electronics

Article

Selected Energy Consumption Aspects of Sensor Data Transmission in Distributed Multi-Microcontroller Embedded Systems

Magdalena Szymczyk and Piotr Augustyniak *

AGH University of Science and Technology, 30-059 Kraków, Poland; magdalena.szymczyk@agh.edu.pl
* Correspondence: august@agh.edu.pl

Abstract: Wireless network devices are currently a hot topic in research related to human health, control systems, smart homes, and the Internet of Things (IoT). In the shadow of the coronavirus pandemic, they have gained even more attention. This remote and contactless distributed sensing technology enabled monitoring of vital signs in real-time. Many of the devices are battery powered, so appropriate management of available energy is crucial for lengthening autonomous operation time without affecting weight, size, maintenance requirement, and user acceptance. In this paper, we discuss energy consumption aspects of sensor data transmission using wireless Bluetooth Low Energy Mesh Long Range (BLE-M-LR) technology. Papers in the field of energy savings in wireless networks do not directly address the problem of the dependence of the energy needed for transmission on the type and degree of data preprocessing, which is the novelty and uniqueness of this work. We built and studied a prototype system designed to work as a multimodal sensing node in a compound IoT application targeted to assisted living. To analyze multiple energy-related aspects, we tested it in various operation and data transmission modes: continuous, periodic, and event-based. We also implemented and tested two alternative sensor-side processing procedures: deterministic data stream reduction and neural network-based recognition and labeling of the states. Our results reveal that event-based or periodic operation allows the node for years-long operating, and the sensor-side processing may degrade the power economy more than it benefits from savings made on transmission of concise data.

Keywords: embedded system; distributed system; multi-microcontroller system; artificial intelligence; intelligence sensor system; wireless transmission sensor network

Citation: Szymczyk, M.; Augustyniak, P. Selected Energy Consumption Aspects of Sensor Data Transmission in Distributed Multi-Microcontroller Embedded Systems. *Electronics* **2022**, *11*, 848. https://doi.org/10.3390/electronics11060848

Academic Editor: Giovanni Crupi

Received: 5 February 2022
Accepted: 4 March 2022
Published: 8 March 2022

1. Introduction

Modern proposals in the field of telemedicine employ microcontroller-based embedded systems with wireless communication. They use several specialized sensors selected for a given application. More and more often, they embed artificial intelligence. These are often mobile, battery-powered devices, where energy saving solutions are essential. Battery operation is primarily required for mobility, but it also provides an additional safety margin for the wearer directly contacted by the sensors.

Wireless devices (WD) have become an extremely attractive information technology in recent years. We can say that they have become a part of our lives in terms of exchange information and knowledge about our health. Wireless network devices are a key element of the currently developing smart wearable industry. The construction of such networks is subject to specific requirements, and the use of various WDs with different degree of complexity only intensifies this problem. Elements or nodes of this network are either sensors, actuators, or hub central nodes. For these nodes, requirements are defined in terms of data transmission quality, operational reliability, and application-specific quality of service (QoS). A wireless area network can of course cooperate with other networks. A wireless area network has several parameters that determine its sensible use for providing an optimal (in a certain sense) and reliable flow of information. These include power consumption, transmission latency, and bandwidth. As mentioned above, most of the network elements are powered by batteries, so effective management of their energy resources is crucial for proper operation of the entire network. The duration, frequency, and method of communication have a significant impact on the battery life, so these parameters must be under strict control.

In this paper, we discuss the energy consumption aspects of sensor data transmission, and a new prototype system for processing and sending signals is proposed [1-4] and tested in various energy-related perspectives.

Motivation

The very rapid development of technology related to the creation of ultraintegrated electronic systems, the possibility of wireless data transmission, and the emergence of modern sensors (including fully or partially implanted in the body of the patient) [5] paves the way for creating complex sensor systems, networks—responding to changes in vital parameters of the patient. Currently, the market for such solutions is growing day by day. The most popular and known single wireless devices include smart health watches [6]—Fitbit Versa 3, Samsung Galaxy Watch 3, and Apple Watch Series 6. These smartwatches can monitor vital signals from users and inform the user if something is wrong. To this group of generally available devices, we can add wearable ECG monitors (AliveCor's KardiaMobile 6L, Wellue's DuoEK, and VivaLNK), wearable blood pressure monitors (Omron Platinum, Withings BPM Connect, and LifeSource Upper Arm monitor), and other biosensors (Philips Biosensor BX100, Philips Wearable biosensor, and BiovitalsHF and Biovitals Sentinel by Biofourmis). Such devices are embedded in clothing, gloves, bandages, or implants [7]. These devices work on the principle of two-way data transmission between the user and, for example, a doctor or other electronic device (another sensor or information collector) and analyze selected aspects of the patient's health condition [8]. WDs are an elementary part of more complex systems such as WD interconnected networks. They are usually wireless networks with mobile nodes that require omnidirectional radio wave propagation. Examples of such networks can be found in numerous articles [9–12]. WDs usually have limited energy resources, mainly batteries, so in this type of networks, the problem arises how to save on the content and schedule of the data packets to ensure the longest lifetime of the network [13]. On the other hand, connectivity problems are known to be a critical feature of power consumption [14]. Low energy consumption is one of the most important goals in designing such networks. In the design of a wireless sensor network, a suitable duty cycle must be found to maintain an optimal point between energy consumption and transmission delay. To ensure uninterrupted, safe, and long-lasting operation of such a network, adaptive duty cyclic methods are proposed [15–22]. Many researchers are focused on developing different MAC (Media Access Control) protocols for wireless sensor networks (WSNs). The MAC protocol is responsible for energy savings in WSNs as it manages data packet transmission, overhearing, idle listening, and sleep/active time [23,24]. Various types of wireless transmission such as Bluetooth, ZigBee, Wi-Fi, Near-Field Communication (NFC), Radiofrequency Identification (RFID), and Infrared (IR) are employed in WD systems to provide wide range of possibilities and applications [25]. For example, a signal recorder with remotely programmable architecture is presented in [26]. The recorder supports wired and wireless body sensor networks. Any remote diagnosis based on a variety of spontaneous physiological signals (e.g., ECG, EMG) may be performed.

The problem of processing and sending biomedical signals in terms of energy efficiency is an important aspect of construction of such systems, which has an impact on energy demand and, consequently, determines the autonomous operation on battery power. This in turn affects the comfort of use and maintenance costs of such devices (frequency of battery replacement). In the following chapters, an analysis will be carried out from this point of view.

In the literature, we can find various types of considerations regarding energy savings in wireless sensor networks [1–4]. These reports concern various algorithms for optimizing energy consumption.

Research is motivated by the importance of power consumption and savings in sending biomedical signals in WBAN in different ways. The problem of characteristics of the transmitted signal or the method of data transmission does not appear very often in the available scientific papers on optimizing the energy consumption of WBANs. Some interesting issues in this regard are contained in [27,28].

The main contributions of this work are as follows:

- A general overview of selected current research papers related to wireless networks, especially Wireless Sensor Body Networks from the perspective of energy efficiency.
- An in-depth insight for currently available works related to data transmission and in particular the data organization-dependent factors of energy efficiency.
- A summary of possible software and hardware solutions related to minimizing energy consumption in these systems.
- A proposal of a prototype distributed telemedicine system made up of nodes with the possibility of an individual operational setting.
- A search and comparison of different methods of data preparation for transmission in order to achieve higher energy efficiency in this system.
- An investigation of the energy-saving aspect depending on the frequency of data transmission, data size, and the degree of processing before sending (from raw signal to semantic status description).
- A recognition of data states in the node using artificial intelligence algorithms (e.g., fall as a fact is recognized from acceleration sensors, instead of sending raw data to the central node—concentrator).

We proposed a general-purpose biomedical sensing node and studied energy-related aspects in continuous, periodic, and event-based data acquisition and transmission modes. We also tested it with two sensor-side processing procedures aiming at making a trade-off between processing and transmission energy requirements.

The paper is organized as follows. In Section 2, some introductory material on wireless networks in telemedicine with a focus on Wireless Body Area Networks (WBANs) is presented. For this type of network, a brief overview of current work in terms of energy-efficient solutions is provided. The possibilities of implementing artificial intelligence on microcontrollers along with a short description of communication based on the Bluetooth Low Energy Mesh Long Range protocol are also included. Finally, in this section, the technological solutions for energy saving in WBANs at the level of hardware and software are summarized. In Section 3, a prototype of a distributed telemedicine system is described. The results obtained from testing this prototype using various data transmission techniques are presented in Section 4. Finally, Section 5 concludes the article and identifies some open research questions.

2. Related Work

2.1. Embedded Systems

Embedded systems are widely used in almost all areas of life, and it is becoming increasingly difficult to find a device that would not have at least one such system. The embedded system usually consists of electronics based on a microcontroller, which has specialized peripherals (sensors, interfaces, etc.) and software that performs specific functions [29]. The role of software is essential as it provides the opportunity to program and reprogram sensor functionality including data-dependent behavior and flexible data transmission and to apply a unified hardware architecture to a wide range of sensors [30].

2.2. Distributed Systems

Since the price of a microcontroller is very low, it is possible to build a telemedicine device in the form of a distributed system, the elements of which are sensors directly (locally) connected to individually dedicated and programmed microcontrollers. This solution allows to minimize the length of connection between the sensor and the microcontroller, which in the case of analog sensors minimizes the problems associated with interference of external fields. The conversion of the read-out analog value to a digital value is performed locally using the analog to digital converters provided in the microcontroller. The resulting data can then be transmitted to a central chip for further analysis or to the cloud for future use. Moreover, digital communication in the sensor network protects data from distortion, and data ciphering is widely used to prevent unauthorized access [31].

2.3. WBANs

The new area in distributed and embedded systems is Wireless Body Area Networks (WBANs) integrated with human body for personal health monitoring. This term was first used by Van Dam et al., in 2001 [32]. It consists of small devices placed on or inside the human body that have the possibility of wireless communication. These solutions can reduce health care costs and have the potential to save human lives. Some researchers [33] treat WBANs as a subpart of WSNs (Wireless Sensor Networks), but very often, technologies designed for this type of network are not suitable for WBANs. One of the main differences between them is that the former have large limits on the computing power, memory, and energy required for data transmission too. These networks are also often heterogeneous. The basic differences between these two types of networks can be found in [32]. Proper operation of such a distributed microsensor network in the human body requires completely new solutions other than WSNs. Especially the problem of longevity of this type of network is very important. The long lifetime of a node with different operational requirements demands the design of a power-safe system at all levels of the system hierarchy, which is a very critical requirement [34]. The problem of designing and optimizing the performance parameters of the wireless sensor network is known to be a very difficult issue. The book [27] gives a foundation for WSNs and can be a good basis for further consideration of WBANs network architectures. An interesting summary of WSBANs, especially in terms of energy efficiency and reliability of operation, can be found in [35]. The authors of this article covered key issues in developing WSBANs applications and analyzed various performance issues of existing "energy-efficient and reliable routing solutions" for WBANs. Information about the energy-efficient protocols used in WSBANs is presented in the form of a table distinguishing protocols on the basis of the techniques used. The paper also presents a comparison of solutions discussed in the literature in terms of critical parameters for this type of network, including no. of dead nodes, pocket dropped ratio, packet received at sink, stability period, and delay. Some interesting aspects of how WBANs work can be found in [36]. The authors present basic aspects of this network and describe important scientific results in this area, especially routing protocols. Some issues and protocols in WBSNs are also discussed in [37–39].

During the design of WSN networks, many optimization tasks are performed which determine their effective operation according to some objective criterion. These networks may have a predetermined structure (topology), and for some tasks, they are sufficient, while for other applications, network architectures that adapt to the requirements are better. Topology control technology can be used to select an appropriate set of neighboring nodes in order to reduce certain undesirable phenomena occurring in them, such as a large number of nodes cooperating with each other or too high signal power to communicate with more distant nodes. This issue is closely related to the control of the transmission power of the node and, therefore, to the reduction of its energy consumption. The articles dealing with this subject include [27,40–43].

Another technology used in WSN for energy savings is transmission power control. This solution is implemented in real time and is aimed at reducing energy losses during signal transmission in the network and minimizing their impact on other devices and nodes of coexisting networks. According to the current state of the channel, the minimum level of signal power is adjusted to ensure effective delivery of the packet to the destination node. Various schemes have been proposed, e.g., [44–50], that can be used to control the transmission power in WSNs.

Some interesting mathematical aspects of combining topology control with network coding (data are encoded and decoded to increase network throughput) are presented in the paper [51].

2.4. Bluetooth Low Energy Mesh Long Range Communication

The data acquired at the local nodes of the distributed system are transmitted using the Bluetooth Low Energy Mesh Long Range (BLE-M-LR) protocol. This protocol is optimized for energy consumption. It also provides high security and connection reliability as a result of network "flooding" technologies. Microcontrollers with built-in BLE modules are universal, so they can be used directly as nodes of distributed systems with locally connected sensors. For more information on this communication standard, see, for instance, [52–59].

2.5. Artificial Intelligence Implemented in Microcontrollers

Today, we have a few applications of artificial intelligence in embedded systems. This component is implemented in various ways at different levels of the system.

Embedded systems with artificial intelligence may be categorized with respect to their autonomy:

- Remote intelligence systems (implemented outside the embedded system);
    - At the "edge" of the local network;
    - In the "cloud" (Google Cloud, Amazon AWS, IBM-Cloud, Microsoft Azure, Oracle AI Cloud.
- Systems with their own "large" computing power (implemented based on TPU—Google, VPU—Intel, GPU—Nvidia, ARM Cortex-A, Raspberry Pi, and STM32MP1).
- Systems with limited resources (with "small" microcontrollers) tailored for a tiny form factor and energy efficiency.

Due to the autonomous execution and local (i.e., sensor-side) availability of processed data, the most interesting is of course the last option. Compared to the remote intelligence option, it does not require transmission of large amounts of data, and this solution allows working even if the connection is lost, which is sometimes critical for safety reasons.

In this case, a special approach is needed to solve the problem of neural network architecture, data collection, and neural network training. It is also necessary to pay great attention to the optimization of memory used for the storage of structure and data of the neural network. Following the guidelines from the literature, we used the TensorFlow Lite library.

More information on embedded systems with artificial intelligence and limited resources is provided in [60–64].

2.6. Power Supply and Energy Saving

Each node in the system needs power. This is supplied either from batteries (single-use or rechargeable batteries) or from the mains with an emergency power backup in case the mains fail. There are also energy harvesting systems, but they will not be considered here. The autonomous operating time of the device depends on the capacity of the battery and the power consumption of the device. The time of autonomous operation is usually a key factor in assisted living systems, where complicated maintenance affects the commodity of use. The capacity of the battery in turn affects its weight, size, and price and consequently affects the user acceptance of the system. Therefore, the aim is to minimize the energy requirement. Energy savings can be achieved by using the appropriate hardware and software.

Hardware solutions to reduce energy consumption include [65–67]:

- Use of energy-efficient components (e.g., very highly efficient inverters instead of linear regulators, "ideal" diodes, and rectifier bridges with MOSFET transistors);
- Use of appropriate electronic designs (e.g., switching off unnecessary peripherals and eliminating the so-called "pull-up" resistor problem);
- Use of an appropriate microcontroller (energy-saving microcontroller with energy-efficient peripherals and power saving capabilities—appropriate operating state);
- Choosing the right supply voltage—the needs of the microcontroller and the peripherals;
- Selection of appropriate batteries (their voltage characteristics, weight, capacity, energy density, etc.)

Software solutions may also be applied to reduce power consumption. Examples include [67–73]:

- Detecting user activity (need for service) and on-demand switching on;
- Use of a suitable energy-efficient communication protocol (e.g., BLE);
- Optimal use of the protocol and transfer of processed data instead of raw measurement values;
- Use of artificial intelligence for the analysis and optimization of power consumption and data transmission;
- Activation of tasks after a defined time or by events (not pooling);
- Bare-metal programming—without an operating system;
- Using library functions;
- Using optimal algorithms and data structures;
- Adjustments of optimization options in a high-level language compiler;
- Global variables and function calls—online and naked functions;
- Pausing the microcontroller;
- Operating mode of the microcontroller (with careful settings of wake-up conditions);
- Pausing individual microcontroller modules;
- Minimization of frequency of the microcontroller oscillator (minimizing internal switching loss and resulting heat dissipation);
- Transmission of relative instead of absolute data (i.e., only what has changed).

3. Prototype Distributed Telemedical System

Based on the observations and information briefly described in the previous chapter, a new system for processing and sending biomedical signals is proposed.

This system consists of several cooperating components, which in turn are built from the hardware part and the corresponding software.

3.1. Hardware Platform

Figure 1 shows the general diagram of the proposed telemedicine system. It consists of nodes (Node #1,..., Node #N) with sensors of number and types selected according to the needs of particular application. These nodes are the multisensory acquisition points of the distributed system and communicate using the BLE-M-LR protocol.

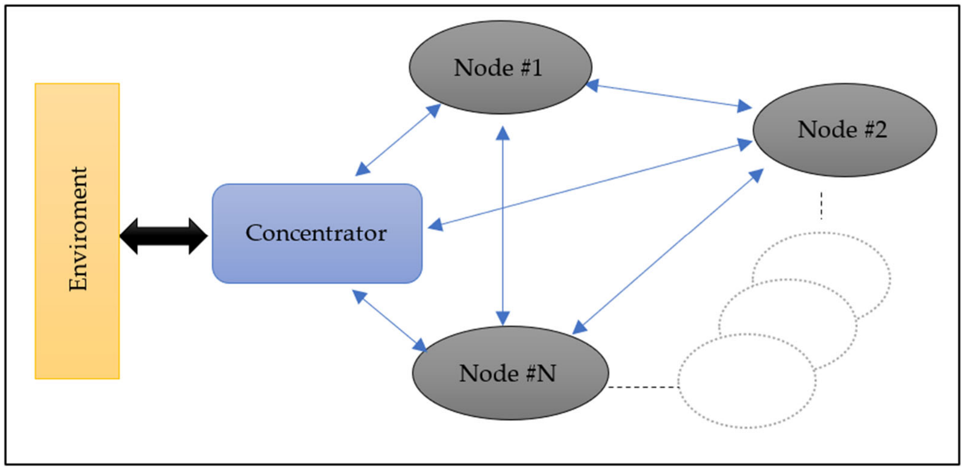

Figure 1. Architecture of the proposed system.

Figure 2 shows the internal design of the node which includes:

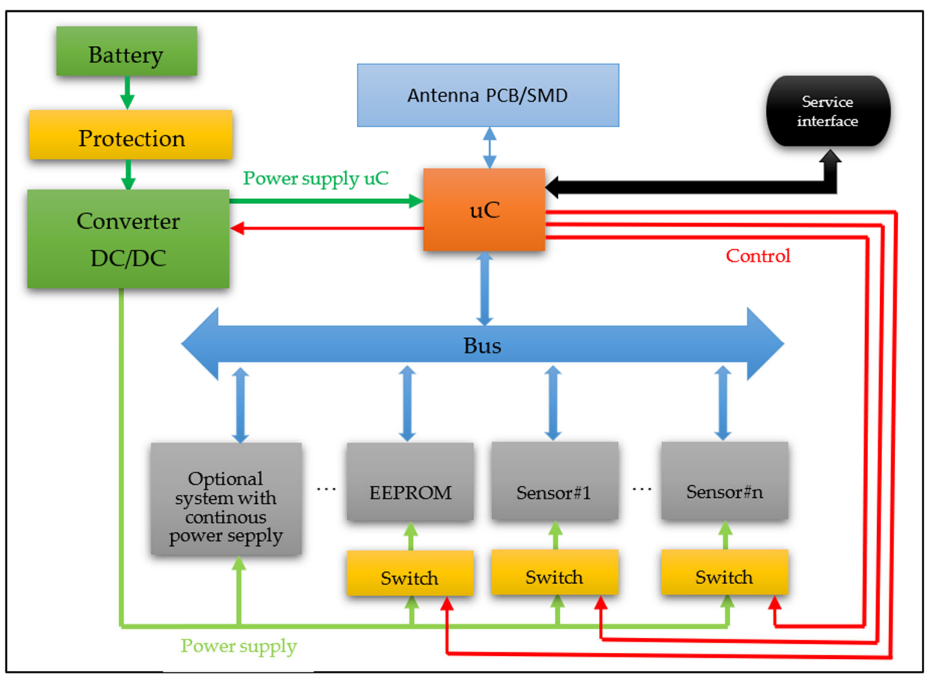

Figure 2. Architecture of Node X.

- Microcontroller;
- BLE antenna;
- