MASTER’S THESIS

DESIGN AND IMPLEMENTATION OF A MULTI-PURPOSE WIRELESS BODY AREA NETWORK

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Second Examiner Matti Hämäläinen

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ABSTRACT

A wireless body area network (WBAN) is a collection of miniaturized and energy efficient wireless sensor nodes which monitor human body functions and its surroundings. It has been observed that WBANs perform single application per network, computation and storage capacities are scarce and there is no or limited mobility support. Technically complex WBAN application solutions today, find refuge in processing computationally complex data external to WBANs, i.e., processing sensor data on a conventional PC which is impractical and clumsy. There is a strong need for WBAN platforms which can perform computationally complex tasks on their own having enough resources in terms of computation and memory but still consuming as low power as possible in order to prolong network uptime.

In this thesis work, an improved WBAN named multipurpose-BodyNet (MP-BodyNet) is implemented. It has enough computational and memory resources and compact software solutions to achieve high performance and fidelity. MP-BodyNet is a self-configuring, multipurpose WBAN which can perform multiple applications and user can switch between applications by a mere push of button. It supports mobility and it acts like an agent network to other networks. MP-BodyNet forms a hierarchy where low-capability networks are supported by higher-capacity networks.

Hardware used for MP-BodyNet has been designed by WSN-Team at Centre for Wireless Communications, University of Oulu and this thesis proposes two application scenarios. Senior citizen protection mode (SPM) deals with a very hot health care issue for elderly people and patients. An algorithm is proposed and implemented that can detect falls or if the subject/patient has fainted. In SPM, MP-BodyNet can generate alarms in case of emergency and events can be seen on a central server as well as a special alarm is generated to the user’s phone (android app.) which can in turn establish an emergency call automatically. Algorithmic efficiency achieved is 100%.

Silent communication mode (SCM) deals with a military hand signal/gesture recognition application. A quite complex pattern recognition algorithm has been proposed with two novelties in it i.e., a sampling process is introduced in the algorithm and the whole algorithmic processing is supposed to be done on the sensor node itself, no processing is supposed to be happening external to the WBAN. Algorithm for SCM is only presented here conceptually after rigorous research about the subject at disposal. It is not implemented in this thesis due to lack of time and is saved for future development. After a gesture would be recognized, an audio message mapped to the gesture will be heard over a headphone.

Keywords: WBAN, WSN, fall-detection, gesture-recognition.
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PREFACE

This master's thesis is based on the research undertaken at the Centre for Wireless Communications (CWC), University of Oulu and it is partially done under Tekes funded WAS project. I would like to thank Professor Jari Iinatti for supervising this thesis, for his expert opinion, valuable instructions and advices. I would like to pay utmost gratitude to my 2nd examiner Matti Hämäläinen, who always just smiled away my problems and always kept me motivated for more and more hardwork. I would give great credit to Martti Huttunen especially, who taught me as one would teach to the kids and helped me a lot in this thesis and in establishing my career. His enthusiastic, expert attitude towards the research work was very educative and motivating. I would also like to thank my technical advisors Heikki Karvonen, and Juha Petäjäjärvi for their support, encouragement and guidance. Credit also goes to my fellow students at the university and colleagues at the CWC Alok Sethi, Helal Chouhdary, and Ijaz Ahmad who have made the working environment comfortable and encouraging.

My heartiest gratitude goes to my parents, Shams-Ul-Haq Virk and Begum Kishwar Sultana, as well as to my spiritual mentor and the greatest scientist of all times, Nicola Tesla because they have been a lifelong inspiration for me. I dedicate this humble work to my honourable grand parents Abd-Ul-Haq Virk, Mumtaz Begum and my beloved sister Maria Shams (may Lord rest their souls in peace).

Oulu, May 2013 Muhammad Hasnain Virk
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Ω</td>
<td>modulation index in case of FM-UWB</td>
</tr>
<tr>
<td>Φ</td>
<td>yaw, angular velocity</td>
</tr>
<tr>
<td>Π</td>
<td>vector of initial state probabilities for HMM</td>
</tr>
<tr>
<td>Ψ</td>
<td>pitch, angular velocity</td>
</tr>
<tr>
<td>Θ</td>
<td>roll, angular velocity</td>
</tr>
<tr>
<td>α</td>
<td>forward variable in case of HMM</td>
</tr>
<tr>
<td>β</td>
<td>backward variable in case of HMM</td>
</tr>
<tr>
<td>γ</td>
<td>probability of system being in a state of HMM</td>
</tr>
<tr>
<td>λ</td>
<td>hidden Markov model</td>
</tr>
<tr>
<td>A</td>
<td>state transition probability matrix for HMM</td>
</tr>
<tr>
<td>A&lt;sub&gt;x&lt;/sub&gt;</td>
<td>static acceleration under &lt;em&gt;g&lt;/em&gt; along x-axis</td>
</tr>
<tr>
<td>A&lt;sub&gt;y&lt;/sub&gt;</td>
<td>static acceleration under &lt;em&gt;g&lt;/em&gt; along y-axis</td>
</tr>
<tr>
<td>A&lt;sub&gt;z&lt;/sub&gt;</td>
<td>static acceleration under &lt;em&gt;g&lt;/em&gt; along z-axis</td>
</tr>
<tr>
<td>B</td>
<td>emission probability matrix for HMM</td>
</tr>
<tr>
<td>d</td>
<td>euclidean distance</td>
</tr>
<tr>
<td>g</td>
<td>acceleration under gravity, 9.8 meter per second squared</td>
</tr>
<tr>
<td>N</td>
<td>code book size</td>
</tr>
<tr>
<td>O</td>
<td>observation vector</td>
</tr>
<tr>
<td>Q</td>
<td>vector quantizer</td>
</tr>
<tr>
<td>Q&lt;sub&gt;(x)&lt;/sub&gt;</td>
<td>quantized input vector</td>
</tr>
<tr>
<td>R&lt;sub&gt;i&lt;/sub&gt;</td>
<td>centroids</td>
</tr>
<tr>
<td>S</td>
<td>set of hidden states of HMM</td>
</tr>
<tr>
<td>V</td>
<td>alphabet of observation symbols</td>
</tr>
<tr>
<td>x&lt;sub&gt;i&lt;/sub&gt;</td>
<td>input vector</td>
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<td>Y</td>
<td>code book</td>
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<tr>
<td>y&lt;sub&gt;i&lt;/sub&gt;</td>
<td>prototype vector</td>
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<td>IPv6 based low power PAN</td>
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<td>8DPSK</td>
<td>8 phase differential phase shift keying</td>
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<td>A/D</td>
<td>analog to digital</td>
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<td>ACF</td>
<td>authentication and capability format</td>
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<td>ACF</td>
<td>network management format</td>
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<tr>
<td>AP</td>
<td>access point</td>
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<tr>
<td>BCI</td>
<td>brain computer interface</td>
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<td>BLE</td>
<td>Bluetooth low energy</td>
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<tr>
<td>BS</td>
<td>base station</td>
</tr>
<tr>
<td>C-app</td>
<td>Android based user application</td>
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<tr>
<td>CA</td>
<td>concentrator advertisement</td>
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<tr>
<td>CCA</td>
<td>clear channel assessment</td>
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<tr>
<td>CFP</td>
<td>contention free period</td>
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<tr>
<td>CFS</td>
<td>coffee file system</td>
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<tr>
<td>CMOS</td>
<td>complementary metal oxide semiconductor</td>
</tr>
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<td>CN</td>
<td>concentrator node</td>
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<tr>
<td>CPU</td>
<td>central processing unit</td>
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<tr>
<td>CRE</td>
<td>close range encounter</td>
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<tr>
<td>CSMA-CA</td>
<td>carrier sense multiple access with collision avoidance</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>CSV</td>
<td>comma separated value</td>
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<tr>
<td>DEF</td>
<td>directional equivalency filter</td>
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<tr>
<td>DMA</td>
<td>dynamic memory allocation</td>
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<tr>
<td>DMIPS</td>
<td>dhrystone million instructions per second</td>
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<tr>
<td>DQPSK</td>
<td>differential quadrature phase shift keying</td>
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<tr>
<td>DSSS</td>
<td>direct sequence spread spectrum</td>
</tr>
<tr>
<td>E-Care</td>
<td>electronic care</td>
</tr>
<tr>
<td>ECoG</td>
<td>electrocorticography</td>
</tr>
<tr>
<td>ED</td>
<td>energy detection</td>
</tr>
<tr>
<td>EEG</td>
<td>electro-encephalography</td>
</tr>
<tr>
<td>EXTI</td>
<td>external interrupt/event controller</td>
</tr>
<tr>
<td>FCS</td>
<td>frame check sequence</td>
</tr>
<tr>
<td>FFD</td>
<td>full function device</td>
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<tr>
<td>FHSS</td>
<td>frequency hopping spread spectrum</td>
</tr>
<tr>
<td>FIFO</td>
<td>first in first out</td>
</tr>
<tr>
<td>FM-UWB</td>
<td>frequency modulation UWB</td>
</tr>
<tr>
<td>FSK</td>
<td>frequency shift keying</td>
</tr>
<tr>
<td>FSMC</td>
<td>flexible static memory controller</td>
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<td>GFSK</td>
<td>Gaussian frequency shift keying</td>
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<tr>
<td>GMSK</td>
<td>Gaussian minimum phase shift keying</td>
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<tr>
<td>GN</td>
<td>gateway node</td>
</tr>
<tr>
<td>GPIO</td>
<td>general purpose input/output</td>
</tr>
<tr>
<td>GTS</td>
<td>guaranteed time slot</td>
</tr>
<tr>
<td>GWG</td>
<td>generic WSN gateway</td>
</tr>
<tr>
<td>HBC</td>
<td>human body communication</td>
</tr>
<tr>
<td>HMM</td>
<td>hidden Markov model</td>
</tr>
<tr>
<td>I/O</td>
<td>input/output</td>
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<tr>
<td>I2C</td>
<td>inter-IC bus</td>
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<tr>
<td>I2S</td>
<td>integrated inter-chip sound</td>
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<tr>
<td>IEEE</td>
<td>The Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IoT</td>
<td>internet of things</td>
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<tr>
<td>IP</td>
<td>internet protocol</td>
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<tr>
<td>IR-UWB</td>
<td>impulse radio UWB</td>
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<tr>
<td>IRQ</td>
<td>interrupt request</td>
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<tr>
<td>ISM</td>
<td>industrial, scientific and medical band</td>
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<tr>
<td>IT</td>
<td>information technology</td>
</tr>
<tr>
<td>LNA</td>
<td>low noise amplifier</td>
</tr>
<tr>
<td>LQI</td>
<td>link quality indication</td>
</tr>
<tr>
<td>LSB</td>
<td>least significant byte</td>
</tr>
<tr>
<td>MAC</td>
<td>medium access control</td>
</tr>
<tr>
<td>MCU</td>
<td>micro-controller unit</td>
</tr>
<tr>
<td>MEDF</td>
<td>meta-data format</td>
</tr>
<tr>
<td>MICS</td>
<td>medical implant communications service</td>
</tr>
<tr>
<td>NASC</td>
<td>node actuator and sensor control</td>
</tr>
<tr>
<td>NB</td>
<td>narrowband</td>
</tr>
<tr>
<td>NDP</td>
<td>neighbor discovery protocol</td>
</tr>
<tr>
<td>NVIC</td>
<td>nested vectored interrupt handler</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>O-QPSK</td>
<td>offset-quadrature phase shift keying</td>
</tr>
<tr>
<td>OOK</td>
<td>on-off keying</td>
</tr>
<tr>
<td>OS</td>
<td>operating system</td>
</tr>
<tr>
<td>PDA</td>
<td>personal digital assistant</td>
</tr>
<tr>
<td>PHY</td>
<td>physical layer</td>
</tr>
<tr>
<td>PLCP</td>
<td>physical layer convergence procedure</td>
</tr>
<tr>
<td>PPDU</td>
<td>physical layer protocol data unit</td>
</tr>
<tr>
<td>PPP</td>
<td>point-to-point protocol</td>
</tr>
<tr>
<td>PS</td>
<td>Personal server</td>
</tr>
<tr>
<td>PSDU</td>
<td>PHY service data unit</td>
</tr>
<tr>
<td>PSK</td>
<td>phase shift keying</td>
</tr>
<tr>
<td>RA</td>
<td>router advertisement</td>
</tr>
<tr>
<td>Radvd</td>
<td>router advertisement daemon</td>
</tr>
<tr>
<td>RDC</td>
<td>radio duty cycling</td>
</tr>
<tr>
<td>RFDF</td>
<td>reduced function device</td>
</tr>
<tr>
<td>RFID</td>
<td>radio frequency identification</td>
</tr>
<tr>
<td>RISC</td>
<td>reduced instruction set computing</td>
</tr>
<tr>
<td>RPL</td>
<td>routing protocol for low power and lossy networks</td>
</tr>
<tr>
<td>RS</td>
<td>router solicitation</td>
</tr>
<tr>
<td>RSSI</td>
<td>receive signal strength indicator</td>
</tr>
<tr>
<td>RTC</td>
<td>real time clock</td>
</tr>
<tr>
<td>RTOS</td>
<td>real time operating system</td>
</tr>
<tr>
<td>SADF</td>
<td>sensor archive data format</td>
</tr>
<tr>
<td>SAR</td>
<td>specific absorption rate</td>
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<tr>
<td>SBC</td>
<td>single board computer</td>
</tr>
<tr>
<td>SCM</td>
<td>silent communication mode</td>
</tr>
<tr>
<td>SDIO</td>
<td>secure digital input/output</td>
</tr>
<tr>
<td>SIDF</td>
<td>sensor information data format</td>
</tr>
<tr>
<td>SMS</td>
<td>short message service</td>
</tr>
<tr>
<td>SN</td>
<td>sensor Node</td>
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<td>SPI</td>
<td>serial peripheral bus</td>
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<td>SPM</td>
<td>senior citizen protection mode</td>
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<tr>
<td>SRAM</td>
<td>static random access memory</td>
</tr>
<tr>
<td>TCP</td>
<td>transmission control protocol</td>
</tr>
<tr>
<td>TDMA</td>
<td>time division multiple access</td>
</tr>
<tr>
<td>UDP</td>
<td>user datagram protocol</td>
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<tr>
<td>uIP</td>
<td>micro IP</td>
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<td>UMTS</td>
<td>universal mobile telecommunication</td>
</tr>
<tr>
<td>USART</td>
<td>universal synchronous/asynchronous receiver/transmitter</td>
</tr>
<tr>
<td>USB-OTG FS/HS</td>
<td>universal serial bus-on-the-go fast speed/high speed</td>
</tr>
<tr>
<td>UWB</td>
<td>ultra wideband</td>
</tr>
<tr>
<td>VLC</td>
<td>visible light communication</td>
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<tr>
<td>WBAN</td>
<td>wireless body area network</td>
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<tr>
<td>WiMAX</td>
<td>worldwide interoperability for microwave access</td>
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<td>WLAN</td>
<td>wireless local area network</td>
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<td>WMTS</td>
<td>wireless medical telemetry services</td>
</tr>
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<td>WPAN</td>
<td>wireless personal area network</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>WSN</td>
<td>wireless sensor network</td>
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<tr>
<td>XML</td>
<td>extensible markup language</td>
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1. INTRODUCTION

Wearable health monitoring systems or wearable human body monitoring coupled with wireless communications are the bedrock of an emerging class of sensor networks known as wireless body area networks (WBANs). Such networks have myriad applications, including diet monitoring, detection of activity or posture or gesture, and health crisis support etc. Recently, there has been increasing interest from researchers, system designers, and application developers on a new type of network architecture generally known as body sensor networks or WBANs, made feasible by novel advances on lightweight, small-size, ultra-low-power, and intelligent monitoring wearable sensors. In WBANs, sensors continuously monitor human’s physiological activities and actions, such as health status and motion pattern. [1–3]

A WBAN is a collection of low-power, miniaturized, invasive/non-invasive lightweight wireless sensor nodes that monitor the human body functions and the surrounding environment. In addition, it supports a number of innovative and interesting applications such as ubiquitous health-care, entertainment, interactive gaming, and military applications. Present day WBANs perform single application per network, computation and storage capacities are scarce and there is no mobility support. Technically complex WBAN application solutions today find refuge in processing computationally complex data external to WBANs, i.e., processing sensor data on a conventional PC which is impractical and clumsy. There is a strong need for WBAN platforms which can perform computationally complex tasks on their own having enough resources in terms of computation and memory but still consuming as low power as possible in order to prolong network uptime.

