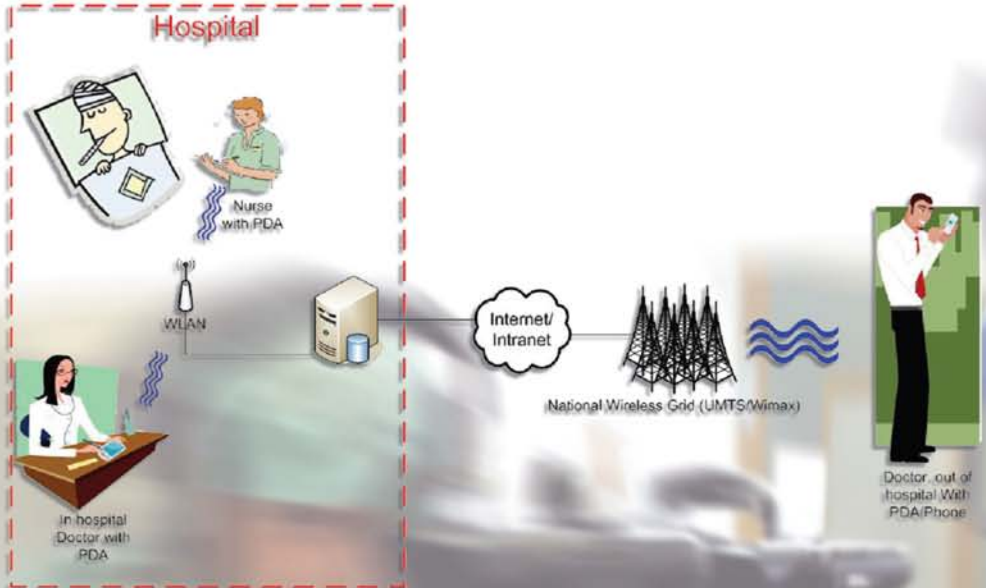
Mobile Telemedicine

A Computing and Networking Perspective



Edited by
Yang Xiao
Hui Chen

CRC Press
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AN AUERBACH BOOK

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Contents

Preface

Wireless and mobile telemedicine has drawn attention from health care providers and recipients, governments, industry, and researchers. Though various practices have been exercised, the realization of telemedicine depends on advances in computing and networking techniques. In recent decades technological development in computing and networking has largely made the delivery of health services, including medical diagnosis and patient care, possible from a distance. Many funded projects have evaluated the use of communications technology in the implementation and performance of telemedicine activities, and examined the impact of telemedicine on medical care in terms of cost, quality, and access. Telemedicine has become a growing new interdisciplinary field, which will eventually contribute to improving the quality of health care for everyone. However, successful implementation of this vision depends not only on innovative telemedicine applications but also networking and computing technical readiness. Furthermore, many ethical, social, and political problems arising in telemedicine need technical solutions.

This book studies computing and networking problems which arise from wireless and mobile telemedicine. It is a contribution of many prominent researchers working on the telemedicine field around the world. The book is divided into six parts: patient care and monitoring, cardiology, diabetes, security and privacy in telemedicine, networking support, and opportunities and challenges, including 20 chapters on a wide range of topics associated with novel telemedicine applications and pertinent networking and computing techniques. The book will shed light on future research of these areas. This book will serve as a good reference for researchers to know the state of the art and to discover uncovered territory and develop new applications, especially from a networking and computing perspective.

Acknowledgments

This book is made possible by the great efforts of our publishers and contributors. First, we are indebted to the contributors, who have sacrificed many days and nights to put write these excellent chapters for our readers. Second, we owe our special thanks to our publishers and staff members. Without their encouragement and quality work, this book would not have been possible. Finally, we would like to thank our families for their support.

About the Editors

Yang Xiao is currently with the Department of Computer Science at The University of Alabama. He worked at Micro Linear as a MAC (Medium Access Control) architect involving the IEEE 802.11 standard enhancement work before he joined the Department of Computer Science at The University of Memphis in 2002. Dr. Xiao is the director of W^4-Net Lab, and was with the CEIA (Center for Information Assurance) at The University of Memphis.

Dr. Xiao is an IEEE senior member and a member of the American Telemedicine Association. He was a voting member of the IEEE 802.11 Working Group from 2001 to 2004. He currently serves as editor-in-chief for *International Journal of Security and Networks (IJSN), International Journal of Sensor Networks (IJSNet),* and *International Journal of Telemedicine and Applications (IJTA)* and as a (lead or associate) guest editor, an associate editor, or on editorial boards of many refereed journals. Dr. Xiao has also served as editor/co-editor for 11 books.

In addition, Dr. Xiao serves as a referee/reviewer for many funding agencies, as well as a panelist for the U.S. National Science Foundation (NSF) and as a member of Canada Foundation for Innovation (CFI)'s Telecommunications Expert Committee. He serves as TPC for more than 90 conferences such as INFOCOM, ICDCS, ICC, GLOBECOM, and WCNC. His research areas are security, telemedicine, sensor networks, and wireless networks. He has published more than 200 papers in major journals (more than 50 in various IEEE journals/magazines) and refereed conference proceedings related to these research areas. Dr. Xiao's research has been supported by the U.S. National Science Foundation (NSF).

Hui Chen is a geophysicist turned computer programmer and researcher. He received his M.S. and Ph.D. degrees in computer science, respectively, in 2003 and 2006 from The University of Memphis. Hui Chen is currently with the Department of Mathematics and Computer Science at Virginia State University. While he retains his interests in studying computational problems in various areas of earth science, he primarily works on computer system and networking research such as design and analysis of personal communications service systems, wireless LANs, wireless sensors, mobile/wireless distributed systems, and cache systems for wireless systems. He is an author of more than 30 scientific papers and articles. He serves as a guest editor for *EURASIP Journal on Wireless Communications and Networking*, special issue on "Wireless Telemedicine and Applications." He is a member of IEEE and ACM.

