit – the body gateway.

Challenge 8: Low-powered devices with energy-efficient communication.

Requirements: There is a demand for low powered devices (nodes) and communication protocols.

The body gateway requires more power and could be charged e.g., by induction or by a normal power charger with the inconvenience for the user and problems with being offline.

9) Economics for a BAN

The technology can help reducing the workload with caregiving, but with a cost of the new healthcare technology. With the high volume of users there are strict requirements to the solutions to be as cheap as possible both in buying, installation and operation.

Challenge 9: Obtaining low total system cost and operation cost.

Requirements: Low system costs and low cost of system operation, especially for the mobile communication part, which currently can be quite expensive.

B. General System Requirements

1) Security and Safety Issues

It is important that the BAN and the rest of the infrastructure are both safe and secure. Person-related information is normally regulated by national law and should be transferred in a safe and secure manner. Another problem could be external hackers which could threaten for example a close-looped application connected to a medicine injection pump. Person-related information is to be handled with confidentiality and a BAN sets strict requirements to the handling of this information.

Challenges 10: Obtaining a safe and secure system.

Requirements: Use of standard encryption techniques and authentication protocols.

2) Healthcare Application Flexibility

The BAN should support the possibility to place the application or business logic code on different components in the architecture. It could be on a sensor node, on the gateways, or on one of the connected servers. Implementing an application on a sensor node, doing pre-processing of the signal, can reduce the communication bandwidth and thereby save power, but at the cost of a more expensive sensor node.

Challenge 11: Obtaining a flexible software and hardware architecture with different processing capabilities.

Requirements: An adjustable software framework or structure for application code and flexible component-oriented hardware architecture.

An automatic configuration of the application and sensor node software is a clear goal.

3) Monitoring Data Types

Data types can be real-time, life-critical application data: ECG data as well as sporadic event data for example alarms and emergency calls for help.

Challenge 12: Very diverse requirements for signal monitoring.

Requirements: Support for continuous real-time monitoring as well as for events. See [57] and [2] for a list of technical requirements for different applications with bit rates from less than 1 kb/s for drug dosage and up to 10 Mb/s for video imaging.

4) User Identification

The BAN should support an identification mean so the user can be unambiguously identified by supporting systems and the identification can be send with the collected data to remote servers.

Challenge 13: To obtain an unambiguous and secure identification.

Requirement: A secure identification of the user is required for the BAN system.

5) Node and Person Matching

The BAN should support a mean for unambiguous identification of sensor and actuator nodes on a given person and connect these devices with the user’s identification code. In this way the sensor data can be linked to a given person. A problem occurs when a sensor node connects to nodes on other persons BAN in near vicinity of the person.

Challenge 14: Matching nodes with the person wearing the wireless node**.**

Requirement: For a secure and easy identification method.

This could for example be obtained by using Body-coupled communication (BCC) where the BCC is used to discover an identify sensor nodes on the same body as presented in [57].

6) Open Standards and Open Source

The BAN should be based on open international standards for supporting as many BAN devices from different vendors as possible and with different types of functionality. The Continua Health Alliance [58], a non-profit coalition of more than 200 member companies, has defined interoperability goals for wireless systems and the IEEE group is working on a standard for wireless personal area networks [57]. The Continua Alliance material and software are mainly openly available for members of the alliance.

Challenge 15: Development of open standards for the BAN.

Requirements: Base BAN on open standards and optionally also open source software solutions for BAN components.

7) Network Topology and Communication

The BAN should work with any kind of network topology from a star network with bidirectional communication between gateway, sensors, and actuators, to a meshed network that allows communication between all nodes. It is critical to have a network infrastructure and related communication protocols that minimize the power consumption of this part of the BAN as well.

Challenge 16: Design a network with ultra-low power, secure and reliable communication.

Requirements: Support for star and mesh topology.

IV. SYSTEM ARCHITECTURE

The system architecture is a conceptual model that allows components to be added, removed, and modified. It allows data to be collected based on information requests. It provides a framework to abstract the underlying hardware resources from the applications and may be implemented as a middleware [59]. The system architecture of ASE-BAN is defined in order to describe the structure, behavior, and the different views of the ASE-BAN system. The architecture can be deployed in both indoor and outdoor environments. It can extend existing healthcare infrastructures such as e.g., OpenCare [2] and can be generally integrated into it infrastructures by use of web services [60].

A. System Context for ASE-BAN

The overall design guideline for the ASE-BAN is to have a body gateway node acting as the link from the body network to external systems, a central server or a home base station as shown in Figure 3.

This body gateway should be the only power demanding component with a longer communication range supporting both wireless Local Area Network (LAN) and Wireless Wide Area Network (WWAN) communication and with a seamless handover between the two network types.

The other BAN nodes should be ultra-low power sensor or actuator nodes with a limited communication range, i.e., less than one meter, where the communication power level can be adjusted to the minimum required for getting a reliable on-body communication.

Figure 3 shows a domain model for a complete healthcare system including the ASE-BAN system which is mounted on the indicated user.

When the user is at home the communication will be over WLAN from the body gateway and it can typically send both alarms and monitored data from the BAN to the home base station component e.g., a touch screen based computer. If the user leaves his or her home the BAN will automatically stop sending real-time monitoring data and store them locally on the BAN gateway component and only communicate alarms and keep-alive signals over the WWAN (e.g., GSM or UMTS).

This solution is previously proposed by Saadaoui and Wolf [61]. It saves communication cost, i.e., both power and money. The principle of having a central server and a home base station is implemented in the OpenCare project described in [2], where the BAN is described as a Mobile Tier component for communicating a single physical value from a user and not as being a part of a body area network.

The idea of having a powerful gateway for the body area network is also described in the work by Jovanov *et al.* [62] and Otto *et al.* [63] where they describe a three tier system consisting of tier 1: wireless BAN nodes, tier 2: personal server and tier 3: central systems. On their wireless BAN each node communicates in a star network topology with the personal server, i.e., the gateway.

For ASE-BAN both a star and a mesh network topology have been used as possible network solutions. The mesh configuration enables ultra-low power communication and communication in difficult setup's e.g., from a person's back to his/her front KKK. Another important difference, in relation to the work described in [61], is the introduction of the home base station component, which gives another level of service to the users living in a private home; for elderly people normally one or two persons. The home base station collects monitoring data from the BANs on the people living in the house and it also supports shared and non-personal related healthcare devices in the home, which assist the residents with staying healthy. This could be medicine dispenser automation, a blood pressure meter or a smart weight scale, which can have one or more users. Using a home base station enables the development of healthcare applications which take decisions based on inputs from several different sources, i.e., BAN sensors or from the shared devices.

Another advantage with the WWAN enabled ASE-BAN is the extra security obtained by having a backup channel for alarms in case of malfunctions in the normal data flow from BAN to home base station and to the central server.

B. ASE-BAN System architecture

The ASE-BAN system architecture, shown in Figure 4, enables continuous transmission of medical data for

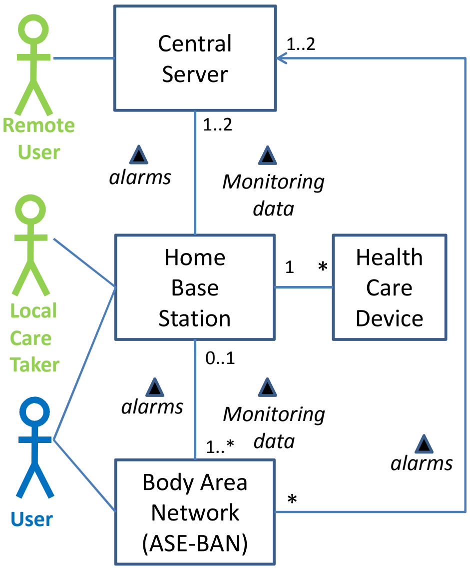

Figure 3. System domain model including ASE-BAN.

the reporting of vital signs as well as transmission of alarms. The architecture scales well in terms of the number of users and the number of sensors and actuators on each user. It supports the normal behavior of an elderly person. The ASE-BAN system is composed of a number of sensor nodes and a body gateway. Each BAN is private for one user.