In this thesis work, an improved WBAN named MP-BodyNet is designed and implemented with enough computational and memory resources and compact software solutions to achieve high performance and fidelity. MP-BodyNet is a self-configuring, multi-purpose WBAN which can perform multiple applications and user can switch between applications by a mere push of button. It supports mobility and it acts like an agent network to other networks. MP-BodyNet forms a hierarchy where low-capability networks are supported by higher-capacity networks.

This master’s thesis is structured as follows. Chapter 2 gives a basic description of WBANs and different tiers of WBANs are discussed along with applications relating to WBANs are identified. In Chapter 3, various wireless communication techniques used in wireless sensor networks were identified and the standards pertaining to those communication techniques were reviewed. Chapter 4 provides an introduction to the MP-BodyNet, the WBAN proposed in this thesis. Chapter 5 discusses in detail all components of MP-BodyNet, its complete architectural design, and the algorithms developed for different modes of MP-BodyNet are evaluated. Overall performance of the MP-BodyNet is also evaluated. Chapter 6 sheds light on discussion and Chapter 7 provides summary of the thesis.
2. WIRELESS BODY AREA NETWORKS

This chapter is an introduction to wireless body area networks (WBAN). An overview is given in Section 2.1. Section 2.2 presents generalized system architecture for WBANs. Section 2.3 gives a bird-eye view of the WBAN communication standards and frequency bands. Section 2.4 focuses on the radio transceivers that can be used in WBANs whereas Section 2.5 finally discusses various interesting applications of WBANs.

2.1. Overview

A WBAN is a collection of miniaturized, multi-functional, and energy efficient wireless sensor nodes which monitor human body functions and its surroundings [2]. Figure 1 depicts a WBAN with a few wireless sensor nodes which are monitoring different parameters relating to human body and are reporting to a central node called as a coordinator node or a sink node. Coordinator node itself can be a sensor node or it can simply be an aggregating and relaying device. Coordinator node in turn transmits monitored data for further processing to the backbone network through wireless access point (AP). In some applications coordinator node serves as an AP as well. [4]

Wireless sensor nodes can be either wearable or implanted into a human body. Nodes communicate with each other using certain short range wireless technology, e.g., Bluetooth, ZigBee, or ultra wide band (UWB) [4]. A WBAN sensor node consists of fundamentally six components, namely:

- Sensing unit,
- Processing unit,
- Analog-to-digital converter (A/D converter),
- Power unit,
- Communication unit (radio transceiver),
- Memory or storage unit.

Sometimes a WBAN sensor node is also equipped with an actuator. Actuator is a device to convert an electrical signal to some action such as a physical phenomenon, e.g., servo motors, insulin pumps, etc. Fundamental task of a sensor node in a WBAN is to sense (monitor) one or more physical, physiological, chemical or biological signal/signals from human body or its surroundings. After sensing, they are responsible for processing the sensed data (signals), i.e., filtration, amplification, digitization, feature extraction etc. This processed data is then stored momentarily and forwarded to the gateway (sink node or coordinator node) through the wireless link. [2, 4, 5]

The gateway or sink is usually a more powerful device with better computational capabilities and is responsible to collect and process the data generated by the WBAN sensor nodes. Depending on the application, the sink may provide direct feedbacks (visual or vocal) to user based on data collected from sensors, or it may forward data through a wireless backbone network, e.g., wireless local area network (WLAN), global system for mobile communication (GSM), general packet radio service (GPRS), universal mobile telecommunication systems (UMTS), worldwide interoperability for microwave access (Wi-MAX), etc. [5], to a remote server where the data can be
processed further and displayed in real-time for user’s inspection and/or stored in a
database for post-analysis.

Figure 1. Illustration of a WBAN.

2.2. Generalized system architecture

Unlike typical wireless sensor networks (WSNs), WBANs are not node-dense. In other
words, there are no redundant nodes to ensure safe operation in case of failures. Sen-
sor/actuator nodes are placed at certain locations on the human body strategically [1].
Nodes are meant to register human physiological activities in a periodic manner and
hence the data stream exhibits relatively stable rates. Such properties make WBAN
system architecture a bit different from other sensor networks. Communication archi-
tecture of a WBAN can be based on either peer-to-peer communication or infrastructure
based communication [1], [6]. Peer-to-peer communication is used in ad hoc networks
whereas infrastructure based networks contain an AP or base station (BS) which forward
the traffic to the intended recipient. In infrastructure based networks all communication
must go through the AP/BS even though the sender and receiver are in radio range
of each other, i.e., the AP/BS is in charge of the network. In Figure 2 (a) an ad-hoc
network is shown where all nodes can send data traffic to all other nodes within radio
range and in Figure 2 (b) the infrastructure mode is depicted [7]. Today, for example
all mobile telephone systems work in infrastructure mode and the same goes for the
WLAN standard IEEE 802.11. However, the latter has support for ad hoc mode as well,
which could be used for example during a meeting when meeting participants want to
exchange documents [6]. Generalized system architecture of a WBAN can be divided
in three fundamental levels or tiers of communication as described in [1, 2, 5]:

i) Tier-1 communication (intra-WBAN)
ii) Tier-2 communication (inter-WBAN)
iii) Tier-3 communication (beyond WBAN).
2.2.1. Tier-1 communication - Intra-WBAN

Tier-1 communication or intra-WBAN communication refers to the radio communication range of about 2 meters around the human body [1]. Intra-WBAN communication can be sub-categorized as follows:

(a) Communication among body sensors
(b) Communication between body sensors and a personal server (PS)

A PS is any machine that can collect data from sensors and do processing on it to generate some meaningful result, e.g., a cell phone or a personal digital assistant (PDA) or a palm top. PS is quite different than a coordinator node or a gateway node because PS is a more complicated multipurpose machine, that is needed to be equipped with some peripheral radio or cable to communicate with the body sensors. PS should also have sensor data manipulating or processing software to generate outputs. Gateway or coordinator nodes are just like sensor nodes, in architecture, from which they collect data. Their task is to forward the data to AP and then AP will route the data on internet to the remote server/database. Design of intra-WBAN tier is far more complicated and challenging than other ones. In existing schemes like MIThrill [8] and SMART [9], the challenges of wirelessly interconnecting sensors and a PS are avoided by utilizing cables to directly connect multiple commercially available sensors with a PS. Alternatively, CodeBlue [7] stipulates that sensors directly communicate with APs without a PS. However, the typical intra-WBAN designs suggests multiple sensors forwarding body signals to a PS that in turn forwards the processed physiological data to an access point, e.g., in WiMoCa [10]. Well known communication techniques for intra-WBAN communication are ZigBee, Bluetooth and UWB.
2.2.2. Tier-2 communication - Inter-WBAN

Inter-WBAN involves communication of PS with the AP, if the network is infrastructure based. In the ad hoc based architecture, multiple APs are deployed to help body sensors to transmit information. Thus, the service coverage is larger than in the infrastructure-based architecture, facilitating users to move around in a building, playground, or in an emergency rescue spot. While the coverage of a WBAN is limited to about two meters, this way of interconnection extends the system to approximately one-hundred meters, which suits both in a short-term setup, and in a long-term setup, e.g., at home. Two categories of nodes exist in this architecture setup, i.e., sensor/actuator nodes in or around a human body, and router nodes around a WBAN, both of which have the same radio hardware to facilitate multi-hop routing. This architecture setup is similar to that of a traditional WSN, and both of them often employ a gateway or a coordinator node to interface with the outside world. In WSNs, however, every node functions as a sensor node and a router node. Tier-2 communication techniques can be WLAN, ZigBee, UWB, GSM or UMTS. [1, 5, 6]

2.2.3. Tier-3 communication - Beyond-WBAN

Tier-3 involves communication between a WBAN and an outside network, e.g., internet or some E-care (electronic care) center. PS and gateway can directly communicate to the outside network and it can also have some base stations involved in between as well. Figure 3 represents a pictorial representation of the tiers of communication for WBANs. A database is an important component of the beyond-WBAN tier. This database maintains, e.g., the user’s profile and medical history. According to user’s service priority and/or doctor’s availability, the doctor may access the user’s information as needed. At the same time, automated notifications can be issued to his/her relatives based on this data via various means of telecommunications. The design of beyond-WBAN communication is application-specific, and should adapt to the requirements of user-specific services. For example, if any abnormalities are found based on the up-to-date body signal transmitted to the database, an alarm can notify patient or doctor through email or short message service (SMS). If necessary, doctors or other care-givers can communicate with patients directly by video conference via the Internet. In fact, it might be possible for the doctor to remotely diagnose a problem by relying on both video communications with the patient and the patient’s physiological data information stored in the database or retrieved by a WBAN worn by the patient. Literature, e.g., [1,2] and [4–6] discuss the above mentioned statements.

2.3. Summary of standards and frequency bands used for WBAN

WBANs are made up of low power, inexpensive and less sophisticated sensor devices, and the design goal is to consume minimum amount of power along with sufficient computational capabilities. This makes WBAN design a real challenge. A WBAN design engineer has to plan intelligently what communication techniques or standards to follow, how much computational capability is needed in devices, how much power is
needed and how to prevent exhaustion of resources (both energy and computational). [1, 4]

Figure 3. A pictorial representation of 3-tier communication in a WBAN.

The Institute of Electrical and Electronics Engineers (IEEE) is a non-profit professional institution dedicated to advancing technological innovation and excellence. IEEE is one of the leading standards-making organizations in the world. IEEE performs its standards making and maintaining functions through the IEEE standards association (IEEE-SA). IEEE standards affect a wide range of industries including power and energy, biomedical and healthcare, information technology (IT), telecommunications, transportation, nano-technology, information assurance, and many more. IEEE has many work groups committed to various scientific research areas. [11]

IEEE 802.15 is the wireless personal area networks (WPAN) workgroup. WPAN constitute a network class which typically refers to communication of devices located in proximity of an individual. Hence, the typical range of such networks is a few or tens of meters. [12]

WBANs fall in the category of WPANs. IEEE has broken down the WPAN working group into 7 task groups, each focused on a different aspect of WPANs. These task groups have issued various standards and exhaustive details about these standards are described in [12]. A brief summary discerned from [12] is as follows:
• Task Group 1 - WPAN / Bluetooth: A WPAN standard initially based on the Bluetooth v1.1 specifications, later updated to include changes from Bluetooth v1.2, and published as IEEE 802.15.1-2005. The most recent version of Bluetooth is v4.0 which was specified in 2010.

• Task Group 2 - Coexistence: A standard that addresses the issue of coexistence of WPANs with other wireless networks and devices operating in unlicensed frequency bands. TG-2 (Task group 2) gave its specifications for IEEE 802.15.2 in 2003 and now this task group is in hibernation until further notice.

• Task Group 3 - High Rate WPAN: A standard for high data rate WPANs. This includes different physical layer definitions. In the original specifications 2.4 GHz physical layer (PHY) was proposed. Then an amendment proposal was considered and it was called as 802.15.3a in which UWB was the candidate PHY to achieve target data rate of 110 Mb. However this proposal was withdrawn later.

• Task Group 4 - Low Rate WPAN: A standard that focuses on low data rate and long battery life known as IEEE 802.15.4.

• Task Group 5 - Mesh Networking: A standard that defines a recommended practice for mash topologies of WPANs.

• Task Group 6 - BAN: This group focuses on technologies for body area networks (BANs). Its goal is the definition of an ultra-low power and short range wireless communication standard.

• Task Group 7 - VLC: This group’s goal is the definition of a standard for visible Light communications (VLC).

Recently IEEE-SA has published a standard for WBANs which is termed as IEEE 802.15.6 [2]. The standard defines three physical layers (PHY) and a sophisticated medium access control (MAC) protocol. More details about it are given in Chapter 3. The available frequencies for WBANs are regulated by local communication authorities in different countries. Figure 4, which is a discerned version from [13] and [3] show a short summary of some of the frequency bands available for WBAN in different countries. Medical implant communications service (MICS) band is a licensed band used for implant communication and has the same frequency range (402-405 MHz) in most of the countries. Wireless medical telemetry services (WMTS) is a licensed band used for medical telemetry system. Neither MICS nor WMTS bandwidths support high data rate applications. The industrial, scientific and medical (ISM) band supports high data rate applications and is available worldwide. However, there are considerable sources of interference as many wireless devices including the ones based on IEEE 802.15.1, IEEE 802.15.4 and IEEE 802.11 (WLAN) operate at ISM band. The UWB is a narrow pulse transmission system whose spectrum is spread across a wide range of frequencies. The UWB is a different solution compared to the carrier based communication. The lack of carrier also implies that the frequency band is not divided into a number of channels. Instead, a number of pseudo-random sequences in the time domain replace what is normally referred as a channel. UWB has really low emission power density and hence it guarantees more battery life plus much larger bandwidth. In case of high rate UWB, this larger bandwidth gives an opportunity to use even multimedia applications. [2,6,14]

Although a standard exclusively for WBAN has emerged, design and development phases for WBAN application architectures are not rigid. Still a lot of work is needed to be done for proper implementation of IEEE 802.15.6. In the past, WBAN application
architectures have been finding roots from LR-WPAN (low-rate WPAN) or IEEE 802.15.4 and from IEEE 802.15.1 (Bluetooth). Bluetooth consumes a lot of power and therefore it is replaced by the IEEE 802.15.4. However, recently Bluetooth has evolved as a technology with significantly lower power consumption, e.g., Bluetooth low energy (BLE) [15]. In near future, most probably IEEE 802.15.6 will be implemented for WBAN applications especially in healthcare and tactical military domains.

The discussion above summarizes that the 802.15.6 standard will determine the dedicated signal structures for future use in WBANs. The existing standards for WBANs are 802.15.4 and its extension 802.15.4a where physical layer is UWB. In 2011, IEEE merged original 802.15.4 and various other related amendments into a single standard termed as IEEE 802.15.4-2011 [16].

Figure 4. Frequency bands for WBAN.

2.4. State-of-the-art transceiver

The choice of off-the-shelf transceiver or designing a custom transceiver for WBANs is a pivotal network design task. What kind of radio system is to select or design depends on what kind of radio enabling technology one is going to use. In the recent past, an off-the-shelf transceiver for IEEE 802.15.4 radio has been used quite a lot for sensor network applications, including WBANs [17]. It is known as CC2420, made by Texas Instruments powered by ChipCon’s SmartRF technology [18]. A lot of research has been done in this respect and various solutions for different air interfaces have emerged. State-of-the-art is pacing quite quickly and a lot of innovations are being added to the IEEE 802.15.4 and 802.15.6 standards [13].

Numerous commercial solutions for IEEE 802.15.4 receiver architecture are available e.g., Atmel AT86RF231 [19], Freescale MC13191 [20], Panasonic PAN4561 [21] etc. For characteristic IEEE 802.15.4 radio, both academia and industry have done exhaustive research and still this area is hot and buzzing. Such receiver architectures are discussed in literature, e.g., [14] and [22–27]. Later in 2007, an amendment was done for the IEEE 802.15.4 standard [28] and it was then called as IEEE 802.15.4a, which proposed UWB as an air interface technology (physical layer) and it proposed higher data rate, more mobility and precision ranging. Different types of UWB based receivers for IEEE 802.15.4a are compared in [29] and [30].