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1

PATIENT CARE AND MONITORING

Chapter 1

Personal Supervision and Alarming Systems

Etienne Hirt and Michael Scheffler

CONTENTS

This chapter describes the motivation for personal supervision and alarming systems, the vital parameters to be measured, and the wearable and environmental sensors required. Such systems are found to be suitable for the supervision of elderly people, outpatients, high-risk populations (i.e., cured cardiac patients), and health-conscious people. Three different solutions are discussed and assessed.

The fusion of these approaches is proposed for working out an optimal solution based on a sophisticated wrist wearable device measuring vital parameters for supervision but not diagnostic. The wrist device is supported by a minimal environmental installation.

1.1 Introduction

Nowadays in the Western world, more and more elderly people live in their own households and without any relatives in their vicinity. Although their physical fitness is continuously decreasing, they want to keep their personal autonomy and want to stay in their own environment as long as possible without sacrificing their medical safety.

Moreover, post-operative intensive care in hospitals is minimized as much as possible to reduce overall health costs, thus causing an increase in hospital outpatients. Additionally, the general population of high-risk patients (e.g., those exhibiting a cardiac deficiency) is becoming larger and larger.

To support all these groups in their daily life and to improve their personal well-being at reasonable cost, personal supervision and alarming devices can fill a gap to alert relatives or activate neighborhood or emergency medical services (EMS) early enough in case of a medical incident. Such personal devices can replace part of the capabilities of a nurse or a caring family member in the same household—the automated version that can identify a medical condition and trigger help.

Apart from the obvious society benefit, also from a commercial perspective such devices are very interesting: the target groups present a significant emerging market. However, it is not a single mass market because the required solutions are still specific to the environment and the target group. Therefore this fact also opens business opportunities for niche players and small- and medium-size enterprises.

This chapter describes sensor technologies suitable for integration into personal supervision and alarming wrist devices, and location and networking technologies required. We present examples of the medical approach of the AMON research project and the network approach of the EMERGE research project, and we propose a fusion approach of both solutions.[1,2]

Cost–benefit calculations are not included in this chapter because they very much depend on usage and the reimbursement of insurances; also descriptions, requirements, and examples for corresponding infrastructures such as telemedicine centers can be found elsewhere.

1.2 Target Groups and Suitable Parameters to Be Measured

The user group of personal supervision and alarming devices is far from being homogeneous. In order to identify their requirements, this section defines typical target applications, their purpose, and the vital parameters to be measured. Also, we present general design guidelines for wearable devices.

1.2.1 Target Groups

For the purpose of this chapter, we divide the target groups into:

- Elderly person surveillance
- Post-trauma care
- Personal health devices

The requirements of these groups are described in the following subsections.

1.2.1.1 Elderly Person Surveillance

A lot of elderly people would like to live in a self-determined way in a familiar environment as long as possible. As long as a person is not living alone, the elderly supervise each other constantly and therefore are not ready for technical supervision. But as soon as a person is living alone at home or even in a managed care facility, an automated alarm system* at least is strongly recommended.

For elderly people not visited daily by relatives or neighbors further supervision of drinking, eating, mobility, and medication should be performed to recognize typical problems early.

In addition, any people having certain health problems shall be supervised specifically, i.e., regular ECG and/or blood pressure measurements as described in the further subsections.

1.2.1.2 Post-Trauma Care

People often have to stay in hospital for supervision only. Health costs can be reduced if these people could be released to go home or even to work, provided they could wear the required supervision and alarming equipment. Such equipment has to provide medical measurements comparable to hospital standard, which is really a challenge.

High-risk populations such as cardiac patients after successful convalescence should be supervised with the same devices. An example for this target group is described in Section 1.0.

* An automated alarm system automatically alerts a care giver, relative, or the EMS on the suspicion that something may be wrong.[3] These systems can continuously monitor variables sensitive to changes in functional health status and behavior. They generate an alarm when significant changes are observed. They can be as simple as consisting of combined movement detectors only. With an intelligent decision-support system using robust algorithms, false alarms are unlikely. These systems are most likely fully integrated within a home network.

1.2.1.3 Personal Health Devices

People interested in continuous supervising of their health are possibly a third target group. Their requirements are lower than those of the other groups, because they neither require an excellent alarming system nor medical-grade measurements. Their focus is rather on unobtrusive devices with many features. Typical examples are pulse watches such as the well-known Polar heart rate monitors.

1.2.2 Vital Parameters to Be Measured

The following vital parameters are assessed for supervision of the target groups.

1.2.2.1 Pulse and Heart Rhythm

Measuring the pulse can give very important information about the health of a person. Any deviation from normal heart rate can indicate a medical condition. Fast pulse may signal the presence of an infection or dehydration.[4] In emergency situations, the pulse rate can help determine if the patient's heart is pumping and allows detecting a cardiac arrest immediately. Furthermore, pulse measurement during or immediately after exercise can give information about the fitness level and the health of a person. A pulse measurement shall be provided for all three target groups.

ECG-type techniques additionally allow measuring the R–R interval (peak-to-peak time in ECG) and provide better supervision because arrhythmias show cardiac problems that are not recognized with pulse measurements. However, the rhythm is usually only required for post-trauma care and often a noncontinuous measurement is sufficient.

1.2.2.2 Movement/Fall

Movement supervision is very important for an automatic alarm device. It enables the device to recognize a fall or a situation where the patient is helpless, and calls for assistance without user intervention. This supervision capability is required especially for elderly people surveillance.

1.2.2.3 Temperature

Of medical relevance is the body (core) temperature, but because fever is usually only an additional medical sign, it is not very important. Body temperature measurement is not required for any of the target groups.

It is much easier for a device to measure the skin temperature, a mixture between body temperature and environment temperature. The skin temperature has no medical value but provides a context for the other vital sensors required, e.g., for temperature compensation.