The body gateway is a powerful, wireless node providing connectivity between the BAN and external systems. It contributes in the collection and processing of physiologic data from the BAN. An ASE-BAN installation can be extended gradually with sensors nodes to fit the intended purpose.

The body gateway is equipped with at least two radio components – one for the communication within the BAN and one for interconnecting with external systems. The BAN forms a Wireless Personal Area Network (WPAN) for its internal communication. When the BAN user is at home the communication will be over WLAN to the Home Base Station whereas the ASE-BAN will rely on public telecommunication networks and use WWAN when the user moves outside his/her premises.

In addition to storage and a CPU, the body gateway may be composed of one or more input-output (IO) units to support human intervention such as keypad, microphone, loudspeaker and a display. Moreover the body gateway may support the interaction with systems in proximity by using Near-Field Communication (NFC) units and can be equipped with sensors that complement the sensor nodes of the BAN such as a GPS receiver, camera etc. The storage module can be used to store physiological data signs in outdoor environments to reduce the high communication costs of WWAN networks.

The sensor node combines one or more sensors with a low power processing unit (CPU) and the WPAN communication unit, i.e., the Radio. Its main function is the sampling and pre-processing of physiological data and to participate in the communication within the BAN. A special sensor node configuration, called the relay node, acts as a relay or a router for the wireless mesh network communication. It may be used to enhance the robustness of the communication by means of multi-hop communication. One possible usage is to ensure that a sensor node located on a person's back can communicate with a body gateway placed on a person's front.

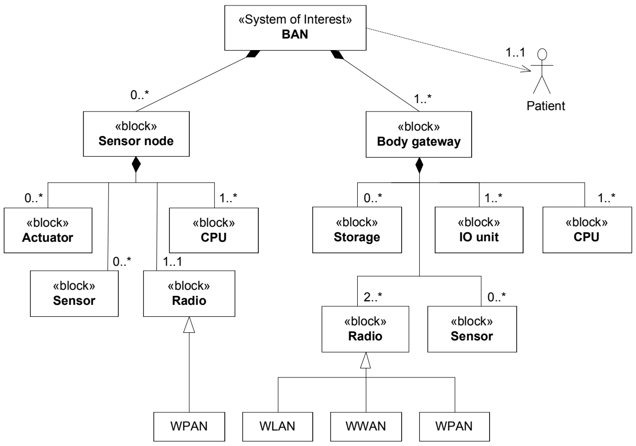

Figure 4. Block definition diagram describing the ASE-BAN architecture.

For more computational demanding sensor nodes an additional CPU such as a Digital Signal Processor (DSP) can be added to the sensor node. This allows for a distributed data processing in the ASE-BAN.

The candidate wireless technologies are based on the standards IEEE 802.11b, IEEE 802.15.1 and IEEE 802.15.4. In the testbed the latter IEEE 802.15.4 standard is used for communication within the BAN.

Table I lists the sensor nodes supported in ASE-BAN. Sensor nodes have been classified according to reaction types: Continuous or Event. Sensor nodes of the Continuous type is used for the continuous monitoring of physiological data whereas the Event type is used for the issuing of alarms when a pre-determined threshold is met e.g., low fluid balance or in case of a fall.

C. *Software platform*

1) Software processing capabilities

The architecture supports running software on different places. The CPU at the sensor node can be of different types from a simple microcontroller to an advanced digital signal processor that allows advanced preprocessing of the sensor signals and the execution of application algorithms. An example of an advanced preprocessing is the Heart Rate Variability (HRV) detection or ECG signal supervision for heart artifacts. This gives the possibility only to send alarms in case of malfunction and in this way limits the power demanding wireless communication. The next application level is on the body gateway, which normally has a powerful processing capability. The software running on this platform can correlate signals from several sensor nodes and in this way take decisions based on multiple sensor inputs.

The next level of processing is performed either on the home base station or on the remote central server communicating with the ASE-BAN via the body gateway component, when the user is away from home.

TABLE I. ASE-BAN SUPPORTED SENSOR NODES.

Sensor node	**Description**		
	Key function	***Reaction type***	***Data rate***
Temperature	Ambient temperature monitoring	Continuous or Event	Low
Fluid balance	Monitoring of the fluid balancing	Continuous or Event	Low
Electrocardiogram (ECG)	Monitoring of heart rate and heart rate variations	Continuous or Event	High /Variable
Fall detection	Detection and reporting of a fall	Event	Low
Relay node	Multi-hop communication	None	Variable

2) Sensor node software: TinyOS

Many of the existing implementations of BANs have been based on tailor-made software that fits the purpose of the application. Most of these software implementations are proprietary, lacking flexibility and openness, and customers are often faced with vendor lock-in and high total cost of ownership. With the emergence of small operating systems such as TinyOS and Contiki a gap between the application and the underlying hardware, available in the sensor world, have been closed. Hence application developers or no longer forced to account for all the lower level details when developing applications.

TinyOS is an open source operating system designed for low-power wireless devices, such as those used in sensor networks and personal area networks [65][66]. The operating system and its associated tools are supported by a worldwide community that counts people from academia as well as the industry.

ASE-BAN sensor devices were based on TinyOS. This gives the following immediate benefits:

- Hardware abstraction layer
- Hardware platform support (MSP430 and CC2420)
- Core operating system functions e.g., memory management, interrupts handling, timer etc.
- An event-driven concurrency model for program execution
- Driver support e.g., for the radio hardware unit
- Networking protocols
- Software development tools
- No license cost (BSD-licensed)

D. Wireless node hardware platform

The hardware architecture reflects the different stakeholders of the platform: sensor, communication, power and embedded processing specialists. The basic elements of the architecture are shown in Figure 5.

Energy, as energy sourcing and power conditioning; *Communication* that implements secondary communication technologies; *Physical IO* containing sensors, actuators and pre- and post-data processing and finally *Processing Element*, for managing the system and optional data processing. The processing element component can also include the primary radio frequency (RF) transceiver that is often integrated with the main CPU. Each wireless sensor node is a mix of these building blocks.

1)Processing Element.

Many of today's wireless sensor node platforms are based on TinyOS and AVR/MSP430 processors. Several ARM Cortex-M0/M3 devices are emerging [67], allowing the nodes to benefit from the 32-bit architecture, thus enabling more processing power in the nodes, which again enables new methods in data aggregation and compression [68].

A comparison of some processors with build-in RF is shown in Table II. Energy consumption is given for the wake-up, the active, the sleep and the transmission and reception phase (*Tx/Rx*) of the node operation. Energy consumption estimations are based on current consumption and wake up time values from the respective data sheets.

The ARM and the AVR processors use 32-/8-bit RISC architectures respectively, whereas the MSP430 uses a 16-bit Von Neumann architecture. The AVR and MSP430 processors are assumed on average to take three clock cycles per normalized instruction compared to an ARM Cortex-M3.

Table II shows how the different CPUs have different strength and weaknesses. For computation intensive applications, the ARM Cortex-M3 CPU is preferred, whereas communication intensive applications would benefit more from the efficient RF front-end of the AVR processor. Applications that wake up regularly, but transmit less data, will benefit from the MSP430's short wake-up time. Hence, the choice of processor depends on the application used.

2)Communication

The primary wireless connection used for the wireless BAN is application dependent as well. Wireless sensor node research extends well beyond near-distance, inter-body wireless communication. Future applications may well extend to agricultural, environmental, and energy surveillance applications. Table III shows several wireless standards which the platform should be prepared to accommodate for.

