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A SURVEY ON PROTOCOL STACK FOR WIRELESS BODY AREA NETWORK

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Abstract. Wireless Body Area Network (WBAN) is a radio-frequency wireless network, with comparatively short coverage range. It consists of a potentially large number of low-power consumption devices with sensor or actuator functionality. Considering the capability of innumerous kinds of sensors, WBAN does have a lot of application scenarios around human body area, among which there is personal healthcare. When applied to scenarios like healthcare, WBAN may then interact with other networks in close proximity to largely extend its communications area. This paper presents a survey on ultra-low-power and low-rate version of WBAN by comparing two non-proprietary protocol stacks, namely ZigBee/IEEE 802.15.4 and Wibree. IEEE 802.15.6 and UWB are two others wireless technologies that can be applied in WBANs, yet each is oriented toward different application requirements. In scenarios where latency is a critical factor - such as arrhythmia detection, emergency alerts, or intraoperative monitoring - ultra-low latency must be prioritized, making IEEE 802.15.6 and UWB more suitable. Conversely, for less time-sensitive applications, including fitness tracking or periodic data collection, BLE and ZigBee provide more energy-efficient solutions. Wibree was initially referred to as Bluetooth Low-End Extension (LEE) and subsequently as Ultra-Low-Power (ULP) Bluetooth. To better illustrate Wibree, Bluetooth's specifications is included into comparison whenever necessary. Moving from physical layer to application layer, we have compared different schemes employed by each protocol stack. After that, we investigated into the application of sensors, with the aim of interconnecting arrays of biomedical sensors.

Keywords. Wireless Body Area Network, ZigBee, Ultra-Low-Power Bluetooth, Biomedical sensors.

1 INTRODUCTION

The concept of WBAN comes from categorizing a network by its range. We already have Wireless Wide Area Network (WWAN), Wireless Metropolitan Area Network (WMAN), and Wireless Personal Area Network (WPAN), with the coverage range getting shorter. WBAN emerges as a complementary part to those radio-frequency wireless networks, focuses on human body area applications, and may interact with other networks in close proximity to largely extend its communications area. For wireless communications, there is always a tradeoff among communications range, transmit power, and data rate. With a fixed data rate, the communications range depends on both the transmit power and receiver sensitivity. Low-power supply will lead to limited communications range or inability of on-device data processing, for example, Near Field Communications (NFC) and Radio-Frequency Identification (RFID) [1, 2]. However, with a fixed requirement of communications range, like WBAN, a higher transmit power always results in a higher data rate, like Wi-Fi/IEEE 802.11 and WiMedia platform-based technologies such as Bluetooth 5.0 and Certified Wireless USB [3, 4]. This is actually the tradeoff between power efficiency and bandwidth efficiency.

In this paper, we focus on the ultra-low-power and low-data-rate version of WBAN specifications, which is suitable for personal healthcare. Because of their miniature, lightweight, ultra-low-power characteristics, devices with sensor or actuator functionality have been designed to be put on or even implanted into the human body to collect vital body parameters and movements. This data can be either processed by a local server or forwarded to a care center by a local gateway in order to detect abnormal conditions early and prevent their serious consequences. Many patients can benefit from continuous monitoring as a part of a diagnostic procedure, during supervised physical recovery [5], or even psychological rehabilitation [6].

In addition to applications like telemedicine, researchers foresee WBAN technology to be widely adopted by peripheral devices and entertainment equipment [7], which may even have context awareness and Artificial Intelligence (AI) functionality [8]. With potential advances in Ultra-Wide Band (UWB) technology and Very-Large-Scale Integration (VLSI), higher physical-layer data rates up to 480 Mbps can be integrated into WBAN/WPAN to support wireless multimedia communications.

Table 1: Trade-off Matrix of WBAN Technologies.

Technology	Power Consumption	Data Rate	Latency	Range	Cost
ZigBee	Low	Low (20–250 kbps)	Moderate	Medium (10–100 m)	Low
Wibree	Very Low	Moderate (1 Mbps)	Low	Short (5–10 m)	Low
Bluetooth Low Energy	Very Low	Moderate (125 kbps–2 Mbps)	Low	Medium (10–100 m)	Low–Medium
IEEE 802.15.6	Low–Very Low	Low–High (75 kbps–15 Mbps)	Low	Short (≤ 10 m)	Medium
Ultra-Wideband (UWB)	High	Very High (110 kbps–480 Mbps)	Very Low	Short (1–10 m)	High

To generalize the wireless technologies of WBAN, we expand beyond ZigBee and Wibree to include IEEE 802.15.6, Bluetooth Low Energy (BLE), and Ultra-Wideband (UWB). As shown in Table 1, IEEE 802.15.6, designed specifically for WBANs, supports multiple physical layers - narrowband, ultra-wideband, and human body communications - making it versatile for medical and non-medical use. BLE has become widely adopted due to smartphone and wearable integration, offering low power consumption and adequate data rates for fitness tracking and patient monitoring. UWB, while more energy-demanding, provides high data rates and precise localization, making it ideal for real-time monitoring and emergency detection. A comparative analysis of these standards highlights trade-offs in latency, throughput, energy efficiency, and cost. ZigBee remains cost-effective for simple monitoring, BLE offers broad ecosystem support with energy efficiency, Wibree has merged into BLE, and UWB enables high-precision applications despite higher power use. Including these technologies ensures a more balance in our survey about WBAN standards [9, 10, 11].

Understanding the trade-offs among WBAN technologies is crucial for selecting the right standard in different domains. A key compromise lies between energy consumption and data rate: ZigBee and BLE favor efficiency for long-term monitoring but lack the throughput of UWB, which offers high data rates and precise localization at the expense of greater power use. Communication range and reliability also differ: ZigBee enables wider coverage with mesh topologies, while BLE and IEEE 802.15.6 provide stronger short-range reliability; UWB, though limited in range, excels in precision within confined spaces. Deployment factors further shape adoption - ZigBee is low-cost and flexible, BLE benefits from integration into consumer devices, IEEE 802.15.6 requires specialized hardware, and UWB remains the costliest, suited mainly for critical applications. Latency is another determinant: IEEE 802.15.6 and UWB support ultra-low delay for real-time care, while BLE and ZigBee meet the needs of less time-sensitive monitoring. In sum, each technology offers a distinct balance of cost, efficiency, and performance, and their selection must align with the priorities of specific WBAN use cases. In this paper, we prefer to further examine two non-proprietary WBAN specifications, namely ZigBee/IEEE 802.15.4 and Wibree.