1.2.2.4 Skin Humidity

Skin humidity is hardly measured by medical people but according to the Mayo Clinic,[5] it would be a good parameter to monitor the (de-)hydration of people and would therefore be recommended for the supervision of elderly people. However, the physicians within the EMERGE[2] project do not support this recommendation.

1.2.2.5 Blood Pressure

High blood pressure increases the risk of heart failure, heart attack, stroke, and kidney failure. For people who have high blood pressure, this test is a way of monitoring the effectiveness of medications and dietary modifications.[4]

Low blood pressure may be a sign of a variety of illnesses, including heart failure, infection, gland disorders, and dehydration.

Repeated measurements are important. A single high measurement does not necessarily mean that the patient has a high blood pressure condition. On the other hand, a single normal measurement does not mean that the patient has no such condition.

Blood pressure readings taken at home can provide important information to the doctor. Such readings may be a better measure of the current blood pressure than those taken at the doctor's office where people are known to become nervous ("white-coat hypertension"), resulting in higher readings than normal.

Continuous blood pressure measurement is recommended for cardiac outpatients but noncontinuous measurements are sufficient and suitable for all target groups.

1.2.2.6 Pulse Wave Velocity (PWV)

The pressure pulse travels much faster than the blood itself. PWV describes how quickly a blood pressure pulse travels from one point to another in the human body. The time difference between these two locations is known as the pulse transit time (PTT). PWV is typically measured between the carotid and the femoral artery. Atherosclerosis causes the arterial walls to become thicker and harder, and narrows the arterial lumen. The increased inflexibility of the arterial walls increases PWV, because the energy of the blood pressure pulse cannot be stored in an inflexible wall. PWV can be used as an index of arterial distensibility.

In terms of medical diagnosis, PWV is a highly interesting subject because it provides an estimate of the condition of the cardiovascular system based on a large area of the human body.

Furthermore, as blood pressure is essentially sensitive on the pulse wave velocity, the velocity pulse, and the arterial diameter, it can be calculated from PWV after an individual initial calibration by means of a standard blood pressure meter.

1.2.2.7 Blood Oxygen Saturation (SpO_2)

The SpO_2 measurement is routinely used for patient supervision as well as supervision during surgery. An SpO_2 monitor is an easily installable device that can be used by rescue teams for patient survey or even triage.[6] Although the measurement provides an easy installable pulse measurement as well as supervision of the oxygen saturation during surgery, the main problem is that the sensor itself requires supervision to ensure proper installation to avoid false readings and alarms. Therefore, continuous SpO_2 measurement is only recommended for post-trauma care.

1.2.2.8 Electrocardiogram (ECG)

An ECG is very useful in determining whether a person has heart disease. If a person has chest pain or palpitations, an ECG is helpful in determining if the heart is beating normally. If a person is on medications that may affect the heart or if the patient is on a pacemaker, an ECG can readily determine the immediate effects of changes in activity or medication levels. Some heart conditions are not detectable all the time, and others may never produce any specific ECG changes. A person who suspects heart disease or has had a heart attack may need more than one ECG.[4]

For cardiac outpatients as well as long-term measurements for heart disease investigations, ECG measurement is required continuously. For all other target groups, no ECG is required.

1.2.2.9 Blood Values

Blood values such as glucose concentration and others are only required for specific patients. These values can hardly be measured without taking blood samples or other (semi-)invasive techniques. Noninvasive measurement[7] methods are still subject to further research and development and are therefore not further considered in this chapter.

1.2.3 Design Guidelines and Challenges of Wrist Wearable Devices

The developer of wearable medical devices (WMD),[8] compared to stationary equipment, has to take additional user requirements into account. Also, instead of first designing a functional prototype and then making it wearable, both tasks need to be tackled concurrently, in order to avoid costly redesigns.

Small and lightweight: To suit the size of a forearm, typical dimensions would be about 60 × 50 × 15 mm.[9] Therefore, the inner dimensions are fixed and volume/weight restrictions apply. These restrictions require mechanical and electrical co-design throughout development. The WMD needs to be unobtrusive in order to be worn as a daily accessory without looking like a medical device.

Low power: Power is required for at least one working day without recharging. For an application with very low power consumption, a primary battery is suitable. Otherwise, a secondary/rechargeable accumulator is required.

Life cycle: High reliability and a minimum four-year field life are necessary in order to be eligible for possible reimbursement by health insurance plans.

Housing: The device needs to be shockproof and must be biocompatible where exposed to the user.

Input–output connection: If a plug and socket are chosen for input–output, there are mechanical issues and relatively large and expensive hardware is required. If wireless connections (see Section 1.3.4) are used, they will require much more power, contradicting the above-mentioned low power postulation.

Sensors: Novel applications depend on new sensor concepts, which cannot easily be integrated into standard electronics or housings. Also, where direct physical contact with the user is required, biocompatibility issues may influence the sensor principles and signal post-processing.

Sensor technologies and the suitable approaches for integration are analyzed in the following section.

1.3 Technologies for Wrist Wearable Devices

The user shall wear one device that incorporates the required and feasible sensors. Other sensors shall be attached to this device or to the infrastructure. The preferred embodiment of this device is a watch-like device that can be worn day and night. This device is also responsible for communication with any room installation.

Besides vital parameters, movement and location of a person shall also be supervised in order to detect emergency situations.

1.3.1 Sensors to Be Integrated into Wrist Wearable Devices

1.3.1.1 Pulse

State-of-the-art pulse measurement methods are

- ECG-type techniques
- Transmissive PPG (photoplethysmography) on ear, finger, or foot, reflective PPG on the forehead
- Pulse detection during oscillometric blood pressure measurement

Because all the above methods have their disadvantages, alternative methods such as using a reflective PPG on the wrist or capacitive or pressure sensor-based approaches should be investigated and research effort invested in order to develop a sensor technology that can be integrated into a wrist device.