Generally, a state-of-the-art receiver for WBAN applications should be robust and reliable but consume ultra-low power, hence having long battery life. It should be
competent against interference; this becomes significant property when it comes to already crowded ISM band. Most of the literature suggests direct-conversion receiver architecture with frequency shift keying (FSK) or on-off keying (OOK) modulation schemes and to use a medium access scheme based on a duty cycled wake-up radio capable of detecting node addresses. Such a transceiver which gives an overall power budget of only 1 mW is proposed in [14]. It is realized in a nanometer complementary metal oxide semiconductor (CMOS) as a single chip, thereby reducing the size and cost. Figure 5 depicts a block diagram of a WBAN application which has a ZL70102 radio system built by ZARLINK Semiconductor™ [31]. This transceiver has a built-in wake-up radio which operates at ISM band (2.45 GHz) thus allows to transmit the wake-up at higher power and the main radio operates at MICS band (400 MHz). It is quite self-contained, complete radio system with very few external components required and consumes extremely low power.

![Figure 5. A simple WBAN using ZL70102 transceiver system.](image)

In WBAN applications, low data rate and low transmit power are required because nodes are located on the body and are quite close to each other as compared to other WPANs. However, still significant signal attenuation can take place because different parts of human body have different dielectric constants and absorption of signal happens differently. It even varies from human to human. [32]

### 2.5. Applications

WBAN is an emerging enabling technology with a broad range of potential applications and use cases in diverse application domains including medical, fitness and wellness management, military, safety and security, sports, social networking and entertainment. These application domains are described in [33] and are presented here as follows:

- In medical domain, a WBAN of medical sensors can be used in different scenarios, for example, sleep staging, computer-assisted physical rehabilitation, monitoring patients at home, at hospital, or anywhere.
• In fitness and wellness management, a WBAN of physical and physiological sensors can be used by health enthusiasts who wish to track their fitness and improve their well-being.

• In military domain, WBAN has a wide spectrum of possible applications. For instance, WBAN of sensors and actuators worn on the body of soldiers can help commanders not just to acquire real-time information about the location and physiological status of their soldiers while in battle fields or during extensive trainings, but also to send instructions/commandos to the soldiers in real-time.

• In safety and security domain, a WBAN of wearable biosensors can be used, for instance, for monitoring firefighters or hazardous material workers (using hazmat sensors), or for detecting chemical and biological attacks, or for automatic identification and authorization, e.g., using RFID (radio frequency identification) tags [34], etc.

• In sports domain, WBAN of physical and physiological sensors worn on the body of athletes can be used, for instance, by coaches/trainers to remotely monitor the physical activities and physiological status of the athletes during trainings/exercises or during real matches.

• In social networking and entertainment domain, WBAN can be used for exchanging digital profile or business cards, match making (hobby, interest, game, and community member), creating groups with same preferences and emotions etc.

IEEE 802.15 TG-6 [35] has proposed many designed cases and application possibilities of WBANs. Mainly those applications are divided in two types.

i) Class B: Non-Medical Applications

ii) Class A: Medical Applications

Table 1 and Table 2 list IEEE proposed WBAN application possibilities as presented in [35] and [36].

Table 1. List of IEEE proposed Class B WBAN applications

<table>
<thead>
<tr>
<th>Class B: Non-Medical Applications</th>
<th>B1 Stream transfer</th>
<th>B2 Entertainment applications</th>
<th>B3 Emergency (non-medical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body motion capture/gesture recognition, position</td>
<td>Gaming applications using BAN</td>
<td>Emergency (non-medical)</td>
<td></td>
</tr>
<tr>
<td>Forgotten things monitor</td>
<td>Social Networking using BAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart Key</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Identification</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vital sign and body information based entertainment service</td>
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<td></td>
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</tr>
</tbody>
</table>

Further details about the use-cases and applications listed in Table 1 and Table 2 can be found from [35] whereas examples of non-medical applications are given in [36].
<table>
<thead>
<tr>
<th>Class A: Medical Applications</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>A 1-1 Wearable WBAN (WMTS)</strong></td>
<td><strong>Electroencephalogram (EEG)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Electromyography (EMG)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Forgotten things monitor</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Vital signals monitoring, e.g., emotions</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Temperature (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Respiration monitor (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Heart rate monitor (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Pulse oximeter SpO2 (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Blood pressure monitor (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>pH monitor (wearable)</strong></td>
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<td></td>
<td></td>
<td><strong>Glucose sensor (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Hearing aid (ear to ear communication)</strong></td>
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<tr>
<td></td>
<td><strong>A1-1a Disability assistance</strong></td>
<td><strong>Muscle tension monitor</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Muscle tension stimulation</strong></td>
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<td></td>
<td></td>
<td><strong>Weighing scale (wearable)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Fall detection (wearable)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>A1-1b Human performance management</strong></td>
<td><strong>Aiding professional and amateur sport training</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Assessing soldier fatigue and battle readiness</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Non-human (Animal)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Assessing emergency service personnel performance</strong></td>
</tr>
<tr>
<td></td>
<td><strong>A1-2a Implant BAN (MICS)</strong></td>
<td><strong>Glucose sensor (implant)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Cardiac arrhythmia monitor/recorder (implant)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Brain liquid pressure sensor (implant)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Endoscope capsule (gastrointestinal)</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Drug delivery capsule</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Deep brain stimulator</strong></td>
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<tr>
<td></td>
<td></td>
<td>(e.g. epilepsy, Parkinson’s therapy)</td>
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<tr>
<td></td>
<td></td>
<td><strong>Cortical stimulator</strong></td>
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<td></td>
<td></td>
<td><strong>Visual neuro-stimulator</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Audio neuro-stimulator</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Brain-computer interface</strong></td>
</tr>
<tr>
<td></td>
<td><strong>A1-2b Remote control of medical devices</strong></td>
<td><strong>Pacemaker</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Implantable cardioverter defibrillator (ICD)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Implanted actuator</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Insulin pump</strong></td>
</tr>
<tr>
<td></td>
<td><strong>A2-1 In hospital</strong></td>
<td><strong>General</strong></td>
</tr>
<tr>
<td></td>
<td><strong>A2-2 Outside hospital</strong></td>
<td><strong>General</strong></td>
</tr>
</tbody>
</table>
3. COMMUNICATION TECHNIQUES

In this chapter, a technical overview of three different short-range wireless communication technologies for intra-WBAN communications is provided.

i) IEEE 802.15.1 - Bluetooth [37],
ii) IEEE 802.15.4 - 2011 [38],
iii) IEEE 802.15.6 - 2012 [39].

IEEE 802.15.6-2012 is the suggested standard for WBANs from now on, but yet the market for 802.15.6 based devices is premature and under-development.

3.1. IEEE 802.15.1 - Bluetooth

Bluetooth is a short-range wireless communication technology originally developed by Ericsson and its partners in the Bluetooth SIG (Special Interest Group) [40] in 1998, which later has been standardized by the IEEE 802.15 WPAN Task Group 1(TG1) [35], and given a standard name, IEEE 802.15.1. Bluetooth was initially intended as a cable replacement, but later has been extended to be used in different networking scenarios and applications. Over the years, many Bluetooth variants appeared in the market.

Bluetooth v4.0 specifications include classic Bluetooth, high speed Bluetooth, and Bluetooth low energy (BLE) protocols. Out of these three, BLE is of utmost significance for low powered systems like WBANs. BLE is a very low power, relatively short range (less than 50 m) technology that promises sensors to be able to communicate using a coin cell battery even up to two years [41]. A comparative study regarding power consumption in BLE and IEEE 802.15.4 (ZigBee) is done in [42]. The results of this study show that the power consumption in BLE is even less than in ZigBee. However in [42], they used single chip mode Texas Instruments implementation of BLE (TI stack) that does not implement adaptive frequency hopping technique, as a consequence, ZigBee outperformed BLE in better resistance against interference. It should be noted that the original specification suggests adaptive frequency hopping [40].

In general, a Bluetooth device communicates non-line-of-sight with peer devices using Bluetooth protocol. The radio operates in unlicensed 2.4 GHz ISM frequency band and supports up to seven simultaneous physical connections with peer devices at a peak data rate of 720 kbps (or up to 3 Mbps with Bluetooth version 2.1). For radio signal modulation, it uses either Gaussian frequency shift keying (GFSK) or phase shift keying (PSK), depending on the data rate mode. In the basic data rate mode, it uses GFSK, and PSK while being in enhanced data rate (EDR) mode. Two variations of PSK are used in EDR, one is called 8DPSK (8 phase differential phase shift keying) which allows data rate up to 3 Mbps, and the other is $\pi/4$ DQPSK (differential quadrature phase shift keying) which supports up to 2 Mbps [43]. Bluetooth version 3.0 provides data rates up to 24 Mbps but not over the Bluetooth link itself. It uses a WLAN link as co-location (i.e. bundles up its link with a WLAN link), and as a result gets higher data rates. [44]

Bluetooth employs a technique called frequency hopping spread spectrum (FHSS), which divides the frequency band into 79 hop channels (each 1 MHz wide). During operation, radio transceivers hop from one channel to another in a pseudo-random
fashion at the speed of up to 1600 hops per second [45], in order to combat fading and the potential interferences caused by other wireless technologies (like WLAN and IEEE 802.15.4) which co-exist in the same frequency band as Bluetooth, i.e., 2.4 GHz ISM band.

Bluetooth devices are classified into three different classes depending on the maximum power they are allowed to transmit. The classes also determine the maximum transmission range of the Bluetooth radio as shown in the Table 3. [43]

Table 3. Bluetooth power classes

<table>
<thead>
<tr>
<th>Power Class</th>
<th>Max. Output Power</th>
<th>Radio Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>100 mW (20 dBm)</td>
<td>~100 meters</td>
</tr>
<tr>
<td>Class 2</td>
<td>2.5 mW (4 dBm)</td>
<td>~10 meters</td>
</tr>
<tr>
<td>Class 3</td>
<td>1 mW (0 dBm)</td>
<td>~1 meters</td>
</tr>
</tbody>
</table>

3.1.1. Protocol stack

Bluetooth core system consists of two major sub-systems:

i) Bluetooth host and
ii) Bluetooth controller.

A host-to-controller interface (HCI) separates the above mentioned subsystems. Bluetooth host is the software system which defines all of the layers below the Bluetooth profiles and above the HCI. A profile is a specification regarding an aspect of Bluetooth based communication between devices. In order to use Bluetooth technology, a device must be compatible with the subset of Bluetooth profiles necessary to use the desired services.

The host can be any operating system (OS), e.g., Windows, Linux, Symbian, Android, Meego, etc., that defines higher level protocols of the Bluetooth stack. Such higher level protocols can be the adopted protocols like transmission control protocol (TCP), user datagram protocol (UDP), internet protocol (IP), point-to-point protocol (PPP), etc. Bluetooth Controller is a controller that defines all of the layers below the HCI, like radio layer, baseband layer, and link manager layer. The controller comprises the hardware, i.e., the micro-chipset which contains the Bluetooth radio transceiver and the firmwares. [46]

Link manager protocol (LMP) is the protocol that handles link establishment between Bluetooth devices and baseband and enables the physical radio frequency (RF) link between Bluetooth units. The logical link control and adaptation layer (L2CAP) handles data transmission from higher layers and service discovery protocol (SDP) discovers Bluetooth devices and services in the surrounding area. RFCOMM (serial cable emulation protocol) is the layer providing for the creation of virtual serial ports and stream data. [40,45,46] Figure 6 depicts Bluetooth protocol stack as a layered architecture [46].
3.1.2. Networking capability

Bluetooth is a pure peer-to-peer communication protocol, i.e., Bluetooth devices or peers do not need to rely on any infrastructure (access point or base station) in order to communicate or to form networks. Instead, they can form ad-hoc networks when they get close to each other. Bluetooth devices are called as peers, because they have identical implementations of the Bluetooth core protocols. However, when two Bluetooth devices communicate, one of them will take the role of a master and the other will become a slave. The one who provides synchronization reference becomes master peer. Once connected, the two devices form a network known as piconet. [40,45]

There can be only 8 peers in a piconet because Bluetooth provides 3-bit MAC addressing scheme. By interconnecting two or more piconets, Bluetooth allows to create a bigger network known as scatternet. Figure 7 depicts two Bluetooth piconets connected through a Master node (the middle node) and forming a scatternet. The middle node acts as a bridge between the two piconets and allows data traffics from one piconet to reach the other and vice versa. [40,45,47]
3.1.3. WBAN perspective

There are a lot of issues that make Bluetooth inadequate from WBAN perspective which are discussed in literature, e.g., [48]. Some of them are listed below.

1. The biggest issue is power consumption. Bluetooth is likely to consume too much power and time due to lengthy frequency hopping (FH) synchronization procedures. Hence, longer battery life cannot be provided.

2. Automatic network formation is not supported, and when the master of an established network moves away, the entire network collapses, which conflicts with the requirements of dynamically changing networks.

3. Only single piconets are supported by the Bluetooth PAN profile. Scatternet is defined but rarely used in practice. In addition, Bluetooth supports only up to 8 nodes in a network (piconet). In contrast, ZigBee supports up to 65536 nodes in a network. [43]

4. Starting up a connection is rather slow, i.e. up to the order of five seconds. Lengthy inquiry procedures interrupt on-going communications and data transfers. In addition, a Bluetooth Inquiry will fail if both devices are simultaneously in inquiry state.

5. Extra overheads, extra memory and processing resources are required to implement Bluetooth stack which may not be available for the resource-restricted sensor devices typically used in WBAN applications.

6. Bluetooth defines link level security that can result in disasters if the application developers do not take extreme care. Because the link layer level details are transparent to application developer. Bluetooth security has been studied in [49] and a lot of flaws are being uncovered.

3.2. IEEE 802.15.4-2011

The original IEEE standard for LR-WPANs, IEEE 802.15.4 was proposed in 2003. It defines PHY and MAC layer specifications for LR-WPAN transceivers. The standard offers two PHY layer options depending upon the frequency band used and both are direct sequence spread spectrum (DSSS) based. MAC layer provides an optional superframe structure and based on the presence of beacons slotted or un-slotted CSMA-CA (carrier sense multiple access with collision avoidance) channel access methods are used. [50]

Many amendments were made to the original standard, which are described as follows:

- Low rate alternative PHY (4a) [51],
- Revision and enhancement (4b) [52],
- PHY amendment for China (4c) [53],
- PHY and MAC amendment for Japan (4d) [54],
- MAC amendment for industrial applications (4e) [55],
- PHY and MAC amendment for active RFID (4f) [56],
- PHY amendment for smart utility networks (4g) [57].
In 2011, IEEE 802.15.4 was revised to include 4a, 4b, 4c and 4d amendments in the original standard and it was named as IEEE 802.15.4-2011 revision [16].

An LR-WPAN is a simple, low-cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol. [16]

The standard endorses following capabilities to a LR-WPAN:

- Star or peer-to-peer topology,
- Unique 64-bit extended address or allocated 16-bit short address,
- Optional allocation of guaranteed time slots (GTSs),
- Carrier sense multiple access with collision avoidance (CSMA-CA) or ALOHA channel access,
- Fully acknowledged protocol for transfer reliability,
- Low power consumption,
- Energy detection (ED),
- Link quality indication (LQI).

3.2.1. Components and Topologies

Two different device types can participate in an IEEE 802.15.4 network, a full-function device (FFD) and a reduced-function device (RFD). An FFD is a device that is capable of serving as a personal area network (PAN) coordinator or a coordinator. As a PAN coordinator, an FFD device will be the in-charge of the whole PAN and as just a coordinator, it will be responsible for relaying messages. An RFD is a device that is not capable of serving as either a PAN coordinator or a coordinator.

A system conforming to this standard consists of several components. The most basic is the device. Two or more devices communicating on the same physical channel constitute a WPAN. However, this WPAN includes at least one FFD, which operates as the PAN coordinator. A well-defined coverage area does not exist for wireless media because propagation characteristics are dynamic and uncertain. Small changes in position or direction often result in drastic differences in the signal strength or quality of the communication link. These effects occur whether a device is stationary or mobile, as moving objects affect station-to-station propagation.