2 RELATED WORKS

2.1 Classification of protocol stacks

A classification of protocol stacks helps position ZigBee and Wibree within the broader WBAN ecosystem, improving clarity and completeness. By mapping technologies across the physical, MAC, network, and application layers, this framework highlights their interoperability and distinct features. ZigBee emphasizes low power and mesh networking, while Wibree (later absorbed into BLE) focuses on ultra-low power and Bluetooth compatibility. Including IEEE 802.15.6 and UWB in the layered model provides a structured comparison, clarifying each standard’s role, strengths, and limitations. This systematic view links technical specifications with application domains as shown in Table 2 in follows [12, 13].

Table 2: Protocol Stack Classification for WBAN Technologies.

Layer	ZigBee	BLE / Wibree	IEEE 802.15.6	UWB
Application	Healthcare monitoring, fitness tracking, emergency alerts, patient localization (all technologies)			

Network	Mesh, tree, star (multi-hop)	Star (smartphone/ central device)	Flexible (mainly star), body-centric	Star, optimized for localization & high throughput
MAC	CSMA/CA + optional GTS for QoS	Connection-oriented, low duty cycle	Multiple access: CSMA/CA, polling, scheduled	Time-hopping, impulse radio (low interference, high accuracy)
Physical (PHY)	Narrowband, 2.4 GHz ISM (sub-GHz variants)	Narrowband, 2.4 GHz ISM, ultra-low power	Narrowband, UWB, Human Body Communication (HBC)	Ultra-wideband (3.1–10.6 GHz), high precision, high data rate

2.2 ZigBee/IEEE802.15.4

ZigBee/IEEE 802.15.4 has been around for years. It has a four-layer protocol stack as shown in Figure 1. The lower two layers, the physical (PHY) layer and the medium access control (MAC) layer, are defined by the IEEE 802.15.4 committee, and the upper two layers, the network (NWK) layer and the application (APL) layer, are defined by the ZigBee Alliance. Application profiles can be specified based on the ZigBee/IEEE 802.15.4 protocol stack. They are either published by the ZigBee Alliance for public applications or specified by manufacturers for interoperability of their own products. These profiles facilitate a wide range of applications, including home automation, industrial control, and health monitoring. By ensuring compatibility across devices, they promote a seamless user experience and encourage innovation within the Internet of Things (IoT) ecosystem. According to [13], however, there is only one public application profile currently available, which is the Home Automation (HA) Public Application Profile. Others that are in the works include the ZigBee Smart Energy Profile, the Telecommunication Applications Profile, and the Personal Home and Hospital Care Profile. These profiles represent common application situations that are the focus of ZigBee/IEEE 802.15.4.

According to ZigBee/IEEE 802.15.4 specifications and application profiles, ZigBee Compliant Platform (ZCP) and ZigBee certified products are being manufactured. ZCPs are modules designed to serve as foundational components for end products. A ZigBee/IEEE802.15.4 end-user product can be either a Full-Function Device (FFD) or a Reduced-Function Device (RFD). Both of them work in the ISM bands, with physical layer data rates ranging from 20 kbps to 250 kbps. Mesh network is supported when FFD acts as a coordinator or router and RFD acts as an end device. As a result, the communication distance between two devices can be as long as 100 meters.

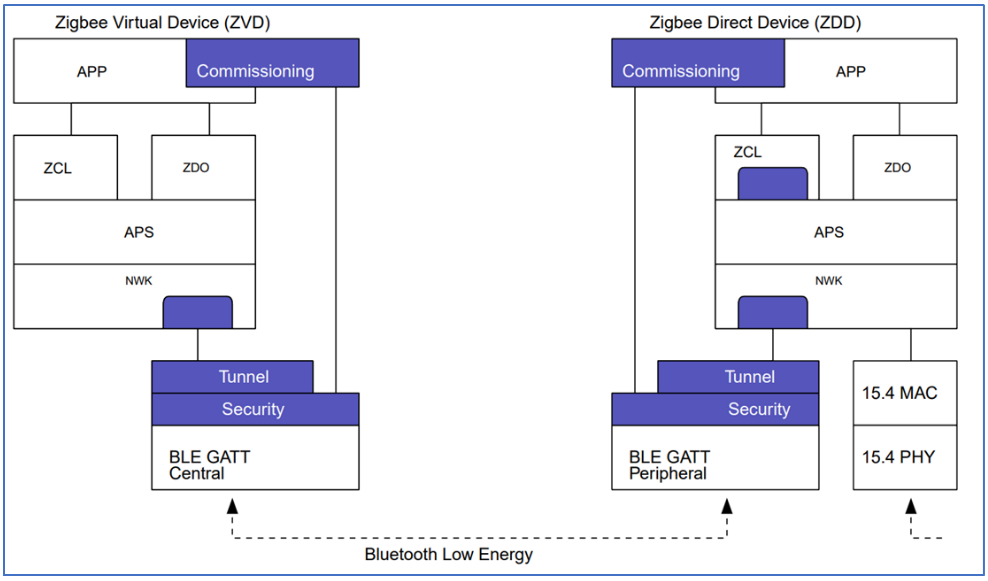

Figure 1: ZigBee/IEEE802.15.4 protocol stack.

2.3 Wibree

Wibree was formerly known as Low-End Extension (LEE) to Bluetooth, to facilitate wirelessly connecting small devices to mobile terminals. Those devices are often too small to handle the power consumption and costs associated with a standard Bluetooth radio. LEE is described as a hardware-optimized radio, indicating that its main differences from Bluetooth lie in the RF transceiver, baseband digital signal, data packet format, and possibly MAC mechanisms.

