Department of Communications and Networking

System Architecture for Mobile-phone-centric Ambient Intelligence Applications

Iiro Jantunen

Aalto University

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System Architecture for Mobile-phone-centric Ambient Intelligence Applications

Iiro Jantunen

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Abstract

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Abstract

The aim of this study is to develop an open architecture platform for mobile-phone-centric ambient intelligence applications. The two main application fields are 1) local wireless sensor networks for health-related applications and 2) ubimedia, meaning digital content embedded in the environment.

In the proposed architecture, a mobile phone acts as a central node hosting applications and connecting a local, e.g. sensor, network to back-end servers in the Internet. The technologies used in the architecture include Simple Sensor Interface (SSI) protocol, nanoIP, and low-power short-range radios, e.g. Bluetooth Low Energy (formerly BTLEE), Radio-frequency Identification (RFID), 5 kHz inductive links, and impulse ultra-wideband (UWB). The sensor network architecture has been implemented and successfully demonstrated using several applications with commercially available mobile phones with add-on electronics.

A system architecture, including both the hardware and software architecture, enabling mobile phones to read Ubimedia with sufficiently high data rates for multimedia applications is also presented. This architecture could also be used as a new type of high-speed wireless internet access.

Keywords ambient intelligence, ubimedia, mobile phone, Bluetooth, RFID, UWB

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Tiivistelmä

Tutkimuksen tavoitteena on avoimen arkkitehtuurialustan kehittäminen älypuhelinkeskeisiin läsnä-älysovellutuksiin. Kaksi merkittävintä sovellutusaluetta ovat 1) lyhyen kantaman langattomat anturiverkot terveyssovellutuksiin sekä 2) ubimedia, tarkoittaen ympäristöön sulautettua digitaalista sisältöä. Esitellyssä arkkitehtuurissa älypuhelin toimii keskusyksikkönä, jossa sovellutusohjelmat voivat toimia, ja joka tarjoaa yhteyden lyhyen kantaman, esimerkiksi anturi-, verkon ja Internetissä sijaitsevien palvelimien välillä.

Arkkitehtuurissa käytettyihin teknologioihin kuuluvat, muun muassa, Simple Sensor Interface (yksinkertainen anturirajapinta, SSI) protokolla, nanoIP ja matalatehoisia lyhyen kantaman radioita, kuten Bluetooth Low Energy (aiemmin BTLEE), RFID (radiotaajuinen tunnistus), 5 kHz induktiiviset linkit, ja impulssi-UWB. Esitelty anturiverkkoarkkitehtuuri on toteutettu ja onnistuneesti demonstroitu käyttäen kaupallisesti saatavilla olevaa älypuhelinta ja siihen liitettyä elektroniikkaa.

Tutkimuksen toisena kohteena oli järjestelmäarkkitehtuuri, sisältäen sekä laitteisto- että ohjelmistoarkkitehtuurin, joka mahdollistaa älypuhelimen käytön ubimedian lukemiseksi riittävän suurella tiedonsiirtonopeudella multimediasovellutuksiin. Kyseinen arkkitehtuuri voisi mahdollistaa myös uuden tyyppisen suurnopeuksisen langattoman internetyhteyden.

Avainsanat läsnä-äly, ubimedia, puhelin, Bluetooth, RFID, UWB

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Preface

My studies have taken me far from where I started. From fundamental physics, I have moved to applied physics and then to microsystems, about which I made my master's thesis. Since then, my focus moved from microsystems to sensor technologies and sensor networks. This has given me broad opportunities for constant learning, something I particularly enjoy.

A doctoral student seldom gets the satisfaction of seeing his work become a part of real products in the hands of consumers. As I write this, Bluetooth Smart — the (final?) trade name of this technology originating in Bluetooth Low End Extension — is a feature in several products in several consumer product categories. The other focus of this thesis, UW-BLEE, is already a well-demonstrated technology, but it remains to be seen if the technology will ever be used commercially. This is typical for the R&D of new wireless interfaces. Bluetooth took about 10 years from inception to market breakthrough. Many other wireless interfaces have been extensively studied, finalized, even brought to market — and then disappeared. Some of those are also discussed in this thesis.

I was lucky to realize the importance of a good supervisor already before my master's thesis. Working with Prof. Jyri Hämäläinen has made this thesis possible. His guidance was invaluable. I am grateful to the Department of Communications and Networking (Comnet) at Aalto University for the working environment where the research for this thesis was finalized.

Nokia Research Center provided me with the project, training, technical support, a most stimulating intellectual working environment as well as significant financial support. Professors Pekka Toivanen and Pasi Karjalainen at the University of Eastern Finland have kindly provided me facilities for the writing of this thesis.

I am indebted to Dr. Vladimir Ermolov, the supervisor of my research in 2004–2006 and my first publications on this field. I thank all my colleagues in MIMOSA, MINAmI, and UBI-SERV for the cooperation in the research forming the base of this thesis, with special thanks to Jarmo Arponen, Sergey Boldyrev, Marion Hermersdorf, Pertti Huuskonen, Jari Hyyryläinen, Joni Jantunen, Hannu Laine, Samuli Silanto, Dirk Trossen, Olli Tyrkkö, Jaakko Varteva, and Mikko Vääräkangas (Nokia Research Center), Bertrand Gomez and Yann Têtu (CEA Laboratoire d'électronique des technologies de l'information), Jörg Eichholz (Fraunhofer-Institut für Siliziumtechnologie), Eija Kaasinen (VTT), Miguel Angel Santiago (Telefónica), Edward Mutafungwa, Sebastian Siikavirta, and Xirui Wang (Aalto University).

Special thanks go to my wife and love, Sanna, for enduring this thesis with me. Also my parents, Matti and Pirjo, and in-laws, Heikki and Leena, have helped a lot. Working in research and writing a dissertation comes with a price, which is only partly paid by the doctoral student himself. The other part is paid by his family, which has sacrificed time and resources to make one's academic aspirations come true. I apologize my children, Ohto and Edith, for the time I have not been with them.

This research has been funded by EU through 6^{th} FP projects MIMOSA (IST-2002-507045) and MINAmI (IST-034690), and Academy of Finland joint Finnish-Chinese project CHI-FIN UBI-SERV (129446), as well as Nokia Research Center and Aalto University.

Kuopio, May 25, 2012,

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Contents

Preface **i**

Contents **iii**

List of Publications **v**

Author's Contribution **vii**

List of Abbreviations **xi**

List of Figures **xv**

List of Tables **xvii**

1. Introduction **1**

1.1 Motivation and research goals 3

1.2 Structural notes 5

2. Ambient Intelligence (AmI) Technology **7**

2.1 AmI Applications 7

2.1.1 Health care, welfare, wellbeing, and fitness 7

2.1.2 Ubimedia 10

2.2 Wireless Access Technologies for AmI Applications 13

2.2.1 Wireless Local Area Networks 14

2.2.2 Wireless Personal Area Networks 15

2.2.3 Body area networks 21

2.2.4 Other Wireless Access Technologies 23

2.3 Lowering the power use of wireless connections 26

2.3.1 Physical layer solutions 27

2.3.2 MAC layer solutions 27

2.3.3 Networking solutions 28

2.3.4 Architecture solutions 28
2.4 AmI Architecture 29
2.4.1 Wireless Sensor Networks 30
2.4.2 RF Memory Tags 31

3. Mobile-phone-centric AmI Architecture 33
3.1 Functional requirements of the system architecture 33
3.2 Mobile-phone-centric Sensor Network 36
3.2.1 Software architecture 37
3.2.2 Architecture implementation 41
3.2.3 Demonstration results 44
3.3 Mobile-phone-readable Memory Tags 49
3.3.1 Hardware architecture 49
3.3.2 UWBLEE Protocol Stack 52

4. Summary of results 55

5. Discussion 57
5.1 Bluetooth Low Energy 57
5.2 RFID sensor tags 59
5.3 Simple Sensor Interface (SSI) 59
5.4 NFC 60
5.5 UWB 60
5.6 UWBLEE 61
5.7 Network-on-terminal Architecture 62
5.8 Sensor API's on mobile phones 62

6. Conclusions 65

Bibliography 69

Errata 81

Publications 83

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I J. Sierra, M. Santiago, I. Jantunen, E. Kaasinen, H. Kaaja, M. Müllenborn, N. Tille, and J. Virtanen. User evaluation of mobile phone as a platform for healthcare applications. *Mobile Web 2.0: Developing and Delivering Services to Mobile Phones*, S.A. Ahson and M. Ilyas, Eds. CRC Press, pp. 491–515, Dec. 2010.

II E. Kaasinen, T. Tuomisto, P. Välkkynen, I. Jantunen, and J. Sierra. Ubimedia based on memory tags. In *MindTrek 2008*, (Tampere, Finland), ACM, pp. 85–89, Oct. 2008.

III E. Kaasinen, M. Niemelä, T. Tuomisto, P. Välkkynen, I. Jantunen, J. Sierra, M. Santiago, and H. Kaaja. Ubimedia based on readable and writable memory tags. *Multimedia Systems*, vol. 16, Springer, pp. 57–74, Feb. 2010.

IV I. Jantunen, H. Laine, V. Ermolov, and P. Huuskonen. Smart sensor architecture for mobile terminal centric ambient intelligence. In *Eurosensors 2006*, (Göteborg, Sweden), vol. 2, pp. 294–295, Sep. 2006.

V J.M. Quero, C.L. Tarrida, J.J. Santana, V. Ermolov, I. Jantunen, H. Laine, and J. Eichholz. Health care applications based on mobile phone centric smart sensor network. In *EMBS 2007*, (Lyon, France), IEEE, pp. 6298–6301, Aug. 2007.

VI I. Jantunen, H. Laine, P. Huuskonen, D. Trossen, and V. Ermolov. Smart sensor architecture for mobile-terminal-centric ambient intelligence. *Sensors & Actuators A: Physical*, vol. 142, Elsevier, pp. 352–360, Mar. 2008.

VII Y. Têtu, I. Jantunen, B. Gomez, and S. Robinet. Mobile-phone-readable 2.45GHz passive digital sensor tag. In *RFID 2009*, (Orlando, USA), IEEE, pp. 88–94, Apr. 2009.

VIII I. Jantunen, S. Siikavirta, V. Nässi, T. Korhonen, and J. Kaasinen. Add-on 5 kHz inductive link for mobile phones using audio port. In *UBI-HEALTH'10*, (Shanghai, PRC), Aalto University Publication Series Science + Technology 6/2011, May–Jun. 2010.

IX I. Jantunen, J. Hämäläinen, T. Korhonen, H. Kaaja, J. Jantunen, and S. Boldyrev. System architecture for mobile-phone-readable RF memory tags. In *UBICOMM 2010*, (Firenze, Italy), IARIA, pp. 310–316, Oct. 2010.

X I. Jantunen, J. Jantunen, H. Kaaja, S. Boldyrev, L. Wang, and J. Hämäläinen. System Architecture for High-speed Close-proximity Low-power RF Memory Tags and Wireless Internet Access. *International Journal on Advances in Telecommunications*, vol. 4, no. 3&4, IARIA, pp. 217–228, 2011.

Author's Contribution

Publication I: "User evaluation of mobile phone as a platform for healthcare applications"

The research was done in cooperation between the authors. My role was in development of the system architecture of the health care application platform.

Publication II: "Ubimedia based on memory tags"

The research was done in cooperation between the authors. I took part in defining the usage scenarios and development of the underlying system architecture enabling reading RF memory tags.

Publication III: "Ubimedia based on readable and writable memory tags"

The research was done in cooperation between the authors. I took part in defining the usage scenarios and development of the underlying system architecture enabling reading and writing RF memory tags.

Publication IV: "Smart sensor architecture for mobile terminal centric ambient intelligence"

The architecture was developed in cooperation between the authors. In addition to being the main author, my role was developing the local and short-range sensor network.

Publication V: "Health care applications based on mobile phone centric smart sensor network"

The research was done in cooperation between the authors. My role was taking part in the development of the system architecture and the measurement platform enabling measurement of health-related physical quantities of human body.

Publication VI: "Smart sensor architecture for mobile-terminal-centric ambient intelligence"

The architecture was developed in cooperation between the authors. In addition to being the main author, my role was developing the local and short-range sensor network.

Publication VII: "Mobile-phone-readable 2.45GHz passive digital sensor tag"

The technology was developed in cooperation between the authors. In this publication, my responsibility was the system architecture.

Publication VIII: "Add-on 5 kHz inductive link for mobile phones using audio port"

The technology demonstrator was developed in cooperation between the authors. In addition to being the main author, I was responsible for the system architecture.

Publication IX: "System architecture for mobile-phone-readable RF memory tags"

The technology was developed in cooperation between the authors. I was the main author, and responsible for the system architecture.

Publication X: "System Architecture for High-speed Close-proximity Low-power RF Memory Tags and Wireless Internet Access"

The technology was developed in cooperation between the authors. I was the main author, and responsible for the system architecture.

List of Abbreviations

3G Third generation mobile phone networks, e.g. UMTS (WCDMA)

3GPP Third Generation Partnership Project, a collaboration group between telecommunications associations to develop mobile phone systems

6loWPAN IPv6 over low power wireless personal area networks

ANT Proprietary 2.45 GHz digital wireless link by Dynastream

B Byte, a unit of digital information in computing and the basic addressable element in many computer architectures. 1 byte is commonly 8 bits, but historically sometimes also 2 or 4 bits. In this thesis, 1 byte = 8 bits.

BAN Body Area Network, a wireless (sensor) network designed to work around the body of the user (range < 2 m)

Bluetooth 2.45 GHz wireless network technology covered by IEEE 802.15.1 standards and managed by Bluetooth Special Interest Group

BTLEE Bluetooth Low End Extension

DVB-H Digital Video Broadcasting — Handheld, a mobile digital broadcast TV format

ECG Electrocardiography, measuring the operation of the heart

EEG Electroenkelography, measuring the electrical field of brain functions

EPC Electronic Product Code, an RFID standard

FM Frequency Modulation, a widely-used analog broadcast radio system around 100 MHz frequency.

GPIO General purpose input/output

GPS Global Positioning System, a satellite-based positioning system

GSM Most widely-used 2nd generation mobile phone network technology

I2C Inter-integrated circuit, a two-wire serial digital bus

IPv4 Internet Protocol version 4

IPv6 Internet Protocol version 6

ISM Industrial, Scientific and Medical radio band. Radio frequency bands reserved internationally to free, unlicenced, use. Best known is 2.40–2.50 GHz band where e.g. Bluetooth, Wi-Fi, and microwave ovens work.

LAN Local area network. A computer subnetwork to the Internet working on a limited area, such as home, school or office.

LTE (3GPP) Long Term Evolution, a wireless data communications technology standard based on GSM and 3G technologies

MCU Microcontroller unit

MIMOSA Microsystems platform for Mobile Services and Applications, an EU 6th framework programme integrated project in years 2004–2006

MINAmI Micro-nano integrated platform for transverse Ambient Intelligence applications, an EU 6th framework programme integrated project in years 2006–2009, partially in continuation to MIMOSA

MIPI Mobile industry processor interface

mmWave Millimeter wave technology, a 60 Ghz wireless radio interface

M-RSA MIMOSA Remote Sensing Architecture

nanoUDP nano User Datagram Protocol, a simplification of UDP, a part of nanoIP protocol

NFC Near-field communications, a commercial 13.56 MHz inductive touch-range wireless link

NoTA Network-on-Terminal Architecture

OSI Open Systems Interconnection model, a system to divide communication systems to functional layers

PAN Personal area network. A (wireless) network designed to work in $<$ 10 m range.

Pop-Port A plug-in port available in many historical Nokia phone models, use discontinued in 2007

RF Radio frequency, range from 3 kHz to 300 GHz, in wireless interfaces meaning also that radiative electromagnetic field is used (as opposed to near field)

RFID Radio-frequency identification

RuBee Inductive wireless near-field communication system standardized within IEEE 1902.1

SPI Serial peripheral interface, a four-wire serial digital bus

SSI Simple sensor interface protocol, an application layer protocol for reading sensor devices, developed by Nokia for research purposes (in Section 3.2)

SSI Synchronous serial interface (in Section 3.3)

TEDS Transducer electronic data sheet

UART Universal asynchronous receiver/transmitter

UDP User datagram protocol, a core message type of the Internet protocol suite

UHF Ultra-high frequency, radio frequency range between 300 MHz and 3 GHz

UPnP Universal Plug-and-Play, a standard for using Wi-Fi for an ad-hoc connection between devices

USART Universal synchronous/asynchronous receiver/transmitter

USB Universal serial bus

UWB Ultra-wideband

UWBLEE UWB Low End Extension, a wireless technology developed within MINAmI project

WCDMA Wideband code division multiplexing

Wi-Fi Commercial name for WLAN networks based on IEEE 802.11 standards

W.I.N.D Wireless integrated network device, a proprietary 2.45 GHz wireless network used by Polar Electro

WPT Wireless power transfer

WLAN Wireless local area network, covered by IEEE 802.11 standards

ZigBee Wireless network technology covered by IEEE 802.15.4 standards

List of Figures

1.1 Wireless interfaces available in contemporary mobile phones 2
1.2 Mobile phone as the central device of sensor network. 4

2.1 Mobile-phone-based home health care system 8
2.2 Ubimedia 11
2.3 Mobile phone with Bluetooth 18

3.1 Overview of the developed mobile terminal architecture . . . 35
3.2 MIMOSA architecture overview 36
3.3 SSI sensor data request 'R' message 38
3.4 SSI sensor data response 'V' message 38
3.5 NanoUDP message format 41
3.6 SSI/UART message format 41
3.7 Wireless sensor network architecture implementation 42
3.8 Sensor management and interfaces 43
3.9 Wireless weather station 45
3.10 Screen captures of MIMOSA demonstrations 46
3.11 ECG sensing over BTLEE to mobile terminal. 47
3.12 Full measurement setup 48
3.13 System architecture on phone for enabling reading mass memory tags 51
3.14 System architecture of a RF memory tag 51
3.15 UWBLEE MAC states 53

5.1 Operational combinations of interacting with RF memory tags 62

List of Tables

2.1 Evolution of sharing digital content in printed media 12
2.2 Some available wireless technologies 16

3.1 SSI v1.2 command set 38
3.2 SSI compatible RFID sensor tag memory map 39
3.3 SSI RFID compatibility with ISO 18000-4 40
3.4 Sensors implemented on the MIMOSA platform 46
3.5 UWBLEE PHY functions in different MAC states 54

1. Introduction

Wireless body area networks (BAN) have been in the market for three decades. In the late 70's, professor Säynäjäkangas of University of Oulu developed the wireless heart beat monitor for fitness applications[1]. The idea involved a heart pulse detector electrode belt around the chest of the user and a display unit in form of a wrist watch. The sensor unit sent a magnetic pulse on a 5 kHz carrier frequency every time the heart beat was detected, and this pulse was detected by a coil on the wrist unit. The short range of about a meter was initially enough to distinguish the sensor, thus no data protocol was needed. Later on, since the technology got more use, the devices have had an overhearing problem (consider a mass sports event, such as a city marathon) and Polar Electro has added more pulses to encode the message.

For a single use case a wrist-top user interface unit with a peripheral sensor is enough. Mobile phones, however, have become the device carried along by most of the world's population [1], providing a user interface, both local network and internet connections, and capability to run applications.

The price and power usage of digital wireless access technologies have decreased while the versatility has increased. Need for standardized solutions to decrease cost by mass production has resulted in the emergence of general-purpose technologies. There are plenty of consumer use cases for mobile-phone-centric ambient intelligence, ranging from cameras to GPS devices, headsets, and heart beat sensors. Multi-vendor solutions are preferable for many use cases to enable the use of various peripheral devices with the same central node. This results in a drive for standards, such as IEEE 802.15[2], which act as a basis for many different radio tech-

[1] www.polar.fi, cited 20 September 2011
[2] www.ieee802.org/15

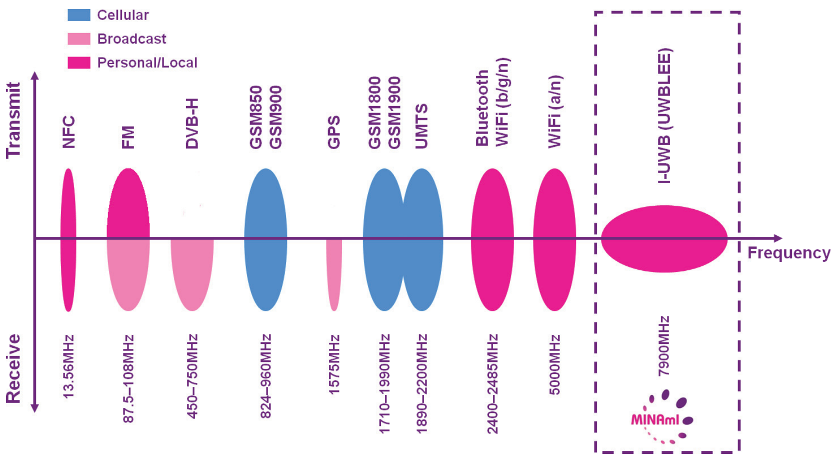


Figure 1.1. Wireless interfaces available in contemporary mobile phones, including the possible future UWBLEE (discussed in Section 3.3).

nologies.

A contemporary mobile phone includes several radios (see Figure 1.1). For example, a *Nokia N8*[3] (brought to market in 2010) phone has *Bluetooth*[4] 3.0, *Wi-Fi*[5], and a low-power FM transmitter for local connectivity, in parallel to GSM/WCDMA long-distance connection, and GPS as well as FM receivers. There also exist commercial mobile phones, e.g. *Nokia 6212*, which include a 13.56 MHz *Near Field Communication*[6] (NFC) reader, providing practically touch-range connectivity. The connectivity provided by a mobile phone can be used both for local and remote networking and for powering passive devices, enabling, e.g., health and fitness applications (see, e.g. [2]). On the other hand, due to the small size, power supply constraint, and multitude of radio interfaces of the current mobile phones, it is difficult to include yet another electromagnetic transmitter/receiver incompatible with the existing ones. This handicap has — up-to-date — prevented the inclusion of a *ZigBee*[7] or *ANT*[8] radio, as well as connectivity to the cheap heart beat sensors with the analog 5 kHz inductive link. The personal area network connection provided by mobile phones, Bluetooth, has had serious limitations with regards to low power peripherals, e.g. button-cell battery-powered sensor nodes.

[3] www.nokia.com
[4] www.bluetooth.org
[5] www.wi-fi.org
[6] www.nfc-forum.org
[7] www.zigbee.org
[8] www.thisisant.com

On the other hand, the requirements (especially power use and data throughput) of wireless sensor use-cases differ, leading to selection of different wireless interfaces [3]. There still exist, for example, the need for a simple pulse connection, such as heart rate. For simple heart beat sensing applications, such as athletics exercises, Bluetooth is an overkill. For that reason, most of the wrist-top heart beat meters are still based on 5 kHz inductive link or use a simple proprietary 2.45 GHz wireless interface (such as ANT).

Wireless sensor network research spans a wide field from mesh networks of autonomous nodes, to point-to-point connections between two devices. When discussing wireless networks developed around a mobile phone, a star network architecture is natural, with the mobile phone as its central node. The phone, however, has also the long-range connectivity to the Internet, granting access to extended services, and to other mobile phones. Thus, creation of wide-area sensor networks using mobile phones as sensor nodes has also been studied (e.g., SensorPlanet[9]).

In this thesis, I first present a few Ambient Intelligence applications that would use the mobile phone in Chapter 2, along with enabling wireless technologies. In Chapter 3, I present a mobile-phone-based architecture for personal Ambient Intelligence applications (based on publications I, II, and III), along with some enabling wireless interfaces that make the applications feasible (based on publications IV, V, VI, VII, VIII, IX, and X). Finally, I discuss the possibilities of the presented technologies and applications in Chapter 5 and present some conclusions in Chapter 6.

1.1 Motivation and research goals

The **motivation** of the research work was *to enable the creation of ambient intelligence (see Chapter 2) services around common networked central nodes such as mobile phones*. The focus of my research is on the system architecture that would enable creation of ambient intelligence services. The applied research methodology is constructive research, meaning developing a set-up and evaluating it by performing tests in a laboratory.

The **research question** of this thesis is *whether it is possible to develop a mobile-phone-centric system architecture which enables creation of ambient intelligence services*. As the **research assumption**, I hold that *the system architecture requires a user interface, central unit, independent*

[9] www.sensorplanet.org

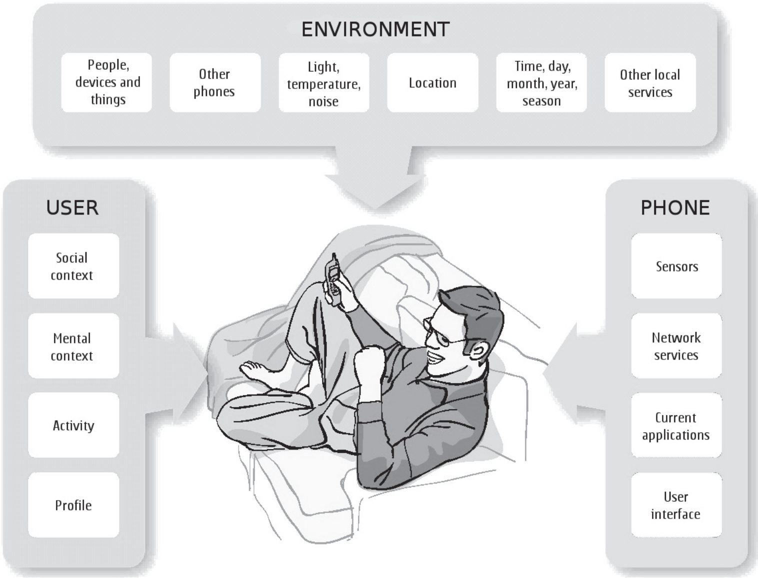


Figure 1.2. Mobile phone as the central device of sensor network.

sensor and memory devices, and wireless interfaces to enable connections to the sensor and memory devices. My **research hypothesis** is that *a mobile-phone-centric system architecture is suitable for creation of ambient intelligence services*.

The architecture requires a user interface and central node, the mobile phone, as well as independent sensor and memory devices along with services in the Internet (see Figure 1.2). The architecture also requires wireless interfaces that enable connections to these devices, some of which should work passively, without own energy sources. Due to the small size of these devices, which limits the size of battery, power consumption is considered to be the single most difficult resource constraint to meet [4, 5]. Thus the possible methods of reducing or distributing power use is discussed in Section 2.3. Other important operational restrictions of wireless access technologies include connection delay and data throughput. These are not in the focus of this thesis. The system architecture, along with the wireless interfaces studied, is presented in the research publications that form the core of this thesis. The research background, the results of my research, and future developments of these technologies is presented.

1.2 Structural notes

Due to the nature of development and market entry of wireless technologies, I have not been able to rely on scientific references (scientific journals and conferences) only. The foundations, however, of the technologies presented in this thesis are scientific, such as wireless network technology research.

Developing a standard (such as GSM or UMTS) on the top of this foundation is not science, but essential for the successfull integration of the technology in mass-market products, such as the mobile phone. Some of these standards, such as the IEEE 802.15 family, have been published by scientific organizations such as the IEEE, enabling a more scientific type of reference, but others are published by commercial standards organizations: for example, Bluetooth is governed and published by the Bluetooth SIG. Thus, we need to rely on Bluetooth SIG for fundamental information about the operation and the future of the Bluetooth.

Then, there are business news about the market success (or failure) of these technologies. For example, there exist a myriad of scientific publications about the development and properties of ultra-wideband (UWB) networks, but one needs to refer to business news to find out how UWB has fared in the market. Without this non-scientific information, it is difficult to find out how the technologies compare as candidates for enabling technologies for mobile-phone-centric ambient intelligence applications. There also exist documents and analysis of market regulation of, e.g., health-care-related technologies.

Thus, I have used three types of footnotes. The first type of footnotes is a reference to a web site of a company, such as a manufacturer of a wireless interface chip or organization responsible for a standard. These references are for the benefit of the reader who might not know the company or organization beforehand and are presented as a simple web address without additional information (especially important in cases the company has already ceased to exist due to corporate mergers or insolvencies). The second type is a reference to a web site where information presented in the thesis is retrieved from (such as market information). In this case, the footnote has a reference date in addition to the web site address. The third type gives additional information about a subject.

The end-note references are also of three different types. First, there are the conventional scientific references used when possible. Then, there are technical references, such as white papers, standards definitions, and public project deliverables. These are referred to for the benefit of the reader to find the actual source of information. The third type is technical news sites, blogs, and press releases (reference date given). These are volatile, and may not exist when this thesis is read years from now. I have striven to find reasonably stable web addresses for reference.

2. Ambient Intelligence (AmI) Technology

Ambient intelligence refers to networked electronic sensory devices embedded in the environment and providing services to the people [6]. Ambient intelligence services should be context-aware and adaptive.

The terms *ambient intelligence*, *pervasive computing or systems*, and *ubiquitous computing* are often all used to define the technological field of embedding smart sensors to everyday objects and environments and providing context-aware applications based on them. The key concepts of ambient intelligence are *sensitivity*, *responsivity*, *adaptivity*, *transparency*, *ubiquity*, and *intelligence* [6]. A detailed analysis on the meaning and contents of these concepts defining ambient intelligence can be found in [7].

This chapter is based on publications I, II, and III. In this chapter, I present some of the application areas of Ambient Intelligence technologies. Section 2.2 presents available and proposed wireless network technologies that can be used in AmI applications. Section 2.3 presents methods available to decrease the power consumption of wireless devices. The wireless networking technologies presented in Chapter 3 have been developed to support or enable the applications presented in this chapter.

2.1 AmI Applications

2.1.1 Health care, welfare, wellbeing, and fitness

As one can deduce from the name of the body area networks (BAN), one of its main application areas is the health, wellbeing and fitness of a human person (user). All of these application areas are interleaved, the main difference being between the health care applications and the wellbeing & fitness applications. This greater difference is caused by the high accuracy and reliability standards required from the health care devices,

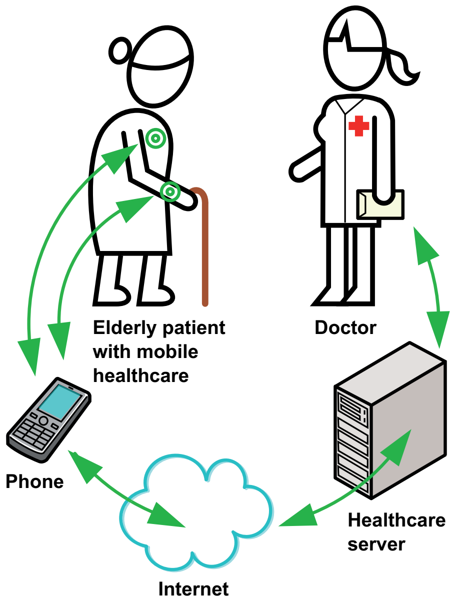


Figure 2.1. Mobile-phone-based home health care system connecting sensors attached to the patient to a health care server, where the data is accessible to the responsible health care professional real time.

and control and regulations imposed on them [8], and the more restricted market, causing also higher costs. International standardization, such as the ISO/IEEE 11073 standards [9], and industry initiatives, such as *Continua Health Alliance*[1] [10], try to improve interoperability of devices and applications from differing manufacturers or service providers [11].

Health care applications for body area networks can be subdivided to inpatient (inside hospitals) and outpatient (outside hospitals, usually at home) care (for the latter, see Figure 2.1). Within hospitals, specialized and expensive systems are used. Outside hospitals, where most of the chronically ill (suffering from, e.g., cardiovascular disease, asthma, diabetes, multiple sclerosis, or epilepsy) people live, there exists a need for cheaper, mobile (and thus smaller and less-power consuming) health monitoring devices. Some mobile-phone-based health care applications are presented in [2, 12, 13, 14, 15, 16, 17]. Another type of application is monitoring medication compliance [18, 19]. As the application field is in health care, the reliability needs are substantially higher than with the other applications [20]. Developing a reliable wireless home health care system can be difficult [21, 22].

Welfare applications refer to supported home applications, overlap-

[1] www.continuaalliance.org

ping with home health care applications. These applications are also referred to as ambient-assisted living, and include, for example, systems detecting accidental falls of an elderly or disabled person, and wrist-top computers with a button for calling help (e.g., from *Vivago*[2]). Some supported home applications are presented in [12, 23, 24, 25, 14].

Wellbeing applications refer here to people managing or observing their health status at home, trying to keep ahead of possible harmful changes to their health. Notable wellbeing devices include, e.g., weight scale (low tech), body fat content analyzers, and blood pressure meters. Wellbeing devices can employ exactly the same technologies used in health care devices, but the need for accuracy and reliability is lower. The manufacturing of such devices also has lower liability level. The borderline between health care and wellbeing or fitness devices is quite unclear and undefined, however [20]. It is predicted that the devices enabling the people to manage their health will become an important market [26].

Fitness applications refer to people managing their fitness, e.g., monitoring or analyzing heart rate, energy consumption, step counting, and running velocity [27, 28]. These are usually in the field of athletics, measuring fitness as well as skill, e.g., analyzing the swing while playing golf (such as *Suunto G6 Pro*[3] wrist-top computer) [12]. Some of the fitness devices, such as step counters and activity meters, are sometimes categorized as wellbeing devices

For all these applications, there are cases that a single device can perform all the functionality needed, such as the body fat content measurement device. Others may need a couple (or several) of devices, such as a sensor device and a user interface device. This is because the user interface often needs to be in a place visible or audible to the user, e.g. on wrist, but the sensor device needs to be installed where the body signals can be measured (e.g. attached on breast to measure heart rate). There is thus a need for a suitable body area network. Reliability is a crucial issue especially in health care and also in welfare applications. Reliability, however, requires specialized research and probably also an architecture, which are out of the scope of this thesis.

Mobile phones provide several wireless interfaces usable for ambient intelligence applications. Cellular and Wi-Fi provide connection to services in the Internet, while Wi-Fi, Bluetooth, and NFC can be used to connect

[2] www.vivago.fi
[3] www.suunto.com

to local services, such as sensors. For local connectivity, Wi-Fi is often an overkill, and so is Classic Bluetooth, providing unnecessary high data rates with the cost of high power consumption. Nevertheless, there exist Bluetooth sensor devices for, e.g., fitness applications (such as *Polar WearLink Bluetooth* heart rate transmitter). To answer the power usage requirements of button-cell battery-powered sensor devices, Bluetooth Low Energy has been developed. Another possibility are RFID sensor tags, enabling even passive sensor devices. Most of the fitness-related sensor devices have traditionally been based on the 5 kHz analog inductive link, that could be added to a mobile phone as external hardware.

A selection of wireless interfaces suitable for these applications and available for mobile phones is presented in Section 2.2. Architectural requirements are discussed in Section 2.4.1. A mobile-phone-centric wireless sensing architecture that makes the applications possible is described in Section 3.2, along with BTLEE (early version of Bluetooth Low Energy), RFID sensor tags, and add-on hardware providing a simple 5 kHz receiver.

2.1.2 Ubimedia

Ubimedia, as referred to within this thesis[4], is a concept where media files are embedded in everyday objects and the environment [29]. Applications of Ubimedia include movie trailers implanted on ads and multimedia content implanted on tourist information brochures, city cards, or concert tickets [14] (see Figure 2.2). The applicability of this concept is limited by the memory capacity of the embedded media. An RFID tag with a small memory can provide a small media file (mostly text) or a link to a source of more information in the Internet. The same is possible with optical barcodes (see Table 2.1). Historically, web links have been printed as text on e.g., newspaper ads, and the reader can copy the link by typing it to a web browser in his/her computer. Connecting to the Internet for downloading the media file is, however, not always preferable for establishing the connection and the download can take too much time, and in many cases, cost too much — especially when roaming abroad.

RFID tags are increasingly a part of our life; transport, traceability, and secure access are some of the main uses of this technology today. Conventional machine-readable wireless tags, e.g. Near Field Communication

[4]Also other meanings exist within scientific literature.

(a) Ubimedia on a magazine

(b) User downloading a movie trailer

Figure 2.2. Ubimedia [29]

(NFC) tags, normally have a very small memory in range of hundreds of bytes or kilobytes [30]. For instance, the popular *MIFARE 4k*[5] tag has 4 kB of memory from which the user can utilize 3480 bytes. An UHF *EPC* tag[6], on the other hand, is designed for product identification with a small memory. For instance, the *UG2 EPC* card by ASK[7] has up to 512 bits (64 B) of user memory [31]. With 1 or 2-dimensional optical tags (e.g., barcodes) memory limitations are even more severe. Use of mobile-phone-readable 2-dimensional optical tags is presented in [32]. Commercial optical tags, such as *Upcode*[8], are also available and used by some newspapers. Optical tags are basically only machine-readable identification codes. Some RFID standards include an option to have a flexible-use memory, but the capacity is low compared to factory-set fixed-content memory. Tag selection is based on reading the content in a selected tag memory address (e.g. tag or manufacturer ID). The reader must know the tag memory structure — thus it has to be pre-defined for an application. As the memory capacity of these tags is small, the amount of data to be transferred is also small and power consumption of RF communication is, thus, not a critical issue.

To get over the data limit on a passive tag, Wu et al. increase effective tag storage sizes with proposed distributed RFID tag storage infrastructure (D-RFID stores) [33]. Pillin et al. have developed a passive far-field

[5] mifare.net
[6] www.gs1.org/epcglobal
[7] www.ask-rfid.com
[8] www.upcode.fi

Table 2.1. Evolution of sharing digital content in printed media

1st generation: Web links on paper	+	Cheap to print No extra technology needed
	–	Threshold to write the link address manually to the web browser on the computer
2nd generation: Web link readable for mobile phone (optical or NFC tag)	+	Optical tag cheap to print, cameras widely available on phones NFC available on mobile phones
	–	Price and energy consumption of data connection Slow download
3rd generation: Digital content implanted on paper (memory tag)	+	Low threshold to use Fast and free download Low energy consumption compared to wireless download from the Internet
	–	Future technology, not yet commercially available

RFID tag using the 2.45 GHz ISM band, with a data rate of 4 Mbit/s on the range of 5.5 cm [34]. As an example of a proprietary solution, *Memory Spot* tag of Hewlett-Packard also works on the 2.45 GHz band and has demonstrated 4 MB memory and 10 Mbit/s data rate [35]. Another proprietary solution is *TransferJet*[9] of Sony working on 4.48 GHz electrical induction, with data rates of max 540 Mbit/s and range of a few cm, but requiring both the communicating parties to be active [36].

The problems of low data reading rate and small memory size provided by contemporary RFID tags become obvious if one considers mobile users reading multimedia files from tags embedded on paper media, such as newspapers. The attention span of a mobile user is about 10 seconds [37]. Within this period, the user could get a single multimedia content file from a memory tag (taking into account simple communication channel establishment and protocol overhead). Considering a movie trailer, the file size for a 2-minute 640×320-pixel 30-fps (3 Mbit/s), encoded with H.264 [38], would be in range of 50 MB [39]. The required minimum data transfer rate from the user point-of-view is thus 50 Mbit/s. This exceeds the maximum data rate available by 13.56 MHz NFC technology, 848 kbit/s, by a factor of 60. Even the maximum data rate for NFC demonstrated on a laboratory set-up, 6.78 Mbit/s [40], is not sufficient. Thus, there is a need for a new high-speed touch-range RFID radio interface.

Architectural requirements are discussed in Section 2.4.2. A system ar-

[9] www.transferjet.org

chitecture making mobile-phone-readable mass memory tags possible is presented in Section 3.3. Future of this application is discussed in Section 5.6.

2.2 Wireless Access Technologies for AmI Applications

In this section I present several possible wireless technologies available for mobile-phone-centric ambient intelligence applications. Networking technologies are divided into a few categories with regards to the range between the nodes and number of nodes within the network. These categories include, in decreasing area, local area networks (LAN), personal area networks (PAN), and body area networks (BAN).

Contemporary mobile phones provide two wireless interfaces that can be used for local wireless networking such as a local sensor network: Bluetooth (WPAN) and Wi-Fi (WLAN). Near-field communications (NFC) has been provided in several phone models since 2007. Some phones provide a proprietary ANT radio as well [41]. Technical demonstration of radio-frequency identification (RFID) technologies as an add-on to a mobile phone has been published as well [42]. Integrating phone-readable RFID tags to wireless sensor networks has been studied [43]. Device-to-device communication as a local area solution is currently considered in Third Generation Partnership Project (3GPP) but standardized solutions for 3GPP Long Term Evolution (LTE) do not exist yet [44].

With all these wireless technologies, one must take into account the physical limitations. For example, the widely used 2.45 GHz frequency is easily absorbed to water, in all forms. Thus, wireless interfaces on that frequency, such as Bluetooth, perform poorly when the signal needs to pass through the human body or through water, like is the case in water sports activities.

The wireless interfaces such as Bluetooth, ZigBee, Wi-Fi, EPC, and NFC are standardized. As the development of standard technologies has lagged behind market demand, several proprietary technologies have also been developed, such as ANT and *W.I.N.D.* The originally proprietary 5 kHz inductive link has become partially free as some of the related patents have run old. The proprietary technologies are of interest primarily on single-use and wrist-top-centered networks.

In this chapter I first present some wireless short-range interfaces available (local, personal, and body-area), wrapped up in Table 2.2. Then I discuss some methods available (or used) to reduce power usage within a wirelessly networked device in Section 2.3. This chapter forms an introduction to the following Chapter 3, where I present an architecture developed to extend the abilities of mobile phones in personal area networking (Section 3.2), and a novel short-range wireless interface (Section 3.3).

2.2.1 Wireless Local Area Networks

Local area networks connect devices within a limited area, such as home, building, or campus, e.g., networking computers. The lower layers of wireless local area networks (WLAN) are developed by the IEEE 802.11[10] standards working group, and sold today with the trade name Wi-Fi.

Wi-Fi

Wireless local area networks (WLAN) are, as the name tells, a wireless replacement for a local area network (LAN) cable. These networks have been standardized within IEEE 802.11 since 1997 and have since been branded as Wi-Fi. Sub-standards for IEEE 802.11 provide bandwidths of 2–540 Mbit/s. Wi-Fi provides a higher data rate than Classic Bluetooth, but with the cost of a higher power usage (per time unit) and more complex and thus expensive hardware. When transmitting large amounts of data, the energy consumption per bit is lower than that of Bluetooth, however [45]. Use cases of Wi-Fi for wireless sensing include multimedia sensors [46] (e.g., surveillance cameras) — whenever high bandwidth is needed. Due to the prevalence of Wi-Fi technology in computer networks, various Wi-Fi sensor nodes are available, some optimized for extended time of working without loading a battery, and some capable of working as internet protocol (IPv4/IPv6) endpoints (such as Aginova *Sentinel*[11] and Redpine Signal *SenSiFi*[12]).

The most popular use of Wi-Fi in mobile phones is as a connection to the Internet. This is in line with the original purpose of Wi-Fi as a wireless local area network. In early 2000's, there was also discussion if Wi-Fi would replace the cellular networks [47], but with the evolution of 3G and later cellular networks has driven the use of Wi-Fi to home, work, and coffee houses, wherever people are somewhat stationary. Today, another impor-

[10] www.ieee802.org/11
[11] www.aginova.com
[12] www.redpinesignals.com

tant use is as UPnP (Universal Plug-and-Play) radio interface, making it possible to, e.g., print out photos wirelessly with a UPnP-enabling mobile phone and printer, or even sensor network applications [48]. Also possible and demonstrated use-case is using Wi-Fi for indoor positioning or navigation [49, 50]. IEEE 802.11 has also been selected as a high-bandwidth radio interface for Bluetooth 3.0 (Bluetooth HR) [51].

For the applications studied within this thesis, Wi-Fi is generally too heavyweight a solution for body sensor networks, and requires an energy source on both ends of the communications, thus being unsuitable for ubimedia applications. It is mentioned here merely as it is available for use in mobile phones and enables the further connection to the Internet along with the cellular network interface.

2.2.2 Wireless Personal Area Networks

Personal area network (PAN) technologies, with ranges of about 10 m, usually connect peripheral devices to a central device, e.g., keyboard, mouse, and headset to a computer or phone. The usual contemporary wired connection is universal serial bus (USB). The lower layers of wireless PAN (WPAN) networks are developed by the IEEE 802.15[13] standards working group, and include technologies sold with trade names Bluetooth, ZigBee, *Wireless USB*[14], and *WirelessHD*[15]. ANT is a common proprietary PAN technology.

Bluetooth

Bluetooth is a low-power radio technology developed within Ericsson in 1994. In 1998 Ericsson opened up Bluetooth for wider use within Bluetooth Special Interest Group (SIG). Bluetooth, as many other short-range wireless interfaces, uses the licence-free 2.45 GHz ISM band. The original use-case of Bluetooth was streaming duplex audio, e.g., to a headset. Bluetooth has become the standard wireless solution for mobile phone peripherals. Bluetooth is prevalent in mobile phones, and also used extensively in computers — there are altogether 3000 million Bluetooth devices in 2011 with the 30 million new units shipping each week[16]. Bluetooth physical and medium access control (MAC) layers were standardized within IEEE 802.15.1 until Bluetooth v1.2 / IEEE 802.15.1-2005.

[13] www.ieee802.org/15
[14] www.usb.org/developers/wusb
[15] www.wirelesshd.org
[16] www.bluetooth.org, cited 20 September 2011

Table 2.2. Some available wireless technologies

	Frequency	Range	Bandwidth	Phy.	Type	Standards
Wi-Fi	2.45 GHz & 5 GHz	100 m	<540 Mbit/s	RF	A	IEEE 802.11
Bluetooth	2.45 GHz	10 m	3 Mbit/s	RF	A	IEEE 802.15.1[a]
Bluetooth LE	2.45 GHz		1 Mbit/s	RF	A	
Bluetooth HS	2.45 GHz			RF	A	
ZigBee	2.45 GHz	50 m	250 kbit/s	RF	A	IEEE 802.15.4
WiMedia / Wireless USB	3.1–10.6 GHz		480 Mbit/s	RF	A	ISO/IEC 26907
mmWave	60 GHz	10 m[b]	Gbit/s	RF	A	IEEE 802.15.3c
ANT	2.45 GHz	5 m	1 Mbit/s	RF	A	proprietary
CB	27 MHz			RF	A	proprietary[c]
EPC RFID	860–930 MHz	8 m[d]		RF	A/P	ISO 18000-6
2.45GHz RFID	2.45 GHz	5 cm	4 Mbit/s	RF	A/P	ISO 18000-4
5 kHz	5 kHz	2 m	100 kbit/s	Ind.	A	proprietary[e]
NFC	13.56 MHz	2 cm	442 kbit/s	Ind.	A/P	ISO 14443
RuBee	132 kHz	15 m	1.2 kbit/s	Ind.	A	IEEE 1902.1
TransferJet	4.48 GHz	2 cm	540 Mbit/s	Ind.	A	proprietary
Memory Spot	2.45 GHz	3 mm	10 Mbit/s	Ind.	P	proprietary
IrDA	875 nm	1 m[b]	3 Mbit/s	Opt.	A	proprietary
UWBLEE[f]	900 MHz & 7.9 GHz	10 cm	112 Mbit/s	RF	A/P	
Narrowband BAN	0.4–2.5 GHz (several)	variable	58–485 kbit/s	RF	A	IEEE 802.15.6[g]
UWB BAN	4 & 8 GHz		0.5–10 Mbit/s	RF	A	IEEE 802.15.6[g]
HBC BAN	16 & 27 MHz	body	?	Cap.	A	IEEE 802.15.6[g]

All values (except frequencies) approximate, advertised, or laboratory demonstrations. Type refers to communication between active devices (A) or between an active and a passive device (P).

[a] Originally, until Bluetooth v1.2 / IEEE 802.15.1-2005.
[b] Requires line-of-sight.
[c] Free band, several proprietary technologies have existed.
[d] Active to active.
[e] Simplest form free, coded becoming free in a few years.
[f] Being developed, see Section 3.3
[g] Draft.

Bluetooth provides a low-power and low-complexity wireless network compared to Wi-Fi, but with lower data rate [52]. Only 8 active devices (1 master, 7 slaves) can exist in one network, a *piconet*, at a given time. A master device, however, can have up to 255 "parked" inactive devices, which can be brought active at any time. The master device controls the piconet by deciding which slave has access to the channel at a given time and synchronizes the common clock for frequency hopping. A unit can be master of one piconet only at a time. Of course, if one wants to create a Bluetooth control device for multiple active piconets, one can have multiple Bluetooth controllers on the same device. There can exist a number of independent piconets in the same geographic location in the same time. Each piconet acts then in its own physical channel with its own master device and synchronizing clock. A master of one piconet can act as a slave in another. In such a situation the combination of multiple piconets is called a *scatternet* [53].

Bluetooth is, as also the other network radio protocols mentioned here, under constant development. From Bluetooth 2.1 onwards, NFC has also been available as a radio interface, for example, for simpler pairing of devices. There were plans to include WiMedia UWB as yet another radio interface used under the Bluetooth stack in Bluetooth 3.0 to provide higher data rates and more flexibility, but IEEE 802.11 (Wi-Fi) was selected instead (Bluetooth High Rate) [51, 54]. The result of this development is that applications can use the same top layers of Bluetooth stack without needing to know which radio interface is used in a given connection [55]. Different Bluetooth profiles may use different types of physical connections. Increased from original 1 Mbps by enhanced data rate (EDR), Bluetooth can provide data rates of about 3 Mbps with its own radio interface [54].

Bluetooth is an interesting radio technology for mobile-phone-based sensor solutions, as most phones provide a Bluetooth radio (see Figure 2.3). Bluetooth sensors, such as heart beat sensors (Polar Wearlink Bluetooth) for mobile-phone-based fitness applications, are already available. Low-power (e.g., button cell powered) sensor devices cannot bear the cost and power consumption associated with Classic Bluetooth, however, and would not require its full duplex bandwidth [56]. This has led to a wide use of proprietary radio networks (e.g., ANT) and development of Bluetooth Low Energy (formerly known as Bluetooth Low End Extension or BT LEE [56]), which is a radio technology specially designed for sensor networks

Figure 2.3. Current uses of Bluetooth connectivity with a mobile phone.

and discussed in Section 3.2. Bluetooth Low Energy solves the cost and power use problem by introducing minor power-saving additions to the Bluetooth chip. It is relatively cheap to provide stand-alone BT LE chips for wireless sensors or add the LE functionality to Bluetooth chips for mobile phones — in contrast to adding another low-power radio technology designed for sensors, e.g., ZigBee.

Bluetooth Low Energy is a part of Bluetooth standard from Bluetooth 4.0 [57]. Some chips are already available, such as Bluegiga[17] *BLE112*, CSR[18] *µENERGY CSR1000*, Nordic Semiconductor[19] *nRF8001* (single-mode Bluetooth Low Energy), and *CSR8000* (full Bluetooth 4.0 including the low energy mode) series. In May 2011, the first Bluetooth Low Energy Profile, Health Thermometer, was published [58].

ZigBee

ZigBee is governed by ZigBee Alliance and is based on the IEEE 802.15.4 standard, adding the upper networking layers [59]. Other networking stacks based on 802.15.4 MAC and PHY layers include standards such as ISA100.11a[20] [60] as well as proprietary *NanoStack*[21] [61], *JenNet*[22] [61],

[17] www.bluegiga.com
[18] www.csr.com
[19] www.nordicsemi.com
[20] www.isa100wci.org
[21] www.sensinode.com
[22] www.jennic.com

and *MiWi* [62], all designed as low-footprint alternatives in case standards compliance and full functionality of ZigBee are not needed. 6low-PAN has been developed to provide simplified IPv6 functionality over IEEE 802.15.4 networks and is being incorporated to ZigBee [63].

ZigBee uses the frequency bands 868 MHz (Europe), 915 MHz (North America), and 2.4 GHz (everywhere). ZigBee is optimized for automation sensor networks, where there is no need for high bandwidth, but low power usage, low latency and high quality-of-service are required. ZigBee networking protocol provides at most 2^{16} nodes (65 536) in one network [59]. ZigBee provides small footprint, low price, and low power usage, with low bandwidth. Although the frist ZigBee phone was unveiled in 2004 [64], and SIM cards with integrated ZigBee have been also available [65], ZigBee is still very rarely available general purpose devices, like mobile phones, PDAs, or personal computers. As Bluetooth is already available in those devices, there has been little drive to include ZigBee as an additional radio interface [66].

ZigBee architecture defines three types of devices: ZigBee Coordinators, ZigBee Routers and ZigBee End Devices. ZigBee Coordinator (ZC) acts as the root of the sensor network. There may only be one ZC per network. It stores information about the network, including possible security keys. ZigBee Routers (ZR) act as immediate routers passing data from other devices if the network forms a mesh. ZigBee End Devices (ZED) are sensor nodes. They contain the least possible amount of memory to be able to communicate with their parent device, which can be a router or a coordinator. They can not pass information from other nodes to another, nor can they be coordinators. Because of these limitations, they are least expensive to manufacture and are thus suitable for lightweight wireless smart sensor use. In star topology configuration, there exists only a ZigBee Coordinator surrounded by ZigBee End Devices. [59]

ZigBee is optimized for control/automation networks for buildings or factory floor. In these applications there usually is little or no need for standard mobile phones to be able to contact the network. ZigBee has, however, been demonstrated for use in medical WPAN [67, 13]. Continua Health Alliance has adopted ZigBee Health Care as the low power local area network (LAN) standard [68]. As ZigBee defines the upper layers of the networking stack, it can be used over other radio interfaces also. The possibility to use UWB as the physical layer has been studied and demonstrated [69].

Ultra-Wideband and 60 GHz technologies

To increase the available data rate one needs a wider bandwidth, available in higher frequencies. There were two major initiatives for ultra-wideband (UWB) based wireless networking, WiMedia and Wireless USB. Wimedia was supposed to be based on IEEE 802.15.3a MAC/PHY layers, but the IEEE task force failed to achieve a consensus on an IEEE UWB standard. The Wimedia MAC/PHY is defined by ISO/IEC 26907:2007 and ISO/IEC 26908:2007 [70]. Wireless USB is based on WiMedia's radio platform.

The so-called *mmWave* technology has been developed to work in the 60 GHz frequencies [71], with MAC and PHY layers standardized within IEEE 802.15.3c-2009 [72]. Commercial applications are also developed with the brand name WirelessHD. As of April 2011, there seems to be no plans yet to include the 60 GHz interface to mobile phones.

ANT and other proprietary technologies

The proprietary ANT radio can be roughly compared with Bluetooth or ZigBee, as it uses the same frequency band (2.45 GHz) and is designed for similar applications. ANT radio has low power usage compared to Bluetooth, but is on the same level as Bluetooth Low Energy and ZigBee. ANT radio is a lightweight and elegant solution for many applications, but does not share the prevalence of Bluetooth nor does it provide the benefits of a standardized, multiple vendor solution. ANT is owned by Dynastream Innocations Inc, a subsidiary of Garmin Ltd., and the only chip manufacturer until 2010 has been Nordic Semiconductor.

For certain applications, however, ANT has its benefits. If one needs to build a single link or a predefined network, e.g., a link between a wrist-top computer and a heart beat sensor, or between a USB dongle and a computer mouse, ANT radio is a widely used solution. ANT provides a possibility to connect 2^{32} devices in a single network (although most networks have 2 to 4 members) and a very low message overhead of 7 bytes. Both star and peer-to-peer (p2p) network topologies are provided. Sony Ericsson Mobile Communications AB has recently begun to ship high-end mobile phones of Xperia series with ANT technology integrated [41]. Recently also researchers have found interest in using ANT for personal health care applications [73].

Polar Electro has its own proprietary digital wireless network solution, W.I.N.D, for its range of high-end wrist-top computers for athletes. As

Polar Electro does not sell the solution to others, there is little public information available on the technology, but it works at the same 2.45 GHz ISM band as Bluetooth and ANT. This is probably a customized radio interface developed by some RF chip manufacturer and given the W.I.N.D brand name by Polar Electro.

Many personal area wireless solutions have also been built on the 27 MHz CB (citizen's radio) band, for instance computer mice and remote-controlled toys. The use of 27 MHz seems to be diminishing, however, with computer appliances moving to 2.45 GHz solutions (such as peripherals produced by Logitech [74]).

2.2.3 Body area networks

Body area networks (BAN) refer to wireless networks centered around a human body (the user) with the range of up to 2 m [17], e.g., heart beat sensors to wrist-top computers. Body area networks include network technologies more constrained in range, such as using the human body as a medium of communications [75]. Most BAN technologies have not been standardized, but some proprietary technologies, such as Polar Electro's, have been available since the 1970's. Developing a standard BAN technology is under way within IEEE 802.15.6[23] with three different physical layers defined for different purposes (narrowband at 400–450 MHz, 863–956 MHz, and 2360–2484 MHz; UWB at 4 GHz and 8 GHz; and Human Body Communications at 16 MHz and 27 MHz) [76]. Network topology requirements for using IEEE 802.15.6 UWB have been studied in [77]. Commonly used technologies for BAN include wireless PAN technologies such as Bluetooth and ZigBee [15]. A commonly available body area network solution are the fitness systems developed and manufactured by Polar Electro[24].

5 kHz analog link The 5 kHz inductive analog link is where the first consumer applications of body area networks were based on since invention in late 70's. The technology is basically analog, even though based on pulses — the information resides in the temporal separation of the pulses. Thus, the technology enables development of very simple sensor devices, such as the heart beat sensor. Both the communicating devices are active but the communications is often one-directional (sensor to user

[23] www.ieee802.org/15/pub/TG6.html
[24] www.polar.fi

interface device). The technology is, naturally, limited in bandwidth, especially when in presence of inter-device interference (such as in mass sports events). The short range of normal wrist-top computer to heart rate transmitters, about 1 m, limits the interference, but using the second pulse to code the signal is preferred ("coded pulse"). The range can be extended, if more powerful end-point devices are used. E.g., a mobile phone instead of a wrist-top computer as a receiver can have better sensitivity and resolution to pick the signal (see Article VIII) due to higher data processing capability and less strigent size constraints for the loop antenna. Unlike the 2.4 GHz wireless solutions, the 5 kHz analog link can be used in water (e.g., while swimming).

The use of 5 kHz inductive link is, however, not limited to heart rate transmissions. An example system consists of Polar *FT60* wrist-top computer with coded inductive 5 kHz peripherals, such as Wearlink heart beat transmitter, *G1 GPS* speedometer/distance counter, and *S1 foot pod* step counter. All these devices share the 5 kHz frequency band, and work on the body area range (<2 m). The limits of the low bandwidth (exact data rate undisclosed by Polar Electro) are visible especially in the use of the GPS speedometer: it does not send location data to the wrist-top device, just enough information to calculate the speed. Full GPS location data is not needed for that, however: it suffices to send, e.g., a coded pulse every time a treshold increment of distance is measured. The step counter may send a coded pulse for each pair of steps (pod only attached to one shoe). The inductive nature of the 5 kHz link makes also possible proximity detection, enabling user interface options not available in similar devices utilizing the 2.45 GHz RF band: moving the wrist-top computer over the heart beat transmitter belt changes the display status (Polar *HeartTouch*).[25]

Being invented in late 1970's, the patents [78] behind the original 5 kHz heart pulse technology have already expired. The so-called coded 5 kHz seems to be protected by Polar Electro's IPR for a few years (filed 1994 [79]), along with the more advanced network solutions.

Due to its simplicity, a 5 kHz inductive link could easily be added to a mobile phone or a computer as a cheap add-on plugged in the microphone

[25] The nature of the proprietary 5 kHz body area network of Polar Electro products is not disclosed in any public documents found with internet search engines. The patents held by the company provide some information, but not in a usable form. Thus, the network information presented in this paragraph is a result of deduction.

port and using simple audio processing software, as discussed in Section 3.2.2.

2.2.4 Other Wireless Access Technologies

Radio Frequency Identification (RFID)

Bearing in mind that powering a wireless sensor adds complexity to the design — a power cable, batteries, or energy scavenging — the possibility of using the reader device to wirelessly power the sensor is an interesting concept for certain sensor network applications. For this, the solution is RFID (Radio Frequency Identification) technology [80, 81]. RFID technology makes possible cheap passive, semi-passive, or active wireless devices [18]. Passive means here that the reading device powers both the sensing and backward communication. Semi-passive means that the reading device powers the communications and a battery (possibly with energy scavenging) powers the sensing. Within active RFID sensor tags, battery or other energy source powers both sensing and communications [82], enabling longer communications range or a higher data rate.

RFID sensor use-cases range from a sensor on the wall read by a passing-by technician with a reader device every now and then to a tag attached to a rotating wheel which comes to reading distance of a immobile reader once per rotation cycle. In the latter case, providing power by wiring can be quite complex. A solution could be a semi-passive RFID sensor tag which scavenges rotation energy or a totally passive tag. Not all types of physical or chemical properties can be reasonably measured with a passive tag, however, and making an integrated (small and cheap) solution depends on the possibility of integrating the sensor in the CMOS chip manufacturing process [82].

Electronic Product Code, or EPC, is an RFID standard which includes carrier frequencies close to GSM 900 MHz band. There is a possibility of developing a suitable radio interface for mobile phones to contain both EPC RFID and GSM/WCDMA 900 MHz on the same front-end, limiting the add of cost. This, however, is yet to be done. Nokia Research Center[26] developed an early add-on EPC functional cover to a *E61i* phone in 2007 [42]. The availability of EPC technology is, however, useful for the development of UWBLEE, discussed in Section 3.3.

The ISO 18000-4 standard [83] covers such an RFID technology that

[26] research.nokia.com

works on the 2.45 GHz ISM band, the same band that is used by, e.g., Bluetooth and Wi-Fi. As with EPC 900 MHz, there thus exists a possibility of a joint front-end for multiple radio interfaces, as discussed in Section 3.2.1.

Inductive links

Inductive links are similar to passive RFID technologies in allowing a device to wirelessly provide remote power to another (possibly passive) device, a tag, via the carrier frequency. Both devices, the reader and the tag, can also be active, as in the case of 5 kHz inductive links used by heart beat sensors in fitness applications. The magnetic field used in inductive (near field) coupling drops proportional to the inverse cube of the distance, making eavesdropping or interference less of a problem compared to RFID or PAN technologies that are based on radiative electromagnetic field.

Near Field Communications (NFC) Near Field Communications (NFC), governed by NFC Forum, is an interesting standard, as it has been already included into commercial mobile phones. It is categorized as an near field RFID standard [80], as it differs from the other (far field) RFID standards mainly on its very limited range. NFC works on 13.56 MHz band and provides a range of a few cm, practically a touch range. The use-cases for NFC include using mobile phone as a touch-to-pay credit card, as well as pairing Bluetooth devices [84]. Mobile phone manufacturers have introduced several phone models, such as *Nokia 3200* (2004) with NFC functionality, but with no business ecosystem yet available [85, 86], there has been little development yet on this field.

The short range of NFC can be considered as an advantage for certain use-cases. Physical selection by touching of a service or device to be connected is intuitive for the user. Bluetooth and Wi-Fi, along with Wireless USB, have incorporated use of NFC as an interface enabling establishing connection by touching[27]. The short range also makes eavesdropping or man-in-the-middle attacks very difficult, if not impossible.

RuBee RuBee is another developed standard (IEEE 1902.1) for low-data-rate and low-power wireless communications between active devices [87]. RuBee works on magnetic long waves and low frequencies (mostly 131 kHz), providing packet size of 128 bits and a data rate of 1200 bit/s. As magnetic long waves are not absorbed by steel or water [17], RuBee has uses, e.g., in implanted medical devices [88, 89]. Such applications of

[27] www.nfc-forum.org, cited 20 September 2011

RuBee have still not been commercialized (as of Summer 2011). Existing RuBee tags are small, in range of a cm^2, but the routers (readers) available (such as Visible SideWinder[28]) seem to be large rack-space devices not easily integrable to mobile phones.

Memory Spot and TransferJet Due to the needs of applications such as ubimedia and high-speed ad-hoc wireless data transfer, with no enabling technology readily available in the markets, some manufacturers have brought on their own initiatives, such as TransferJet (Sony Corp.) and Memory Spot (Hewlett-Packard) mentioned in Section 2.1.2.

Memory Spot is similar to NFC technology in range and allowing one of the communicating devices to be passive, but provides much higher data rate (10 Mbit/s) than NFC. The communications frequency is 2.45 GHz but near-field induction [35]. Higher frequency, induction, and requirement of power transfer make the reading range to be around 2 mm, thus even shorter than that of NFC. On the other hand, also the coil antenna is smaller, approximately 3 mm in diameter. Despite being demonstrated and standardized (within ECMA [90]), Memory Spot technology has not adopted to be used anywhere yet.

TransferJet is another inductive communications technology, but working on a yet higher frequency band of 4.48 GHz, enabling 540 Mbit/s data rates on a range of a few cm [36]. This technology requires both of the communicating devices to be active, so the technology does not share all the use-cases of NFC or Memory Spot. From the user's point-of-view, using NFC to intitiate a Bluetooth connection and using IEEE 802.11n as the wireless interface for Bluetooth HR, one would get a similar touch-initiated high-data-rate data transfer as with TransferJet, but with far better range once the communication has been initiated. Sony is driving this technology to use through TransferJet Consortium, with little success so far (as of Summer 2011).

Infrared Data Association

Infrared communication has a long history compared to the other wireless networking technologies used for personal area networks (early examples include Hewlett-Packard's *HP-28* programmable pocket calculator from 1986). The stardardized Infrared Data Association[29] (IrDA), founded in 1993, was quite commonly available in mobile phones until 2007 (Nokia

[28] www.rubee.com
[29] www.irda.org

N95 and *E90* as some of the last phone models). It seems IrDA has been quietly dropped from new mobile phone models after 2007[30]. As IrDA provides only low data bandwidth with the cost of fixed positioning of the communicating devices with a direct line-of-sight, Bluetooth has supplanted IrDA in most applications. It could still have some use especially in the cases where radio interference is not tolerated.

For e.g., body area network applications, IrDA is unusable due to the requirement of line-of-sight and alignment between the communicating devices [15]. For ubimedia applications, the main problem is with the limited bandwidth.

Human body as a wireless medium

The above mentioned technologies all rely in transmission of electromagnetic field through air. Another possibility for body area networks is using the human body as a transmission medium. There are basically three possible different techniques: using the human body as a conductor (wire) [75, 91], electrostatic coupling via the body [75], and the human body as a waveguide [75]. There are some commercial applications which may be brought to market [92], such as personal authentication [93, 94]. Philips has studied use of capacitive coupling intra-body communications for setting up a personal health sensor network [95]. Transmission frequency was 125 kHz and data rate only 4 kbit/s, but enough for authenticating communicating devices to each other for starting a more regular data connection over a wireless network (such as ZigBee or Bluetooth). Also transmitting real-time audio signal through a human body (as a conductor at 2 MHz frequency) has been demonstrated [96, 97, 91], with a data rate of 2 Mbit/s. IEEE 802.15.6 standard for body area networks defines two human body communications (HBC) channels, based on electrostatic field, centered at 16 and 27 MHz with bandwidth of 4 MHz [76].

2.3 Lowering the power use of wireless connections

There are several possible methods to constrain or reduce power usage of wireless personal area networks. Some of the methods are presented below, ordered by respective OSI layers from physical layer to application layer.

[30]Information retrieved by looking through data sheets of different phone models.

2.3.1 Physical layer solutions

For a physical connection, there are several technological possibilities that can affect power usage. The most fundamental is the type of the connection: is it inductive (NFC, 5 kHz, Memory Spot, TransferJet), capacitive, magnetic (RuBee), radio (Wi-Fi, Bluetooth, ZigBee, ANT, UWB), or optical (IrDA). There is the choice of frequency band, modulation type (UWB is being developed in two flavors: orthogonal frequency division multiplexing and direct sequence), and also the choice between analog (5 kHz) and digital.

There are also physical solutions that are not related to communications. These include making passive (remote-powered) or semi-passive (partially remote-powered) devices [81]. The latter include, for example, RFID sensor tags whose communications are remotely powered, while sensing is battery-powered.

There is also the possibility of remote wake-up of the device. A device can have a passive RFID tag included, which when powered by a remote transmission, wakes up the whole device, making possible any type of radio connection, e.g. Bluetooth or Wi-Fi [98]. Thus, the device needs not use battery power to maintain readiness.

2.3.2 MAC layer solutions

On medium access control (MAC) layer, there are also many possibilities affecting the power needs. The MAC layer design should prevent energy-wasting overhearing, packet collisions, excessive retransmissions, control overheads, and idle listening. It should also adapt to network changes (such as adding new sensors or removal of a sensor due to battery outage) efficiently [99]. An important aspect is idling, like in the case of BT LEE [56]. A device can spend most of the time in an idle state, spending minimal amount of energy. On pre-defined intervals the device can then send an advertising message or listen to a possible message. If more active communication is needed, there can be a state for continuous communications.

Another possibility is controlling the packet size. For example, BTLEE uses variable size packets. For constant streaming like for duplex audio, there is little or no difference between constant or variable packet size, but for lesser amounts of data, e.g. for wireless keyboards, packet size can have a great effect on power usage. Another method for BTLEE lowering the power use compared to Bluetooth is by using fewer (one default and two secondary) initialization channels, resulting in shorter scanning times [56].

2.3.3 Networking solutions

On networking level, the technological choices affecting power usage include routing, message confirmation, network overhead, data rate, and scalability. Of these, network overhead is dependent on the other factors: for example, addressing needs more bytes, the better the scalability is. That is the reason many network solutions are limited in the amount of nodes in a single network, e.g., for Bluetooth 8 devices, for ANT 2^{32} devices. Large-scale scalability like with TCP/IP is seldom needed within personal area networks, but can be achieved with 6loWPAN [63].

Message acknowledgment and retransmission (e.g., nanoTCP) use more power than unacknowledged messages (e.g. nanoUDP) due to the need of more messages and more network overhead per message (nanoTCP 9 bytes vs. nanoUDP 5 bytes) [100]. In many sensor streaming applications, retransmission and acknowledgment is not really needed, as retransmitted data would already be outdated (e.g., with direct audio or heart data). Thus, sensor networks often do not use TCP-type messaging. On the other hand, with applications like wireless keyboards, the payload of a single message is important while the message frequency is low, making the case for nanoTCP or similar message types.

2.3.4 Architecture solutions

Dividing power use between the devices is often a feasible way to reduce power consumption on some parts of the architecture. For example, RFID technology makes possible that the peripheral device does not need to have a power source of its own, as the reader (e.g., mobile phone) gives the power with its radio transmission. In the case that the central node is a mobile phone, there is also the possibility of sending data to a networked server for further processing or storage [101]. One needs to take into account that moving process and storage load to a remote server often increases network traffic, which also consumes energy, usually more than pre-processing on the node [102].

Security is a more difficult aspect of the network for limiting the power usage. In principle, security requires data storage and processing capacity [84, 99], generating more power usage [84]. Standard wireless protocols, such as Bluetooth, Wi-Fi and ZigBee all include security [52, 45, 84]. Using an inductive link or intra-body communications, the reading distance is strongly limited, providing some security against unwanted overhearing.

Also the topology of the network has an effect on power efficiency. In general, star architecture with a central node has the possibility of being much more power efficient than is possible with mesh, especially ad-hoc, architecture, due to, e.g., the requirement of nodes being listening for (and relaying) messages [103, 104, 105].

2.4 AmI Architecture

The focus of this thesis is development a mobile-phone-centric architecture enabling AmI applications. The term *system architecture* includes both the hardware and the software architecture. The term *network architecture* includes different nodes, the wired and wireless access technologies between the nodes, and the software protocol for communications between the nodes. *Open architecture* means that the software and hardware interfaces, as well as the wired or wireless access technologies are open for 3rd party developers, applications, and manufacturers.

As the motivation of this thesis is to develop a mobile-phone-centric system architecture for AmI applications, those wireless access technologies which are readily available, or easily integratable, in mobile phones are preferable. Compared to other alternatives for a user-carried interface device — such as laptop computers, portable media players, wrist-top computers, or palm-top computers — mobile phones have several advantages: highest penetration and acceptance amongst users, relatively low cost and small size, both local and long range wireless connections from everywhere to everywhere, access to a wide range of services via the Internet, data storage possibility and local computational capacity, and that no additional user interfaces need to be carried by the user.

The architecture requirements are openness, modularity, scalability, and energy efficiency. Openness and modularity are needed to enable creation of novel ambient intelligence applications and services by different industry players. Scalability is needed to enable development of vertical applications of different scale on different application areas, such as health or wellbeing.

2.4.1 Wireless Sensor Networks

The wireless sensor network architecture enabling ambient intelligence applications on fields of health and wellbeing is discussed here and developed in Section 3.2. Wireless sensor network architecture research provides three main topologies available for ambient intelligence applications: mesh, star (1-hop), and extended star (2-hop). Of these, the star topologies are usually used in body area networks [77]. The IEEE 802.15.6 standard for body area networks endorses the 1 or 2-hop star architectures [106]. ZigBee technology enables all the three topologies [59]. Commonly used for existing BAN solutions is 1-hop star.

As wireless sensors should be small and not require changing or charging batteries often, low energy use is a key parameter in developing sensor networks. Networking, both protocols and radio interface, should consume as little energy as possible. Also low price is of prime importance to allow widespread use of the architecture. In our architecture, reading active (battery-powered) wireless sensor devices is based on Bluetooth, which is the standard wireless personal area network (PAN) technology. The fact that the devices are active increases considerably the distance allowed between the reader and the sensor during the communications, but requires the sensors to have a power source of their own (e.g., battery). Autonomous sensor devices can periodically collect and send sensor measurements, the sensor data can be streamed to the phone with a predefined rate, or the sensor devices can be polled at freely configurable intervals.

There is also a possibility of further reducing the power usage of the sensor device by making it rely on the power provided by the electromagnetic transmission of the mobile phone (reader device) [107]. Reading sensor tags is based on RFID (radio frequency identification) communication, enabling passive, semi-passive, or active operation (see Section 2.2.4). Normally RFID sensor tags are limited with memory size (examples include Microsensys *TELID311*[31]) or have no memory at all (examples include [108] and [109]) and with how often the measurements are available, unless there are regular readings performed by the reader device. In our RFID sensor tags, reading the tag releases the tag's memory for new measurements.

[31] www.microsensys.de

2.4.2 RF Memory Tags

The system architecture enabling reading and writing ubimedia is discussed here and developed in Section 3.3. As the hand-held devices have larger screens with more pixels, the multimedia (video) files become larger. Thus, scalability of data rate is needed to enable evolution of the technology along with the improved multimedia services. Energy efficiency is essential to enable passive operation of the tags as well as to conserve the phone's battery, in contrast to many NFC services, such as public transport ticketing, where the reader/writer device is within infrastructure and has power line connection. The proposed architecture is modular, enabling simpler and faster development of new technical extensions. Modularity also allows faster prototyping of possible new use cases (e.g., reading memory tags with a mobile phone).

As memory tags for ubimedia have high data storage capacity, a high-speed radio is needed for communication to enable reading even all the contents of the tag in an acceptable time. Currently available mobile phones contain several radio transceivers, such as cellular, Bluetooth, and Wi-Fi, along with NFC. Most of the technologies are made for well-established communication between active devices, consuming a relatively large amount of power. These technologies, with the exception of NFC, are also not inherently designed for ad-hoc, possibly one-time, connections between devices that have not communicated with each other before, resulting in long latency in establishing the communications. For example, in an environment with many unknown Bluetooth devices, the Bluetooth connection setup latency can be over 10 seconds [110]. NFC enables communications between an active and a passive battery-less device and is physically more selective; its communication range is almost in touch. However, it has severe limitations in data transfer speed, as discussed in Section 2.1.2.

Network on Terminal Architecture (NoTA) [111] is an open modular service-based system architecture for mobile and embedded devices offering services and applications to each other. NoTA allows direct connections between different nodes, within subsystem or between subsystems. This architecture supports both messaging and streaming services. The beauty in the architecture resides in modularity and transport independency. Direct connection between subsystems improves the efficiency as they do not necessarily require any processor involvement, when subsystems have all the needed functionalities available for their independent operations. Transport-specific portion is hidden underneath the NoTA communication layering.

3. Mobile-phone-centric AmI Architecture

This chapter, based on publications IV, V, VI, VII, VIII, IX, and X, forms the core of this thesis. The research has been done within EU 6th framework integrated projects MIMOSA[1] [112] and MINAMI[2] [113], as well as within Academy of Finland Finnish-Chinese joint research project UBI-SERV[3] [114].

This Chapter is organized as follows. First, I present the functional requirements and design phases of the architecture in Section 3.1. Then, I present a wireless sensor network architecture (MIMOSA) for mobile-phone-centric ambient intelligence applications in Section 3.2 as well as implementation of the architecture and demonstration of its capabilities. The architecture includes a Bluetooth Low End Extension radio for wireless sensor networking, and an RFID radio for reading passive wireless sensors. Also an add-on 5 kHz link to cheap analog wireless sensors is discussed. Then I present a system architecture for a high-speed access to passive memory tags for ubimedia applications in Section 3.3.

3.1 Functional requirements of the system architecture

This architecture has been developed within projects MIMOSA and MINAmI. The architecture is referred to as MIMOSA architecture in this thesis. The requirements for the mobile-phone-centric sensor network architecture (see Section 3.2) were identified in MIMOSA Work Package (WP) 1 Applications and Services [112]. The requirements for the system architecture for mobile-phone-readable memory tags (see Section 3.3) were identified in the MINAmI WP 1 Usage & Ethical Issues. The require-

[1] www.mimosa-fp6.com
[2] www.fp6-minami.org
[3] www.ubi-serv.org

ments were discussed in Section 2.4.

Architecture development was divided to three phases: (1) identification of the requirements (not the focus of this thesis); (2) definition of the design parts, software layers, and interfaces; and (3) testing the design against the initial requirements with a laboratory table setup. The requirements have been discussed in Section 2.1. The design parts, software layers, and interfaces are discussed in this chapter. Testing the design with a laboratory table implementation against the initial requirements for the mobile-phone-centric sensor network architecture is also presented in this chapter. Testing the design of the system architecture for mobile-phone-readable memory tags is out of the scope of this thesis, but has been done within a separate project [115].

In our vision, personal mobile devices provide trusted intelligent user interfaces and wireless gateways to sensors, networks of sensors, local networks, and the Internet. We have been developing a mobile-phone-based architecture, which includes the personal mobile terminal with access to wireless sensors and tags in near proximity (Figure 3.1). To simplify development of ambient intelligence services, we use a (1-hop) star topology, in which a mobile phone acts as the trusted user interface device, providing both local network and internet connections and capability to run application software to provide functionality, e.g., context awareness. 1-hop star topology has been typically used for personal body area network (BAN) fitness solutions (wrist-top computer with heart beat and possibly other sensors).

There exist other common user interface devices with short range wireless access technologies, such as laptop, tablet, or palm-top computers (a.k.a personal digital assistants, PDAs), portable game consoles, and wrist-top computers. Laptop and tablet computers are quite large, however, and ill suitable for, e.g., fitness purposes. Wrist-top computers are widely used for fitness and welfare applications, but are limited in the display size and often without any long-range connectivity to the Internet. A palmtop computer or portable game console with long-range Internet connectivity is a (mobile) smart phone.

In our architecture, the mobile phone searches and reads sensors, stores and analyzes sensor data to extract context information, hosts sensor network applications and forwards the appropriate data to servers in the Internet to provide extra services and functionality. Functionality offered by different sensors and tags can be integrated into independent modular

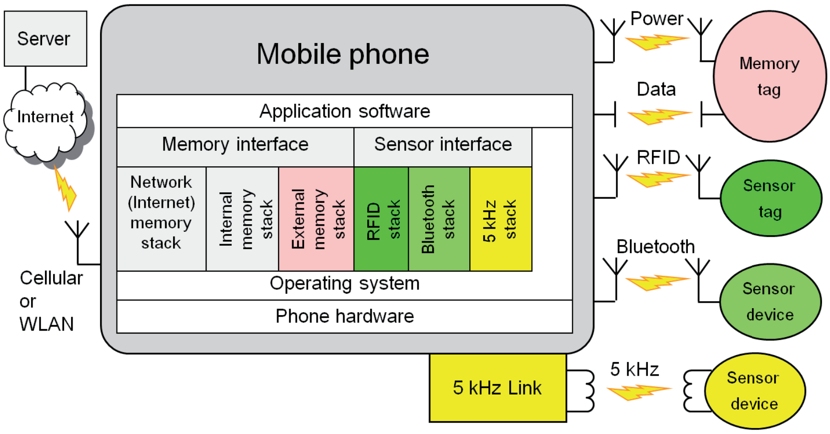


Figure 3.1. Overview of the developed mobile terminal architecture

subsystems that applications in the mobile phone can interact with [16].

There are two types of RFID radios available, one backscattering on the 2.45 GHz frequency band co-existing with Bluetooth (see Section 3.2.1 and [34]), and one high-data-rate dual-channel (see Section 3.3) for moving large amounts of data (in gigabit range). The latter one is interesting for RF memory tags, which combine both memory capacity and high data rate requirements. RF memory tags can also be used for ubimedia (see Section 2.1.2). The operating system of the mobile phone provides application protocol interfaces (APIs) to application software for using integrated or wirelessly connected sensors and memory.

The main mobile-phone-centric architectural challenges, when adding an RF memory tag reader solution, reside on the autonomy of the added functionality: whether it requires other functionalities or host intervention, or should it even operate on its own. Another challenge is minimizing changes to existing system communication layering. Our RF memory tag solution affects only the external memory stack block shown in Figure 3.1. With the chosen design, the affected entities within the mobile phone and an RF memory tag should be minimum and as independent as possible from the rest of the system architecture. The choices in the system architecture were able to support both existing standard radios and the high-rate high capacity memory tags.

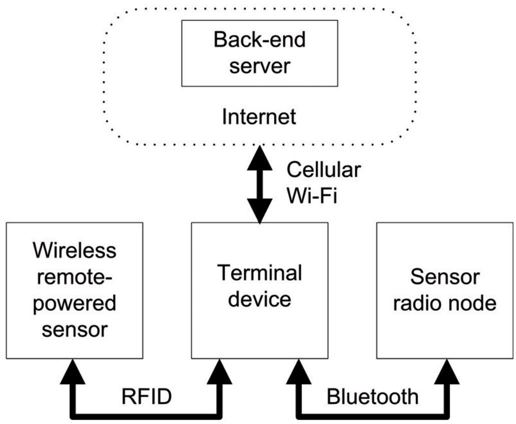


Figure 3.2. MIMOSA architecture overview

3.2 Mobile-phone-centric Sensor Network

The MIMOSA architecture is designed to be modular and freely scalable. The software architecture is based on three layers: Context Layer, Sensor Layer, and Local Connectivity Layer. The APIs of the layers are open for 3rd parties. These layers, and remote sensing middleware, will be presented in the following sections. Open interfaces for 3rd party sensor hardware are also provided.

The MIMOSA architecture (see Figure 3.2 [116, 101]) defines four types of entities: terminal devices (mobile phones) with built-in sensors, sensor radio nodes, wireless remote-powered sensors, and back-end servers.

The terminal device provides capacity to run applications based on sensor data, and in addition to a cellular network connection, has Bluetooth and RFID radio interfaces. Back-end servers are computers providing data storage, data processing and extra services.

To answer different power usage and price requirements in various smart sensor applications, we employ two classes of sensor devices: sensor radio nodes that are wireless battery-powered smart sensors running sensor server software, and wireless remote-powered sensors that are passive RFID tags with a sensor. To simplify the terminal by removing the need of yet another radio front-end, the ISO 18000-4 RFID [83] was chosen as it works on the 2.45 GHz ISM band already used by Bluetooth [101].

In this section, I first present the software layers required for operation of the mobile-phone-centric wireless sensor network. Then I present the architecture implementation (BTLEE, RFID, and 5 kHz analog) and demonstration results of the technologies.

3.2.1 Software architecture

Plug-in type implementation of sensors is the key to modularity. The Sensor API detects what sensors are available regardless of their location within the system: directly connected on the terminal, in a sensor radio node, or in an RFID tag. The Sensor API on the host device keeps a list of available sensors and provides functions for accessing them.

Sensor layer

The Sensor Layer provides a sensor client, an RFID sensor tag reading interface and a Sensor API for upper level or 3rd party software. The layer finds and reads both locally connected and wireless sensors.

Simple Sensor Interface (SSI) protocol [117] was originally developed within the WIRSU [118, 119] project and further within MIMOSA with me taking part in specifying streaming and RFID sensor support. SSI defines a method for reading sensors regardless their type, location or connection between the sensor and the reader. SSI is based on a client-server architecture, where sensor devices act as SSI servers and terminal devices as SSI clients. A single sensor device can have multiple sensors. Both polling sensors by client terminals and streaming data from sensor servers are supported (see Table 3.1). SSI is an application level protocol that can be used over any network environment.

The command-answer pairs Q-A and C-N handle finding sensor devices and information about the sensors available on them. Sensor reading (polling) is done with the command-answer pair R-V (see Figures 3.3 and 3.4). In streaming, the sensor device is called "sensor observer" and the reading device is "sensor listener". The SSI client can request a sensor observer and the SSI server can request a sensor listener. To speed up data transfer in streaming, the SSI server can buffer data points to send them in messages of type M. The number of data points that can be sent in a single M message depends on the communications buffer length, which in our implementation was limited to 128 bytes[4] due to the experimental hardware, resulting in a limit of 29 data points, each 4 bytes.

SSI-compatible RFID tags In the proposed architecture, a SSI-compatible RFID sensor tag is a Mode 1 (passive backscatter RFID system) tag as defined by the ISO 18000-4 standard. SSI protocol specification defines the memory layout of RFID sensor tags (see Table 3.2). RFID sensor tag

[4] compare to BTLEE providing variable data size up to 255 bytes.

Table 3.1. SSI v1.2 command set

Cmd	Dir	Description
Q / q	C→	Query for sensor devices
A / a	←S	Query reply
C / c	C→	Discover sensors on device
N / n	←S	Discovery reply
Z / z	C→	Reset SSI device
G / g	C→	Get configuration data of a sensor
X / x	←S	Configuration data response
S / s	C→	Set configuration data for a sensor
R / r	C→	Request sensor data, see Figure 3.3
V / v	←S	Sensor data response, see Figure 3.4
D / d	←S	Sensor data response with one byte status field
M / m	←S	Sensor data response with many data points
O / o	C→	Create sensor observer
Y / y	←S	Sensor observer created
K / k	C→	Delete sensor observer
L / l	←S	Request sensor listener
J / j	C→	Sensor listener created
E / e	↔	Error messages
F / f	↔	Free data for custom purposes

All commands are one byte ASCII. If the command is in lower case, a CRC checksum (see Figures 3.5 and 3.6) is calculated and attached to the end of the message. On direction (Dir) column, C and S are client and server.

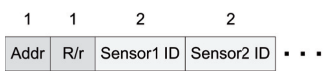


Figure 3.3. SSI sensor data request 'R' message. Addr is the device address, one byte, followed by the message type 'R' or 'r' and list of sensor identifications (SensorID). If no SensorIDs are sent, the response will consist of values of all the sensors in the device.

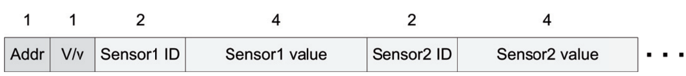


Figure 3.4. SSI sensor data response 'V' message. Addr is the device address, one byte, followed by the message type 'V' or 'v'. Either only values of the requested sensors are sent (if SensorIDs are listed in the reques command 'R' or 'r') or all the sensor values requested are sent (if no SensorIDs listed).

Table 3.2. SSI compatible RFID sensor tag memory map

B	Byte address	Description
8	0x00–0x07	Tag ID
4	0x08–0x09	Tag manufacturer
	0x0A–0x0B	Tag hardware type
6	0x0C	Tag memory layout: Embedded Application Code. 0x53 for SSI compliant tags.
	0x0D–0x11	Tag memory layout: Tag Memory Map Allocation
8	0x12–0x15	Sensor value (variable)
	0x16	Sensor value type (0x00 = floating point, 0x01 = signed integer...)
	0x17	Floating point multiplier
	0x18	Sensor status flags. Bit 0 indicates if the sensor value is valid data (bit 0 = 1) or not yet valid (bit 0 = 0).
	0x19	For future use. Could be, e.g., number of sensors on RFID tag.
16	0x1A–0x29	Sensor description in ASCII.
8	0x2A–0x31	Unit description in ASCII.
8	0x32–0x35	Minimum value the sensor can provide.
	0x36–0x39	Maximum value the sensor can provide.
4	0x3A	Activate sensor. Bit 0 written by the reader to request the tag to write the sensor data. Bits 1–7 free for future use.
	0x3B–0x3D	Free for future use.

Memory area 0x00–0x11 is defined by ISO 18000-4 standard. 0x12– is defined by SSI specification. Memory area 0x3E– can be used, for instance, for having more than one sensor on the tag.

reader toggles the sensor activation bit (byte address 0x3A), waits until the sensor status is "ready" (0x18) and then reads the memory area, where the sensor value is stored (0x12–0x15). After reading the sensor value, the sensor status bit is cleared by the reader. Compatibility with ISO 18000-4 is also ensured on command level (see Table 3.3).

RFID Sensor Tag is a wireless remote-powered sensor designed for low-cost sensing. The RFID interrogator powers the tag and writes the number 1 to the corresponding bit of the activation byte address (see Table 3.2). The sensor control hardware then writes the sensor value to its memory and sets the sensor status bit to ready (1). The sensor value is then read by the Sensor API of the terminal device.

Table 3.3. SSI RFID compatibility with ISO 18000-4

Command		Comments
SSI	ISO 18000-4	
Q/q	GROUP_SELECT	Tag hardware type must be "SSI"
A/a	REPLY	Compatible
C/c	READ	Compatible
N/n	reply READ	Compatible
Z/z	INITIALIZE	Compatible
G/g	READ	Compatible
X/x	reply READ	Compatible
S/s	WRITE	Compatible
R/r	READ	Compatible
V/v	reply READ	Compatible
D/d	reply READ	Compatible

Local connectivity layer

The Local Connectivity Layer provides a Local Connectivity API to send and receive messages to and from locally connected sensors and remote devices over BTLEE radio and RFID tags. For this purpose commercial low overhead networking solutions are available (e.g., nanoIP [100]). Traffic control or message tracking is not needed for lightweight sensor applications, since loss of an individual sensor value is often not so important. To make possible wide use of the proposed architecture, we chose an open source networking solution, nanoIP [100]. For future development, 6loWPAN may be preferable as it enables traffic of IPv6 packets [120].

NanoIP was selected as a networking solution because it has less overhead than TCP/IP and it is also freely usable. The small overhead of 5 bytes is achieved, for instance, by relying on the MAC (medium access control) layer for addressing. We use the nanoUDP message type (see Figure 3.5), that includes a protocol byte, 2-byte length of message, source and destination port numbers and the SSI message as payload. NanoUDP is designed for situations where an individual message is not critical, and so does not provide proof of message receive nor retransmission. If getting the messages through is considered critical, nanoTCP should be used, as it provides flow control and retransmission if needed. The price for this, however, is heavier message overhead (9 bytes) and increased network traffic.

Considering the need of retransmission in case of lost packages: if the case is of a streaming sensor application, recovering the lost package can

1	2	1	1	n	2
Prtcl	Length	Src	Dst	Payload	CRC

Figure 3.5. NanoUDP message format. Prtcl is the protocol and flag byte. Length is the total length of payload and possible CRC. Src and Dst are source and destination port numbers, both 0x28 for SSI. CRC checksum is used if requested by the application.

1	2	2	n	2
Start	Length	~Length	Payload	CRC

Figure 3.6. SSI/UART message format. Start byte indicating beginning of message is 0xFE. Length and ~Length are length and bitwise not of length of message payload with optional CRC.

be unnecessary and even harmful if the processing and power resources are low. If the case is of an remote keyboard, on the other hand, recovering a lost package is essential, as each keystroke is required to get through to the processing unit and the package rate is relatively low.

The Bluetooth API provides methods for device discovery, connection setup and data delivery over BTLEE radio. The RFID API provides methods to identify tags and read or write tag memory content using an RFID interrogator. For locally connected sensors (add-on hardware), point-to-point wired connections (UART, SPI, I2C) are used instead of nanoIP networking. For such situations, the SSI/UART message format (see Figure 3.6) is used. For the case that several Bluetooth devices are active in the proximity, there is a possibility of interference between different Bluetooth networks [110].

3.2.2 Architecture implementation

The proposed architecture (see Figure 3.1) has been demonstrated with an implementation with four different hardware entities: terminal device with add-on sensors, sensor radio node, RFID sensor tag, and back-end server (see Figure 3.7).

The Terminal Device is a 3G mobile phone, a *Nokia 6630* (*Symbian*[5]), with add-on electronics and software layers to provide MIMOSA functionality. The mobile phone runs local sensor applications, and acts as a gateway between the local sensor environment and the Internet, where remote servers can provide extra functionality.

The MIMOSA terminal provides Bluetooth, BTLEE and RFID radios for

[5]symbian.nokia.com

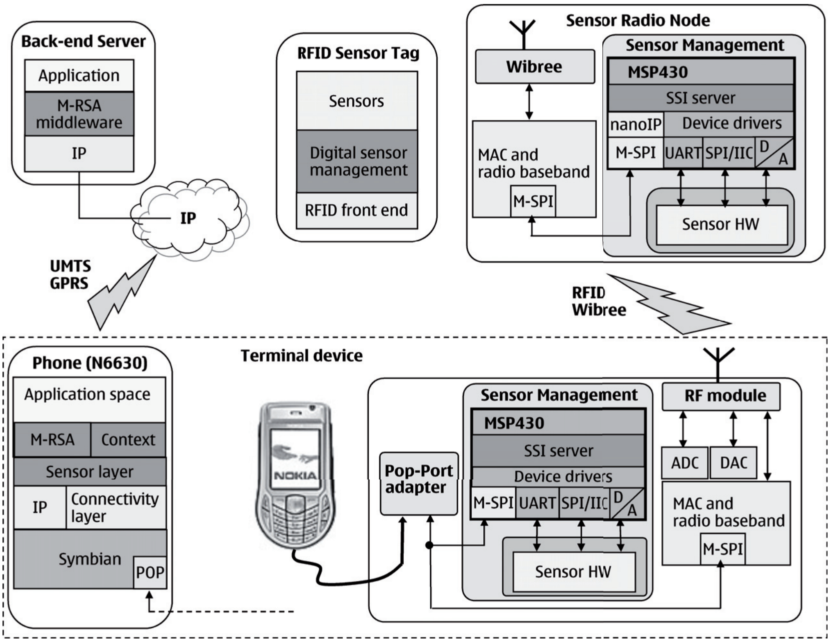


Figure 3.7. Mobile-phone-centric wireless sensor network architecture implementation. Wibree was the first version of BTLEE designed for commercial market [62, 121, 101].

reading sensors. Both BTLEE and RFID technologies use the same analog RF module. Medium access control protocols of the systems are implemented on an FPGA included in the MIMOSA hardware. The BTLEE and RFID protocols are independent of each other but the RF resource arbitrator knows which one of the systems is using the RF resources and prevents the other system using them if already allocated.

The connection from phone to MIMOSA hardware is over an USB to SPI converter (Pop-Port[6] adapter). The MIMOSA SPI (M-SPI) is an SPI bus with extra interrupt lines for local sensor management board, BTLEE, and RFID systems. The add-on sensors are interfaced and managed by a sensor management board of the same kind as in the Sensor Radio Node (see next paragraph). The only difference is in networking, which is done by point-to-point SSI/UART protocol over the M-SPI bus.

The Sensor Radio Node is a wireless battery-powered smart sensor with BTLEE radio, nanoIP networking, and SSI server software. Sensors are managed with a Texas Instruments *MSP430*[7] mixed-signal microcontroller

[6] A proprietary plug-in port providing audio input/output, power output, and serial port, available in many Nokia mobile phones in 2004 to 2007. It was phased out in favor of Micro-USB and standard audio socket in 2007.
[7] www.ti.com

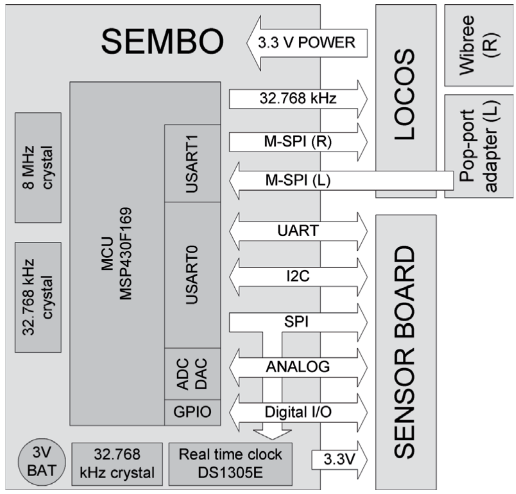


Figure 3.8. Sensor management and interfaces. SEMBO is sensor management board, LOCOS is local connectivity board. On a Sensor Radio Node (R), Wibree (BTLEE) board is used. On a Terminal Device (L), a pop-port adapter is used. See photograph in Figure 3.9

(MCU) which runs the SSI server, nanoIP networking, and drivers for sensor and communications hardware. There is also a real time clock, which can be used as a time "sensor". The same sensor management board is used in both sensor radio nodes and terminal devices, the difference being in communications software (see Figure 3.8).

Sensor management board provides a standard connector for sensor hardware, providing a +3.3 V power supply, and including standard UART, SPI and I2C digital interfaces, 8 analog input lines and 15 configurable general digital input/output lines. The latter can be used, for example, to implement a non-standard digital interface to the sensor(s), or to provide sensor enable or clock signals. In our laboratory table implementation, the battery provides power to the real time clock only.

As a back-end server, a laptop computer with MIMOSA Remote Sensing Architecture (M-RSA) middleware in another location was used to read sensor data over the network. The terminal device acts here as the link that forwards sensor readings from the sensors to the computer.

In the implemented architecture, an RFID sensor tag is an SSI-compatible RFID sensor tag (see Section 3.2.1). In MIMOSA architecture, RFID sensor tags work on the same frequency as the low power Bluetooth, 2.45GHz, to enable possible cooperation on radio front-end.

Add-on feature: 5 kHz inductive link

Connectivity to the de facto standard wearable heart beat sensors has been lacking from mobile phones. These usual accessories for fitness and wellness applications, most often use a 5 kHz inductive link (see Section 2.2.3). We have developed, for mobile phones, a simple add-on device (hardware) that can be plugged to the audio port of a mobile phone, and simple add-on software based on *GStreamer*[8] audio library together capable of reading the heart beat signal (see Publication VIII).

We have implemented the electronics and software to a Ubuntu Linux laptop computer. The add-on hardware is not phone platform specific, but the software naturally is. The implementation is not limited to receiving just the signal from wearable heart beat sensors. Any low-bandwidth sensor could use this communication method, as discussed in Section 2.2.3 Thus, the add-on link could make possible various health, fitness, and wellness use-cases not catered by the more power-consuming Bluetooth technology. The solution was also ported to a *Nokia N900* Maemo[9] Linux phone, but making the phone accept a device connected to the audio port needs negotiating the issue with the phone manufacturer. For commercial adaptation of this technology, this should not be an issue.

3.2.3 Demonstration results

MIMOSA architecture has been successfully demonstrated in a laboratory environment with a wireless weather station (see Figure 3.9) as an application (see Publications IV and Publication VI). The demonstration consists of a MIMOSA terminal with a user interface application using the Sensor API to read the environmental sensor values (temperature, pressure and humidity) over BTLEE radio. The MIMOSA Remote Sensing Architecture (M-RSA) application on the terminal forwards selected values over the 3G cellular network and the Internet to a laptop computer that is acting as a back-end server.

The wireless weather station consists of a BTLEE board, a connectivity board (LOCOS) with an FPGA running the medium access control protocols and providing connections between the other boards, a sensor management board with a microcontroller running device drivers and an SSI server, and a sensor board with Intersema[10] MS5534 pressure/temperature

[8] gstreamer.freedesktop.org

[9] maemo.org

[10] Acquired in 2008 by Measurement Specialties, www.meas-spec.com

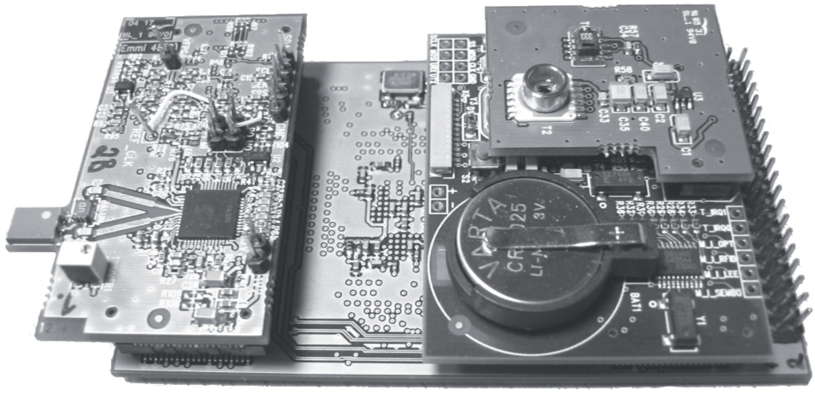


Figure 3.9. Wireless weather station. BTLEE board on the left, connectivity (LOCOS) board on the bottom, sensor management (SEMBO) board on right with sensor board on top right.

and Sensirion[11] SHT11 humidity/dew point/temperature sensors. All sensors implemented and tested on the MIMOSA platform are presented in Table 3.4. The sensors use custom digital interfaces, thus the general digital input/output pins (GPIO) of the sensor management board are used. The demonstration included searching for sensor devices, discovery of sensors in a found device and reading the sensors (polling) with a mobile phone, along with forwarding the selected sensor values to the back-up server (see Figure 3.10) [101].

The RFID sensor tag was demonstrated successfully by reading the sensor value from the tag memory using the proposed architecture (see Publication VII). In the implementation, the analog part included the tag front end (rectifier, voltage limitation, and backscattering), RFID analog circuitry (demodulator, clock, regulation, current and voltage references, and power-on reset) and analog sensor interface (sigma delta based). The digital part included RFID protocol management, state machine, sensor interface, and sensor filters. A standalone capacitive pressure sensor was used. All the expected features of the passive RFID sensor tag were achieved: antenna features (impedance matching and radiation pattern), more than 40cm communication distance, low power consumption, high sensor resolution, and accurate and reliable sensor measurements.

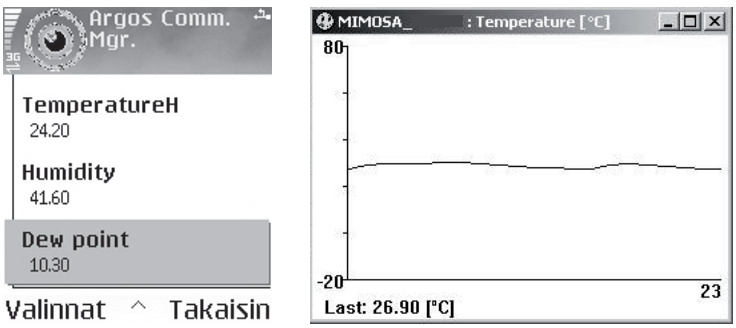
Another application implemented over MIMOSA platform consists of an ECG sensor, which provides an analog signal to a sensor management board (SEMBO) card (see Publication V). This signal was transmitted to

[11]www.sensirion.com

Table 3.4. Sensors implemented on the MIMOSA platform

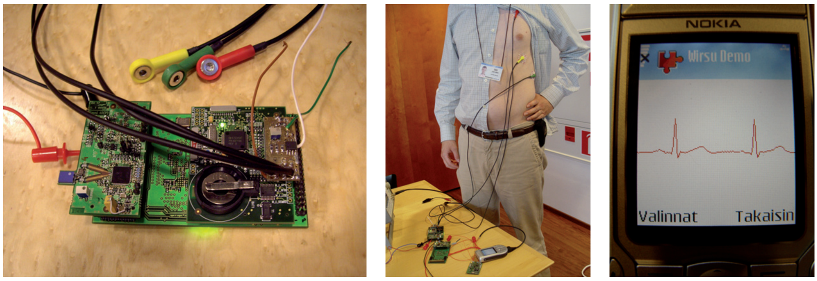
Sensor	Description and purpose
ECG / Cardiplus[a]	Heart rate and pulse analysis (health), SSI/nanoIP streaming over BTLEE
Temperature, pressure, and humidity	Weather station demonstrator, SSI/nanoIP polling over BTLEE
Lactate and glucose sensors / Fraunhofer-ISIT[b] and Åmic[c]	Fitness and health (Figure 3.12)
Body water content and galvanic skin response (GSR) [122] / Nokia Research Center[d]	Body water content → Fat percentage (long-term health) → Dehydration (sports & elderly) GSR (stress, health), local sensor reading

[a] www.cardiplus.com
[b] www.isit.fraunhofer.de
[c] Acquired in 2008 by Johnson & Johnson, www.jnj.com
[d] research.nokia.com



(a) Terminal **(b)** Back-end server

Figure 3.10. Screen capture from a MIMOSA terminal reading the wireless weather station and from a back-end server reading temperature values from the wireless weather station via a MIMOSA terminal.



(a) Electronics **(b)** Patient with sensor **(c)** Data on terminal

Figure 3.11. ECG sensing over BTLEE to mobile terminal.

a mobile telephone using BTLEE connection with M-type SSI messages consisting of 28 measured ECG samples per message and 4.3 kbit/s data throughput. The data were not sent in individual packages (V-type messages) due to the limited radio throughput of the experimental BTLEE circuitry. The ECG signal was displayed on the mobile screen (see Figure 3.11).

The main features in the ECG subsystem were amplification and signal adaptation using three electrodes, 8-bit acquisition, sampling rate of 100Hz, power supply 100 µA max 3.3 V, BTLEE wireless connection, and some signal processing for noise filtering. To improve the quality of the signal, a 50Hz notch filter was implemented as software.

In the ECG mobile subprogram, the user indicated the starting and the ending of its acquisition. Data was sent to the call centre where a doctor could supervise the ECG and communicate with the patient if it is needed.

The MIMOSA terminal also had local (add-on) sensor interface (see Figure 3.2). Body water content was measured with the local sensors [122], requiring a four-point contact with the user's hands (two contacts in both hands, as in [27]). In an fully operational prototype, the contacts would be around the phone, e.g. on buttons. The SEMBO board connected to the mobile phone via the Pop-Port provided the measurements a 50 kHz signal, and the resistance value calculated from the current gone through the upper body was input to a experiment-based equation (similar to [123]), with body water content, body fat content (percentage), and possible dehydration (difference to a preceding measurement) as results. By changing the set-up to a 2-point measurement, galvanic skin response (GSR) could be calculated, the changes of which could indicate, e.g., stress (conductivity of skin changing with perspiration).

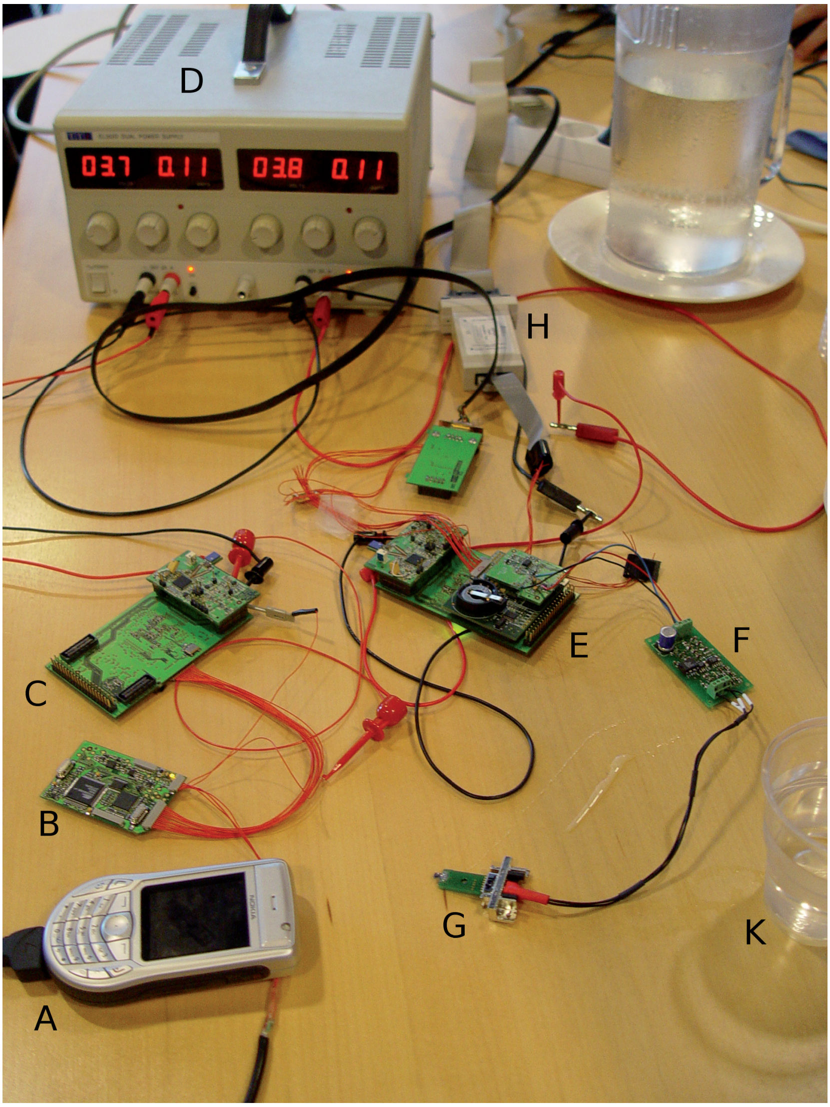


Figure 3.12. Full measurement setup with the phone (A), Pop-Port adapter (B), and add-on electronics (C) on the left, wireless sensor node (E) with an sensor front-end board (F), and an attached lactate sensor (G) on right. On top a laboratory power supply (D) and programming cable (H) for debugging the wireless sensor node. Glass of water (K) is for testing the operation of the sensor.

3.3 Mobile-phone-readable Memory Tags

In this section we describe and specify a system architecture enabling mobile phones to read and write passive RF memory tags for Ubimedia applications (see also Section 2.1.2 and Publications IX and X). The described architecture has been developed and demonstrated in the EU 6th framework integrated project MINAmI. In the technical demonstrations high data-rates up to 112 Mbit/s have been achieved [124], showing that the concept of mobile-phone-readable RF memory tags is implementable. Also usability studies have been done with a fully functional mock-up device[12] based on NFC (see Publication III).

The proposed system architecture makes use of the mobile phone's capability of running software and providing several radio interfaces (see Figure 3.1). From local networking point-of-view, a tag in proximity (range about 10 cm) has a point-to-point network with the mobile phone. In case of several tags is the proximity, the network resembles a star network with the phone communicating with a selected tag.

3.3.1 Hardware architecture

The hardware architecture developed to enable mobile phones to read and write RF mass memory tags was based on three new technologies: Network on Terminal Architecture (NoTA) (discussed in Section 2.4.2), phase-change memory (PCM) [126], and a novel wireless interface, UWB Low End Extension (UWBLEE) [115].

NoTA subsystem structure takes into account possibility to add different types of independent (service/application) subsystems to the architecture. MINAmI technology forms one high data rate high capacity subsystem within NoTA. The MINAmI subsystem offers memory tag read/write, storage and local connectivity services to other subsystems within mobile device, and its architecture is compatible with NoTA communication layering. The MINAmI subsystem includes both the mobile phone (Mobile Reader/Writer) and the tag and all the relating hardware and software resources. Mobile Reader/Writer sees the contents of the memory of a passive RF memory tag only when there is an established connection, i.e.,

[12] A Nokia NFC phone with read-and-writable NFC tags. The multimedia content was not stored on the tags, but on the phone. The phone software mimicked the operation of reading the multimedia content from the tag with a pre-defined rate and interrupted the "reading" if the phone was taken away from the tag too soon. See [125] for details.

power field and data connection exists.

The proposed RF memory tag technology was also made possible by modern trends in non-volatile memory technologies, according to which the power consumption, physical size, and price of memory are continuously decreasing. The main reason to pick up phase-change memory (PCM) in favor of any other memory technology [126] were the benefits of PCM technology, e.g., the estimated high number of read/write cycles, low power requirements, and bit alterability (lack of need of block erase cycles), as compared with flash memory.

UWB Low End Extension

As discussed in Section 2.1.2, the large file sizes required by ubimedia (in the range of 50 MB) also require a data transfer rate higher than the technologies provided by the wireless access technologies currently available in mobile phones. To provide higher data rates, a wider frequency band available on higher frequencies needs to be used. On the other hand, the efficiency of wireless power transfer (WPT) decreases as a function of center frequency. To solve the problem of providing high-speed communication (a wide frequency band available at a high frequency is needed) while simultaneously providing power wirelessly to the tag, we have proposed a dual-band radio interface [127]. One narrowband signal on RFID frequencies (frequency bands globally available on 860–960 MHz) is used to power the tag and to provide a mutual clock reference for both ends of the communication link, whereas the communication link itself is based on impulse UWB technology to provide a wide communication bandwidth and scalability for even higher data rates.

As the selected RFID frequencies are close to the frequency range as GSM/WCDMA 900 MHz, in the reader there is a possibility of integrating the WPT function to the existing Phone Radio Subsystem, as presented in Figure 3.13. In that case, Phone Radio Subsystem is designed so that the WPT Physical (PHY) Layer function may request a direct access to control the activation of the narrowband transmitter. Especially, the time-domain interleaving of different functions is important to support co-existence of GSM/WCDMA and WPT signaling.

The architecture of the proposed RF memory tag (Figure 3.14) is similar to the MINAmI subsystem on the mobile phone. For simple RF memory tags, no network layer implementation is needed to take care of the point-to-point communication between the reader and the tag, and therefore is

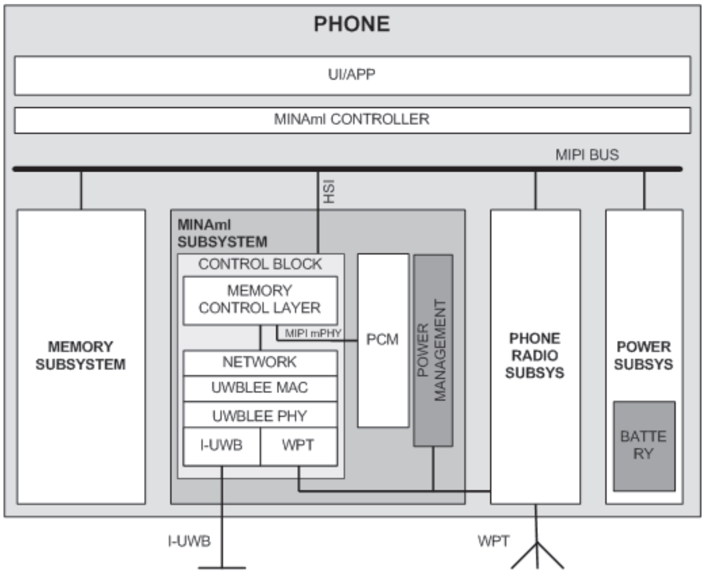


Figure 3.13. System architecture on phone for enabling reading mass memory tags

handled on Medium Access Control (MAC) layer.

As an option for use-cases like data-logging sensor devices (a use case of sleep quality measurement with EEG presented in [16]), the memory control layer provides a sensor interface. During the sensing, the sensor data is stored to the Phase-Change Memory (PCM) block and the low data-rate data capturing is powered from a battery or with energy harvested from the environment. For fast downloading of the logged data, the reader powers the sensor tag wirelessly.

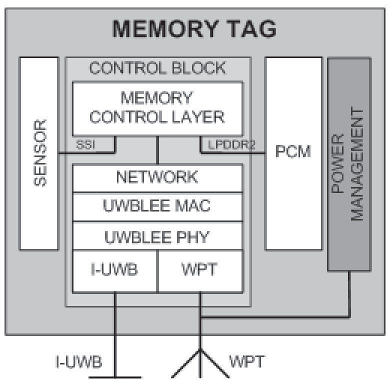


Figure 3.14. System architecture of a RF memory tag

3.3.2 UWBLEE Protocol Stack

The proposed software architecture (protocol stack) for UWBLEE is designed to be modular and scalable. The protocol stack is based on three layers: Network Layer, Medium Access Control (MAC) Layer, and Physical (PHY) Layer. These layers will be presented in the following sections. The protocol stack has been developed taking into account future compatibility with NoTA architecture.

Network layer
Network Layer will first only provide point-to-point connections regardless of state. In future, also applications using multiple targets could become feasible when MINAmI Subsystem is in active mode. If a point-to-multipoint network protocol is needed, nanoIP is easily implementable [100]. However, to get full internet support, a classical IP protocol (IPv4 or IPv6), or its reduced version such as 6loWPAN [63] may be required. In the final architecture (NoTA) solution, the network layer would consist of Device Interconnect Protocol (DIP), as a middleware, which guarantees the compatibility with NoTA. For example DIP TCP L_IN is ready to be used within one device and between several devices in a sub-network as such. Multicasting must be enabled in IP interface in order for device discovery to work. Packet size is an important parameter and depends on what is feasible for MAC and PHY layers.

Medium access control layer
The medium access control (MAC) of the novel dual-band radio interface has three different operational modes: the passive mode, where no internal power source is available or used; and the active and semi-passive modes, where internal power source is available and in use. Tags on battery-less objects without power wire connection (e.g., implanted on paper) are passive.

In the active mode, the mobile phone actively searches and selects the target tags, transmits the WPT signal (received by the tags) for powering and for frequency synchronization of the communication link, reads/writes data on the tags, and closes the connection to the target when active connection is no longer required. This operation can be an automatic feature, or enabled by the user (initiating the application for reading and writing the tag). In the semi-passive mode the phone receives data sent by an outside device, but powers itself, allowing a longer communication range,

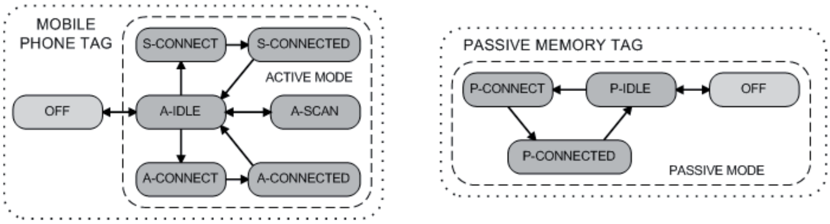


Figure 3.15. On the left: Active (and semi-passive) UWBLEE MAC states on a mobile phone. Active states denoted with A, semi-passive with S. On the right: Passive UWBLEE MAC states on a RF memory tag.

which would otherwise be limited by the WPT link. In semi-passive mode, however, the initiator device takes care of the synchronization of the I-UWB communication link.

Active mode states are used by battery-powered mobile devices, whereas passive mode states are applied for passive devices and tags. In passive mode, possible connections are powered by an outside device with WPT. In the passive operating mode the default state — when powered by an outside device — is P-IDLE, i.e. ready to receive any data, after the boot-up sequence.

The main operational states of UWBLEE MAC are shown in Figure 3.15. In addition to the shown directions of movement from state to state, there need to be possibility of built-in error recovery operation from any operational state to the corresponding idle state (A-IDLE or P-IDLE).

As UWBLEE connectivity is built to work on a short range of around 10 cm only naturally limits the risk of different UWBLEE connections interferencing with each other. The WPT link has a longer range and is thus more suspectible to interference. The interference of other narrowband transmitters has not yet been studied [115].

Physical layer

UWBLEE PHY (physical layer) controls both the I-UWB communications and Wireless Power Transfer (WPT) transmission. The direction and purpose of the WPT link depends on the operational mode (active or passive). UWBLEE PHY is divided to two sub-blocks: I-UWB PHY and WPT PHY. I-UWB PHY controls the Impulse-UWB radio interface and WPT PHY controls the Wireless Power Transfer interface. I-UWB PHY and WPT PHY are coordinated by UWBLEE PHY so that I-UWB transmission is synchronized with the WPT transmission. The function performed by UWBLEE PHY is defined by UWBLEE MAC, as shown in Table 3.5.

Table 3.5. UWBLEE PHY functions in different MAC states

	MAC mode		
	Passive	Semi-passive	Active
I-UWB	Transmit / receive		
WPT synch	Receive		Transmit
WPT power	Receive		Transmit
Power source	WPT reception	Battery	Battery
Remarks	Being read or written		Reading or writing other devices

4. Summary of results

The research question of this thesis was *whether it is possible to develop a mobile-phone-centric system architecture which enables creation of ambient intelligence services*. The research hypothesis was that *a mobile-phone-centric system architecture is suitable to creation of ambient intelligence services*.

The mobile-phone-centric architecture enables the use of local wireless sensor nodes and provides a connection to the Internet which profoundly increases its functionality. The success of mobile phones as the default user interface device is highlighted by the fact that the earlier palmtop computer market has almost totally been assimilated by the mobile (smart) phone market. The ambient intelligence applications for mobile phones in the area of health & wellbeing and in ubimedia as well as their architectural requirements have been presented (Chapter 2). The design parts of the architecture were defined as a mobile phone (central node), active Bluetooth sensor radio nodes, passive RFID sensor tags, and RF memory tags, and back-end servers in the Internet providing extra functionality (Chapter 3). The required communication layers were identified to be the physical, medium access control, network, and sensor layers.

The development of the mobile-phone-centric sensor network architecture has been presented (Section 3.2). To test the designed architecture against the requirements set by the applications, an implementation setup was built and evaluated (Section 3.2.3). Demonstrations include reading weather data and ECG from an active sensor node over a Bluetooth Low End Extension connection, reading air pressure data over an 2.45 GHz RFID link, and reading local, add-on, sensors plugged to the terminal device (Section 3.2.3).

The system architecture for mobile-phone-readable memory tags for ubimedia applications has been presented (Section 3.3). The major architectural challenge was identified to be providing a high data rate (a wide frequency band available in high frequency is needed) in the same time as providing power to a passive tag (easier with low frequency). The defined architecture solves this problem by defining a subsystem to mobile phone providing a new dual-channel short-range wireless interface enabling high-data-rate and low-power reading of even passive RF memory tags. The novel wireless interface is optimized for easy integration in mobile phones using an 900 MHz UHF RFID interface for wireless power transfer and synchronization, and an impulse ultra-wideband interface as the actual communication link. The architecture also allows data-logging RF sensor devices. The RF memory tags can be active, semi-passive, or passive. Later, the architecture has been demonstrated to work on laboratory table implementations [127, 115] and commercial demonstrations [128]. Also usability studies of mobile-phone readable ubimedia have been done with a mock-up service based on near field communications (NFC) (see Publications II and III).

5. Discussion

In the previous sections, as a part of mobile-phone-centric architecture development, I considered some new or existing technologies: Bluetooth Low Energy, RFID, 5 kHz links, NoTA, and UWBLEE. I did my research on the field of BTLEE in 2004–2006, RFID 2005–2009, UWBLEE (including NoTA) 2006–2009, and 5 kHz in 2010. With the rapid development of ICT and wireless technologies, much has happened after my research. In this section I discuss recent developments and the future of the studied technologies.

5.1 Bluetooth Low Energy

Recently, Bluetooth Low Energy has been included in the new Bluetooth Core Specification Version 4.0 [57]. The road to widespread adoption of the technology is now open, with three vendors already providing Bluetooth LE chips.

The history of Bluetooth Low Energy, however, teaches us a lesson on the time scale of these developments. The core innovations lead to the first publication of BTLEE in 2004 [56]. During the years 2004 to 2006, the development of BTLEE happened within the MIMOSA project, resulting in demonstrations of the technology that proved its feasibility and lucrativeness ([101], [121]). As the Bluetooth community (Bluetooth SIG) as a whole was still not prepared to accept a new extension to the technology, Nokia released the technology first as a separate — but co-existing — platform, Wibree in 2006 [62]. This lead to Bluetooth SIG members finally agreeing in accepting the technology as a part of Bluetooth Standard in June 2007 [129], with a preliminary name of Ultra Low Power (ULP) Bluetooth. Development within the Bluetooth SIG proved to be slow, however, taking three full years to be complete. Only in May 2011, almost four years after the agreement, the first Bluetooth Low Energy profile was published (Health Thermometer Profile [130]).

The reason for the long development time scale is not in the complexity of the technology. Even as making the technology fully compatible and integrateable with Classic Bluetooth was naturally more complex a task than a laboratory experiment of the technology, most of the time was taken by complex political negotiations first within a single company, then between many companies with differing requirements and views on the uses, and differing intellectual property portfolios. One must remember that Classic Bluetooth took about the same time from research results (1993) to founding Bluetooth SIG (1998), and being included in most mobile phones and computers (2003).

Bluetooth on mobile phones also may have market difficulties in countries where the telecommunications companies control the mobile device market, such as in the USA. For example, Verizon Wireless restricted the Bluetooth capabilites of Motorola[1] *V710* phone [131], and Apple has until recently restricted the Bluetooth on iPhones to connections to the wireless audio headsets only (see, e.g., [132]). Whether new sensor applications will be allowed, remains to be seen. In Europe, most of the smart phones have for a long time had "full" Bluetooth functionality, such as file transfer.

Due to the lack of standard low-power wireless sensor network solutions, the ANT radio (see Section 2.2.2) was developed and gained wide use within single-link applications, such as connections between a wristtop computer and a heart beat sensors. The additional price of integrating this non-compatible (with the existing Bluetooth) new wireless interface kept ANT radio from being adopted by the mobile phone industry. As the need for lower power wireless interfaces grew, and Bluetooth Low Energy was not readily usable, ANT radio interface has been implemented in some commercial mobile phones. ANT radio may be more likely to be accepted by the US telecommunications companies as the applications of the proprietary connection can probably be better controlled and restricted.

In the future, Bluetooth Low Energy will probably gain upper hand in the mobile phone and computer market, however. Even though Texas Instruments produces dual-mode chips capable of both Bluetooth and ANT+, integrating ANT to the same silicon as Bluetooth can be expected to remain more expensive than making a dual-mode Bluetooth and Bluetooth

[1] Acquired by Google Inc. in 2011, www.google.com

Low Energy chip, as Bluetooth Low Energy was designed to be an extension to Bluetooth from the beginning. Bluetooth Low Energy already has more chip manufacturers (Nordic Semiconductor, Bluegiga, Texas Instruments and CSR). The extensive existing sports market ecosystem of ANT, with hear beat transmitters and other body sensors, and sports machinery (such as Concept2 *PM4* indoor rowers[2]), gives ANT a head start in this competition, however.

5.2 RFID sensor tags

In the time of the research presented in Section 3.2.1, the development of standards for RFID and other wireless smart sensors was still incomplete. Recently, international standard IEEE 1415.7-2010 [133] has been finalized, including a standardized communication protocol and memory layout for RFID sensor tags.

The future IEEE 1451 compatible smart sensors should have a standardized transducer electronic data sheets (TEDS) [62]. The radio interfaces catered by the IEEE 1451.7-2010 standard include the ISO 18000-4 used in our research. In short, the memory layout of IEEE 1451.7-2010 provides a 64 bit sensor (device) identifier, a 128 bit field for sensor characteristics TEDS identifying the sensor's functional capabilities, records for sample and configuration, event administration, and event records (measurements). The TEDS provides many types of information not available within SSI, such as the measurement type (present value, maximum/minimum over certain timeframe or average, variance and standard deviation, count of values used for max/min/average determination etc).

5.3 Simple Sensor Interface (SSI)

Simple Sensor Interface SSI can be regarded as one of the early steps towards wireless sensor systems interoperability and standards, as well as full sensor support on mobile phone operating systems. As SSI was developed for research and development purposes, it does not include all the functionality and definitions provided by, e.g., the IEEE 1451 standard. Nevertheless, SSI can still be used for R&D purposes when needed. For instance, the NanoStack wireless sensor network uses SSI as an application-

[2] www.concept2.com

level sensor interface [134].

If RFID sensor tags are produced with self-made electronics or tags made of discrete components, SSI may be of value for technology demonstration or proof-of-concept purposes. When developing or manufacturing prototypes or real production devices, off-the-self RFID sensor chips will be a more suitable choice, and will probably comply with the IEEE standard. Such chips seem not to be available yet (as of August 2011).

5.4 NFC

Even though NFC Forum was founded in 2004 and Nokia has sold mobile phones with integrated NFC since March 2007, the market breakthrough is yet (as of April 2011) to occur. Nokia and Apple have both, however, announced availability of NFC in most of their smartphones in 2011. *Android*[3] support for NFC has existed since version 2.3, with the first Android phone supporting NFC (Google *Nexus S*) on market since March 2011. RIM has announced to add NFC support to its smartphones by the end of 2011. According to industry rumors (March 2011), also *Windows Phone 7*[4] will get NFC support by the end of 2011. Thus, after years of indecision, NFC is finally gaining momentum within the mobile phone industry.

Phones with NFC support are still not enough, however. NFC needs a full ecosystem with the full support of credit card and public transport companies to enable the use of mobile phones with NFC for mobile payment, for instance. Using NFC for pairing two Bluetooth devices has already been possible since April 2008 (Nokia 6212) but that has evidently not been a killer application for NFC.

5.5 UWB

There was widespread enthusiasm on implementing UWB as the radio interface for high-speed wireless networking solutions in 2003–2007. The developments of that time include effort to implement UWB as the high-data-rate interface for Bluetooth [55] and ZigBee [69], in Wireless USB [55], and as a wireless solution of its own, WiMedia, with standardization within IEEE 802.15.3a. All these projects have since died or withered

[3] www.android.com

[4] www.microsoft.com/windowsphone

away, due to technical difficulties [135, 66, 136] and standardization quarrels between proponents of different solutions. WiMedia Alliance has since ceased existence, and merged its activities and IP to Bluetooth SIG and organizations developing the Wireless USB technology [137]. Wireless USB, on the other hand, has not gained much popularity yet.

5.6 UWBLEE

There exist high-speed proprietary solutions that answer the requirements how Ubimedia, such as the Memory Spot since 2006, but failing to gain any business momentum. Also TransferJet has been introduced already in 2008, but that requires both communicating devices to be active. TranferJet has gained enough momentum to form a technology alliance, but commercial success has not yet happened.

The UWBLEE wireless connection technology presented in this paper provides data rates (112 Mbit/s) significantly exceeding the existing NFC technology already in the market. The technical difficulties with UWB relating to the rapid reduction of data rate with distance are not a problem for UWBLEE which is limited for very short range due to its transponder tehnology. From technology ecosystem point-of-view there is little sense in developing UWBLEE as an independent technology. UWBLEE can thus be seen as a possible future high-speed extension to existing RFID or NFC technologies. The long delay from agreement to market with Bluetooth Low Energy (see above), however, makes one think that this road might be too long.

The possibility of using a mobile phone to read a passive tag is, naturally, not the only operational combination of these devices, as shown in Figure 5.1. One should note, that as with other wireless interfaces provided by mobile phones (cellular, Wi-Fi, and Bluetooth), also UWBLEE could be used to provide a connection to the Internet (discussed in Publication X). Due to the its short range, the internet connection provided with UWBLEE would require the user to stay in the front of the kiosk, enabling e.g. funding the operation of the kiosk with ads.

In a multi-device environment one device can work as a proxy for the memory tag and provide other devices with access to its services (see Publication III). There are also possibilities to have active memory tags with their own power sources, which eliminate the need of wireless powering. In that case, the reading range can be extended or power use within the

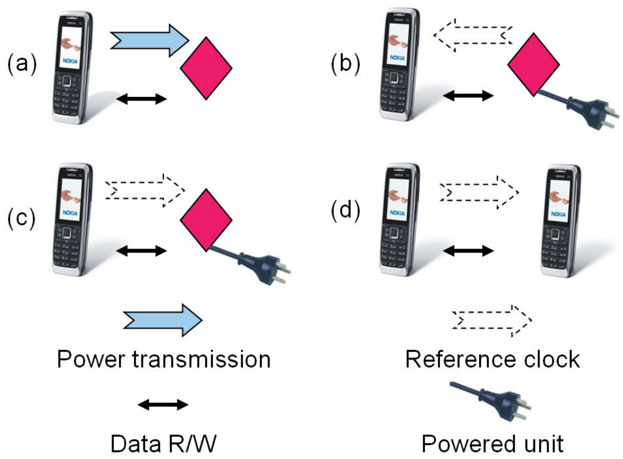


Figure 5.1. Some possible operational combinations of mobile phones interacting with RF memory tags. (a) a phone reading a RF memory tag, (b) Internet kiosk based on a RF memory tag, (c) a variant of (b), and (d) data transfer between mobile phones.

mobile phone can be reduced, without hindering the performance of the connection. The phone can also communicate directly with other similarly equipped phones.

The UWBLEE-based memory tag solution presented in this thesis supports Nokia's *Explore and Share* concept, a new way of transferring content (e.g. multimedia, maps, and applications) to a mobile phone [138, 128].

5.7 Network-on-terminal Architecture

In spite of support of both Nokia and Intel, the Network-on-terminal Architecture seems to have died quietly, with the last NoTA conference held in 2009 and the website lacking maintenance since Fall 2009. The technology has been made open-source, with spesifications publicly available. Little is known if the technology is actually used anywhere anymore.

5.8 Sensor API's on mobile phones

From separate demonstrations of reading sensors with smartphones, such as the WIRSU demo in 2002 [139], using sensors with smartphones has become a commodity, with all major smartphone platforms (Symbian since

2009, *iOS*[5], Android, and Windows Phone) providing a usable Sensor API in April 2011.

[5] www.apple.com/ios

6. Conclusions

Mobile phone has no real competitor as the central node of personal area networks due to its versatile capabilities. For some special applications, such as sports, wrist-top computers have their advantages, but the ubiquity of mobile phones along with their versatility as programmable user interfaces and internet connection makes them the first choice for many applications.

Not all use-cases can be answered to with a single wireless technology, however. For example, a wireless memory containing an advertisement on a newspaper should have no need to contain a battery, ruling out many available wireless network technologies, such as Bluetooth or Wi-Fi. There are also sensor use-cases which would benefit from being able to work without a battery. Thus, there is a need for new wireless interfaces on mobile phones.

MIMOSA architecture is a smart sensor architecture optimized for flexibility and low power use. The key entities included in the architecture are terminal devices which are mobile phones with add-on electronics to provide extra functionality, active wireless sensor nodes with their own power sources, passive RFID sensor tags which are powered by the reading signal, and back-end servers. Terminal device provides, along with the capability to run applications, connection to the Internet, and thus acts as a link between the sensors in the vicinity to back-end servers via cellular network and the Internet. The sensors can be either directly attached to the terminal device, or linked via an RFID or Bluetooth (BTLEE) connection. The proposed architecture offers an open architecture platform for implementing mobile-phone-centric ambient intelligence in various application areas.

Bluetooth Low End Extension (BTLEE) has, since our research, become a part of the Bluetooth standard (4.0) and chips are already available from several manufacturers. The long delay in making the standard has resulted in non-standard proprietary technologies, such as ANT, finding a way to mobile phones.

For RFID sensor tags, an international IEEE standard has been defined, paving way for wider use. Several standard wireless interfaces are available, such 13.56 MHz inductive or RF, 900 MHz RF, and 2.45 GHz RF. Our demonstration of a 2.45 GHz digital sensor tag is a part of this development. Also the UWBLEE technology presented in this thesis is usable for sensing. A studied use-case for this are sensor tags is a EEG sleep quality logger that stores the data to an integrated memory, and can be later read with UWBLEE.

It is also possible to easily add connectivity from the mobile phones to the common 5 kHz wireless devices used in, e.g., heart beat sensing. As the connection is analog, and on the audio frequency range, this only requires technically simple electronics, a connector to the phone's audio port, and simple audio processing software. The applications already used for 5 kHz wireless network show that the capacity could be extended to many types of low-data-rate sensing. It is not clear, however, if the solution is commercially competitive enough, considering the availability and versatility of Bluetooth and ANT.

Sensor layer research done within these projects has contributed to the development of sensor architectures implemented in mobile phone platforms. This has resulted in easy implementation of sensor-based software applications, using, e.g., the accelerometers within phone camera modules.

We have been developing a technical infrastructure for ubimedia, including high-speed low-power memory tags, and a mobile phone platform architecture that facilitates interacting with the tags. This technical infrastructure enables many different applications of ubimedia that utilize media embedded in everyday objects in our environment. Parallel to the technical development we have been studying usage possibilities of ubimedia and user acceptance of future ubimedia services. The dual-band radio interface, UWBLEE introduced in this paper provides the required data rate and possibility for future scalability as memory sizes become larger. Power consumption of the mobile reader/writer is efficiently minimized with an independent sub-system keeping the involvement of the main processor at the minimum. In contrast to conventional radio systems, the main processor only triggers the communication and the independent sub-system handles the transfer and storage of the data. Thus, the main processor does not have to be involved in the low level communication processes.

Near-field Communication (NFC) has been implemented on some commercial mobile phones, and other RFID technologies, such as UWBLEE may follow. The memory tag solution presented in this thesis supports Nokia's *Explore and Share* concept. The price of adding new technologies to mobile phones, however, requires clear and profitable use-cases for such technologies, and a suitable business ecosystem.

Overall, one should note that developing a new wireless technology in a laboratory set-up, be it BTLEE or UWBLEE, is relatively easy compared to making it a part of a new or existing industry standard. There are several reasons for this. 1) Technically, a laboratory set-up does not have to care about co-existence with other wireless connections on the same radio frequency band, and does not need to ensure multi-vendor interoperability. 2) Business-wise the several industry members of a standardization body have all different native use-cases and intellectual property (IPR) bases; adding an extension to an existing standard will naturally affect the relative weights of IPR portfolios of the different corporations. Also creation of an industry standard can, on the other hand, be way easier than creating a living business ecosystem around it — as is visible within the long history of NFC — due to the differing point-of-views and business foci of the different companies. As an example, consider the possible differences between a mobile phone manufacturer and a credit card company.

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Errata

In Chapter 2, on the pages 16, 21, and 26, it is mentioned that IEEE 802.15.6 Standard for Body Area Networks includes human body (in-body) communications on carrier frequencies 16 and 27 MHz. The information is from Kwak et al. "An overview of IEEE 802.15.6 standard" [76]. It seems, however, that this information is either out of date or inaccurate, as the standard itself, in its most current drafts [106], defines 21 and 32 MHz as the carrier frequencies for human body communications.

Aalto-DD 81/2012

Local connectivity, in form of classic Bluetooth or Wi-Fi, has been commonly available in mobile phones for more than a decade. The power and computation requirements of this connectivity, however, have been too cumbersome for small button-cell-powered or passive personal devices. In this thesis, a low-power extension of Bluetooth was implemented and tested, pawing way to integration of the technology to the Bluetooth Standard in 2010. A system architecture enabling mobile-phone-readable and writable mass memory tags is also presented.

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