An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; it does not have the need to send large amounts of data and only associates with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. [16]

The standard defines two topologies:

i) Star network topology and
ii) Peer-to-peer topology.
In the star topology, the communication is established between devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. A PAN coordinator can also have a specific application, but it can be used to initiate, terminate, or route communication around the network. The PAN coordinator is the primary controller of the PAN. All devices operating on a network of either topology have unique addresses, referred to as extended addresses. A device will use either the extended address for direct communication within the PAN or the short address that was allocated by the PAN coordinator when the device associated. The PAN coordinator will often be mains powered, while the devices will most likely be battery powered. Applications that benefit from a star topology include home automation, personal computer (PC) peripherals, games, and personal health care. [16]

The peer-to-peer topology also has a PAN coordinator; however, it differs from the star topology in that any device is able to communicate with any other device as long as they are in a range of one another. Peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security would benefit from such a network topology. A peer-to-peer network allows multiple hops to route messages from any device to any other device on the network. Such functions can be added at the higher layer, but they are not part of this standard. [16]

### 3.2.2. Layered architecture

IEEE 802.15.4 has a layered architecture and each layer is responsible for one part of the standard that offers services to the higher layers. The layered structure is shown in Figure 8 [16]. The interfaces between the layers serve to define the logical links that are also described in this standard. An LR-WPAN device comprises at least one PHY, which contains the RF transceiver along with its low-level control mechanism, and a MAC sub-layer that provides access to the physical channel for all types of transfer. Upper layers are out of the scope and thus are not presented in the standard. [16]

![Layered architecture of IEEE 802.15.4 devices.](image)
3.2.3. Physical layer specifications

The physical layer (PHY) provides two services, the PHY data service through physical data service access point (PD-SAP) logical link and the PHY management service through physical layer management entity service access point (PLME-SAP) logical link. The PHY data service enables the transmission and reception of PHY protocol data units (PPDUs) across the physical radio channel. IEEE 802.15.4-2011 provides seven PHY layer options based on various modulation methods. These physical layers and their brief description are given below [16]:

i) **O-QPSK PHY**: direct sequence spread spectrum (DSSS) PHY employing offset quadrature phase shift keying (O-QPSK) modulation, operating in the 780 MHz, 868 MHz, 915 MHz, and 2450 MHz bands.

ii) **BPSK PHY**: DSSS PHY employing binary phase-shift keying (BPSK) modulation, operating in the 868 MHz, 915 MHz, and 950 MHz bands.

iii) **ASK PHY**: parallel sequence spread spectrum (PSSS) PHY employing amplitude shift keying (ASK) and BPSK modulation, operating in the 868 MHz and 915 MHz bands.

iv) **CSS PHY**: chirp spread spectrum (CSS) employing differential quadrature phase-shift keying (DQPSK) modulation, operating in the 2450 MHz band.

v) **UWB PHY**: combined burst position modulation (BPM) and BPSK modulation, operating in the sub-gigahertz and 3-10 GHz bands.

vi) **MPSK PHY**: M-ary phase-shift keying (MPSK) modulation, operating in the 780 MHz band.

vii) **GFSK PHY**: Gaussian frequency-shift keying (GFSK), operating in the 950 MHz band.

In general physical layer is responsible for activation/deactivation of radio transceiver, actual data transmission/reception, clear channel assessment (CCA) for CSMA-CA, and link quality indication (LQI). In case of UWB PHY, precision ranging is also done.

3.2.4. MAC layer specifications

The responsibilities of the MAC sub-layer are beacon management, channel access, guaranteed time slot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the MAC sub-layer provides hooks for implementing application-appropriate security mechanisms. The MAC sub-layer provides two services, MAC data service and MAC management service interfacing to the MAC sub-layer management entity (MLME) service access point (SAP) (known as MLME-SAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDUs) across the PHY data service. [16]

This standard allows the optional use of a super-frame structure. The format of the super-frame is defined by the coordinator. The super-frame is bounded by network beacons sent by the coordinator, as illustrated in Figure 9(a), and is divided into 16 slots of equal duration. Optionally, the super-frame can have an active and an inactive portion, as illustrated in Figure 9(b).
During the inactive portion, the coordinator is able to enter a low-power mode. The beacon frame transmission starts at the beginning of the first slot of each super-frame. If a coordinator does not wish to use a super-frame structure, it will turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the super-frames. [16]

Any device wishing to communicate during the contention access period (CAP) between two beacons competes with other devices using a slotted CSMA-CA [58] or ALOHA [59] mechanism, as appropriate. In ALOHA, a device transmits whenever there is a packet to be sent at its disposal and in case of unsuccessful delivery, packet is retransmitted. Next packet is not sent until the previous one is reached. However, CSMA-CA mechanism involves carrier sensing and in case of contention, random back-offs are employed. For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator dedicates portions of the active super-frame to that application. These portions are called guaranteed time slots. The GTSs form the contention-free period (CFP), which always appears at the end of the active super-frame starting at a slot boundary immediately following the CAP, as shown in Figure 10. The PAN coordinator allocates up to seven of these GTSs, and a GTS is allowed to occupy more than one slot period. However, a sufficient portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions are completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP. [16]
IEEE 802.15.6-2012 is a standard for short-range, wireless communications in the vicinity of, or inside, a human body (but not limited to humans) [60]. It uses ISM band and other frequency bands, e.g., medical implant communication service (MICS) and wireless medical telemetry service (WMTS) in compliance with applicable medical and communication regulatory authorities. It allows devices to operate on very low transmit power for safety to minimize the specific absorption rate (SAR) into the body and also increase the battery life. It supports quality of service (QoS), for example, to provide emergency messaging. Since some communications can carry sensitive information, it also provides strong security. [39]

General framework features are given as follows:

- All nodes and hubs are to be organized into logical sets, referred to as body area networks (BANs) in this specification, and coordinated by their respective hubs for medium access and power management. There can be only one hub in a single BAN.
- All nodes and hubs are internally partitioned into a PHY layer and a medium access control MAC sub-layer, in accordance with the IEEE 802 reference model [61].
- All nodes and hubs are to establish a time reference base, if their medium access is to be scheduled in time, where the time axis is divided into beacon periods (super-frames) of equal length and each beacon period (super-frame) is composed of allocation slots of equal length. [39]

The standard defines three distinct PHY layers: ultra wideband (UWB) PHY, narrow-band PHY, and human body PHY. MAC layer is characterized by two options, either a contention based channel access or a scheduling based channel access. In contention based channel access paradigm, the standard describes CSMA-CA and slotted ALOHA whereas in scheduling based paradigm, parameters are given for scheduled channel access in uplink and downlink. However by name time division multiple access (TDMA) is not mentioned. MAC layer provides the following functionalities as given in [39]:

- Frame preparing, transmission and reception.
- Clock synchronization and power management.
- Different channel access methods.
- Creation of a BAN by a hub and connection/disconnection of a node to a hub.
- Specific access methods for tightly regulated MICS band.
- Provides access continuation, termination, and timeout rules in allocation intervals.

3.3.1. Ultra wideband PHY layer specification

The UWB PHY provides a data interface to the MAC layer under the control of the physical layer convergence protocol (PLCP). There are two modes in which a BAN can operate. A default mode that can be used in medical and non-medical applications and a high quality of service mode (QoS) that can be used in high priority medical applications. [60] The UWB PHY provides three levels of functionality, as follows:
i) Activation and deactivation of the radio transceivers.

ii) The PLCP constructs the PHY layer protocol data unit (PPDU) by concatenating the synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU), respectively. Moreover, the PPDU bits are converted into RF signals for transmission in the wireless medium.

iii) The UWB PHY may provide CCA indication to the MAC in order to verify activity in the wireless medium.

There are two different types of UWB technologies included in the specification, namely, impulse radio UWB (IR-UWB) and ultra-wideband frequency modulation (FM-UWB). For co-existence, the hub of the BAN should implement IR-UWB transceiver only, or IR-UWB and FM-UWB transceivers both in the same hub. Nodes in a BAN can have either IR-UWB or FM-UWB transceiver, or even both at the same time. The default mode should mandatorily use IR-UWB as PHY layer and optionally FM-UWB. However, high QoS mode should exclusively use IR-UWB as a PHY layer. [39, 60, 62]

IR-UWB transceivers for BANs are based on the transmission of a single and relative long pulse per symbol (new paradigm in UWB) or a concatenation or burst of short pulses per symbol (legacy). The UWB PHY frame format or physical layer protocol data unit (PPDU) is formed by concatenating the synchronization header (SHR), the physical layer header (PHR) and the physical layer service data unit (PSDU), respectively as illustrated in Figure 11. In a nutshell, the SHR contains the preamble and start-of-frame delimiter. The PHR contains information about the data rate of the PSDU, size of the frame, scrambler seed, etc. The PSDU contains the information bits passed from the MAC, also known as MAC protocol data unit (MPDU) and possibly parity bits from BCH (Bose-Chaudhury-Hocquenghem) encoding of the MPDU. Furthermore, the SHR and PHR are transmitted at the same mandatory data rate always, while the PSDU may be transmitted with optional data rates. [39, 60, 62, 63]

![Figure 11. Creation of PPDU.](image)

The PPDU bits of the UWB frame format are transformed into RF signals for transmission. In the default mode, OOK is the mandatory modulation and in the case of high QoS mode, DPSK modulation scheme is used. Mandatory data rate for IR-UWB is 0.485 Mbps [60]. FM-UWB is an optional PHY in the default mode targeting low data rate medical BAN. FM-UWB exploits high modulation index of frequency modulation (FM) to obtain an ultrawideband signal. Frequency modulation has the unique property that the radio frequency (RF) bandwidth $B_{RF}$ is not only related to the bandwidth of the modulating signal, but also to the modulation index $\Omega$ that can be chosen freely. This yields either a bandwidth efficient narrowband (NB) FM signal ($\Omega < 1$) or a wideband or ultrawideband signal ($\Omega \gg 1$) (wideband FM) that can occupy any required bandwidth. [62]
Therefore, FM-UWB implements processing gain by increasing the transmission bandwidth of a message signal similarly to a spread-spectrum system. This constant-envelope approach, where peak power equals average power, yields a flat spectrum with steep spectral roll-off. After wideband FM demodulation (equivalent to de-spreading) in the receiver, the FM-UWB radio behaves like an NB continuous phase binary FSK (CP-BFSK) radio from a synchronization and detection point of view. FM-UWB transceivers are based on the concatenation of a CP-2FSK signal and a wideband FM signal (FM with high modulation index) as shown in the Figure 12.

![Figure 12. FM-UWB transmitter block diagram.](image)

### 3.3.2. Narrow-band PHY layer specification

The narrow-band (NB) PHY is responsible for activation/deactivation of the radio transceiver, clear channel assessment within the current channel and data transmission/reception. A WBAN device should be able to support transmission and reception in one of the frequency bands summarized in Table 4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Frequency Band (MHz)</th>
<th>Packet Component</th>
<th>Modulation</th>
<th>Symbol Rate (kbps)</th>
<th>Code Rate BCH (n, k)</th>
<th>Information Data Rate (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>402-405</td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>187.5</td>
<td>(31, 19)</td>
<td>57.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>187.5</td>
<td>(63, 51)</td>
<td>75.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/4 DQPSK</td>
<td>187.5</td>
<td>(63, 51)</td>
<td>303.6</td>
</tr>
<tr>
<td></td>
<td>420-450</td>
<td>PLCP Header</td>
<td>GMSK</td>
<td>187.5</td>
<td>(31, 19)</td>
<td>57.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>GMSK</td>
<td>187.5</td>
<td>(63, 51)</td>
<td>75.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>GMSK</td>
<td>187.5</td>
<td>(63, 51)</td>
<td>151.8</td>
</tr>
<tr>
<td></td>
<td>863-870</td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>250</td>
<td>(31, 19)</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>250</td>
<td>(63, 51)</td>
<td>101.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/4 DQPSK</td>
<td>250</td>
<td>(63, 51)</td>
<td>404.8</td>
</tr>
<tr>
<td></td>
<td>902-928</td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>300</td>
<td>(31, 19)</td>
<td>91.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>300</td>
<td>(63, 51)</td>
<td>121.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/4 DQPSK</td>
<td>300</td>
<td>(63, 51)</td>
<td>485.7</td>
</tr>
<tr>
<td></td>
<td>950-956</td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>250</td>
<td>(31, 19)</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>250</td>
<td>(63, 51)</td>
<td>101.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/4 DQPSK</td>
<td>250</td>
<td>(63, 51)</td>
<td>404.8</td>
</tr>
<tr>
<td></td>
<td>2360-2400</td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>600</td>
<td>(31, 19)</td>
<td>91.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>600</td>
<td>(63, 51)</td>
<td>121.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLCP Header</td>
<td>π/2 DBPSK</td>
<td>600</td>
<td>(63, 51)</td>
<td>485.7</td>
</tr>
</tbody>
</table>
The physical protocol data unit (PPDU) frame of NB PHY contains a physical layer convergence procedure (PLCP) preamble, a PLCP header, and a PHY Service Data Unit (PSDU). The PLCP preamble helps the receiver in the timing synchronization and carrier-offset recovery. It is the first component being transmitted. The PLCP header conveys information necessary for a successful decoding of a packet to the receiver. The PLCP header is transmitted after PLCP preamble using the given header data rate in the operating frequency band. The last component of PPDU is PSDU which consists of a MAC header, MAC frame body, and frame check sequence (FCS) and is transmitted after PLCP header using any of the available data rates in the operating frequency band. The table further shows the data-rate dependent modulations parameters for PLCP header and PSDU. In NB PHY, the standard uses DBPSK, differential quadrature phase-shift keying (DQPSK), and differential 8-phase-shift keying (D8PSK) modulation techniques except 420-450 MHz which uses a Gaussian minimum shift keying (GMSK) technique. [39, 60, 63]

### 3.3.3. Human body PHY layer specification

Human body communication (HBC) PHY operates in two frequency bands centered at 16 MHz and 27 MHz with the bandwidth of 4 MHz. Both operating bands are valid in United States, Japan, and Korea, and the operating band at 27 MHz is valid in Europe [60]. HBC is the electrostatic field communication (EFC) specification of PHY, which covers the entire protocol for WBAN such as packet structure, modulation, preamble/start-frame-delimiter (SFD), etc.

Figure 13 describes the PPDU structure of EFC, which is composed of a preamble, SFD, PHY header and a PSDU. The preamble and SFD are fixed data patterns. They are pre-generated and sent ahead of the packet header and payload. The preamble sequence is transmitted four times in order to ensure packet synchronization while the SFD is transmitted only once. When the packet is received by the receiver, it finds the start of the packet by detecting the preamble sequence, and then it finds the start of the frame by detecting the SFD as described in [39, 60, 62].

![Figure 13. IEEE 802.15.6 EFC PPDU structure.](image-url)
4. MP-BODYNET - A MULTI PURPOSE WBAN

This chapter fabricates the rudiments of a multi-purpose smart clothing WBAN application scenario. Section 4.1 highlights the design goals set for the WBAN application and Section 4.2 introduces a WBAN named as Multi-purpose BodyNet (MP-BodyNet) and identifies its modes as well as puts sufficient light upon the past research, which is a precursor and a motivation towards MP-BodyNet. Section 4.3 briefly discusses features of MP-BodyNet and finally Section 4.4 picturise its basic network architecture.

4.1. Design goals

Design goals for the consequent WBAN were outlined with sufficient flexibility by WAS project\(^1\) which develops a hierarchical network architecture for WSNs. This architecture consists of three hierarchical layers, which include various types of devices based upon their capabilities and functionalities they provide to the system. Interfaces between the layers are designed to enable efficient data and control information exchange. The hierarchical architecture and well defined interfaces between the layers enable intelligent tasking of the network devices in order to maximize the energy efficiency and performance of the system. From the energy efficiency point of view, the main feature of the WAS architecture is that the simplest, low power devices can be awake continuously and they would wake-up more complex devices when required from the application point of view. The WBAN demonstration work design goals set up by the project are:

- Designing an application scenario for WBANs, utilizing smart clothing which would exploit key WAS architecture features,
- Establishing communication among different entities in the network,
- Algorithm development and implementation for the designed WBAN application,
- Proof of concept, i.e., implementation of the suggested network.

4.2. Introduction to MP-BodyNet

A WBAN named as MP-BodyNet has been partly designed and implemented at Centre for Wireless Communications (CWC), University of Oulu. It is a multi-dimensional WBAN with a single hardware configuration which can serve as two different WBAN applications with a simple selector button. MP-BodyNet would serve in two modes:

- Senior citizen protection mode (SPM) - Health care
- Silent communication mode (SCM) - Military application

\(^1\)Was project is partly funded by the Finnish Funding Agency for Technology and Innovation (Tekes) and some other companies. It has been a joint venture with Tampere University of Technology (TUT)
4.2.1. Motivation for applications

To say it all while saying nothing had been more metaphoric than a reality in the recent past, but not any more. Science fictions use to show highly advanced cosmic beings or galactic super powers communicating without speech telepathically. However, now its being realized. Brain-computer interfaces (BCI) [64] might allow people who are paralyzed to communicate with and control their environment, and there might also be applications in military situations wherever silent user-to-user communication is desirable [65]. Previous studies have shown that BCI systems can use brain signals related to movements and movement imagery [66] or attention-based character selection [67]. Although these systems have successfully demonstrated the possibility to control devices using brain function, directly inferring which word a person intends to communicate has been elusive.

Recently, in [68] it has been shown that it is possible to use brain signals to predict the vowels and consonants in spoken or imagined words. Furthermore, this decoding is possible based on single utterances rather than requiring brain signals to be averaged over hundreds of task repetitions, as in more traditional brain imaging. This is an encouraging sign that it may be feasible in the near future to decode complete words in real time, thereby allowing users to silently communicate without the need for muscle movements. It further underscores the potential usefulness of electrocorticography (ECoG) as a basis for neural engineering applications, both within clinical contexts (e.g., as a speech prosthesis for paralyzed users) and outside (e.g., as a silent communication method in military and security applications). The brain-wave propagation method employed in [68] is ECoG, whereas another common method is electro-encephalography (EEG). Apart from brain wave signalling, electronic lip reading is another method discussed in literature with reference to silent communication e.g., in [69]. Both brain-wave and electronic lip reading methods are computationally complex, expensive and not very practical still.

Finland is one of the fastest ageing nations in Europe. In 2009, 18% of the population was 65 or over, and the share of 75+ people was 8%. According to prognoses, the share of 65+ people will grow to 26% in twenty years, and the share of 75+ people will go up to 14%. [70]

Increasing number of senior citizens reflects increasing number of health issues. According to the U.S. Census Bureau, worldwide population of elderly people aged 65 and over are expected to more than double by 2020, and more than triple by 2050. In recent years, the electronic health (e-health) concept has evolved from telehealth into a mobile health (m-health) paradigm, enabling long-term ambulatory monitoring, and point-of-care. Moreover, research projects have produced implantable or wearable devices for patients, disabled, aging people, pregnant women, and neonates. Despite extensive preventive efforts, falls continue to be a major source of morbidity and mortality among older adults. Falls often lead to serious injuries such as hip fractures, hospitalization and death. Even when no serious injury occurs, the resultant fear of falling and self-imposed restrictions in mobility and function may contribute to nursing home admission and lead to a loss of personal autonomy that directly affects the quality of life of subjects. Real-time detection of falls allows for the immediate communication of these adverse events to a telecare center so that medical assistance can be supplied quickly. Such assistance is needed to promote the sense of security of older adults,
especially among those who are living alone, and to reduce fear of falling and the subsequent negative impact of falls. A great amount of research work has been done in this respect and plenty of quality papers exist on this subject e.g., [71–75].

4.3. Application features

Following are the features that MP-BodyNet is supposed to achieve.

Application related features:

- Ambulatory wearable system for senior citizens including muscular tension, ECG, and orientation/fall detection.
- Precise recognition of hand signals with a robust algorithm and accurate conversion to speech in SCM case.

Communication related features are as under:

- Self-configuring network.
- Seamless communication of WBAN with different gateways ensuring reliability.
- One button push to interchange among modes.
- Hierarchy in communication.
- Zero configuration network.
- Wake-up radios for less power consumption

4.3.1. Senior citizen protection mode - SPM

SPM in MP-BodyNet employs a similar mechanism for orientation/fall detection as described in [71] and [73]. SPM uses two primary sensors, one is tied to the leg and the other is worn on waist. The leg sensor contains a 3D accelerometer. In addition to primary sensors, SPM also includes an auxiliary ECG sensor which obviously have no role in actual orientation/fall detection. However, it can be useful in order to know that either the subject is choking or not while the rescue is enroute. The orientation/fall detection algorithm decides, based on the accelerometric data from primary sensors, whether a fall has occurred or not. The idea is to measure free fall, the posture of the subject and the impact acceleration. Posture and impact acceleration can be deceptive, because it might be the case that the subject is just trying to lie down naturally, e.g., for sleeping or might be trying to sit on a couch or chair and couldn’t keep balance. In such cases subject never fell but data might suggest that. So for sufficient accuracy, the fall detection algorithm checks that whether the angle between waist worn sensor and leg worn sensor is more than 60 degree plus the impact acceleration is more than a certain threshold. If the subject falls down and is not able to get up or to show significant movement, the algorithm will generate a critical alarm after 20 seconds, declaring the subject/patient has fainted.
4.3.2. Silent communication mode - SCM

The approach discussed in this thesis is simple, cheaper, comfortably wearable and thus quite practical as compared to brain wave communication or lip reading. That particular approach is a motion sensors based hand motion/gesture recognition system. Although this system also have some limitations but at this point it is more feasible, readily deployable and computationally simple. Hand motion/gesture detection techniques are not new to science instead they date back to early 80’s. Some of these techniques are based on visual recognition or image analysis as discussed in [76–80] etc. Other techniques are sensor based as discussed in [81–86] etc. Hand motion/gesture recognition has now been used extensively in gaming industry, e.g., Wii and Nintendo [87]. Silent communication mode proposed in MP-BodyNet employs a solution based on accelerometer sensor. SCM is not implemented because of time constraints, but it is quite probable that by employing the theoretical solution proposed in this thesis, one would get at least two novelties regarding hand gesture recognition algorithms as explained in Chapter 5.

SCM in MP-BodyNet will learn from specific gestures made by the user with his/her hand, and cast them as messages to nearby receivers. Those receivers would identify the casted message and generate a corresponding speech message for the recipient. Consider a scenario, where a captain is leading his soldiers in a close range encounter (CRE). Now as per standard procedures, soldiers do not talk to each other instead they use a sort of sign language and with particular hand gestures they convey their messages to each other. Suppose, captain is beyond a wall and soldiers are behind that wall, now soldiers can not see their captain and hence can not receive their captain’s order. Here comes the role of SCM, captain will follow standard procedure and make particular gestures with hand and the sensors incorporated in his glove will record the movement of his hand. After that, the message from captain is sent to his soldiers nearby but behind the wall and their MP-BodyNets will receive that message, and convert it into a voice signal which might be a recorded message bound against the actual data message received from captain.

4.4. Network architecture

Figure 14 represents a pictorial manifestation of MP-BodyNet. IEEE 802.15.4 [38] has been chosen as the communication technology. Architecturally, MP-BodyNet consists of three main components namely sensor-nodes (SN), concentrator-node (CN), and a gateway node (GN). Beyond-WBAN components include a generic WSN gateway (GWG), a client Android application (C-app) to show measurements, alarms or messages to intended staff or personnel and an ear-piece in case of SCM. In SPM, ear-piece is not needed. MP-BodyNet not only fulfills the requirements laid down by the WAS project, it provides flexible and versatile WBAN with multiple applications. All SNs communicate with a single CN and the CN communicates with a GN. Complexity of the nodes grows from SNs to GN. Architecture and functionality of each entity in WBAN is given in Chapter 5.

Figure 15 depicts the block diagram of beyond-WBAN communication in MP-BodyNet. Link between concentrator node and gateway node is IEEE 802.15.4 based whereas the link between gateway node and GWG is WLAN based.
GN has two front-ends, an IEEE 802.15.4 frontend serving as a bridge for MP-BodyNet, and a WLAN front-end serving as gateway. C-apps are connected to GWG. SNs, CN, GN and C-app are designed and developed at CWC whereas GWG is developed at Tampere University of Technology (TUT) [88]. Hardware for the network entities is mostly developed by the WSN-Team at CWC and partly acquired from industry. Software for SN, CN, GN (gateway) is developed during the course of this thesis except GWG and GN (bridge).

Figure 14. MP-BodyNet full configuration.

Figure 15. Beyond-WBAN communication in MP-BodyNet.
5. IMPLEMENTATION AND RESULTS

This chapter describes the actual implementation and realization of the concepts shown in the previous chapters. Various tools and components that shape up MP-BodyNet are discussed here. Section 5.1 sheds light on the hardware components of MP-BodyNet whereas Section 5.2 introduces software components. Section 5.3 explains the algorithms designed for different modes of MP-BodyNet. Of course these algorithms are a part of software platform or software base for MP-BodyNet, however, they are explained in a separate section. Finally, Section 5.4 discusses the outcomes and results.

5.1. Hardware platform

Any computing platform, from embedded computing platforms to super computer architectures, are basically made up of two fundamental platforms, i.e.,

- Hardware architecture/Hardware platform
- Software framework including application frameworks.

This combination allows software framework especially application framework to execute its defined operation. Hardware platform includes a computer architecture i.e., central processing unit (CPU) and peripherals. Generally, WSNs and WBANs perform a single application per network, application specific routing and there is poor or no support for mobility. Coordination among different networks is worked through a central entity, i.e., a control server. This happens because of obvious computing limitations of embedded platforms that form WSNs and WBANs. Sole purpose of MP-BodyNet is to provide a concept of multiple applications per network, where self-configuring sensor nodes make a hierarchy in which higher capability nodes support lower capability nodes and maintain over all homogenous performance. Future of WSNs will be such that the applications will enter and leave a network according to the situation, i.e., on the basis of link quality and agent networks like WBANs will be able to operate within any standardized core WSN independently. For such WSNs or WBANs like MP-BodyNet, computing requirements are significantly high but still there is a fundamental limitation, which is power consumption.

CWCWSN platform is a cutting edge hardware platform/hardware architecture for future research on WSNs and WBANs designed by WSN-Team at CWC, University of Oulu. It is designed to provide remarkable computing power, multiple radios, in-house built wake-up radios and a variety of extension pin heads for future integration, research and testing etc., yet consuming relatively low power. CWCWSN platform is the hardware platform for MP-BodyNet, however, in this case it includes a single radio. Following sub-sections describe most important components of MP-BodyNet hardware platform and in the end the nodes themselves.

5.1.1. STM32F217 micro-controller

A micro-controller or a micro-controller unit (MCU) is a miniature computer on a single integrated circuit (IC) containing a processor core, memory and input/output
(I/O) peripherals. STM32F217 MCU designed by ST-Microelectronics is based on the high performance 32-bit ARM-Cortex M3 reduced instruction set computing (RISC) processor core, operating at 120 MHz clock frequency. The MCU also incorporates advanced, high-speed embedded memories providing 1 MB of flash memory and 128+4 KB of static random access memory (SRAM). The breakdown of SRAM is like that the 128 kB are for system SRAM and 4 kB are for backup SRAM. The MCU also provides an adaptive real-time memory accelerator (ART-Accelerator) to achieve a performance equivalent to 0 wait-state program execution from flash memory and an extensive range of enhanced I/Os and peripherals connected to two advanced peripheral buses (APB), three advanced high-performance buses (AHB) and a 32-bit multi-AHB bus matrix. An exclusive feature of this hardware platform is the external flash memory support achieved by an SD card slot. Additionally, an external real time clock (RTC) allows very low power sleep mode in which the essential wake-up sequence is stored in 4 KB backup SRAM. The MCU provides 150 DMIPS (DMIPS) at 120 MHz and dynamic power consumption is only 200 µA/MHz. DMIPS is a benchmarking system for CPUs [89]. In RTC sleep mode, power consumption is less than 9µA. The platform features two general-purpose dual-port dynamic memory allocation controllers (DMA) with 8 streams each. They are able to manage memory-to-memory, peripheral-to-memory and memory-to-peripheral transfers. DMAs can be used by all main peripherals. An embedded flexible static memory controller (FSMC) controls which memory will be selected for a particular operation. STM32F217 also provides embedded nested vectored interrupt handler (NVIC) in order to provide flexible interrupt management features with minimum interrupt latency, and an external interrupt/event controller (EXTI) used to generate interrupt/event requests to processor core. NVIC is able to manage 16 priority levels, and handle up to 81 maskable interrupt channels plus the 16 interrupt lines of Cortex-M3 processor core itself. 114 general purpose input/output (GPIO) pins can be mapped to 16 external interrupt lines. Processor provides the system timing using a special system timer named as SysTick which is a 24 bit countdown timer. It is used as a tick timer for real time operating systems (RTOS). [90]

A summary of peripherals can be written as follows:

- Serial peripheral busses (SPI).
- Inter-IC busses (I2C).
- Integrated inter-chip sound (I2S).
- Universal serial bus-on-the-go fast speed/high speed (USB-OTG FS/HS).
- Universal synchronous/asynchronous receiver/transmitter (USART).
- Secure digital input/output (SDIO).
- Ethernet IEEE 1588 support (present in both CN and SN but enabled only in CN).
- Crypto/hash processor (present but not enabled).
- 12-bit ADC.
- JTAG for debugging (Joint test action group, JTAG is the common name for the IEEE 1149.1 standard test access port).
5.1.2. AT86RF231 radio transceiver

Radio transceiver used in preliminary MP-BodyNet is AT86RF231 designed by Atmel Corp. AT86RF231 [19] is a high performance RF-CMOS 2.4 GHz transceiver targeted for IEEE 802.15.4 applications with very low link budget and ultra low power consumption. Salient features of AT86RF231 can be summarized as follows:

- -101 dBm receiver sensitivity.
- Programmable output power from -17 dBm up to +3 dBm.
- Ultra-low supply voltage (1.8V to 3.6V) with internal regulator.
- Ultra-low current consumption in various operating modes:
  - SLEEP = 0.02 µA
  - TRX_OFF = 0.4 mA
  - RX_ON = 12.3 mA
  - BUSY_TX = 14 mA (at maximum transmit power of +3 dBm)
- 128-byte FIFO (SRAM) for data buffering.
- Programmable clock output, to clock the host micro-controller or as timer reference.
- Integrated RX/TX switch.
- One interrupt pin from radio transceiver.
- Only two micro-controller GPIO lines necessary.
- FCS Computation and CCA.
- RSSI measurement, ED and LQI.
- Automated acknowledgement, CSMA-CA and retransmission.

The radio transceiver is a true SPI-to-antenna solution. All RF-critical components except the antenna, crystal and decoupling capacitors are integrated on-chip. Therefore, AT86RF231 is particularly suitable for applications like:

- 2.4 GHz IEEE 802.15.4 and ZigBee systems.
- 6LoWPAN.
- Wireless sensor networks.
- Industrial control, sensing and automation.
- Residential and commercial automation.
- Health care.
- Consumer electronics.
- PC peripherals.

This single-chip radio transceiver provides a complete radio transceiver interface between an antenna and a microcontroller. It comprises the analog radio, digital modulation and demodulation including time and frequency synchronization and data buffering. The number of external components is minimized such that only the antenna, the crystal and decoupling capacitors are required. Figure 16 depicts a functional block diagram of AT86RF231 radio transceiver [19].

There are bidirectional differential transmission and reception antenna, so no external antenna switch is needed. The received RF signal is differentially fed through the low-noise amplifier (LNA) to the RF filter in order to generate a complex signal, which is then passed through a band pass filter. The amplifier provides sufficient gain to drive
the succeeding analog-to-digital converter (ADC) and generates a digital RSSI signal. The transmit modulation scheme is offset-QPSK. The frequency modulated signal is fed to the power amplifier in transmit mode. The configuration of the AT86RF231, reading and writing is controlled by the SPI interface and additional control lines. For long-range applications or to improve the reliability of an RF connection, performance can further be improved by using an external RF front-end or antenna Diversity. Both operation modes are supported by the AT86RF231 with dedicated control pins without the interaction of the micro-controller. [19]

![Figure 16. Block diagram of AT86RF231 radio transceiver.](image)

### 5.1.3. ADXL345 accelerometer

The ADXL345 is a small, thin, ultra-low power, 3-axis digital accelerometer with high resolution (13-bit) measurement at up to ±16 g. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3 or 4 wire) or I2C digital interface. It measures the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (3.9 mg/LSB) enables measurement of inclination changes less than 1 degree. Several special sensing functions are provided. Activity and inactivity sensing detect the presence or lack of motion by comparing the acceleration on any axis with user-set thresholds. Tap sensing detects single and double taps in any direction. Free-fall sensing detects if the device is falling. These functions can be mapped individually to either of two interrupt output pins. An integrated, memory management system with a 32-level first in, first out (FIFO) buffer can be used to store data to minimize host processor activity and lower overall system power consumption. In measurement mode, ADXL345 consumes only 23 µA and in standby mode it consumes only 0.1 µA. [91]
The ADXL345 is a complete tri-axis acceleration measurement system with a selectable measurement range of ±2 g, ±4 g, ±8 g, or ±16 g. It measures both dynamic acceleration resulting from motion or shock and static acceleration, such as gravity, that allows the device to be used as a tilt sensor. Figure 17 shows a functional block diagram of a 3D ADXL345 accelerometer [91].

![Figure 17. Functional block diagram of ADXL345 accelerometer.](image)

The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against forces due to applied acceleration. Deflection of the structure is measured using differential capacitors that consist of independent fixed plates and plates attached to the moving mass. Acceleration deflects the proof mass and unbalances the differential capacitor, resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation is used to determine the magnitude and polarity of the acceleration. [91]

Both CN and SNs in MP-BodyNet contain ADXL345 accelerometer although the roles are differently defined in both types of nodes. SPI is used as the communication bus to write commands to accelerometer and also to read measurement values from the device. Only one interrupt pin is being used in MP-BodyNet. All interrupts share the same pin. Interrupt enabling is controlled by software and the device remains always in measurement mode when powered up and initialized. Otherwise, when not initialized, it remains in standby mode or no power mode depending upon the application. In MP-BodyNet, ADXL345 is used both to measure dynamic accelerations and static accelerations because MP-BodyNet needs motion, free-fall, as well as tilt/orientation detection in its applications.
5.1.4. Concentrator node platform - CN

A concentrator node serves as a router in MP-BodyNet. At initialization, it looks for available gateways, and establishes a connection with the gateway from which it receives maximum RSSI. This gateway selection decision happens at MAC layer rather than radio driver level. Currently a CN can remember three gateways and can establish or tear off connection based upon RSSI levels. Figures 18 and 19 show labeled photographs of a concentrator node present at CWC premises in University of Oulu.

IPv6 based communication takes place between a CN and gateway and also among CN and SNs. Figure 18 displays the upper-side where STM32F217 micro-controller, AT86RF231 radio transceiver, and different pin heads can be seen. ADXL345 is not visible, but it is there underneath the radio transceiver daughter board.

![Concentrator Node Platform for MP-BodyNet](image)

Figure 18. Concentrator node platform upper-side (CN).

CN supports integration of multiple radios which allows integration of wake-up radio scenarios which have extensively been studied in literature. In future, an in-house wake-up radio solution will be developed, integrated in CWCWSN platform for further research and development. However, for the time being, and for the sake of this thesis, MP-BodyNet involves single conventional radio. Figure 19 displays the lower side of the platform and important components present there are labelled.

A CN awaits a request for connection establishment from an SN and replies to it by sending a special advertisement packet and hence establishes communication with SNs. The complete operational procedures involving communication among nodes and all other entities, largely comprising the whole network, are described in the end of this chapter. Salient features of a CN can be summarized as follows:
• Collecting data from SNs and send it immediately to gateway.
• Depending upon application, a CN can also take part in sensing.
• Finding appropriate, available gateway for MP-BodyNet. Note that the gateway is not a part of MP-BodyNet, instead it is a beyond-WBAN component.
• A CN can incorporate multiple radios for wake-up radio scenarios. However, in this preliminary phase of research and development, MP-BodyNet incorporates only one radio which communicates with both SNs and gateways.
• CN can provide Ethernet support, i.e., it can work as a fixed gateway or base station. This feature is not exploited in MP-BodyNet.

5.1.5. Sensor node platform - SN

A sensor node or an SN is the actual sensing platform and it can operate as an individual sensor node as well as an integrator node, i.e., it can integrate proprietary sensor platforms to MP-BodyNet. For example in SCM mode, an SN integrates MyOnTec [92] smart glove to MP-BodyNet. At initialization, an SN looks for a CN by multi-casting a request for connection. When it receives a reply from a concentrator node, it saves its IPv6 address and then communicates with the concentrator node using that IPv6 address. This communication is governed by UDP protocol. Figure 20 displays a labelled photograph of an SN, which is equipped with ADXL345 accelerometer sensor, an SHT11 temperature/humidity sensor and ATRF231 radio transceiver.
Initial plan was to equip SNs with 3D gyroscopes and ECG sensors as well, but due to power profile limitations and lack of time regarding production, integration of 3D gyroscopes plus ECG have been saved for future development. Exclusion of gyroscopes surely have an impact on performance of some of the algorithms designed in this thesis, however, the proof of concept can be delivered even without gyroscopes. Moreover, it was easy to skip ECG sensors incorporated in a smart shirt, because they do not have any direct role in the applications designed for the purpose of this thesis.

![Sensor Node Platform for MP-BodyNet](image)

Figure 20. Sensor node platform (SN).

5.1.6. Gateway node platform - GN

In order to connect MP-BodyNet with the outside world, i.e., Internet, a special AP named as MP-BodyNet gateway node or GN is used. In hardware, it is actually a single board computer (SBC) known as Mini6410 manufactured by FriendlyArm China [93]. The processor core in this SBC is 533 MHz Samsung S3C6410 ARM11 processor with 256 MB DDR (double drive rate) and 1 GB flash memory. It is capable to run embedded Linux as well as Android operating systems. It includes a lot of useful peripherals, e.g., touch LCD. For MP-BodyNet purposes, embedded Linux is installed and a TelosB Sky mote (manufactured by Crossbow Inc.) is attached to one of the USB ports and a WLAN card is attached to another USB port. TelosB Sky mote itself is a sensor platform with MSP430F1611 MCU made by Texas Instruments, 48 kB of flash memory and a Chipcon CC2420 transceiver for IEEE 802.15.4 radio. The Sky mote actually provides an IEEE 802.15.4 interface to the ARM board which essentially communicates with
the CN of MP-BodyNet, and then makes the received packet from CN to be available at the Linux stack using SLIP (serial line internet protocol) [94]. The WLAN card provides an interface to an available WLAN and hence to the Internet. When the packet is available at Linux stack, it is read by a GN software gateway which is written in Java and is installed on GN. The packet is then forwarded via a WLAN to GWG for storage and further processing. Figure 22 displays the above mentioned setup for GN.

Figure 21. MP-BodyNet gateway node (GN).

5.1.7. Smart glove

Smart glove is another off-the-shelf component in MP-BodyNet. It is designed and produced by an emerging Finnish company known for producing wearable sensory solutions, named as MyOnTec [92]. It includes three patented, printed pressure sensors or bend sensors that detect amount of pressure or an event of bending in two fingers and a thumb of right hand. SN designed at CWC integrates this glove into MP-BodyNet and provides interrupt lines to those above mentioned bend sensors. Hence, in case of a bend event, an interrupt request (IRQ) is generated, handled and processed accordingly by the application. Smart glove and SN will coordinate in SCM for gesture detection. Figure 21 displays an SN and the MyOnTec smart glove.
Figure 22. Smart glove.

5.2. Software platform

A software platform or a software architecture allows the user to interact with the hardware platform and get advantage out of it. Software platform is like a skin to the bones of a hardware platform, would be a quite naive analogy. Actually software platform is much more than just a skin to the bones, without it, a piece of hardware is useless. A carefully designed and well written software architecture increases the overall performance of the system by manifolds. Such an architecture is carefully planned and designed for MP-BodyNet. It involves an open source RTOS known as Contiki developed at SICS (Swedish Institute of Computer Sciences) [95], applications written in C for Contiki, two gateways written in Java and an Android based user application.

5.2.1. Contiki-2.5 operating system

Contiki is an open source operating system for networked, memory-constrained systems with a particular focus on low-power wireless internet of things (IoT) devices. It is designed to run on classes of hardware devices that are severely constrained in terms of memory, power, processing power, and communication bandwidth. A typical Contiki system has memory in the order of kilobytes, a power budget on the order of milliwatts, processing speed measured in megahertz, and communication bandwidth on the order of hundreds of kilobits/second. This class of systems includes both various types of embedded systems as well as a number of old 8-bit computers. [95]

Contiki provides three network mechanisms: the uIP TCP/IP stack, which provides IPv4 networking, the uIPv6 stack, which provides IPv6 networking, and the Rime stack,
which is a set of custom lightweight networking protocols designed specifically for low-power wireless networks. The IPv6 stack was contributed by Cisco and was, at the time of release, the smallest IPv6 stack to receive the IPv6 Ready certification. The IPv6 stack also contains RPL and the 6LoWPAN header compression and adaptation layer for IEEE 802.15.4 links. RPL is a routing protocol for low power lossy networks [96]. The Rime stack is an alternative network stack that is intended to be used when the overhead of the IPv4 or IPv6 stacks is prohibitive. The Rime stack provides a set of communication primitives for low-power wireless systems. The default primitives are single-hop unicast, single-hop broadcast, multi-hop unicast, network flooding, and address-free data collection. The primitives can be used on their own or combined to form more complex protocols and mechanisms. [95]

Contiki is implemented in the C language and has been ported to a number of microcontroller architectures. It has an event-driven kernel and to run efficiently on memory-constrained systems, the Contiki programming model is based on protothreads. A protothread is a memory-efficient programming abstraction that shares features of both multi-threading and event-driven programming to attain a low memory overhead of each protothread. The kernel invokes the protothread of a process in response to an internal or external event. Examples of internal events are timers that fire or messages being posted from other processes. Examples of external events are sensors that trigger or incoming packets from a radio neighbor. Protothreads are cooperatively scheduled. This means that a Contiki process must always explicitly yield control back to the kernel at regular intervals. Contiki processes may use a special protothread construct to block waiting for events while yielding control to the kernel between each event invocation. [95]

STM32F217 micro-controller architecture has been successfully ported to Contiki by CWC WSN-Team, and the port runs with very small memory OS footprint. Additionally, drivers for radio transceiver and accelerometer have also been incorporated in the Contiki system. The version of Contiki RTOS used for MP-BodyNet is Contiki 2.5, although the port is also valid for Contiki 2.6 and with a little modification to Contiki 2.4 for also.

5.2.2. WSN OpenAPI framework

In today’s WSNs, a key challenge is the utilization of heterogeneous sensor values to allow collaboration and data fusion between sensor networks. Sensor devices use various protocols, different interfaces for accessing sensors, and incompatible sensor data formats, which makes combining data from different sources hard. In order to address this problem, Department of Computer Systems Tampere University of Technology, developed a unified service access architecture, interfaces collectively referred to as WSN OpenAPI gateway or generic WSN gateway (GWG). The architecture of GWG comprises sensing, actuation, data storage, and metadata services. A GWG connects sensor networks to clients. A sensor device can interact with the gateway directly with WSN OpenAPI framework, but for compatibility, an adapter may be used to convert between WSN OpenAPI and proprietary data formats. Data archive service stores measurement values for later examination and can be realized, e.g., with a file or database. Meta-data archive is a data storage that holds node and sensor related
information such as sensing accuracy, manufacturer, and model. GWG consists of several interfaces that can be used separately. Thus, a WSN OpenAPI client need to implement only the interfaces that are required for its functionality. [97]

The interfaces are:

- Authentication and capability format (ACF) - defines message formats for authenticating to the gateway and querying the list of supported interfaces. Thus, this is the only mandatory interface for an implementation.
- Network management format (NMF) - describes message formats for querying network structure and status, configuring measurement collection, and setting alerts.
- Meta-data format (MEDF) - defines an interface for querying node capabilities and sensors.
- Sensor information data format (SIDF) - describes the format to present measurement data.
- Sensor archive data format (SADF) - defines request and response data formats for accessing values stored in a WSN data archive.
- Node actuator and sensor control (NASC) - presents an interface for sending actuator commands to sensors.

GWG messages are defined both in XML and comma separated value (CSV) formats. Figure 23 shows two sample GWG SIDF messages/packets.

Example WSN OpenAPI Gateway messages

In MP-BodyNet, all the communication involving IEEE 802.15.4 takes place using GWG CSV format messages. Whereas all higher level communication involving WLAN and system level database access takes place using GWG XML format messages. In this way, MP-BodyNet incorporates itself in a larger network as a mobile agent network. This larger network contains three sub-networks namely, Sky network, TUTWSN
network [98], and WIREPAS network [99] which are being maintained at WSN lab in CWC premises. All these networks share the same high level infrastructure i.e., GWG which itself incorporates WSN OpenAPI infrastructure. Although different adaptation layers, i.e., gateways are required in certain networks to make them work with WSN OpenAPI data formats e.g., in case of WIREPAS networks. However, this aspect is not important for this thesis. MP-BodyNet employs only two interface types SIDF for real time measurement data and ACF for authentication and registration to the network.

5.2.3. Contiki application design

In this thesis two separate Contiki applications have been designed and one is acquired from previous Contiki implementations, to run over Contiki 2.5 RTOS:

1. Contiki concentrator application meant to run on CN device.
2. Contiki sensor application meant to run on SN device.
3. Contiki bridge application meant to run on the IEEE 802.15.4 front-end (Sky mote) of GN device has been taken from the Sky port of Contiki.

Communication among above mentioned devices is governed by UDP/uIPv6 stack of Contiki RTOS. Communication mechanism is designed to minimize traffic as well as to achieve a zero configuration, i.e., a self configuring network. Communication mechanism is summarized in following paragraphs.

Contiki bridge application runs over TelosB Sky mote connected to ARM board forming a GN. The bridge application utilizes radvd [100] service of Linux stack. The radvd is an open-source software product that implements link-local advertisements of IPv6 router addresses and IPv6 routing prefixes using the neighbor discovery protocol (NDP). When IPv6 hosts configure their network interfaces, they multicast router solicitation (RS) requests onto the network to discover available routers. The radvd software answers requests with router advertisement (RA) messages. In addition, radvd periodically multicasts RA packets to the attached link to update network hosts. In MP-BodyNet’s case RAs are set to be sent every 3 seconds in order to have network convergence in less than 3 seconds and more chances of connectivity for newly added networks. Power consumption at GN’s end is not an issue as it is connected to the mains. The RA generation time is a tradeoff between power consumption performance and vigorous connectivity. If RA generation time is too small, MP-BodyNet or any other network will be overwhelmed with packets as the nodes are in idle listening mode and if the RA generation time is too large, more time needed to reconnect to GN in case of disconnection resulting in packet loss. RA message contains IPv6 address of the mote itself and other ICMPv6 related information. There are two tasks defined for a bridge application:

1. RA generation every 3 seconds.
2. Transfer of valid SIDF, CSV formatted, received packets from CN to Linux IP stack.

Concentrator node application runs over a CN node and it awaits three types of packets whereas generating essentially two types of packets. CN application extracts
GN’s IPv6 address from the RA received, and it saves it into memory. A CN can currently save three different GN IPv6 addresses in its memory. The decision to make a connection with a GN depends upon the RSSI. During mobility scenarios, a CN can tear off a connection with one GN and establish the connection with another GN with better RSSI. The message types that a CN awaits are as follows:

1. Router advertisements from GNs.
2. Sensor available messages from SNs.
3. Data packets from available SNs in the network.

Figure 24 below shows a simplified block diagram of MP-BodyNet initialization process. RAs are used to determine GN devices. Sensor available messages are actually multicast messages from SNs that advertise the availability of a SN to CN. After reception of an availability packet, a CN extracts the IPv6 address of the SN from the multicast packet and sends a concentrator advertisement (CA) packet to the corresponding SN and the SN stops sending multicasts. A CA packet tells SNs that a CN is available with a particular IPv6 address. SNs then extract the IPv6 address of the CN from the CA packet and save it to their memory and then start sending periodic unicast packets or unicast packets with application dependent delay to the CN. Eventually, measurement packets from SNs are forwarded by CN to the GN, and also some times depending upon the application, CN sends its own measurements to the GN. Or, it can even combine its own measurements with the SN measurements to form a unified packet, which means something according to the application. All these above mentioned packets/messages are CSV formatted SIDF messages.

Figure 24. Simplified block diagram of initialization/self-configuration phase.

Figure 25 shows simplified block diagram of measurement phase, i.e., after the devices are initialized and actual measurements are being taken place. Even in measurement phase, CN is looking for discovery of new SNs. So if a new SN appears, CN will accommodate it.
CN can initiate Initialization phase for any newly added SN in the network. Also it can tear off connection from one GN and establish connection with a new one at any time during measurement phase.

Figure 25. Simplified block diagram of measurement phase in MP-BodyNet.

### 5.2.4. Gateways and Android user application

There are two software gateway applications serving in MP-BodyNet. One is running on the GN device and the other one is running over a server PC. The GN software application implemented for this thesis, actually serves as a gateway for the MP-BodyNet and brings Internet access to MP-BodyNet. On the other hand, it serves as an adaptation layer for central PC server which holds the main gateway and attached databases for all the WSNs in CWC. This main central gateway has been discussed in previous chapters with the name of GWG. Both these gateways are written in Java. Implemented java gateway meant to run on GN, has been assigned the following tasks:

- To extract packets from the underlying Linux stack using UDP socket programming, i.e., communicating with IEEE 802.15.4 front-end for data retrieval.
- To convert CSV formatted received SIDF messages to XML formatted SIDF messages, i.e., data adaptation for GWG.
- To send these converted packets to GWG using TCP socket programming, i.e., connecting MP-BodyNet to central network.

GWG employs WSN OpenAPI infrastructure and stands in the middle of all the available WSNs in WSN lab. MP-BodyNet, in some applications, act like a self-sustaining agent network and does not need GN and GWG, e.g., in SCM. However, in alarm generating systems like SPM, it is necessary to include a GWG in the picture. Main responsibilities of GWG are:

- To provide authentication to different sensor nodes to send messages in their mapped networks.
- To receive SIDF messages from GNs and sort them according to their corresponding network mapping.
- To save the measurements in archives using database system.
- To respond to any client requests for measurement data retrieval.
For measurement data retrieval from GWG, a client application has been designed and developed for Android 2.3.3 Ginger Bread and other distributions above Ginger Bread. Figure 26 displays screenshot of main activity of the application.

![Figure 26. A screenshot of C-app.](image)

This client application, referred to as C-app was preliminarily designed to show all real time measurements from all the nodes from all the networks which were connected to GWG in WSN lab. Now it has been updated to include MP-BodyNet as well. Main responsibilities of C-app are:

- To establish an authenticated connection to GWG.
- To subscribe to desired networks and hence receiving their real time or archived data.
- To notify user about discovery of some particular node in a particular network.
- To notify user about some alarm situation, e.g., intrusion detection, fall detection etc.
- To display different sensor values with their fullest details to the user in a user friendly manner.
- To provide user with easy to use GUI and easy to configure network parameters.

### 5.3. Algorithms

Algorithms proposed for two modes of MP-BodyNet are described in the sub-sections below. Fall/orientation detection algorithm is quite simple to implement, but hand
gesture recognition algorithm is a hard nut to crack. In the literature, e.g., [83, 84, 87] etc., almost similar algorithms are proposed. They have computed their algorithms either online or off-line on a PC machine and very high level tools like Matlab were used for signal analysis. The algorithm proposed in this thesis takes up a challenge to provide hand gesture recognition while employing very limited resources of a sensor platform. All computation is supposed to be done in the sensor node itself, that would be the novelty of this algorithm. The algorithm is not implemented in this thesis due to lack of time. However, a method to achieve this goal is discussed here and implementation will be done in later times. The major issues regarding implementing such an algorithm on a sensor platform are processing power, and large overhead of computations. MP-BodyNet provides just the right amount of fire power to undertake such a bold initiative to implement a machine learning algorithm on an embedded platform in its entirety. Moreover, a method of sampling is introduced in the beginning of the algorithm which essentially refines the whole process and reduces the amount of data produced for analysis. All signal processing will be done in software.

### 5.3.1. Fall detection/orientation detection for SPM

The basic ideas behind fall/orientation detection algorithm are the facts that:

- When a body falls under the force of gravity, the acceleration produced in that body tends to slow down and plunge towards zero due to the pull of gravity.
- When a body hits the ground after a fall, a significantly high acceleration is produced due to the impact.

The algorithm implemented in this thesis employs both the conditions described above and tries to detect an event of fall. In SCM scenario of MP-BodyNet, an SN is tied to the waist, which runs the fall detection algorithm, and another node tied to the leg assists regarding tilt information. CN also takes part in orientation determination alongwith leg worn SN. Figure 27 shows the flow chart of fall detection algorithm. When the subject falls, momentarily acceleration due to gravity acting on the body tends towards zero and at that moment an event of weightlessness is recorded. This is termed as free-fall from now on. After a free-fall happens, algorithm now waits for the impact with the ground. If the impact doesn’t happen, it means it was a false alarm. However, if an impact is recorded, algorithm starts to look for reduced or complete in-activity after fall. If there is significant activity shown by the subject before 10 sec of timeout, algorithm sets itself back to initial state considering the event as a false alarm. If activity is there but it is reduced, algorithm generates a fall alarm. And eventually, if there is no activity at all after time out of 20 sec, algorithm generates a critical alarm declaring out that the patient has fainted. The alarms are routed through CN to GWG and then a C-app notifies the doctor with a siren and also an emergency service phone call is established from the C-app automatically. The leg worn SN and and CN are tied to the subject in such a geometry that Z-axis of both nodes is parallel to earth’s gravity. So it provides the algorithm with a way to measure the tilt of the body during fall and after fall.
Figure 27. Flowchart of fall detection algorithm for SPM.

Pitch, roll and yaw for both nodes are being monitored in the application and depending upon those values, algorithm determines whether the body fell in forward, backward or lateral direction. Formulae used for pitch, roll and yaw as in [101] are given as

\[
Roll, \quad \Theta = \tan^{-1}\left( \frac{A_x}{\sqrt{A_y^2 + A_z^2}} \right)
\] (1)
Pitch, \[ \Psi = \tan^{-1} \left( \frac{A_y}{\sqrt{A_x^2 + A_z^2}} \right) \]  \hspace{1cm} (2)

Yaw, \[ \Phi = \tan^{-1} \left( \frac{\sqrt{A_x^2 + A_y^2}}{A_z} \right) \]  \hspace{1cm} (3)

where \( A_x, A_y \) and \( A_z \) are the static accelerations in reference to gravity, \( g \), and \( 1g = 9.8 m/s^2 \).

5.3.2. Hand gesture recognition algorithm for SCM

Hand gesture detection algorithm for silent communication mode of MP-BodyNet is quite complex as compared to fall detection algorithm. This algorithm is itself composed of many other algorithms. It is based on complex statistical modeling and machine learning. It employs hidden Markov model (HMM) [102] as recognition method. There are many variants of HMMs as discussed in [83, 102] etc. The type of HMM used in this algorithm is discrete HMM. However to apply HMM in a practical application, some pre and post processing steps are needed. Algorithm for SCM is only proposed here, its not implemented. However, a method is proposed here which can serve as the basis for an implementation with novelties.

The goal is to run the algorithm on the sensor node without any post-processing external ro WBAN. A method of sampling is introduced, which generates 60 samples over a time period of 2 seconds. Although the sampling rate is 60 Hz, but collected samples are 60 instead of 120 because a delay of approximately 16.66 ms is added and the sampling process is terminated as soon as 60 samples are collected. In this way, very little amount of data is collected. It should be noted that, while making gestures, most of the vectors arriving from accelerometer are just the same or very slowly varying. So important information will not be lost by adding delay of 16.66 ms. Such sort of sampling is not discussed in the literature, because they implemented the algorithm on conventional computers where resources were abundant and they could afford huge amounts of data.

The recognition of accelerometer based hand gestures is primarily a task of pattern recognition. As the smart glove can be freely moved in space, temporally varying 3-dimensional signal data is obtained from the ADXL345 3-axis acceleration sensor present on the SN attached to the smart glove. The sample data generated in this way, needs to be classified into a set of preliminary defined reference gestures. Gestures should be freely trainable, with minimal training effort. Data samples that do not match one of the predefined gestures well enough, should not be classified as one of them, but instead stated separately, as an unclassifiable, unknown gestures.

Based on the study of related papers [83, 84, 87], etc., further literature on HMM [102, 103] and by keeping in mind the limitations of hardware available to MP-BodyNet, a recognition and training process pipeline is proposed which will be used to implement this algorithm in future. Procedure is shown in Figure 28.
Acquisition of 3 Dimensional acceleration vectors from ADXL345

Sampling at 1/60 Hz (60 Samples) i.e. 60 samples characterize 1 gesture

Directional Equivalency Filter (DEF)

Vector Quantization i.e., Mapping of input vectors to the CodeBook vectors

HMM Trainer

HMM Recognizer

Bayes Classifier

Recognized Gesture

Figure 28. Block diagram of processes involved in hand gesture recognition.

Acquisition of data from ADXL345 will start with a special gesture, i.e., shaking the hand twice and it is characterized by a double tap interrupt from accelerometer. This double tap is a signal to the algorithm that now a gesture is going to be made by the user. The algorithm will then record 60 equally spaced samples, i.e., measurements with a delay of approximately 16.66 ms in total time period of 2 seconds. It means the user have 2 seconds time to make a gesture either for training or actual recognition. This time period is totally specific to SCM because all the gestures employed in SCM can be
made in a time window less than 2 sec. After that algorithm stops taking any samples and send the acquired samples to a filter named as directional equivalency filter (DEF), which filters the data. The principle behind DEF is to remove those data vectors from the data which are not very different from each other. Accelerometer data is continuous and while making a gesture, sometimes acceleration values does not change much, so there are many vectors which inherently give same information.

After filtration, algorithm sends filtered data vectors to a vector quantizer. Vector quantization process involves two different processes. One process takes part in training, i.e., the phase in which machine learns the gesture made by user and the other process takes part in recognition of gestures. Training will be done off-line and only recognition is done online, i.e., modelling for gestures to be recognized later, is done prior to the actual use of application. It’s done in this way for the sake of simplicity only, and in the end, data vectors are mapped to a code book. Code book is actually a data structure of so called prototype vectors which is made by a separate algorithm named as Lloyd’s algorithm also known as k-means algorithm [104].

The number of prototype vectors is referred to as the code book size. Code book size is an important parameter having a significant effect upon quality of the whole recognition algorithm. Code book size for SCM is chosen heuristically to be 14, i.e., N=14 and the code book is initialized by picking up 14 vectors from the input data and arrange them as points on a sphere, e.g., in Figure 29 adopted from [87]. Number 14 is chosen because literature reflects that this is the minimum code book size for 3 dimensional data for acceptable convergence. Any bigger size could have been proposed, but it should be kept in mind that MP-BodyNet is a constrained environment.

![Figure 29. Distribution of cluster centers for k-mean algorithm.](image)

The next step in Lloyd’s algorithm is to map all the vectors in the input sequence to the prototype vectors in the code book, i.e., clustering of similar vectors is done in this stage. Let the code book be defined as the set \(Y = y_1, y_2, \ldots y_N\). As a vector quantizer \(Q\) of size \(N\) maps, every vector \(x\) form the input space to exactly one prototype vector \(y_i\), it defines a complete and disjoint partition of K-dimensional vector space \(R_k\) into regions or cells \(R_1, R_2, \ldots R_N\). In the cell \(R_i\) lie all those vectors \(x \in R_k\), which were mapped to the prototype vector or code word \(y_i\). The so called nearest-neighbour condition describes the optimal selection of the partition \(R_i\) for a given code book \(Y\). Every partition cell \(R_i\) needs to be determined so that it contains all vectors \(x \in R_k\), which have minimal distance from the associated prototype vector \(y_i\). This means that the corresponding vector quantizer \(Q\) maps a sample vector \(x\) onto its nearest prototype
vector of the code book. These distances are Euclidean distances for the purpose of this thesis as shown in [105]

\[
Q(x) = y_i \quad \text{if} \quad d(x, y_i) \leq d(x, y_j) \forall j \neq i
\]  

(4)

The Lloyd’s algorithm is an iterative algorithm, achieving a better solution at each iteration. As mentioned earlier that 20 training sequences will be generated for each of the 10 gestures in SCM, every time when a sequence will arrive at quantizer during training, Lloyd’s algorithm will update the code book by updating mapping to prototype vectors, i.e., it will map every vector \( x_t \) from the sample set to the nearest prototype vector \( y_{im} \) of the current code book \( Y^m \). This mapping also determines the partitions \( R_{im} \). From the newly formed partitions, an updated code book will be computed. The centroids of the new partitions serve as the prototype vectors for the updated code book. As Euclidean distance is used for the centroid condition, a centroid for a given partition can simply be calculated as the mean vector of that partition. Lloyd’s algorithm will be implemented using formulae given in Equation 5 and 6. [105]

For current code book \( y^m \), mapping to centroids \( R_{im} \) as

\[
y_{im} = \left\{ x \mid y_{im} = \arg\min_{y \in Y^m} d(x, y) \right\},
\]  

(5)

and updated code book will be

\[
R_{im}^m + 1 = cent(R_{im}^m).
\]  

(6)

where \( cent(R_{im}^m) \) is the updated centroid condition for the new arriving vector.

After vector quantization while training, next step involves preparing an HMM and updating it with training sequences for each gesture. Training of HMMs is done using modified Baum-Welch algorithm. HMMs describe a two-stage stochastic process. In an HMM, a Markov chain represents the so-called hidden part of the model. It is called hidden, because in an HMM, the individual states do not directly correspond to some observable event and are therefore hidden. Instead, the observable event is itself another probabilistic function. It is a probabilistic function that depends (and only depends) on the current state. This probabilistic function represents the second stage of the HMM process. [105]

Suppose \( S = \{1, 2, 3, \ldots, N\} \) is the set of \( N \) hidden states and \( V = \{o_1, o_2, o_3 \ldots o_K\} \) is the alphabet of \( K \) observation symbols coming from quantizer, then an HMM can be formally denoted as \( \lambda = (A, B, \Pi) \) where

- \( A = \{a_{ij}\} \) - the state transition probability matrix, each \( a_{ij} \) represents the probability that the system changes from state \( i \) to state \( j \).
- \( B = \{b_{jk}\} \) - the emission probability matrix, each \( b_{jk} \) represents the probability that state \( j \) generates observation \( o_k \).
- \( \Pi = \{\Pi_i\} \) - the vector of initial state probabilities, each \( \Pi_i \) representing the probability that the system starts in state \( i \).

At HMM machine learning stage of the algorithm for SCM, training of the HMM models during training phase and evaluation of observation gesture as being generated
by one of the models will be done. Baum-Welch algorithm, which trains the HMM models, is sometimes referred to as forward-backward algorithm. The forward search part of the algorithm provides a solution to calculate the likelihood that a particular observation sequence \( O \) was generated by a given hidden Markov model. Formally this can be written as \( P(O \mid \lambda) \). First, an auxiliary variable called as forward variable \( \alpha_t(i) \) is introduced. It defines for a given model \( \lambda \), the probability that the first part of an observation sequence up to \( O_t \) is generated and that at time \( t \), the system is in state \( i \), i.e., \( \alpha_t(i) = P(O_1, O_2 \ldots O_t \mid \lambda) \). Finally, all \( N \) probabilities \( \alpha \) at time \( T \) are summed up to give \( P(O \mid \lambda) = \sum_{i=1}^N \alpha_T(i) \).