Although Wibree's exact specifications remain unknown, there is no detailed specification that has been published yet, as a datasheet is available from the Wibree Alliance, which presents the possible architecture and application scenarios of Wibree. As shown in Figure 2, one clear indication derived from the data sheet is that Wibree's protocol stack is expected to be a simplified Bluetooth edition. As a ULP extension to Bluetooth, Wibree aims at short-range applications only, shorter than the distance supported by ZigBee/IEEE802.15.4. That's why the first expected interoperability specification of Wibree will include these three profiles: Watch profile, Human Interface Device (HID) profile, and Sensor profile [14, 15, 16].

Similar to ZigBee/IEEE802.15.4 as shown in Figure 2, Wibree products are divided into two categories: Bluetooth-Wibree dual-mode chips and Wibree stand-alone chips. The latter are small devices powered by button cell batteries. Both types operate within the ISM 2.4 GHz band. Different from ZigBee/IEEE802.15.4, however, Wibree provides no mesh networking functionality and only supports a 10-meter communications distance with a 1 Mbps physical layer data rate. Output power of Wibree radio is reported to be around -6 dBm.

Because of collaboration and incorporation, the appearing Wibree specifications will probably differ from its initial proposed edition in some respects [14]. Take the physical data rate as an example; the originally proposed rate to LEE was 333 kbps, one-third of the expected Wibree data rate, taking advantage of a larger modulation index. Other examples may include logical channel assignment strategy, etc. In this paper, however, we refer to the very first paper presenting the idea of Bluetooth LE for PHY- and MAC-layer-related topics, refer to available resources concerning the MIMOSA project for middleware-related topics, and refer to both of these two, as well as the datasheet from the Wibree Alliance, for architecture-related topics.

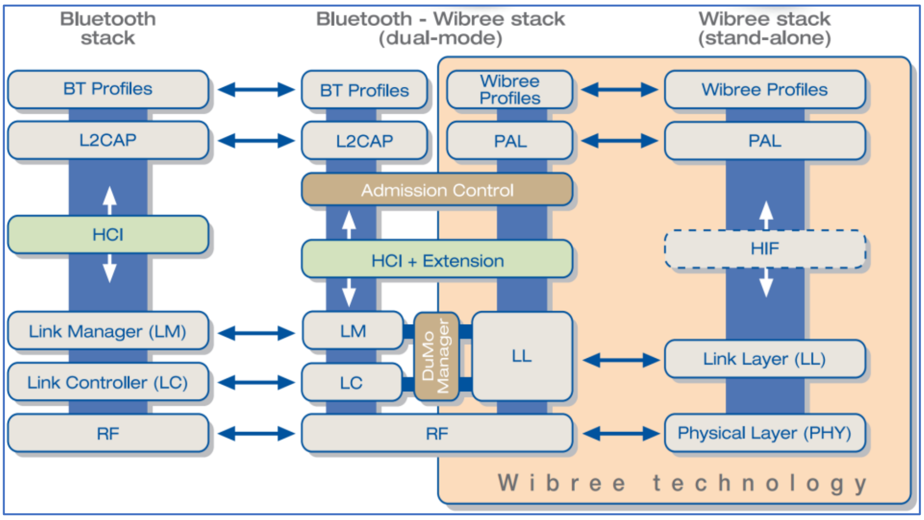

Figure 2: Wibree protocol stack.

3 PROTOCOL STACK DESIGN AND IMPLEMENTATION

3.1 Physical Layer

Wibree, as its second name ULP Bluetooth tells, has power consumption as its main concern. Early research [17] shows that two main sources that consume power are listed as follows:

- The 2.4 GHz RF components of the device (the current consumption ratio between the analog baseband stages and the RF components was approximately 90/10, according to the results).

- Current leakage while the chip is in sleep mode.

As a result, optimization of the transceiver has two corresponding aims:

- Replace analog stages with digital logic as much as possible.
- Design the IC circuit carefully to avoid current leakage to some extent.

Some of the physical layer parameters of IEEE 802.15.4 and LEE are summarized in Table 3 for comparison.

Table 3: IEEE802.15.4 and LEE's physical layer parameters.

	IEEE 802.15.4			LEE
Frequency band (MHz)	868-868.6	902-928	2400-2483.5	2400-2483.5
Carrier spacing (MHz)	1	2	5	1
Number of channels	1	10	16	27
Modulation	BPSK	BPSK	OQPSK	2GFSK
Spread Spectrum Technique	DS-SS	DS-SS	DS-SS	No hopping
Physical symbol rate (kbps)	20	40	62.5	166.5
Physical bit rate (kbps)	20	40	250	333

IEEE 802.15.4 provides three choices of frequency bands and corresponding data rates. As stated in [13], lower frequency provides longer range due to lower propagation losses. Low rate can be translated into better sensitivity and a larger coverage area. A higher rate means higher throughput, lower latency, or a lower duty cycle. Compared to radio parameters specified in IEEE 802.15.4, LEE has a higher bit rate and simpler modulation technique. 2GFSK can be demodulated using a non-coherent demodulator. Also, LEE deploys no spread spectrum technique, which should lead to a lower cost on chips. As compensation, however, LEE supports a shorter communications range and is subject to larger interference when compared to IEEE 802.15.4. The requirement for the Bluetooth RF to be reusable at a dual-mode device may be LEE's drawback. Since a dual-mode device will only have one transceiver, Bluetooth and Wi-Fi must share the transceiver in a reasonable manner. This may result in lower cost and less interference, but at the same time, lower efficiency.

3.2 MAC Layer

a) Responsibilities

Network beacon generation (coordinator), synchronization to network beacons, MAC association and disassociation support, MAC encryption support, unslotted/slotted CSMA-CA channel access, and GTS allocation and management are the duties of IEEE 802.15.4's MAC layer [13]. Four frame structures, *e.g.*, beacon, data, acknowledgement, and MAC command frames, are defined by IEEE 802.15.4. There are three different kinds of transactions for data transfer: between two peer devices, from a coordinator to a device, and from a device to a coordinator. The devices, not the coordinator, have total control over data transmissions. Depending on the application-defined rate, a device can either poll the coordinator for data or transfer data to the coordinator. By allowing the device to sleep whenever possible instead of keeping its receiver active all the time, this offers the ZigBee/IEEE 802.15.4 network's energy-saving feature.