1.3.1.1.1 ECG-Type Technique

Sensors for measuring heart activity continuously (such as Polar heart rate monitors) are built into separate chest-worn belts or integrated into a shirt. This shall be avoided for all applications but for cardiac outpatients. A further disadvantage is that even if the electrical signal for the heart is present the heart might no longer or only insufficiently transport the blood. This can only be detected by measuring the pulse that is not present or weak. This failure is not detected with the ECG-type technique. However, the ECG measurement technique can be used for heart rate measurement on demand by pressing a finger of the other hand onto a wrist device. This approach is not recommended for integration into a wrist device.

1.3.1.1.2 Photoplethysmography (PPG)

The commercially available devices require an optical measurement at the ear lobe (www.sentec.ch, www.csem.ch), a finger clip (ChipOx module from www.corescience.de, www.spo-medical.com, and others), or the measurement might be integrated into a finger ring (MIT[9]). All successful devices use the transmission PPG configuration (left side of Figure 1.1).

1.3.1.1.3 Oscillometric Blood Pressure Measurement

During oscillometric blood pressure measurement by means of a cuff, provided by Omron and other manufacturers, the pulse is also measured. However, these devices are intended for periodic use and not for continuous wear. Further, sufficient battery power is required (11 mAh per measurements for pump and valve) to pump

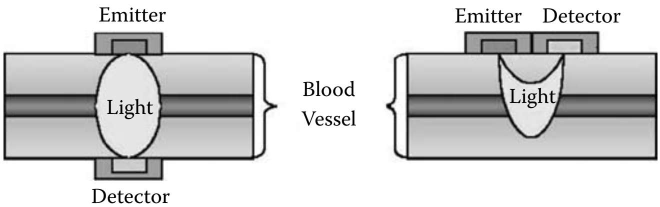

Figure 1.1 Transmissive versus reflective PPG measurement for pulse and oxygen saturation.

up the cuff for blood pressure measurement. This technique is not recommended for integration into a wrist device because an obstructive cuff is required.

1.3.1.1.4 Capacitive or Pressure Sensor-Based

In order to integrate a pulse measurement into a wrist device using minimum power, the most promising approaches are piezoelectric pressure sensors and capacitive pulse measurements quite similar to the pressure sensor approach. These approaches demonstrated promising results in prototype pre-tests but they also showed that the signal-to-noise ratio and the sensor placement are very critical.

1.3.1.2 Movement/Fall

Fall detection is provided by several commercial devices. The only known approach at the wrist is a research device of ETH[10]. According to their findings, fall detection cannot be 100% warranted because it causes too many false alarms (e.g., hits of the arm on a table). This sensor requires further research in order to identify positively a situation in which a person is rendered helpless. The most difficult situations to detect are faints, falls against a wall, and unconscious and seated, as illustrated in Figure 1.2.

1.3.1.3 Skin Temperature

Skin temperature measurement can easily be integrated into a wrist device by means of analog or digital off-the-shelf temperature sensors. To do so, a good thermal path between the skin and the sensor has to be ensured through the enclosure. However, as skin temperature is different from body temperature, this information can be used only to recognize if the device is worn.

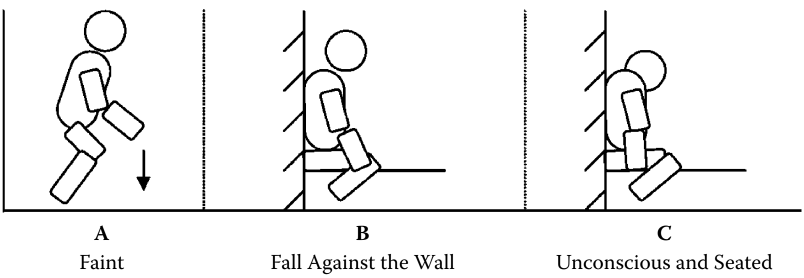

Figure 1.2 Difficult-to-detect fall situations. (*Source:* **Noury, N., Barralon, P., Virone, G., Boissy, P., Hamel, M., and Rumeau, P., A smart sensor based on rules and its evaluation in daily routines,** *Proceedings of the IEEE EMBS 2003*. **With permission.)**

1.3.1.4 Skin Humidity

Skin humidity can be estimated by electrical skin impedance spectroscopy.[12] The measurement frequencies range from 10 Hz to 5 MHz with a driven current of 1 uA to 5 mA. However, most approaches use 1 to 1000 kHz with a current below 1 mA. The frequency selection depends on the target to be measured. In Martinsen, Grimness, and Haug[13] it is found that the impedance measured mainly reflects the stratum corneum at low frequencies, in this case below 1 kHz, and that the viable skin dominates at higher frequencies. At 1 MHz the stratum corneum only accounts for 5.4% of the measured impedance.

The used electrodes are either one concentric ring electrodes[13] or a four-point measurement with two driving electrodes and two measurement electrodes.

1.3.2 Location

In outdoor environments, we can obtain precise location information ranging from 1 to 10 m from GPS (global positioning system) but only at the price of significant power consumption.* But with GPS alone, only self-location is possible. For location by emergency personnel, this information then needs to be transmitted.

1.3.2.1 Indoor Location

For indoor location, GPS availability is limited. Besides intelligent (sensor-equipped) carpets, the following common transmission technologies can be used:

- Ultrasonic
- Infrared
- Microwave
- RF

The transmission-based technologies (RF) are all active technologies requiring the user to wear a device. A completely different technology to be mentioned is the use of cameras.

1.3.2.1.1 Passive Infrared (PIR) Motion Detection Sensors

Infrared systems rely on the user taking explicit actions to identify their presence. The sensor measures the changes in the received infrared signal radiated from every human being as well as animals. These sensors are very inexpensive but usually require movements, at least small ones, and they often detect pets, too.

* 3 mAh for one position per minute and 35 mAh for one position per second based on the u-blox LEA 4A module.