Like the forward part of algorithm, backward search algorithm also calculates the probability \( P(O \mid \lambda) \). But it starts at time \( t = T \), i.e., the end of the observation sequence, working backwards, while the forward algorithm starts with time \( t = 1 \). Backward variable \( \beta_t(i) \) is found by looking for probabilities starting from time \( T \) to 1 and in the end, all \( N \) probabilities at time \( T = 1 \) are summed i.e., \( P(O \mid \lambda) = \sum_{i=1}^N \pi_i b_1(O_1) \beta_1(i) \). Baum-Welch will be implemented using the formulae given below. [105]

Let \( \gamma_t(i) \) represents the probability of the system being in state \( i \) at time \( t \). It can be calculated as follows, by drawing on the forward and backward variables defined above and assuming another variable \( \gamma_t(i, j) \) that defines the probability of a transition from state \( i \) to state \( j \) at time \( t \) as

\[
\gamma_t(i) = P(S_t = i \mid O, \lambda) = \frac{\alpha_t(i) \beta_t(i)}{P(O \mid \lambda)},
\]

\[
\gamma_t(i, j) = P(S_t = i, S_{t+1} = j \mid O, \lambda) = \frac{\alpha_t(i) a_{ij} b_j(O_{t+1}) \beta_{t+1}(j)}{P(O \mid \lambda)}.
\]

By using the above formulae and the concept of counting event occurrences, the re-estimates of the parameters of an HMM can be written as

\[
a_{ij} = \frac{\sum_{i=1}^{T-1} \gamma_t(i, j)}{\sum_{i=1}^{T-1} \gamma_t(i)},
\]

\[
b_j(\hat{O}_k) = \frac{\sum_{t:O_t = o_k} \gamma_t(j)}{\sum_{i=1}^{T} \gamma_t(i)}.
\]

The start probabilities \( \pi_i \) can be seen as a special case of the transition probabilities \( a_{ij} \). At each iteration, the Baum-Welch algorithm produces new estimates for the model parameters, the new model and parameters are hence denoted as \( \hat{\lambda} = (\hat{A}, \hat{B}, \hat{\Pi}) \). 10 different gestures shown in Figure 30 will be trained to their respective HMM model and hence a gesture pool of 10 HMM models will come into being.

Now in recognition phase of the SCM algorithm, training parts, i.e., Lloyd’s algorithm and Baum-Welch will be off, and an observation sequence will be created in the quantizer. Now the question is, which model \( \lambda_j \), is most likely to generate that sort of observation sequence, i.e., \( P(\lambda_j \mid O) \). One problem with HMMs is that \( P(O \mid \lambda_j) \), the emission probability of observations \( O \) given the model \( \lambda_j \), yields probability values that are varying in scale depending on the actual gesture model. Therefore, these probabilities can not be directly compared with each other to find out which of the N
HMMs can most likely generate the observation $O$. By taking into account average probability of training sequences of a model $\lambda_j$, the probability $P(\lambda_j \mid O)$ can be computed by applying Bayes’ rule [105] as

$$P(\lambda_j \mid O) = \frac{P(O \mid \lambda_j)P(\lambda_j)}{\sum_{i=1}^{N} P(O \mid \lambda_i)P(\lambda_i)}. \quad (11)$$

Equation (11) classifies the gesture and the gesture is recognized. The model $\lambda_j$ with the biggest value for $P(\lambda_j \mid O)$ will represent the recognized gesture from the gesture pool. After recognition, SCM algorithm will generates an SIDF packet to the CN containing id of the recognized gesture. Then, CN will multicast that packet and all the CNs present nearby will receive it. After successful reception, I2S will be initialized on the recipient CN board and the audio clips stored on the flash will start to get sorted. A specific audio clip will be mapped to a specific message. For example, if the gesture would be made for the message freeze, the recipient CNs will generate an audio clip mapped to message freeze, and it will be heard from the head phones attached to the audio pin.

One thing is worth mentioning here that prior to the training of a hidden Markov model, a fresh HMM needs to be instantiated. According to [102], the various HMM parameters, such as the state transition matrix $A$ and the emission probability matrix $B$, should be initialized as neutral as possible.

5.4. Results and evaluation

This thesis partially implements a mobile, self-configuring, multi-purpose wireless body area network with hierarchical communication pattern and manifesting its application specific resilience using real world applications. Hardware for MP-BodyNet, the implemented WBAN, is designed partially at CWC by WSN-Team. Software framework is partially developed in this thesis. There is a plenty of room for future research/study, development and integration.

5.4.1. Hardware/software efficiencies achieved

Initial total network convergence time is recorded to be less than 3 seconds. However, when being mobile it can not be guaranteed because of the mobility dynamics. Mobility is tested by creating a pseudo environment. Transmit power is set to -17 dBm (minimum transmit power) for both the CN and GN (IEEE 802.15.4) front-end. Then, a GN was placed in the lab and another GN was placed in the corridor approximately 10 meters away, so that if MP-BodyNet move from first GN to the second GN in corridor, it would lose connectivity with the first one or at least maximum RSSI condition would suffice. Maximum RSSI condition is that the CN will communicate with a GN from whom better RSSI is received. As only SPM is implemented, if any fall event happens at the time when connection is being re-established, packet loss occurs and vital information is lost. Also, it was assumed that no other network is communicating with that particular GN. Because radio channel access technique is CSMA-CA, if there are more networks on the same GN, packet loss can occur. It was noticed that if MP-BodyNet is totally
out of coverage of one GN but it is in the coverage area of another GN, it will converge inside 3 seconds time window, i.e., it will establish a connection with GN. If it is in the coverage region of multiple GNs then it will continue communicating with the GN with lesser RSSI until an RA packet with better RSSI from a GN is received. Obviously, no packet loss was seen among SNs and CN because they are fixed on the body.

In wireless sensor nodes most of the power consumption is because of the radio transceivers. In MP-BodyNet, radio transceivers mostly remain in idle listening state utilizing a radio duty cycling (RDC) protocol inherent to Contiki operating system. Another component which can consume a lot of power is an accelerometer. In MP-BodyNet, ADXL345 remains in power saving stand bye mode when it is not being used for measurements to conserve power. In order to achieve low power consumption performance, initial plan of using gyroscopes along with accelerometers was dropped. No RDC is being used on the IEEE 802.15.4 front-end of GNs because GNs are connected to the power mains. RDC is being used on SNs and CNs because they are battery powered. Table 5 shows salient hardware/software related performance efficiencies achieved.

Table 5. Salient HW/SW features achieved

<table>
<thead>
<tr>
<th>Feature</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCU Power Profile</td>
<td>200 µA, only 9 µA with RTC</td>
</tr>
<tr>
<td>AT86RF231 Power Profile</td>
<td>10 mA average, 0.02 mA sleep mode</td>
</tr>
<tr>
<td>Radio Duty Cycling Power Saving Achieved</td>
<td>95%</td>
</tr>
<tr>
<td>ADXL345 Power Profile</td>
<td>23 mA, only 0.01 µA in stand-bye mode</td>
</tr>
<tr>
<td>N/W Convergence Time</td>
<td>≤ 3 Sec</td>
</tr>
<tr>
<td>Packet Delivery From SN-to-CN(immobile)</td>
<td>No packet loss</td>
</tr>
<tr>
<td>Packet Delivery From SN-to-CN(mobile)</td>
<td>No packet loss</td>
</tr>
<tr>
<td>Packet Delivery From CN-to-GN(immobile)</td>
<td>No packet loss</td>
</tr>
<tr>
<td>Packet Delivery From CN-to-GN(mobile)</td>
<td>Some packet loss</td>
</tr>
<tr>
<td>GN Software Gateway Efficiency</td>
<td>Satisfactory, no data loss</td>
</tr>
<tr>
<td>GWG Efficiency</td>
<td>Satisfactory, no data loss</td>
</tr>
<tr>
<td>Android App. efficiency</td>
<td>Satisfactory, no data loss</td>
</tr>
</tbody>
</table>

5.4.2. Performance evaluation for SPM

Fall detection algorithm designed for senior citizen protection mode was tested with 80 falls, 10 fall events in 4 directions each. In first round of tests, 40 fall events were observed in which after the fall, subject was asked to get up or show some significant movements. And then in another round of tests, 40 faint events were observed in which after the fall, subject was asked to be motionless to mimic a condition of being fainted. The CWCWSN platform is designed to provide extensive flexibility and integration. That’s why there are a lot of open pin heads and other open circuitry, e.g., radio is not soldered to the board, instead radio daughter boards can be attached to pin heads and can be replaced very easily. So is the case of batteries which are hanging lose from the board’s battery pinout. During fall detection, when body falls, due to impact sometimes batteries cut lose and sometimes some extension daughter boards cut lose, resulting into shutting down of board or abnormal behaviour.
CWCWSN platform is just in its infancy and no hard covers are employed yet. So, any undetected fall due to hardware failure is not considered as a failure of algorithm. This was learnt from first set of experiments and then nodes were covered in protective packages and then tied to the body. The events when hardware was restarted, stuck or powered off due to battering of impacts cannot be considered as lawful events. So those events were regarded as hardware failure rather than software or algorithmic failure. It was observed that by exclusion of hardware related failed events, all events were successfully detected in order to get 100% efficiency of the algorithm. Table 6 shows the results of tests.

**Table 6. Evaluation of algorithm for SPM**

<table>
<thead>
<tr>
<th>Events</th>
<th>Orientation</th>
<th>Total obs.</th>
<th>Detected obs.</th>
<th>% Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall Event</td>
<td>Fall Forward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Backward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Rightward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Leftward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Faint Event</td>
<td>Fall Forward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Backward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Rightward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fall Leftward</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

**5.4.3. Proposal for SCM**

Hand gesture recognition algorithm for silent communication mode of MP-BodyNet is proposed. It is not implemented because of time constraints over the project. However, it is proposed that training of each gesture should be made by 20 training sequences. After training the hidden Markov models created for the gestures should be saved on the flash memory of the SN. For that purpose, either a driver for a file system is needed to be written or a port to coffee file system (CFS) which is the inherent file system of Contiki operating system is needed. Even if one would like to use SD card, still a port to CFS is required. Training phase of the algorithm should be performed off-line. Less complicated way would be a port to CFS in Contiki.

Small number of acquired samples, and using a small codebook size is expected to pose negative effects on the overall performance of the algorithm, but this gamble is worth taking. Sampling may provide enough detail or the required information because there is always a repetition of similar sort of data vectors and they do not add anything to the information base. That’s why, sampling process with uniformly spaced samples will reduce the data vector space greatly and still not that much of information is expected to be lost. Regarding data vector creation, a suggestion would be to use some vector or hashmap library implemented in C, rather than using 3 dimensional arrays to represent 3 dimensional accelerometric data.

The Contiki application should be designed in such a way that the user would need to define a macro in the application before loading it on the SN board that either the mode is training or recognition. For example, if the macro is set to 0, the device is in training mode. In this case, the application allows user to train the gestures and the models
are saved on the flash but user cannot test recognition in this mode. If macro is set to 1, the device is in recognition mode. In that case, user could make any one of the 10 defined gestures and the algorithm would try to recognize it. Shift between training and recognition should be explicit and manual in the beginning so that accidental, wrong training may not corrupt the trained model or model being trained. Figure 30 presents the flow chart of proposed algorithm.

Figure 30. Flowchart of algorithm for Silent Communication Mode.
6. DISCUSSION

The goal of this thesis was to partially implement a self-configuring, hierarchical, multi-purpose wireless body area network with mobility, which is able to run multiple applications with same WBAN configuration. Current WSNs and WBANs have low resources regarding computing power and storage. Software footprint on the hardware nodes needs to be as low as possible so that all complex calculations are done external to the sensor boards in PC environment. Present-day networks perform single application per network. Networks use a single gateway node, interaction between networks is done by the central server and routing plus network parameters are application-specific. Also, mobility in today’s WSNs and WBANs is either absent or very limited.

Future WSNs and WBANs are supposed to perform multiple applications per network and applications should enter or leave a network dynamically. Networks would form a hierarchy, low-capability networks would be supported by higher-capacity networks or by devices with better capacity and capability. Agent environments, i.e., WBANs may operate within networks independently. Having these premises in mind, a state of the art wireless sensor network board was developed by WSN-Team at CWC to overcome the computation and communication limitations of current WSN boards available. The performance of the developed hardware was manifested by developing real life WBAN applications in this thesis. Resulting WBAN named as MP-BodyNet distinguishes itself from other WBANs discussed in literature (to-date), in many ways that, it offers:

i) Zero configuration/self-configuring network.

ii) High capacity computing capability, 100 MHz 32-bit processor core.

iii) High capacity memory, 1 MB flash, SD-card support.

iv) Multiple applications per network i.e., SCM, SPM with single configuration and code footprint.

v) Competitively less power consumption.

vi) Mobility among different networks i.e., roaming from one GN to another GN.

vii) Generic data packet structure common to all networks at CWC premises.

viii) Senior citizen protection mode - a health care application, fall/orientation detection for older citizens.

ix) Silent communication mode - a military application, military hand signal recognition and conversion to speech (proposal, not implemented).

This thesis partially developed the software framework for the network and an application algorithm for fall detection. Another algorithm for hand gesture recognition is proposed but not implemented. By employing the proposal presented here, at least two novelties in hand gesture recognition can be achieved and in this way for the first time, a machine learning algorithm will be implemented on a sensor board without any external processing. Many other algorithms and applications can be implemented by utilizing the architecture explained in this thesis, e.g., resting tremor detection in Parkinson’s disease etc.

The network is highly portable and the hardware plus software platform developed for MP-BodyNet can be used for various industry projects or research. Hardware platform provides several pin heads for future integration and development, e.g., a CN can have multiple radios with which wake-up radio scenarios can be studied and evaluated. A
software defined, cognitive radio transceiver is under development at CWC which will be integrated to this hardware platform. It can also be used for educational purposes in a lab environment because of its high portability and easy to integrate pin-out. There are a lot of possibilities and still a lot of potential un-explored in it which will be unleashed with future research, integration and development. For example the current setup of MP-BodyNet can be used for resting tremor detection and other motor disabilities in Parkinson’s disease.
7. SUMMARY

Wearable health monitoring systems or wearable human body monitoring coupled with wireless communications are the bedrock of an emerging class of sensor networks WBANs. Such networks have myriad applications, including diet monitoring, detection of activity or posture or gesture, and health crisis support etc. Recently, there has been increasing interest from researchers, system designers, and application developers on a new type of network architecture generally known as body sensor networks or WBANs, made feasible by novel advances on lightweight, small-size, ultra-low-power, and intelligent monitoring wearable sensors. In WBANs, sensors continuously monitor human’s physiological activities and actions, such as health status and motion pattern.

Generalized system architecture of a WBAN can be divided in three fundamental levels or tiers of communication namely intra-WBAN, inter-WBAN, and beyond-WBAN. Various identified frequency bands available for WBANs include ISM band, MICS band, WMTS band, UWB etc. Two major classes of WBAN applications have been listed by IEEE namely, class A (medical applications) and class B (non-medical applications).

Three different short-range wireless communication technologies for intra-WBAN communications can be considered as potential candidates namely IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (ZigBee) and IEEE 802.15.6. Bluetooth is not suitable in general for WBAN or WSN applications because of excessive power consumption although Bluetooth low energy is a good candidate. IEEE 802.15.4 has been used mostly for WSNs and is a strong candidate for WBANs as well. IEEE 802.15.6 is the standard exclusively for WBANs. It offers three different physical layers and huge bandwidth with less power consumption. However, it is not still implemented on industry level.

In this thesis, a wireless body area network named MP-BodyNet was partially implemented. The network can perform multiple applications and two modes of applications were devised, i.e., senior citizen protection mode (SPM) and silent communication mode (SCM). IEEE 802.15.4 was chosen as a communication technique for implementation. MP-BodyNet has enough computational and memory resources and compact software solutions to achieve high performance and fidelity. MP-BodyNet is a self-configuring, multipurpose WBAN which can perform multiple applications and user can switch between applications by a mere push of button. It supports mobility and it acts like an agent network to other networks. MP-BodyNet forms a hierarchy where low-capability networks are supported by higher-capacity networks. Algorithm for fall detection in SPM was developed and implemented. Due to lack of time, algorithm for SCM could not be implemented. However, the proposed algorithm is presented.
8. REFERENCES


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