3)Energy

Being open to different applications also effects how energy should be sourced and conditioned. Rechargeable batteries require a charging circuit, and even during shut

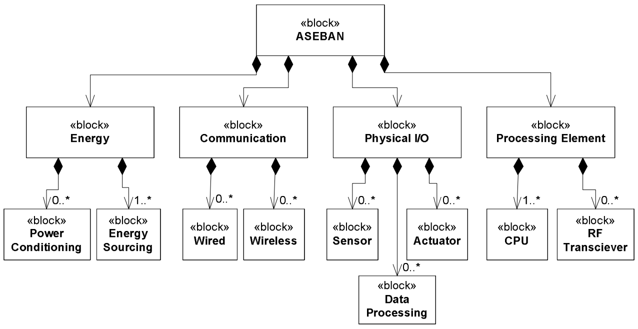

Figure 5. ASE-BAN node hardware block diagram.

TABLE II. ENERGY CONSUMPTION COMPARISON.

Processor	**Energy Consumption** (1.8 volt)			
	Wake-up [nJ]	***Active*** [nJ/instr.]	***Sleep*** [nJ/s]	***Tx/Rx*** [nJ/bit]
ATmega128RF1 (AVR) [69]	147	0.620	1800 (PDX)	100
CC430F6126 (MSP430) [70]	14	0.860	3600 (LPM3)	150
EM357 (ARM, Cortex-M3) [71]	1188	0.460	1440 (DS1)	200

TABLE III. COMPARISON OF WIRELESS TECHNOLOGIES.

	Z-Wave	IEEE	Dash-7	ANT	Bluetooth Low E
Standard	Proprietary	IEEE 802.15.4	ISO 18000-7	Proprietary	IEEE 802.15.1
Target	Home automation	Health-care	Military, Industry	Health-care	Health-care
Frequency	900 MHz	2.4 GHz	433 MHz	2.4 GHz	2.4 GHz
Topology	Mesh	Mesh, Star	Mesh	Mesh, Star, P2P	Star, P2P
Range	30M	30M	1000M	30M	1M
Data Rate	40 kb/s	250 kb/s	200 kb/s	20 kb/s	200 kb/s

down its internal transistors (FETs) will drain a small quiescent current. A coin-cell battery provides a higher capacity and a lower self-discharge than rechargeable battery. For applications that require medium power and have short operational life, a rechargeable battery is preferred. This is illustrated in the following example: A sensor node based on the EM357 samples an analogue value, preprocesses the sample, receives and transmits an IEEE 802.15.4 packet and goes back to deep sleep at a fixed interval. Figure 6 illustrates the achievable battery life with different wake-up periods.

For applications running up till a month, the rechargeable battery will be the right choice. For applications that have low activity, but a long lifespan, the coin cell battery (e.g., CR2032) is the preferred choice. The ASE-BAN platform is prepared for both.

Secondary communication forms include Universal Serial Bus (USB) for debugging and the base station applications as well as different wireless interfaces such as Bluetooth for body gateway applications.

4) *Physical I/O*

The Physical I/O should be able to interface to most sensors and actuators. This interface should be kept open as sensor technology is a key design requirement. A list of the required interfaces for current sensors is given in Table IV. As the table indicates, GPIO, SPI, I2C and analogue interfaces will be sufficient. Interfaces such as USB host or LVDS does not match the requirements of a low-power wireless node. A DSP is included for computation intense pre- and post-data processing.

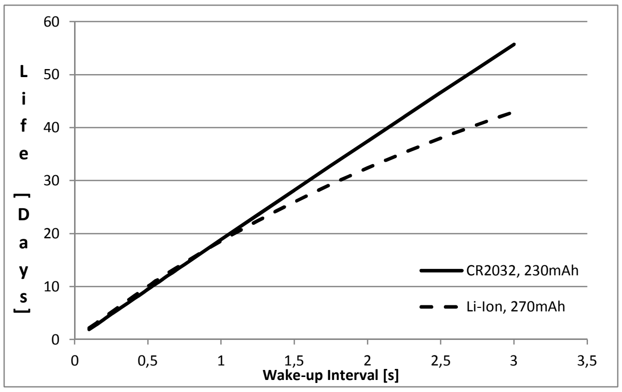

Figure 6. Example of battery life vs. wake-up interval.

TABLE IV. SENSOR CHARACTERISTICS AND INTERFACES.

Application	Digital I/F	Analog I/F	Inter-rupt	Supply	Example
Acceleration	SPI	x3	Yes	1.8-3.3V	ADXL345
Temperature	I2C	x1	Yes/No	2.7-5.5V	AD7414
Microphone	No	x1	Yes		
Codec	I2C/SPI	No	No	5V	AD1877
Impedance	I2C	No	No	2.7-5.5V	AD5933
Gyro	SPI	x1	No	5V	ADXR520
Digital Potentiometer	I2C	No	No	2.7-5.5V	AD5175
Strain Gauge	No	x2	No	2.7-5.5V	
DSP	SPI/I2C/TDM	No	Yes	1.2+3.3V	BF533
I/O Extender	I2C/SPI	No	Yes	3.3V	
H-Bridge	4xGPIO	No	No	3.3V	

The mechanical properties of the nodes are important as well. In order to make the nodes usable in real applications, they should be compact and have a self-supporting ruggedized structure. These properties are not found in many research nodes created so far.

V. IMPLEMENTATION OF ASE-BAN

This section describes the implementation of the ASE-BAN platform covering hardware, software, protocols, body gateway and the different sensors.

A. *Hardware platform*

The ASE-BAN hardware platform shown in Figure 7 is built from hardware modules attached to a common base Printed Circuit Board (PCB) as illustrated in Figure 8 and pictured in Figure 9.

The modules are soldered together with the base PCB by

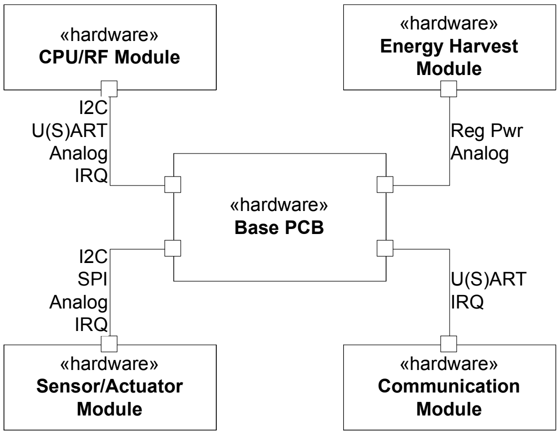

Figure 7. ASE-BAN's modular node design

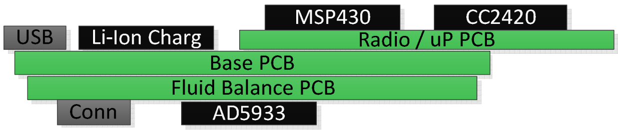

Figure 8. ASE-BANs physical layering with the fluid balance sensor stacked to the base PCB.

using edge-plating technique on the modules. This technique is well-known from Bluetooth modules. Using this approach is quite beneficial, since the design becomes very modular and the structure becomes quite robust and compact as no connectors are involved. The edge plating technique allows easy assembly and the construction of new modules. This is in contrast to use of fine pitch connectors or BGA techniques.

The modules support the architecture described earlier. The base PCB acts as a passive backplane, processing is placed in the CPU/RF module, sensors on the sensor module and so on. This allows us to select among a variety of communication forms, sensors and energy sources, while maintaining the basic functions of the system.

The base PCB includes sensors such as, temperature, 3D acceleration and proximity. These sensors are placed on the PCB backside and may be replaced by a sensor module with other sensors attached. It also has a build-in Li-Ion charger, power conditioning, debugging LEDs, buttons and a micro USB connector for charging and possible wired communication.

Similar design techniques exist for the energy sourcing and conditioning circuits. They may e.g., also be replaced by an energy harvesting module or a CR2032 battery. The solder terminals are placed along the PCB edge allowing the sensor modules only to use a fraction of the full base PCB length. Connections such as power and serial IO are duplicated to support this.

An example of a sensor node is the fluid balance node shown in Figure 10. Through impedance measurements in skin tissue the node estimates the current fluid balance. The battery chosen is a 270 mAh Li-Polymer battery. The fluid balance sensor consumes a lot of energy, and the sensor is not intended to be fitted for long periods of time without service. The application allows us to recharge the node when the user is in bed at night. The charging circuit takes power from the micro-USB connector and a matching power adapter should be a commodity in today's smartphone households.

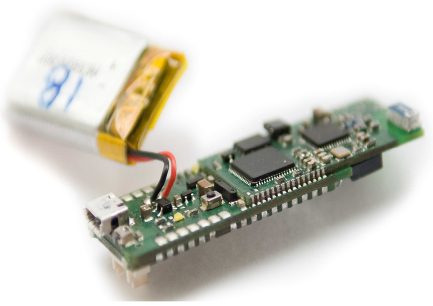

Figure 9. ASE-BAN node (processing and energy side).

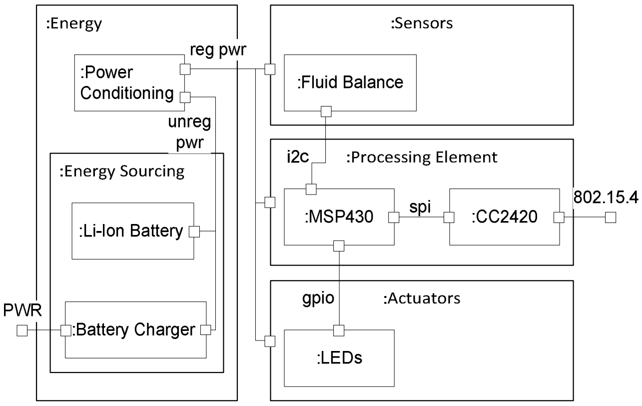

Figure 10. Fluid balance sensor node internal block diagram.

Power conditioning is done by means of LDO regulators, as the quiescent current of switched-mode regulators becomes dominant over the improved power conversion efficiency.

As the processing element, the MSP430 processor [72] from Texas Instruments was chosen in conjunction with the CC2420 radio transceiver [73] also from Texas Instruments. This is a rather common set-up seen in sensor nodes such as the TelosB [74]. This setup allows easier integration with TinyOS, as this is the target operating system. As mentioned in the architecture section, the MSP430 provides overall good performance for medium processing applications, so it fits this application quite well. The CC2420 is a well-established IEEE 802.15.4 radio transceiver used in related research [75][76]. Actuators are LEDs for this application, but buzzers and vibrators are being considered for stand-alone fluid balance applications.

The fluid balance sensor itself, shown in Figure 11, is based on an impedance measurement integrated circuit from Analog Devices. The primary interface to the processor is I2C used for sending commands and receiving measurements. The sensor module has a local LDO regulator that can be shut down by the processor to minimize power consumption during node sleeping periods. The fluid balance sensor is described in more detail in a later section.

The fluid balance sensor node has a small connector for attaching external electrodes. It is 8x20x55 mm in size and weights 9 grams, excluding battery. This allows the node to be placed in a wristband for realistic application evaluation.

The current setup enables the creation of sensor nodes for a wide range of applications: Temperature sensors that wake up every minute but has years of service time, thus requiring a coin cell battery and a very basic CPU/RF module. HRV sensors are very processing intensive using an additional DSP for HRV estimation, have only 2-3 days operating time and require rechargeable Li-Ion batteries.

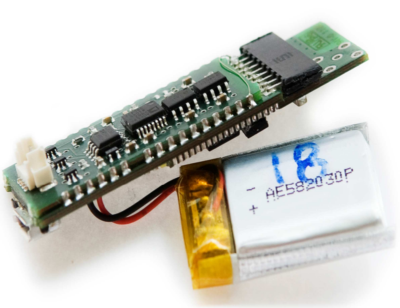

Figure 11. ASE-BAN node (fluid balance sensor side).

The hardware construction has proven to be convenient and robust obtained by the close attachment of the PCBs. The hardware design accomplishes the goals for the ASE-BAN platform, namely to provide a flexible platform for interdisciplinary research and development of sensors for a wide range of healthcare applications.

B. *Software and protocols*

The network interface abstraction that comes with TinyOS provides a generic way to use the network regardless of the underlying hardware instance.

The core TinyOS communication abstraction is based on Active Messages. Active Messages provides an unreliable, single-hop datagram protocol, and provides a unified communication interface to both the radio and the built-in serial port.

More recently TinyOS has been extended with a IPv6 protocol stack, called the Berkeley Low power IP (BLIP) stack [66]. The BLIP protocol stack is adapted to the IEEE 802.15.4 radios and has been optimized to run on sensor nodes with limited resource characteristics [77]. This implementation of IPv6 over IEEE 802.15.4 communication, commonly known as the 6LoWPAN protocol stack, has been standardized by the Internet Engineering Task Force (IETF). This provides an Application Program Interface (API) for communication that is then implemented for the particular interface(s) of the sensor device. Furthermore, one can seamlessly connect sensor devices to the Internet or to networks based on Internet technology such as e.g., the OpenCare project [2].

1) *Protocols*

In ASE-BAN experiments with the usage of Active Messages as well as BLIP have been made. Figure 12 shows an example of the protocol stacks for an end-to-end system based on 6LoWPAN. Looking at communication end-to-end one finds IPv6 as the common denominator that connects the home base station (or a remote central server accessible over the Internet).

The use of IPv6 at the network layer allows us to connect sensor devices to the Internet and to support multi-hop communication based on standardized, light-weighted routing protocols [78].

To bridge the gap between the healthcare sensor application and the communication interface, it was decided to rely on the UDP socket interface provided by the BLIP protocol stack or to rely on embedded web services [79]. In the latter case a middleware layer, which is able to map applications' requirements to the sensor network resources, was used.

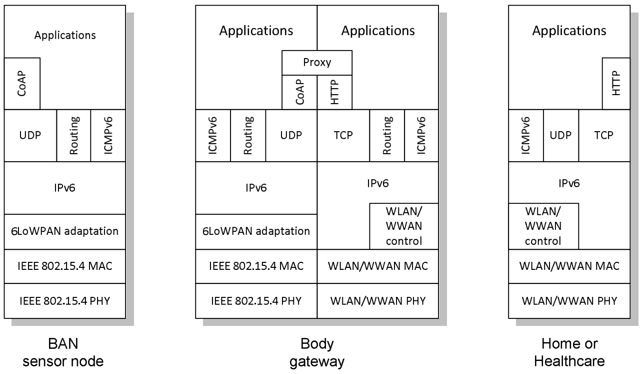

Figure 12. ASE-BAN protocol stack.

These server controlled resources are accessed by clients in a synchronous request/response fashion using methods such as GET, PUT, POST, and DELETE of HTTP/CoAP, as shown in Figure 13.

IETF is proposing the Constrained Application Protocol (CoAP) to support RESTful web services in constrained environments such as wireless sensor networks. In ASE-BAN we have chosen to follow this path and have implemented a TinyOS implementation of CoAP similar to [80] .

Hence, healthcare services can be provided end-to-end with open, flexible and scalable software which eventually leads to an attractive total cost of ownership for the healthcare provider, i.e., often the society in general.

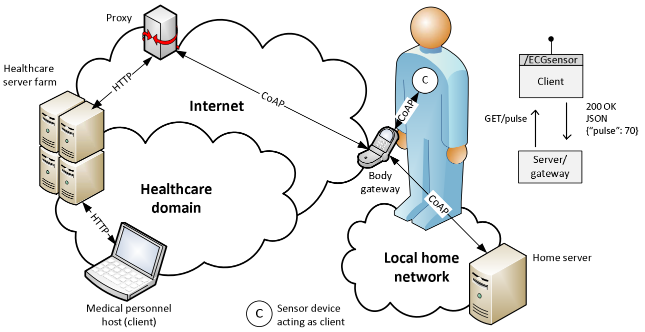

Figure 13. Example of web service architecture for interoperable healthcare services for ASE-BAN.

C. *Body gateway and node software components*

1) Smartphone as a body gateway

The body gateway was developed using a smartphone (a Google Nexus One), but was also imagined as an embedded solution. The gateway is responsible for relaying information from the internal wireless BAN to an external IP network. A smartphone based on the Android operating system was chosen as the target platform [81][82], since it allowed for easy prototyping using high-level code.

The first prototype of the body gateway used a Bluetooth Serial Port Profile (SPP) to communicate with the bridge node of the wireless BAN. This is not an optional solution as the bridge node requires daily recharging caused by the power demand of the Bluetooth protocol.

The second prototype still needed the bridge node, but used a directly wired serial port. This was possible due to the openness of the Android platform, which allowed compiling and replacing the driver module for the USB connector on the phone. This reduced the power consumption and minimized the footprint. A third option was considered, where the master node is connected to the same battery as the phone and directly inserted into the phone via the microSD card interface.

2) System Software Components and communication

The actual ASE-BAN consists of 4 different types of nodes with software: a central server, a body gateway (the smartphone), a bridge node and the sensor nodes.

The central server and the body gateway software components shown in Figure 14 use essentially the same code to handle incoming events and differ only in the way they receive these events.

The central server receives incoming events via the HTTP protocol from the body gateway, while the body gateway receives these using a serial port connected to the bridge node.

The bridge node software component shown in Figure 15 is designed to bridge data from the wireless BAN to the serial port. The wireless BAN software uses the Active Message protocol, where data is delivered as datagrams, while the serial port uses a simple frame stuffing algorithm to isolate each datagram.

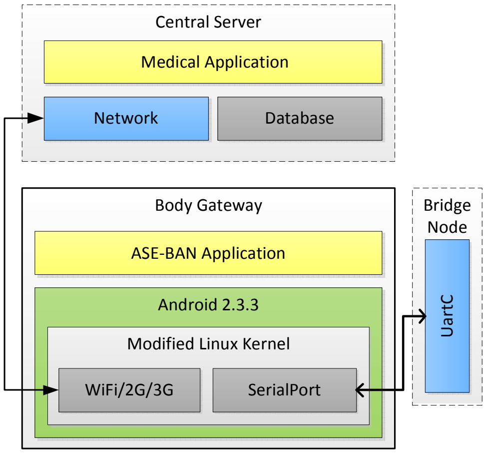

Figure 14. Central server and body gateway software components.

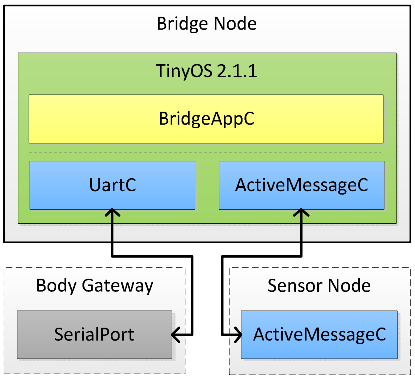

Figure 15. Bridge node software components

Figure 16 shows the sensor node software components for a sensor node equipped with a fluid balance sensor and an on-board accelerometer. The SoftI2cC component implements the I2C communication for two general purpose I/O pins. The accelerometer component is the software driver for the physical accelerometer which communicates through the I2C interface. The FallDetectionC component implements a fall detection algorithm. The SensorAppC component binds the software components together and delegates the received events e.g., a fall event and a fluid balance alarm event to the ActiveMessageC component, which implement the Active Message protocol.

D. *Sensors*

1) Fluid Balance sensor

The fluid balance sensor enables wireless BAN to issue alarms when the body fluid level of the user becomes critically low. The fluid balance sensor is designed for measurement of the electrical-biological impedance (EBI) of adult humans. The focus is on the detection of the dehydration, typical for elderly or demented people, who may benefit from some kind of feedback when water intake is needed. However, the sensor may also be implemented

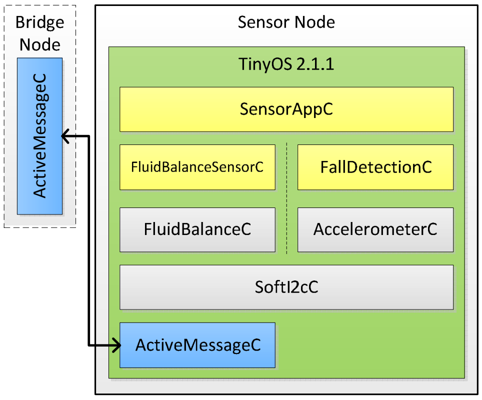

Figure 16. Sensor node software components.

within areas such as total body composition, lungs composition and respiration rate if the software is adjusted accordingly [83].

Biological tissues are composed of groups of cells with each cell consisting of a cell membrane separating the internal fluid from the external fluid. The conductivity of the fluid may be represented through a resistance between any two points and the impedance of the tissue becomes modeled as the resistance of the external fluid in parallel with the resistance of the internal fluid and separated by the capacitance of the cell membrane, thus leading to equivalent models by Fricke (1924) and Cole (1928). They are commonly called "2R-1C" networks since they consist of two resistance values and one capacitance shown in Figure 17 [83]. Typical resistance levels are from 10 Ω to 200 Ω and the average capacitance value is within the 100 nF range depending on the measurement principle being used, such as from arm to arm or from arm to leg. The impedance is within the ASE-BAN circuit monitored from 5 kHz to 100 kHz.

The present design uses the AD5933 impedance measurement device from Analog Devices, which comprises a programmable sine wave oscillator and discrete single-frequency Fourier transform circuitry converting the measured quantity into real and imaginary values representing the complex impedance. External circuitry is used to convert the AD5933 oscillator output voltage into current, which is routed through the skin to the tissue to be analyzed using two electrodes. Two additional electrodes are used to monitor the voltage created across the tissue and this voltage is correlated with the excitation signal thus determining the relative magnitude and phase of the impedance. Calibration uses a fixed resistor for scaling of the numerical value output from the AD5933 back into resistance thus reducing errors related to component tolerances.

Fluid balance measurements must be determined with approximately 1 Ω of accuracy for determination of the change in impedance due to dehydration. The contact resistance from electrode to skin may exceed 1 kΩ at the frequency range of interest. Four electrodes are needed to unload the measurement electrodes from the excitation current. The present design uses an AC current level of 40 µA, which is far below the detectable range [84]. A plot of the impedance in the complex plane approximates a half circle in the fourth quadrant, usually called a Cole plot, is shown in Figure 18. Impedance measurement is conducted by fitting the measured values with the periphery of a half circle, and then extrapolating the half circle to zero and infinite frequency for determination of the resistance of the external and internal fluids as well as the bulk capacitance of the cell membrane. At infinite frequency the impedance reduces to the series resistance of the Cole model and at zero frequency the impedance becomes the sum of the resistance components. The capacitance value is determined from the frequency at the extreme imaginary value. The degree of dehydration is detected as a change within the resistance pattern, and examination is currently being conducted to determine this correlation, the effect of electrode contamination and the required monitoring precision.

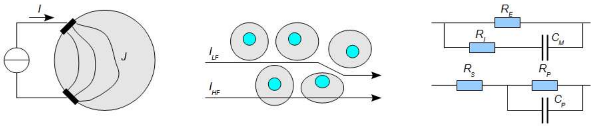

Figure 17. The electrical-biological impedance measurement principle is shown with the current path at low and high frequency (LF and HF respectively). To the right the Fricke model (top) and Cole model (bottom).

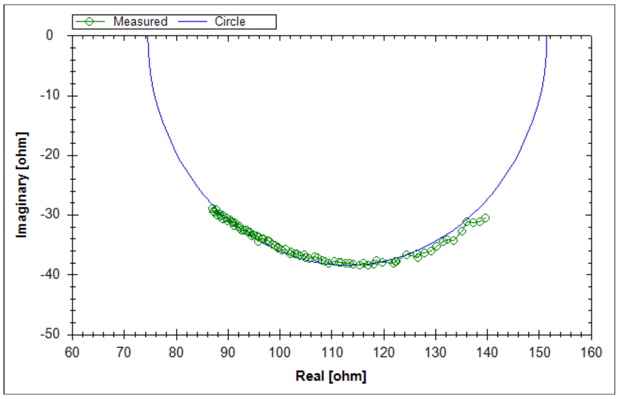

Figure 18. Cole plot of a network with two series-connected resistors of 75 Ω each and one capacitor of 220 nF in parallel to one of the resistors with the approximating circle. The frequency range was from 5 kHz (rightmost data point) up to 25 kHz using 250 Hz of step size.

A result is shown within the picture using a 2R-1C model network. The analysis is to be carried out autonomously by the fluid balance sensor and the result is either uplinked using the radio transmitter or alternatively output directly to the user as an audible or visible indication of the need to drink water.

2) ECG sensor

Monitoring of heart activity uses an analogue interface with an instrumentation amplifier. The signal from the heart is less than 5 mV of peak amplitude so the interface amplifies the signal to fit the input range of the A/D converter. The input is differential to reduce mains hum and a third electrode is used for suppression of common-mode disturbance. The required bandwidth is 40 Hz for heart rate determination but sampling at 500 times per second resolves frequencies up to 150 Hz for diagnostic use. Digital filtering may implement a filter for additional hum suppression, such as notch filtering at the frequency of the disturbance without serious impact upon bandwidth or low pass filtering with high order slope and cut off around 40 Hz.

The interface is general-purpose and may be used for any low-voltage analogue interfacing with bandwidth set by the sampling rate at the A/D converter.

A more advanced interface is offered through the DSP based ECG sensor, which is interfaced to the ASE-BAN PCB base module and is intended to unload the microcomputer and radio link through the use of a dedicated signal processor device.

From the electrical signal, the HRV can be derived [85]. The complete electric signal: the electrocardiogram (ECG) and the HRV is measured by the sensor. The ECG and the HRV are widely used for medical surveillance and diagnostic purposes.

The ECG sensor module measures two lead ECG signals on the chest of the user. The sensor is intended to be worn for several days without intervention; hence appropriate electrodes are used, to provide for high signal quality and user comfort. The prototype uses insulated bioelectrodes which provides good signal quality and reduced risk for skin irritation [86]. The module amplifies the weak ECG signal (peak to peak amplitude of approximately 2 mV), before the signal is AD-converted. The sampling rate is 500 Hz in 16 bits to provide for sufficient signal quality for diagnostic purposes [87]. Figure 19 shows a recorded ECG on the home base station.

The processor module shown in Figure 20 for the ECG sensor is a small foot-print DSP platform equipped with a Blackfin BF533 signal processor from Analog Devices [88]. The Blackfin BF533 is a high-performance fix-point processor with two 16-bits Multiply-And-Accumulate units, capable of parallel processing. The processor is capable of handle clock-speeds up to 600 MHz. The on-chip Real-Time-Clock is connected to a 32 kHz crystal.

The DSP processor module is used for sensor local analysis of the ECG signal. This is done to save node energy, since processing data is more energy efficient that transmission of data. Commercial radios typically dissipate *Te* ~150 nJ/bit [89]-[91], versus the processor referenced in Table II dissipate on the order of *Ce* ~1 nJ/sample [92]. This indicates a break-even between transmission and processing of data at ~2500 instructions per sample (16 times 150 inst./sample) [93].

Equations for the energy budget can be setup as follows:

$$K \cdot Ce + n \cdot Te = N \cdot Te\,, \tag{1}$$

K is the number of instructions needed to reduce *N* samples to *n* samples. *Ce* is the energy-use per instruction and *Te* is the energy-use per transmit of one sample. Rearranging Equation (1), one arrives at Equation (2):

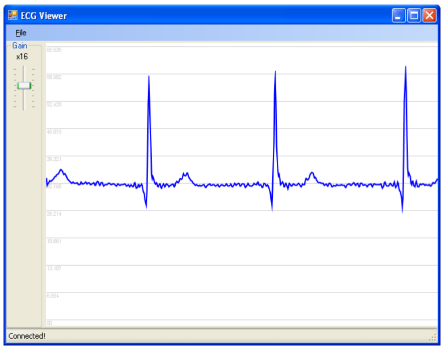

Figure 19. ASE-BAN measurement of an ECG signal.

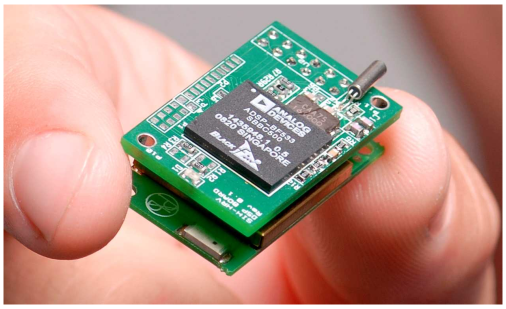

Figure 20. The ASE-BAN ECG sensor module with DSP. The size is 13 mm x 18 mm x 30 mm. The weight is 6 g.

$$\frac{K}{N} = \left(1 - \frac{n}{N}\right) \cdot \left(\frac{Te}{Ce}\right), \tag{2}$$

Our application aims at reducing bandwidth by a factor *n*/*N* ~1000 times (HRV transmission at 0.5 Hz, and ECG sampling rate at 500 Hz). According to the analysis above *Te/Ce* is set to 2500 inst./sample and hence *K*/*N* attain a value of ~2500 inst./samples.

ASE-BAN software runs standard adaptive noise removing techniques to remove hum in the ECG. The R-peak in the ECG signal is calculated using the Pan Thomkins algorithm [56] and the ECG signals is finally analysed, calculating standard Heart Rate Variability pNN50 [85]. This algorithmic data reduction can be run on the processor module. An efficient implementation is estimated to be using 500 inst./sample or less. This is significantly below the 2500 inst./sample break-even limit calculated above.

3) HRV sensor

A dedicated module for high-speed processing of the data is offered using the BF533 digital signal processing device of the BlackFin-series from Analog Devices. The module was developed for evaluation of algorithms and interfaces to the ASE-BAN module.

4) Accelerometer sensor

Acceleration detection is a versatile instrument with applications for user-orientation (standing or lying), fall detection, and alarm generation for users that do not move at all following a fall, in addition to motion and tap detection. The project interfaces to LIS331 or MMA8452Q, which are tree-axis seismic accelerometers interfacing through I2C. A mass is part of a capacitive half bridge for each of the axis within the device, so the sensor is capable of detecting static gravitation such as monitoring the physical orientation along earth's gravity as well as detection of shock and vibration. The sensors may generate an interrupt request to the micro controller if the acceleration crosses through programmed limits.

5) Fall detector

For use in the demonstrators a fall detector application was designed. The fall detection algorithm is based on the movement pattern during a fall. When a person falls either from a standing or sitting position or when walking the sensor will experience the same basic pattern. First, the sensor will sense close to 1 g of downwards force due to gravity. Then, during the first phase of the fall, a free or near free fall condition will be experienced. The free fall condition will be followed by the impact phase in which the person will hit the ground. The sensor will see this as a series of large spikes in the sensed acceleration. This detection state machine is shown in Figure 21.

The algorithm could be improved to track the fall after the impact to determine if the person is unconscious or is trying to get back up. The fall detector is currently able to detect the laboratory reproductions of a fall but optimizations such as lowering the 50 Hz sample rate to reduce energy consumption or adjusting acceleration and timing thresholds to increase detection reliability has not been performed.

6) *Proximity detector*

Applications include the substitution of mechanical switches and proximity detection, such as the presence of a user of the ASE-BAN circuitry. The interface uses the AT42QT1010 chip, which detects the change within capacitance due to the presence or absence of the human body or one of the fingers within the proximity of a conductive plate. The interface is one bit so the output is detected or not detected, and the device includes options for reducing sensitivity to electrical noise or transients from quick brushes with an object, such as during cleaning.

7) *Temperature sensor*

The project includes several temperature monitoring points due to the build-in sensors at the micro controller and the fluid balance sensor, but they are not externally accessible and the measurement precision is limited.

VI. DEMONSTARTOR AND RESULTS

This section describes the ASE-BAN demonstrator and the results. Since this is work in progress only preliminary results will be presented together with a prototype design of a casing for an ASE-BAN sensor node.

A. *Demonstrator*

A fully integrated ASE-BAN demonstrator, to be used by a test person, is under preparation. The objective of this demonstrator is to show the integration of the developed ASE-BAN components as well as the feasibility of integration into a complete healthcare system.

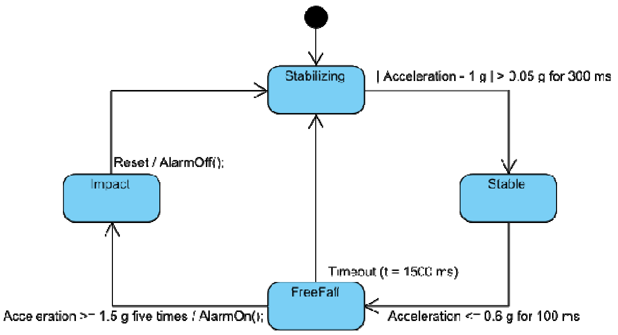

Figure 21. The four states of the fall detection algorithm.

From a sensor point of view the demonstrator consists of fluid balance sensor nodes, an ECG sensor node, an ambient temperature sensor node and a fall detection sensor node. All sensor nodes except the fall detection sensor are installed on the front of the test person. The fall detection sensor device is installed on the back at the person's waist. To provide connectivity to sensors on the back an ASE-BAN relay node is installed. Figure 22 shows the positioning of sensor nodes and how they are connected in the network.

To demonstrate the feasibility of the integration with a healthcare system it is shown how sensor nodes can be monitored remotely via the Internet as well as from the OpenCare project infrastructure installed in the user's home.

The two fluid balance sensor nodes – one attached to the upper arm and the other attached to the person's thigh are used in order to test the consistency of sensor readings.

In the demonstrator an Android smartphone is used to act as ASE-BAN body gateway. The smartphone connects to the sensor nodes by using one of the sensor nodes e.g., the ambient temperature sensor node as a bridge node. A serial connection between the smartphone and the bridge node is configured. Both a wired and a wireless option are viable. In the former case the bridge node is piggy-backed onto the smartphone whereas in the latter case a serial Bluetooth connection is used between the bridge node and the body gateway.

The demonstrator is able to push data to the home base station and/or an external web server residing in the healthcare domain, i.e., a central server. In the latter case a global IPv6 network infrastructure with the 6LoWPAN networking capabilities of the BAN is established. For this part of the demonstrator a Linux PC is used as a 6LoWPAN due to the lack of support for IPv6 in Android. Effort is ongoing to include IPv6 support and to port the 6LoWPAN edge router software to Android. The results with 6LoWPAN

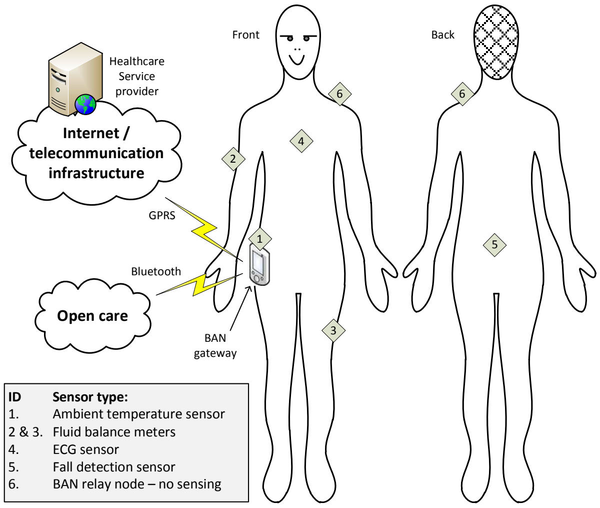

Figure 22. BAN with four sensor devices connected to a global network infrastructure.

are described as Result 2. Another experiment with the demonstrator used the smartphone with the Active Messages protocol as described in Results 3. In both cases data can be displayed on the smartphone as well as on a remote central server.

B. Results

1) Result 1– Radio communication channel

The human body has a significant impact on the radio communication in a wireless BAN. To gain a better understanding of this effect a dedicated test environment has been created for this. This consists of a boiler suit fitted with an array of IEEE 802.15.4 compatible radio modules. These radio modules are connected to a PC through a cable to form a wired network for test purpose. This setup is illustrated in Figure 23 which also shows the actual boiler suit.

The radio modules continuously broadcast packets containing their network id. These packets are received by some or all of the other radio modules depending on the radio conditions. As all modules transmit at the same power level each receiving module is able to calculate the loss in signal strength by subtracting the Received Signal Strength Indicator (RSSI) value recorded when the packet was received from the known transmission power level. The cost of all links is transferred to the PC through the wired network and stored in a log file. Simultaneously a camera connected to the PC records the actions of the wearer of the boiler suit.

These images are stored in the log file together with the link quality data from the same instance in time that the image was taken.

By creating log files of standard everyday scenarios (sitting down on a chair and getting back up, walking etc.) the expected signal conditions in an actual wireless BAN were identified. It was evident from the tests that the communication in a wireless BAN often relies on reflections from the surroundings for the radio waves to reach their destination as there is often no line of sight path. Areas that should receive special attentions were also identified. The effect of a swinging arm during a walk was for instance very significant between certain nodes but barely visible on other links. Calculations indicate that packet loss can be reduced significantly and energy consumption lowered due to improved link quality if automatic power control is employed. The information obtained with these tests where used to design the network for the demonstrator.

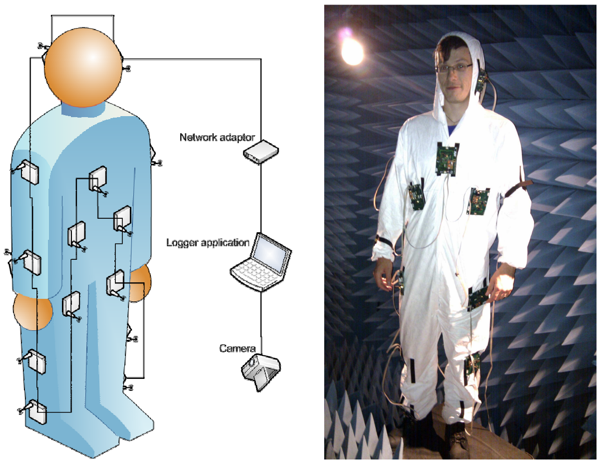

Figure 23. The test environment (left) and the actual boiler suit (right).

For a detailed explanation of the full test environment and a deeper analysis of the results please refer to [94].

2) Result 2 – 6LoWPAN network

This part of the demonstration focus on body area networking aspects and global IPv6 Internet connectivity. Our experimental setup consists of up to 6 sensor nodes and a base station. In order to demonstrate interoperability a mix of ASE-BAN nodes and the TelosB nodes, that offer similar hardware architecture, have been used [74]. For the base station a Linux PC with a TelosB node for the IEEE 802.15.4 connectivity has been used. The Linux PC is configured as a 6LoWPAN edge router.

The ASE-BAN nodes implements the 6LoWPAN protocol standards based on the open source TinyOS stack called BLIP. Global IPv6 connectivity will be provided by using an IPv6 deployment and tunnel broker service provider such as SixXS [95]. Over this global IPv6 infrastructure sensor data is delivered by using web services.

The ASE-BAN testbed successfully demonstrates many networking aspects that are of importance and relevance for body area networking. The following list provides a few highlights of this demonstrator:

- Sensor device network interoperability (TelosB and ASE-BAN hardware)
- Multi-hop communication in the BAN (mesh-networking)
- 6LoWPAN networking
- Dynamic routing by using Hydro routing protocol
- Global IPv6 connectivity using a tunnel broker
- Web services for BAN

3) Result 3 – ASE-BAN applications

The demonstrator contains software applications that were developed to handle issues from different parts of the ASE-BAN. In this section a fall detection application based on accelerometer readings will be described.

A central issue was how to connect the smartphone to the actual wireless BAN, originally the solutions was to use a Bluetooth connection, since this seemed to be the easiest and most compatible solution. To gain battery life and a smaller footprint solutions that allowed using the USB connector of Android as a serial port, as shown in Figure 24, were implemented.

For the gateway a Google Nexus One (HTC) Android smartphone with CyanogenMod 7.0.2.1 was used [96]. CyanogenMod is a customized, aftermarket firmware based on Android 2.3.3. The platform allowed using the USB connector as a serial port.

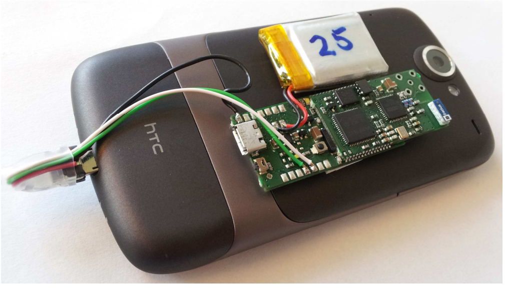

Figure 24. Body gateway with bridge node.

ASE-BAN needed to be modular, and support sensor types which are not defined yet. Therefore a highly flexible way to handle data transport and data presentation was designed. For data transport Java Script Object Notation (JSON) was chosen [97]. JSON is a lightweight alternative to XML, and is native to the JavaScript language.

First data is collected on the fall detector node shown in Figure 25, #1 and is transferred to the body gateway. The actual data is formatted as JSON.

Data example from the fall detector node:

```
{"d":0.156,"f":"fd"}.
```

This is a simple JSON byte array with two fields: “`d`” is data as a JSON Object, and “`f`” is a unique data format identifier. In this case the format identifier “`fd`” is used, which tells us that the data is a fall detection format and that the data is in G (gravity).

Next data is received at the body gateway, where data will be relayed to the Central Server, Figure 25, #2:

```
{"d":0.156,"f":"fb","t":69585742574,
 "u":"Foo Bar","s":"Accelerometer"}.
```

Here additional fields are added, “`t`” is a timestamp in Unix time. “`u`” is the unique name for the BAN user, “`s`” is the unique sensor the data originated from.

The last step is when data enters the database and is stored for later usage, Figure 25,# 3.

For data presentation it was decided to use a combination of JavaScript and HTML5. This allowed us to reuse UI code for both the Android smartphone and the central server.

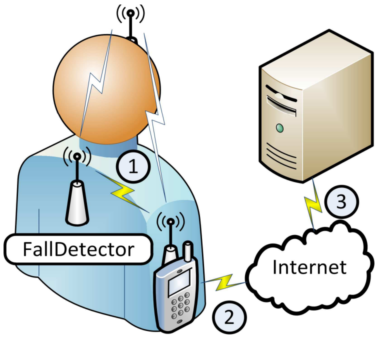

Figure 25. Communication flow.

Figure 26. Body gateway accelerometer curve.

An example is shown in Figure 26 with accelerometer data displayed on the Android smartphone while Figure 27 shows the same data presented in a browser that accesses the central server.

C. *Prototype casing for the ASE-BAN module*

To bring the ASE-BAN module out of the laboratory and into the hands of the user group a casing has been designed by an industrial designer. The design is based on the fall detection application but is open enough to be adapted to any application supported by the ASE-BAN platform. Figure 28 shows the casing being used by a potential user.

The black circle in the middle is a button for user while the green circle is a multi-color LED used to inform the user of system events. The back side features a secondary button used to test remaining battery capacity. When this button is pressed the LED will light up in green, orange or red depending on battery status. The bottom of the casing exposes two metal pads which mates with two matching pads when inserted into the charger as illustrated in Figure 29.

The driving force behind the design has been to create something that the user would naturally embrace and think of as a decorative object. Both the center piece of the casing and the two “wings” come in different colors to allow users to make their individual unit unique. Furthermore, the design

Figure 27. Central server accelerometer curve.

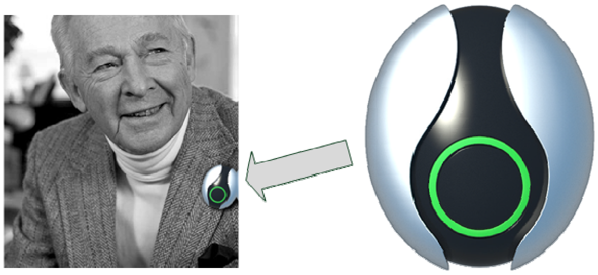

Figure 28. The ASE-BAN casing being worn by a user.

of the backside of the casing makes it possible to wear it either as a broche or as a necklace.

VII. DISCUSSION AND FUTURE WORK

With additional personalized healthcare assistance a more comprehensive and affordable healthcare solution is provided to the BAN user. It is absolute vital that the solution is highly reliable and easy to configure and operate. Furthermore, it must be energy-efficient to ensure a long battery life-time.

The next generation of wireless technologies is being driven by the rapid convergence of three key technologies: MicroElectroMechanical systems (MEMS), digital circuitry, and the explosive growth of wireless communications. Common to all three are reductions in size, weight, power consumption, and cost associated with the large number of units produced, as well as reductions in complexity and functionality.

In sensor networks, energy consumption is of highest priority and the RF communication design blocks consume the most energy. Wireless sensor network designers strive to reduce the power consumption of the blocks in general. The improvement for wireless sensor network is likely to be used to reduce size and power consumptions instead of increasing capacity and speed. The use of energy harvesting is an important aspect of sensor devices. With a smart combination of energy efficient protocols and energy harvesting methods, the optimal solution for achieving autonomous and long-lasting BANs can be reached.

Efficient protocol support is also needed for the IP based wireless sensor networks and the ongoing work of the IETF 6LoWPAN working group is heading in this direction. This includes protocol optimization for small devices such as neighbor discovery, compression mechanisms for TCP, light-weighted key management protocols as well as energy efficient routing protocols.

Figure 29. The ASE-BAN casing and its charger.

In essence, the implemented, modular wireless BAN testbed is flexible and can be customized to the individual needs of users. Our hardware platform is energy-efficient and has a low footprint. Whilst the basic capabilities of the testbed have been demonstrated there is still effort to be done in particular with respect to the software and protocol parts. As an example a plan exists to adapt the ASE-BAN testbed to the Medical / health device communication standards, i.e., the IEEE 11073 standards [51]. The IEEE 11073 standards specify the communication between medical/healthcare devices and external computer systems in a client-server architecture. Features such as automatic and detailed electronic data capture of client-related and vital signs information as well as device operational data can be communicated, from the BAN node application to servers residing at e.g., a hospital, over an IP network. Standards like IEEE 11073 are critically important to ensure multi-vendor interoperability thus enabling the personal healthcare to converge from today's defragmented market where isolated solutions exist.

The long term plan is to design a low-cost plug-and-play biomedical wearable computing network that can be integrated as part of a future ambient assisted living network, to be used e.g., for local personal real-time monitoring of an elderly person at home.

To succeed there is a need to combine a number of competences like integrated electronics, communication technology, embedded real-time systems, software and digital signal processing. For the integrated electronics part, work with issues like power optimization is ongoing. With respect to communication technology the key issue is to design a wireless wearable and human centric network based on the communication channel in a near human body environment. For the software part plans are made for developing application frameworks for the different system components. Finally, with respect to signal processing, some of the data processing will be performed locally on the testbed. For certain applications the system must run in real-time and have a very high reliability as e.g., with continuous heart-rate-variability monitoring.

In future generation of ASE-BAN much more emphasis will be put into the security and privacy aspects. A security framework adapted to wireless body area network has to be sufficiently light-weighted to meet the constraints of the sensor devices. On the other hand it also needs to be capable of providing the in-depth security and privacy required for the wireless sensor applications. Flexible security mechanisms must be developed and new generation of system on chips must offer basic security features as an embedded part of the chip.

Besides a more complete integration and intentions to apply the platform with trial users plans for a third generation platform are under preparation.

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