A usual range is around 10 m, but the covering area cannot be well adjusted. Wireless ZigBee PIR sensors are available.

1.3.2.1.2 Microwave Motion Detection Sensor

Microwave sensors are usually based on Doppler shift radar technology in order to detect movements. The required movements can be as small as 6 mm per sec, thus recognizing a person sitting.

Unlike passive infrared detectors, the low power radar beam may be aimed to cover a specific area. Also, the range, or sensitivity, is easily adjusted over a range of approximately 1 to 10 m.

1.3.2.1.3 RF Received Signal Strength Indication (RSSI)

By measuring the received signal strength from several fixed nodes, a location accuracy of 1.6 for 80% of the measurements was achieved.[14] The accuracy mainly depends on the algorithm and fingerprinting and can further be improved by utilizing sophisticated antennas that have a uniform radiation pattern and by considering that the best distance measurement accuracy is achieved within proximity of a fixed node due to exponential decrease of the received signal strength. According to theoretical analysis by TI with their CC2430, this is within 7 m from any fixed node as shown in Figure 1.3.

This technique is promising primarily if an RF sensor network is installed in an apartment providing fixed nodes for free. The disadvantage is that due to multipath reflections and other noise sources the RSSI value is quite noisy and might be smaller than expected from the distance due to unexpected damping.

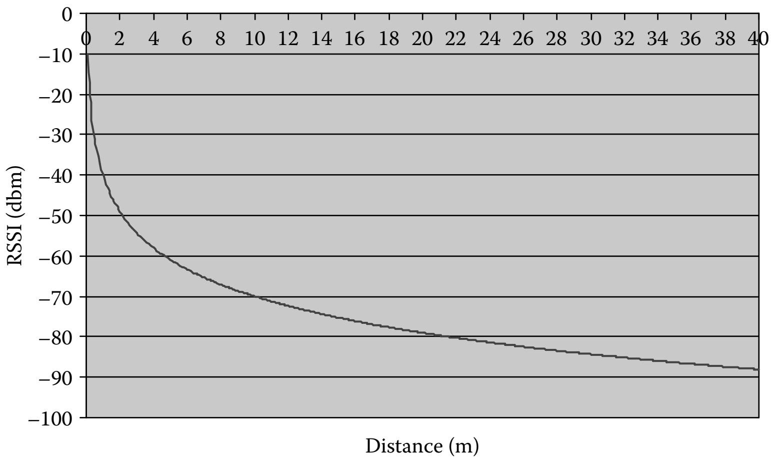

Figure 1.3 RSSI versus distance.

1.3.2.1.4 RF Angle of Arrival

Another option for determining an active nodes position is to measure the angle of arrival of an RF signal and perform a triangulation. To do so, sophisticated antennas and receiving circuits are required that are very different from the transceiver systems used in off-the-shelf sensors with RF communication. Therefore, this approach is not recommended.

1.3.2.1.5 RF Ultra-Wide Band

Based on the IEEE802.15.4a ultra-wideband (UWB) technology, first products are available for very accurately determining the location of an object or a person. With a combined approach that uses both time difference of arrival (TDOA) and angle of arrival (AOA) only two to four fixed nodes are required to reach a standard deviation of the position as low as 15 cm.[15] The UWB approach is much less affected by multipath distortion than conventional RF systems and the calculation is not based on signal strength.

UWB technology can also be used for data communication, which makes it very attractive at first glance. Unfortunately, components for integration into a wrist wearable device are not yet available and the stand-alone devices are expensive. Therefore this technology can only be used as an additional device worn separately, which is not recommended.

1.3.2.1.6 Ultrasonic

Ultrasonic devices offer a low-cost solution providing a high accuracy of measured positions. Accuracy varies between 0.03 to 0.5 m depending on the specific system.

The clear disadvantage of ultrasonic waves compared to an RF-based location sensing system is that infrastructure is more complicated and needs to be installed very precisely. In fact, all narrowband ultrasonic positioning systems are faced with the problem of loss of signal due to obstruction, false signals by reflections, and interference from high-frequency sounds. However, most of these limitations can be reduced through careful planning, resulting in a highly accurate system. But as this is a completely separate infrastructure in addition to other sensor installations, it is not recommended for this application. For distance measurement, however, it is a very promising approach.

1.3.2.1.7 Camera

Location tracking can also be performed by means of a camera. It further allows a good insight in case of an emergency but will not be investigated further in this chapter.

1.3.2.2 Horizontal Position

A specific location task is a horizontal position determination, a critical item in order to distinguish between someone lying on a bed or chair (normal for a certain time) and lying on the floor.

Currently there is no specialized method to determine the height of a person relative to the ground. Even worse, when using triangulation with signal strength indication, it is a requirement that the floor, where the person is, is estimated. This allows taking into account the signal loss of an RF signal passing through the ceiling, usually built of concrete and steel.

A novel approach is currently investigating the possibility of using an altitude sensor for horizontal position tracking. A change of 4 Pa is equivalent of 27 cm and the noise of the sensor is ±1 Pa. Thus, an accuracy of better than ±10 cm was found. However, these are only first trials and many effects such as several rooms, several base stations, sensor orientations, etc., have to be investigated before such an approach is ready for implementation.

Besides the air pressure sensor in the wearable device, a base station with a known "height" is required to track the environmental pressure that can change rapidly, dependent on the weather condition.

1.3.3 Additional Sensors for Further Patient Surveillance

The additional sensors might be added separately into a sensor network or communicate their readings to the wearable device. It is, however, better not to integrate them into it. This is mainly recommended for medical-grade vital parameter measurement.

1.3.3.1 Blood Pressure

A blood pressure sensor shall not be integrated into the wrist device because no ready-to-use technology is available. A big research effort would be required. However, there are commercially available stand-alone devices available that might be integrated into a sensor network.

1.3.3.2 Blood Oxygen Saturation

The technology is well known[17] but not easy to implement on a wrist. For reliable measurements, a transmissive measurement device (Figure 1.1.) shall be used. As SPO_2 saturation measurement is not required for continuous supervision, it is recommended to add this parameter by means of a commercial device referenced in Section 1.3.1.1.2.

1.3.3.3 ECG

A one-lead ECG can be integrated into a wrist device by providing one electrode on the device bottom and a second on the device top. The top electrode shall be in contact with a finger of the second hand in order to measure the derivation I. A similar result is achieved with the belt described in Section 1.3.1.1.1.

For reliable and medical-grade measurements including more derivations, glued electrodes are required but not appropriate for a wrist device. An alternative approach is the newly developed dry electrode technology that can be built into common items of clothing like bras, shorts, or waist belts.[18] Because the clothing-integrated ECG is not yet commercially available, a stand-alone device is recommended even for target groups requiring a continuous supervision.

1.3.3.4 Pulse Wave Velocity (PWV)

In principle there are three methods to determine pulse transit time (PTT) used to calculate PWV:

1. ECG pulse to laser Doppler flow pulse on arm or leg as shown in Figure 1.4
2. ECG pulse to PPG pulse on arm or leg
3. Time between two PPG pulses or laser Doppler flow pulses measured at least 100 mm apart on arm or leg

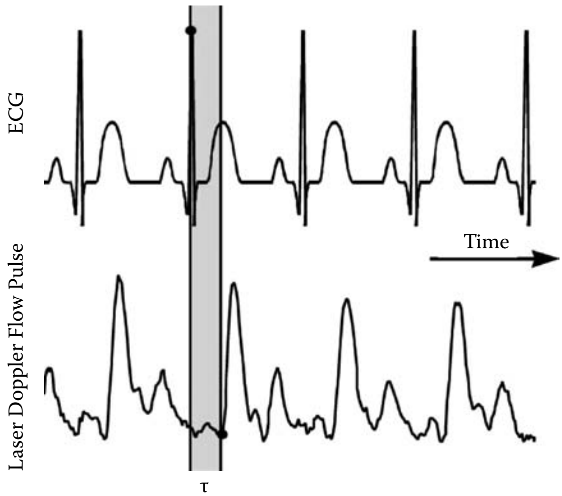

Figure 1.4 Principle of the determination of the pulse transit time using an ECG R-wave and the footpoint of a laser Doppler flow pulse. (*Source:* **Elter, P. et al., Noninvasive and nonocclusive determination of blood pressure using laser Doppler flowmetry,** *Proceedings of SPIE Specialty Fiber Optics for Medical Applications*, **3596: 188–196. With permission.)**

The laser Doppler flow meters are very large and therefore not suited for integration. Methods 2 and 3 might be used as a combination of the sensors described in Section 1.3.3.2 and Section 1.3.3.3.

1.3.4 Networking and Communication Technologies

There are many communication technologies available. The analysis required to select the appropriate one is not the intention of this subsection—instead we only provide an overview.

For long-range communication a device has to rely on available infrastructure. Therefore, a cellular standard such as GSM/UMTS/CDMA2000 is the best choice. However, any cellular standard requires regular power in the range of 30 mA* and therefore a large battery that makes a device obstructive and heavy.

For indoor and local communication the following standards might be considered:

- 433/868/2400 MHz proprietary ISM band communication or 869 MHz European social alarm frequency
- ZigBee
- Bluetooth
- UWB

The most promising standard is ZigBee because it is a nonproprietary standard, low power, and fully integrated components are available. It can further be used for localization as described in Section 1.3.2.1.3. UWB might be considered as soon as the required components are available.

1.4 System Examples

For supervision of the target groups many research and commercial approaches exist or are ongoing. The purpose of this section is to provide a few examples. There are some further commercial approaches and many other research projects other than the two described in detail here.

1.4.1 Commercially Available Devices

1.4.1.1 OMRON Medical Home-Use Devices

OMRON does not provide a supervision system but provides medical devices for home use for measuring blood pressure, one-lead ECG, and digital temperature. These devices are a good supplement for other approaches that require supervision.

* Telit GE 864PY GSM/GPRS modem assuming 1.2 min data transmission per hour but being logged-in all the time.

1.4.1.2 BodyMedia® Lifestyle Monitoring

The SenseWear® armband from BodyMedia, worn on the back of the upper arm, provides personal metabolic, physical activity, and lifestyle monitoring. The integrated sensors and algorithms determine the following parameters:

- Total energy expenditure (calories burned)
- Active energy expenditure
- Physical activity duration
- Number of steps
- Sleep duration

The data collected on the device can be transferred to a physician by means of a USB connection to the PC. The analysis is therefore a-posterior without any alarming function.

1.4.1.3 Tunstall Supervision Approach

Tunstall provides a broad range of (environmental) sensors, as summarized in Section 1.4.1.3.1). These self-contained sensors raise individual alarms that are collected at a central device. The interconnection of these sensors is a proprietary wireless solution on the 869 MHz European social alarm frequency.

1.4.1.3.1 Sensors and Signs

The Tunstall solution uses the sensors listed below in order to supervise a person. Their description is based on Tunstall's Website.[20] Tunstall further provides environmental sensors for gas alarm, smoke alarm, etc. (not listed).

Bed/chair occupancy sensor: Provides an early warning by alerting that the user has left his bed or chair and not returned within a preset time period, indicating a potential fall. The sensor can also be programmed to switch on lights.

Enuresis sensor: Placed between mattress and sheet, this sensor provides immediate warning on detection of moisture, allowing effective action to be taken.

Epilepsy sensor: This sensor monitors the user's vital signs including heart rate and breathing patterns to detect a range of epileptic seizures.

Fall detector: See Section 1.4.1.3.2 for a description.

Medication dispenser: Automatically dispenses medication and provides audible and visual alerts to the user each time medication should be taken. If the user fails to access the medication, an alert is raised to the monitoring center or designated care giver.

Movement detector: A passive infrared (PIR) movement detector that can be used for both activity and inactivity monitoring.

Pressure mat: Detects if somebody is in a specific area.

Door opening sensor: Monitors, for example, the main exit door.
Wireless alarm button: Wearable on the neck or to be installed at fixed locations.
Vibration alarm: Designed to support hearing-impaired people, the device vibrates to provide a smoke alarm to a sleeping user.

1.4.1.3.2 Wearable Devices

Tunstall provides two wearable devices. One is only a wireless alarm button. The other one is a fall detector that is part of a fall management system. The fall detector is worn on the belt or in a pocket around the waist and will automatically raise an alarm if the unit senses a fall. The detector senses both impact and angle in order to distinguish between normal impact (user is vertical) and fall. Trials showed that this sensor is able to detect the worst falls but we must assume that this approach is not able to detect the falls sketched in Figure 1.2.

A further disadvantage is that it is a single function device only and it does not enable further reasoning together with other sensors on the body or in the apartment.

1.4.1.3.3 Infrastructure

All the sensors are wirelessly attached to a main unit called a lifeline. Upon alarm of any sensors a call of the 24-h response center or a local alarm is initiated based in the main unit's configuration.

1.4.2 AMON Approach

Designed to be worn by cardiac outpatients and high-risk people, the AMON device allows remote monitoring of vital signs such as blood pressure, pulse, oxygen saturation, skin temperature, and two-channel ECG signals (heart rate, QRS duration, ST-elevation, etc.). Operating autonomously, the wearer can be continuously monitored and all the data is stored on-device. A built-in expert system can issue a warning or alarm locally or to a telemedicine center if necessary; together with a built-in GSM link, doctors at the health center can download this data for immediate or later analysis and emergency care as, sketched in Figure 1.5.

After the development of AMON, Telcomed developed and now markets the WristClinic™[21] that integrates similar sensors but uses a wireless transmission to a separate gateway for data transmission to a center. Also, an expert system is not included in this commercial device.

1.4.2.1 Wrist Device

Due to the design decision to use off-the-shelf modules with no miniaturization potential, the first prototype was rather bulky, at 6 × 60 × 30 mm^3 in size (see Figure 1.6). It consisted of 10 submodules, folded together in order to embrace

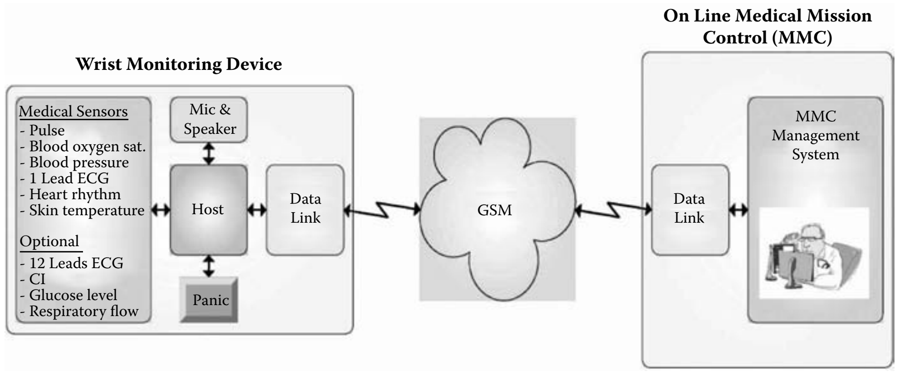

Figure 1.5 AMON system overview: Wrist worn medical device with GSM/ UMTS link to the telemedicine center.

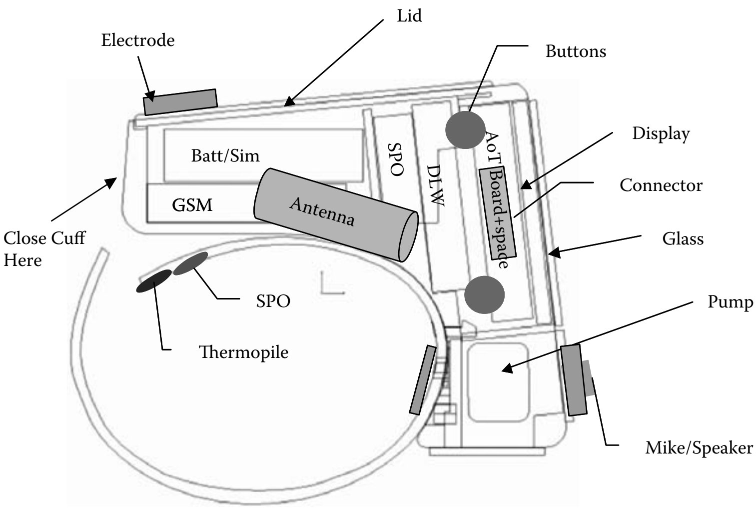

Figure 1.6 Cross-section of first (milled) AMON enclosure.

the wrist. Electronics and sensors are mounted in a plastic enclosure containing a blood pressure cuff. The enclosure was built with a rapid prototyping, laser sintering method to avoid an injection molding tool or complicated milling processes. The second enclosure version (see Figure 1.7) was an improved design.

In principle, four measuring devices plus a mobile phone can be miniaturized to meet the form factor of a conventional off-the-shelf blood pressure monitor.

1.4.2.2 Sensors and Clinical Results

The blood oxygen saturation (SpO_2) sensor is a prototype for wrist measurements, based on a reflective sensor principle (standard sensors transmit light through the

Figure 1.7 Second AMON enclosure on wrist.

fingertip). The ECG sensor and the blood pressure measurements are standard but adapted to the WMD requirements.

A thermopile was chosen for temperature measurement. This should provide better results than a simple thermistor but the relationship between the measurement, skin temperature, and body temperature is still a topic for research. Therefore, this sensor has not yet been validated.

The AMON device also included acceleration sensors but due to effort constraints no algorithm was implemented at all.

The ECG, the SpO2 sensor, and the blood pressure meter were tested with 29 subjects, using two AMON devices. The sensors were found to be functional, but as expected the data processing algorithms will need some fine-tuning.

1.4.2.3 Infrastructure

AMON does not require any infrastructure in an apartment. All required sensors are integrated into the wrist device as described above. For alarms and data communication AMON uses the GSM network over which it sends encrypted data to a telemedicine center.

The AMON telemedicine center software provides data storage for vital signs history and display of the actual measurement values including rating, as shown in Figure 1.8.

1.4.3 EMERGE Approach

The approach in EMERGE[2] is to reason about situations based on information collected from ambient, unobtrusive, and noninvasive sensors in the home

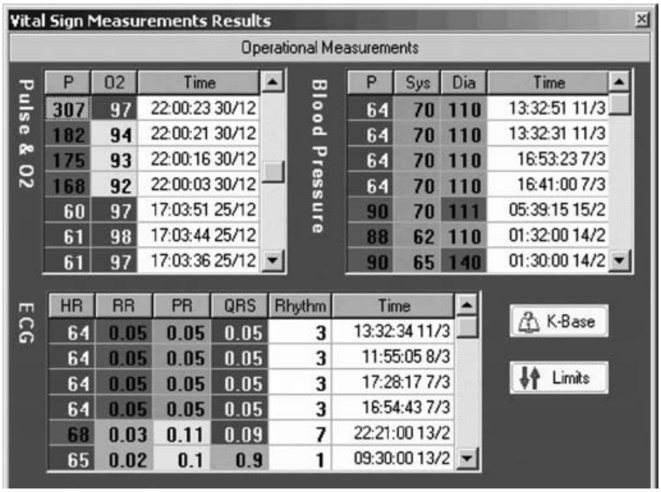

Figure 1.8 AMON telemedicine center vital sign display including rating shown in case of an alarm.

environment of elderly people. This raises the challenge to cope with inherently unreliable and imprecise data as well as the need to adapt the system to the specific conditions and demands of the assisted persons.

EMERGE tackles this problem with an intelligent sensor fusion approach in combination with a sound emergency model, describing the environment, individual diseases, parameters to monitor, potential emergency situations, and corresponding treatment options.

In case of emergency detection the system will automatically connect to an emergency dispatch center for immediate intervention if required. In case of longer-term events such as change in behavior due to depression or starting dementia the family doctor or relatives are informed.

1.4.3.1 Wrist Device and Its Integrated Sensors

The concept of EMERGE is to use environmental (installed) sensors whenever possible. The wrist device sensors are therefore reduced to the required minimum. Furthermore, no external accessories such as ECG belts shall be used but everything should, if possible, be integrated into the wrist device. The wrist device is designed to be worn day and night. The wrist device will therefore feature

- Pulse measurements by means of PPG (Section 1.3.1.1.2) or capacitive/pressure sensor (Section 1.3.1.1.4)
- Fall/movement and motionlessness detection by means of triaxial acceleration sensors (Section 1.3.1.2)

- Skin temperature (Section 1.3.1.3)
- Horizontal position (Section 1.3.2.2)
- Alarm button
- Rechargeable battery and watch display
- RF communication (ZigBee or similar)

and optionally:

- Skin impedance (Section 1.3.1.4)
- RSSI location (Section 1.3.2.1.3)

The wrist device controls the integrated sensors and extracts the measurement values from the raw data. In case of event detection (and also regularly), the wrist device sends measurement data to the gateway for further processing and/or alarm.

1.4.3.2 Other Sensors and Signs

In order to provide supervision of people for at least the following actions:

- Toilet usage
- Sleeping behavior
- Meal preparation
- General movement including wandering and remaining at the same place

and for supervision of their weight, the sensors described next might be installed. The preferred sensor communication (see Section 1.3.4) is the ZigBee wireless standard. For users that require regular medical-grade measurements the sensors described in Section 1.3.3 can be added.

1.4.3.2.1 Activity Sensors

- Bed occupancy sensors including vital data such as biomedical bed-clothes[22]
- Chair occupancy sensors (see Section 1.4.1.3.1)
- Door exit/entry sensor (see Section 1.4.1.3.1)
- Video: Location tracking and communication with the user in case of emergency
- Pressure mat/floor sensors (see Section 1.4.1.3.1)
- Intelligent cups supervise drinking
- Intelligent walking stick raises an alarm if not vertical for a longer time in order to detect a fall
- Intelligent medicine bottle allows tracking of medicine consumed

- Location tracking (see Section 1.3.2)
- Intelligent light switches and dimmers report switching by means of RF or X-10

1.4.3.2.2 Environmental Sensors

- Temperature and humidity sensors
- Gas detector sensor/activator
- Smoke detector sensor
- Carbon monoxide detector
- Flood detector sensor/activator

1.4.3.2.3 Weight Sensors

The weight of a person is measured daily by means of a wireless scale or better by a scale integrated into the bed(-posts) or similar.

1.4.3.3 Infrastructure

As EMERGE relies mainly on environmental sensors, a major infrastructure and therefore installation is required. Most of the installations are the sensors listed in Section 1.4.3.2. In addition a central server and a gateway to it are required. The central server is further connected to communication installations for a direct connection to the local emergency dispatch center as well as telemedical center and to the family doctor and the relatives. The external centers have to provide means to integrate the extended information from the EMERGE system, as most of them are prepared for phone connections only.

1.5 Conclusions and Outlook

Supervision of elderly persons, patients in post-trauma care, and personal health devices are only partly available. There is ongoing research, also supported by the EU IST frameworks. The provided system examples are concluded below, and based on them a fusion approach is proposed.

1.5.1 Tunstall Solution

The approach provides an environmental supervision for elderly and impaired people. Their approach does not include a wrist device but is limited to two wearable devices that do not collect any vital data from the user. Besides the lack of vital data