As shown in Figure 2, the link layer of Wibree is a simplified version of Bluetooth's link control layer and link manager layer. Also, simplified frame structures and a logical channel assignment mechanism for LEE have been proposed in [14].

b) Frame Structure

To keep the transistor count minimal, the smaller the number of frame structures defined, the better. As aforementioned, there are four frame structures in IEEE 802.15.4. Though four different MAC frame structures existed for IEEE 802.15.4, they share one common underlying frame format, which is known as PHY Protocol Data Unit (PPDU). This is different from the scheme employed by LEE/Bluetooth and probably appearing in Wibree. LEE does not differentiate frame structures in the MAC layer, but in the physical layer, which are known as the baseband packets. Two frame structures are suggested for LEE, as shown in Figure 3.

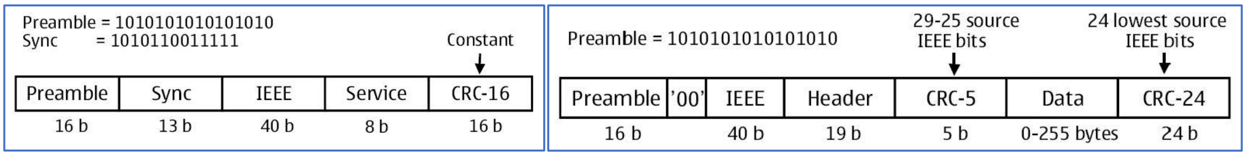

Figure 3: Schematic views of ID packet and DATA packet of LEE baseband packets.

The ID packet, as shown in Figure 3, is used to broadcast to all nearby devices, while the DATA packet is intended for a specific device. Comparatively, Bluetooth has two basic packet structures, but each of them is much more complicated.

c) Channel Assignment

Both IEEE 802.15.4 and LEE apply similar interference avoidance methods concerning how to allocate physical/logical channels. The interferences in the 2.4 GHz band come mainly from Wi-Fi and Bluetooth radios. By choosing channels that utilize the empty space between two nearby 802.11 channels, 15 and 20, as well as channels 25 and 26, IEEE 802.15.4 can prevent interference, as shown in Figure 4. LEE employs a similar channel assignment strategy to avoid interference. LEE maps its logical channels to physical channels according to frequency. There are two categories of logical channels in LEE: initialization and data channels. It is recommended that a default initialization channel be set at 2481 MHz, the maximum center frequency, away from Bluetooth and Wi-Fi interference. Another two secondary channels are introduced for jamming avoidance, with one in the middle of the spectrum (2463 MHz) and the other one at the bottom (2403 MHz). These are shown in Figure 5.

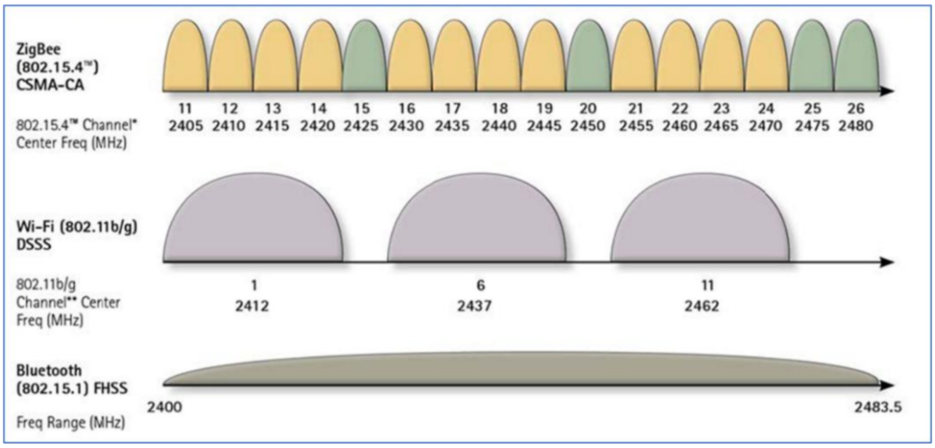

Figure 4: Channel assignment strategy of IEEE 802.15.4.

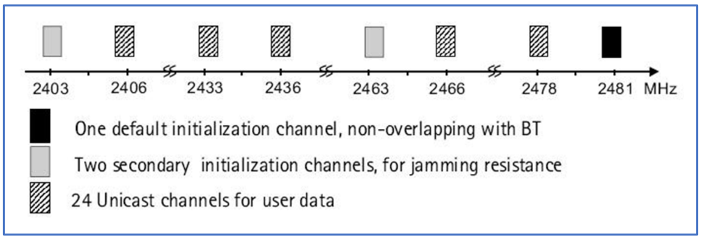

Figure 5: Channel assignment strategy of LEE.

d) Multiple-Access and Duplex Schemes

The IEEE 802.15.4 multiple-access system has two modes: beacon-enabled and non-beacon-enabled. A The IEEE 802.15.4 multiple-access system has two modes: beacon-enabled and non-beacon-enabled. A super frame structure is used when beacons are enabled. Active and inactive sections are the two divisions of a super frame. Depending on the needs of the application, devices may switch to a low-power mode during the inactive period. As shown in Figure 6, the Contention Access Period (CAP) and Contention Free

Period (CFP) make up the active portion. In the CFP, there are guaranteed time slots where there is no contention, whereas in the CAP, every device that wants to communicate must compete with other devices utilizing a slotted CSMA-CA method. Nevertheless, a coordinator may disable beacon transmissions and employ the unslotted CSMA-CA algorithm if they would rather not use the beacon-enabled option. For the same resources, uplink and downlink are in competition. There is no duplex scheme mentioned. Compared to IEEE 802.15.4, LEE only uses the contention-based access scheme CSMA for the connection setup channel (initialization channel). Only the contention-free access scheme FDMA is used for data delivery (data channel), and TDD is suggested to be the duplex scheme.

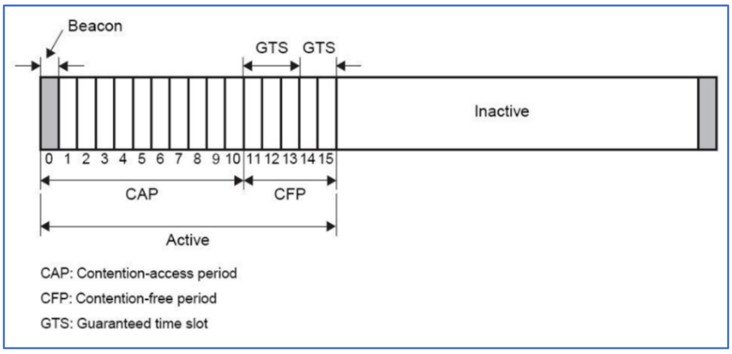

Figure 6: Super frame structure of IEEE 802.15.4.

e) Addressing

ZigBee uses the EUI-64 address format, while Bluetooth uses, and probably Wibree will use, EUI-48 address format. Though those address formats are defined for MAC layer, we have seen that both ZigBee and LEE middleware use MAC address for network layer routing.

3.3 Network Layer

a) Topology

Figure 7 illustrates the three topologies that ZigBee supports: mesh network, cluster tree, and star. A coordinator starts and manages the network in a star topology. Parameters about the network are chosen and stored by the coordinator. In a cluster tree topology, devices are organized with a tree-like hierarchy. A coordinator acts as the root of the tree, and some routers extend the network coverage by supporting child devices. Both star and cluster tree topologies are centralized networks. However, devices in a mesh network topology work in a peer-to-peer manner. It is made up of a network of linked routers and endpoints. A router can relay communications for its neighbors and is usually connected via two or more paths. In order to choose a dependable communications link and economical route, multi-hop communications are supported.

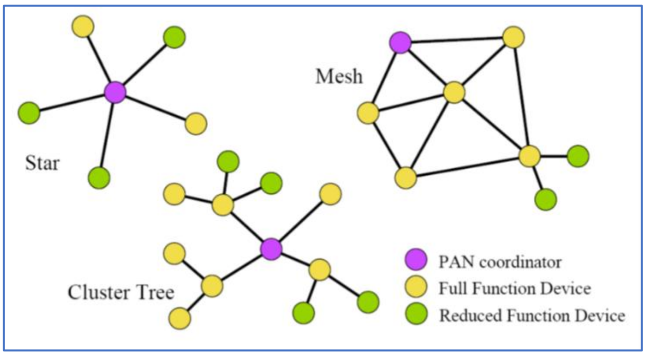

Figure 7: ZigBee network topology models.

Wibree's network topology can be inferred from Bluetooth's. Bluetooth supports two types of topologies: piconet and scatternet. Two or more devices that share a physical channel, meaning they are synchronized to a common clock and hopping sequence, make up a piconet. The Bluetooth clock of one of the piconet's devices, called the master, is the same as the common piconet clock. Slaves are all other devices that are synced. In ZigBee, this is actually a star architecture, where slaves are end devices and the master serves as a coordinator. The limited number of slaves that a single piconet can sustain is one of Bluetooth's prominent drawbacks. Although one slave engaging in multiple piconets can increase the maximum number of active slaves operating concurrently in a piconet to seven, this is not an effective method of linking nodes.

On a time-division multiplexing basis, a Bluetooth device can engage concurrently in two or more piconets, serving as a slave in both or all of them, or as a master or slave in each of them. A Bluetooth device is considered to be a part of a scatternet if it is a member of two or more piconets. The aforementioned cluster tree topology is a special case of a scatternet. The primary goal of supporting scatternet topology in Bluetooth is to reduce collisions, in addition to the advantage of adding cluster tree topology to ZigBee, which aims to increase a coverage area. This is because frequency-hopping spread spectrum systems often experience a graceful degradation of performance as more piconets in the same area are initiated.

b) Routing

When feasible, table-driven optimizations are used in the ZigBee routing algorithm, which may be viewed as a hierarchical routing method. The well-researched public-domain algorithms Ad hoc On Demand Distance Vector (AODV) and Motorola's Cluster-Tree algorithm are considered to be the first in the network layer. According to ZigBee’s specification, routing algorithms are based on either the 16-bit network address or the 64-bit IEEE address in a ZigBee network and are assigned during association by a coordinator. Each of the two addresses is the same as the corresponding part in the IEEE 802.15.4 MAC packet header. In other words, ZigBee uses MAC addresses for network layer routing.

On the contrary, the Bluetooth core protocols do not and are not intended to offer any routing functionality, which is the responsibility of higher-level protocols, *e.g.*, the middleware protocols. So will the Wibree protocol stack. Nano Internet Protocol (nanoIP) is an example of a middleware protocol that offers embedded and sensor devices networking capabilities similar to those of the Internet [18, 19]. Researchers from the University of Oulu in Finland created NanoIP with local addressing, wireless networking, and low overheads in mind. Since a local network does not require a huge address space, it uses the MAC address of the underlying network technology instead of IP addresses, which is the same method as ZigBee described above.

3.4 Transport-like Layer

Compared to the TCP/IP protocol stack, the APS sublayer in ZigBee and the L2CAP layer in Bluetooth function similarly to the transport layer in TCP/IP. The similarities reside in what services those layers provide to upper layers and how they provide these services.

a) Transport Layer in TCP/IP

The transport layer in TCP/IP provides to the application layer the end-to-end communications through a virtual private communications channel, the port. It assumes an unreliable network and thus can provide both unreliable services (UDP) for real-time applications and reliable services (TCP) whenever necessary. The reliability is achieved by deploying flow control and congestion control. The transport layer also provides assembly and disassembly functionalities through ports. A port uniquely identifies one communications entity through which end-to-end communications can happen.

b) APS Sublayer in ZigBee

The APS sublayer in ZigBee assumes a reliable underlying network because of the ARQ mechanism employed in the MAC layer. Thus, APS sublayers enhance this reliability and only provide reliable communications to the application layer through ports. With a different name to port, ZigBee calls this an endpoint. An endpoint is a device's internal communication channel that carries a particular application. Up to 241 endpoints, each with a number between 0 and 240, can be supported by a single ZigBee node; 0 is set aside for a single ZigBee Device Object (ZDO). Apart from offering endpoints, ZigBee also outlines certain administration features for connecting two or more endpoints.

c) L2CAP layer in Bluetooth and PAL Layer in Wibree

The L2CAP layer in Bluetooth also provides reliable communication between two Bluetooth devices. In a Bluetooth network, the protocol stack has already distinguished between voice and data transmission at a lower layer, where there is no retransmission for the voice channel. So as a higher layer focusing on data transmissions, L2CAP aims at providing only reliable communications channels. However, it distinguishes between its services in three categories: connectionless, connection-oriented, and signaling. The connectionless service corresponds to UDP in TCP/IP, but it's reliable and used for broadcasting. As a result, there is only one channel of this kind in a network. The connection service corresponds to TCP. Each connection is identified by a Channel Identifier (CID), which acts like a port or an endpoint. Each direction of the connection is assigned to a QoS flow specification, which is used for flow control of the transmitting packets.

Although no details of the PAL layer in Wibree have been released yet, with the corresponding location in the protocol stack as shown in Figure 2, the author speculates that the basic functionality of the PAL layer is multiplexing and demultiplexing, providing reliable/unreliable transmission services to Wibree devices through CID-like entities.

3.5 Implementation

A specification becomes a standard only when it is implemented. A protocol stack can be implemented completely in hardware, software, or firmware, or in any kind of combination of them. Taking both the time and cost of developing a product into consideration, normally, lower layers (the radio) of a protocol stack are implemented in hardware, middle layers in firmware, and higher layers in software. These are true for either ZigBee/IEEE802.15.4 or Bluetooth and Wibree.

a) ZigBee/IEEE802.15.4

A typical ZigBee/IEEE802.15.4 transceiver is CC2420, developed by Chipcon (now Texas Instruments). It integrates the 2.4 GHz radio part and implements the MAC layer partially in hardware. Software stacks (part of the MAC layer to application layer implementation) in the form of codes can be downloaded to flash memory and run by those microcontrollers, designed for low-power-consumption embedded applications. An example of this kind of platform is illustrated in Figure 8.

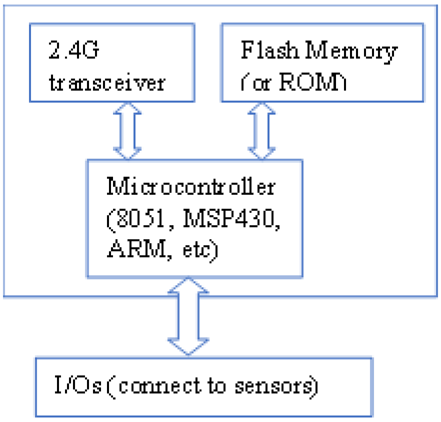

Figure 8. An example of ZigBee IEEE802.15.4 platform.

Software developers can either choose to develop their own software stack or pick those existing software stacks as long as they're compatible with the ZigBee specification. Two ZigBee software stacks are now being offered by chip vendors. One of these is Z-Stack, free from TI, and the other one is BeeStack, from Freescale. Chip vendors have integrated their software stacks into their platforms and made it a single chip with the system-on-chip technology. A SoC chip, *e.g.*, CC2430, combines CC2420, 8051MCU, memory, and Z-Stack together. It's easy to run chip vendor-provided software stacks on its chip, but one disadvantage associated with this is that this kind of software is designed for their chips and platforms only. Therefore, researchers from the University of California, Berkeley, and Intel Research developed an TinyOS operating system, which is a free and open-source component-based operating system targeting wireless sensor networks. TinyOS is compatible with other ZigBee/IEEE 802.15.4 software stacks but does not necessarily need to be implemented in the same way. It supports chips from different vendors, various MAC and network layer algorithms, as well as platforms. Currently, there is a huge number of ongoing research projects that are using TinyOS as the operating system. Companies like Sentilla (formerly Moteiv) and Ember have designed a few platforms with TinyOS as the software implementation. More ZigBee-compliant platforms can be found on the website of the ZigBee Alliance.

b) Wibree

Since its early collaboration with partners within the EU FP6 project MIMOSA, Wibree has been incorporated as one choice of radio connection for the MIMOSA architecture [20]. An alternative radio connection is RFID, for connecting remote-powered sensors, while Wibree is used for connecting battery-powered sensors. The Local MIMOSA device architecture is shown in Figure 9. The terminal, sensor radio node, and RFID sensor are the three distinct entities that make up the Local MIMOSA device architecture, which is seen in Figure 9. In order to integrate all of the many systems and provide ambient intelligence surrounding the user, each of these entities has the capacity to connect locally. The terminal offers remote connectivity to connect to distant application servers for additional functionality if needed by the use case. The sensor radio node in Figure 9 does actually have the same architecture as that in Figure 8. Compared to those concepts in the Wibree data sheet, a sensor radio node can be understood as a stand-alone device, and a terminal device as a dual-mode or maybe multi-mode device.

The global aim of MIMOSA is to make ambient intelligence a reality by developing a mobile-phone-centric open technology platform. One advantage of this mobile-phone-centric architecture over other sensor networks is that it requires less computational and networking capacity on sensor nodes. Also, a mobile phone can efficiently relay data from local sensors to a remote data processing center whenever necessary.

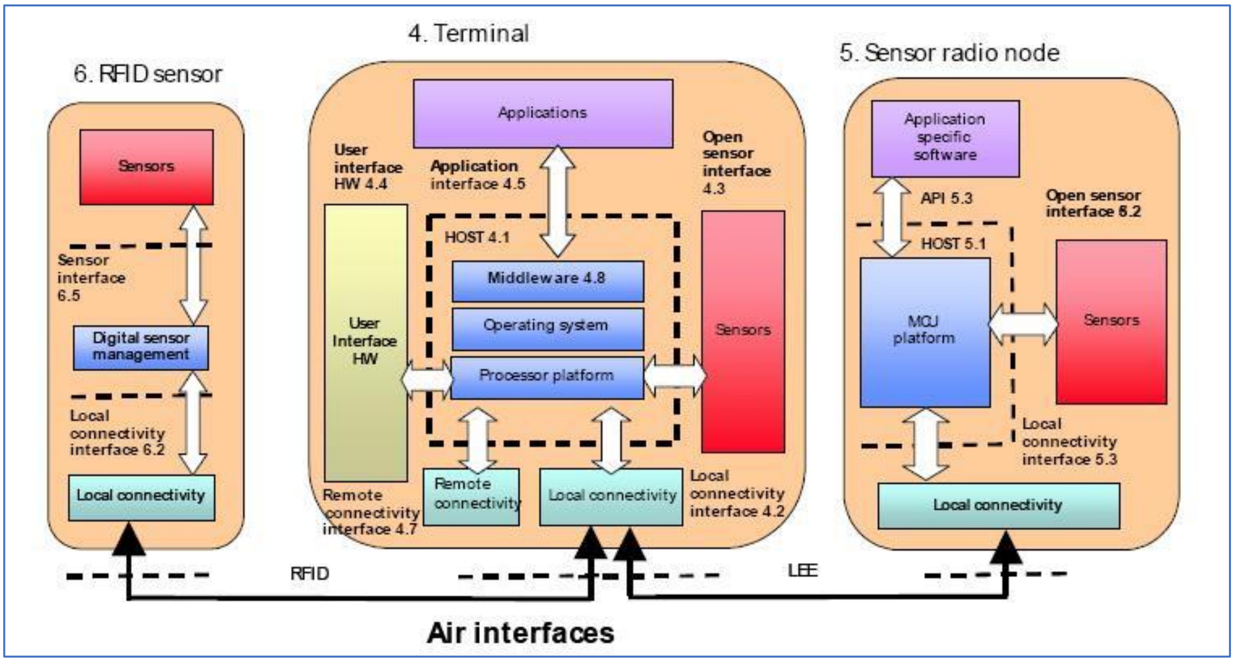

Figure 9: The Local MIMOSA device architecture.

Based on Figure 9, [21] has suggested a sensor network architecture in which a mobile phone serves as the main node that hosts apps and links a local sensor network to Internet back-end servers. A smartphone with add-on circuits has been used to effectively implement and illustrate the architecture. Additionally, in [22], a health care application built on this architecture was introduced. In [22], they focus on the sensor radio node and its counterpart at the terminal device end, which is known as an add-on sensor node. Basically, the two corresponding entities are implemented on management boards of the same kind except for their networking protocols. Compared to the Wibree stack (Bluetooth stack), the RF module here corresponds to its physical layer (RF radio in Bluetooth); MAC and radio baseband correspond to its link layer (baseband in Bluetooth, including link manager and link controller); M-SPI, which is a point-to-point wired connection protocol, corresponds to its HIF (HCI in Bluetooth); nanoIP corresponds to its PAL layer (L2CAP in Bluetooth, though they are not providing any routing functionality, the idea of multiplexing/demultiplexing is the same); and Simple Sensor Interface (SSI) corresponds to its profile

(profile in Bluetooth). The idea of making use of available protocols whenever possible is the same as that of Bluetooth.

3.6 Sensors

Although there are many different types of sensors, they can be broadly divided into mechanical, chemical, thermal, acoustic, and other types. The application scenario and the system infrastructure play a major role in determining the type and quantity of sensors that a system utilizes. Accelerometers are the type of sensors that are most frequently used in personal healthcare systems. The device may efficiently record the subject's movement by placing three orthogonally oriented accelerometers on certain body parts [23]. Gyroscopes have been shown to be an additional technique for applications including ambulatory gait monitoring and analysis, and they are a benefit or substitute for accelerometers. Researchers from ETH Zurich, Switzerland, and Lancaster University, United Kingdom, have built systems with 30 and 48 sensors separately because they believe that a few sensors are insufficient to identify a human's location and mobility [24, 25]. Many commercially accessible sensors, such as ECG/EMG/EEG, pulse oximetry, respiration, blood pressure, blood sugar, humidity, temperature, and CO_2 sensors, can be used to better monitor human activity and even its surroundings [26, 27].

a) Sensor Board

One crucial problem concerning a number of sensors is how signals from those sensors are integrated and processed. A general approach is described as this - sensors transfer other forms of energy to analog electronic signals, then signals are passed through a series of bandpass filters, after which a set of analog-to-digital (A/D) converters are used to digitalize those signals for processing. Sensors, A/Ds, and a microprocessor (or a DSP) are often implemented on one board as a module, which is shown in Figure 10. Note the N sensors in Figure 10 are in proximity. Normally more than one sensor board, each with a couple of sensors, will be deployed on the human body. The sensor board illustrated in Figure 10 is connected to the ZigBee/Wibree platform to access radios and thus can communicate with other nodes or a central processing unit. The interface between a sensor board and a ZigBee/Wibree platform can be of many choices, among which are UART, I2C, and SPI. A sensor management board developed as an implementation of MIMOSA architecture is shown in Figure 11. In this implementation, A/Ds are not on the sensor board but on the sensor management board, which only involves minor changes in signaling messages between these two boards.

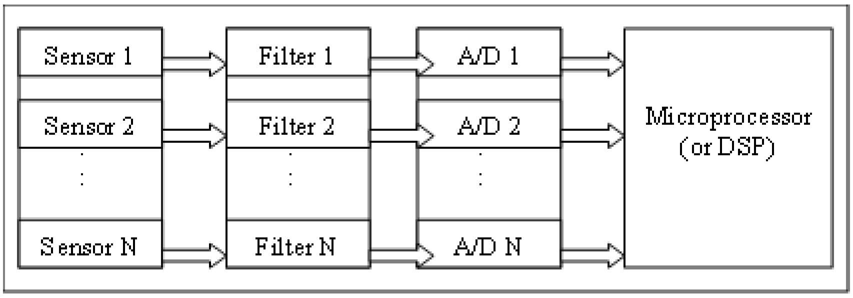

Figure 10: Architecture of a typical sensor board.

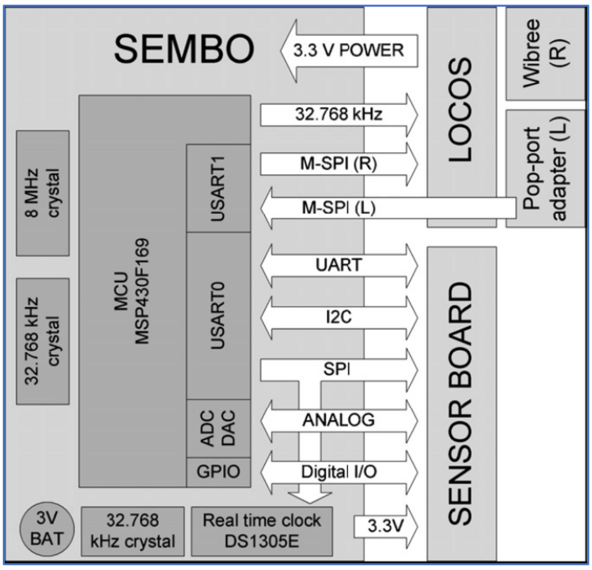

Figure 11: Sensor management board.

b) Signal Processing

Human daily movement has a relatively low frequency and amplitude range, as demonstrated by earlier research [26], which leads to a low sampling frequency and poor data transmission rate. According to different application scenarios, signal processing can apply to a sensor board, sensor management board, or a central unit collecting data from multiple sensors. For physical rehabilitation applications, which aim at simply monitoring a subject and making alerts, locomotion signals can be processed at each node (on a sensor management board) and transmitted to a remote server [6]. When applications involve more about psychological issues, the rehabilitation or monitoring of which may ask for context-computing, machine-learning techniques should be deployed at a central or remote processing center. Coupled hidden Markov models are used in [29] to describe interactions between two people; support vector machines and Bayesian theorem as well as graphical models may be used for classification, and Kohonen self-organizing maps may be used for mapping similar signals [27, 28].

4 FUTURE DEVELOPEMENT

Future development of WBAN technologies will be shaped by advances in energy efficiency, interoperability, security, and intelligent data processing. One of the foremost challenges is power consumption, as wearable and implantable devices require long operational lifetimes without frequent battery replacement. Research into energy harvesting techniques, such as exploiting body heat, movement, or ambient radio frequency signals, offers promising directions to extend device lifespan.

Another critical issue is interoperability among heterogeneous devices and standards. As healthcare increasingly relies on integrating sensors, wearables, and cloud services, seamless communication between ZigBee, BLE, IEEE 802.15.6, and emerging protocols will be essential. Future WBAN systems should support adaptive, cross-standard communication frameworks to ensure compatibility and scalability.

Security and privacy will remain central concerns due to the sensitive nature of medical data. Lightweight cryptographic protocols, secure authentication schemes, and privacy-preserving mechanisms must be developed to protect patients while maintaining low power consumption.

Finally, the integration of artificial intelligence (AI) and machine learning (ML) will play a transformative role in WBAN evolution. By enabling intelligent data processing at the device, edge, or fog-computing layer, AI/ML can enhance real-time decision-making, anomaly detection, and personalized healthcare monitoring. Coupled with edge/fog computing architectures, this will reduce latency and dependence on centralized cloud services, improving both responsiveness and reliability.

In summary, the future of WBAN technologies lies in achieving a balance between ultra-low power operation, secure and interoperable communication, and intelligent data-driven services, ultimately paving the way for robust and patient-centered healthcare systems.

5 CONCLUSION

We have examined, in this paper, issues concerning layered protocol stacks and system architecture, as well as hardware and software implementations of both ZigBee/IEEE802.15.4 and Wibree (LEE) protocol stacks. ZigBee/IEEE 802.15.4 and Wibree are probably the only two non-proprietary standards suitable for personal healthcare applications. Compared to each other, ZigBee/IEEE 802.15.4 supports a longer communications range and has more complicated protocols, which are designed for general wireless sensor networks; without complex routing algorithms, Wibree is likely to prefer simpler techniques and concentrate solely on short-range wireless networks. ZigBee may have a better chance of being accepted in the fields of home automation and industrial automation and control, but Wibree, given its association with Bluetooth, has a greater chance of becoming extensively utilized in the field of connecting peripheral devices surrounding the human body.

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KHẢO SÁT VỀ NGĂN XẾP GIAO THỨC CHO MẠNG CẢM BIẾN CƠ THỂ KHÔNG DÂY

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Tóm tắt. Mạng cảm biến cơ thể không dây (WBAN) là mạng tần số vô tuyến có độ phủ sóng tương đối ngắn. WBAN bao gồm một số lượng lớn các thiết bị tiêu thụ điện năng thấp có chức năng cảm biến hoặc bộ truyền động. Xét đến tính năng của nhiều loại cảm biến, WBAN có rất nhiều ứng dụng liên quan con người, trong đó có chăm sóc sức khỏe cá nhân. Khi được áp dụng cho các tình huống như chăm sóc sức khỏe, WBAN có thể tương tác với các mạng khác ở gần để mở rộng phạm vi truyền thông. Vì tính đa dạng trong ứng dụng của WBAN, bài báo này trình bày về các phiên bản WBAN công suất cực thấp và tốc độ thấp bằng cách so sánh hai ngăn xếp giao thức ZigBee/IEEE 802.15.4 và Wibree. IEEE 802.15.6 và UWB là hai công nghệ không dây khác có thể được ứng dụng trong WBAN, mỗi công nghệ lại phù hợp với những yêu cầu ứng dụng khác nhau. Trong các tình huống mà độ trễ đóng vai trò then chốt - chẳng hạn như phát hiện rối loạn nhịp tim, cảnh báo khẩn cấp, hoặc giám sát trong phẫu thuật - việc ưu tiên độ trễ siêu thấp khiến IEEE 802.15.6 và UWB trở thành lựa chọn phù hợp hơn. Ngược lại, đối với các ứng dụng ít nhạy cảm về thời gian hơn, bao gồm theo dõi thể chất hoặc thu thập dữ liệu định kỳ, Wibree và ZigBee mang lại giải pháp tiết kiệm năng lượng hơn. Wibree ban đầu được gọi là Bluetooth mở rộng tần số thấp và sau đó là Bluetooth công suất cực thấp. Để minh họa rõ hơn về Wibree, các thông số kỹ thuật của Bluetooth được đưa vào phần so sánh khi cần thiết. Chúng tôi đã so sánh các bối cảnh khác nhau được sử dụng bởi từng ngăn xếp giao thức chuyển từ lớp vật lý sang lớp ứng dụng. Sau đó, chúng tôi nghiên cứu các ứng dụng của cảm biến, với mục đích kết nối các mảng cảm biến y sinh.

Từ khóa. Mạng cảm biến cơ thể không dây, ZigBee, Bluetooth công suất cực thấp, cảm biến y sinh.

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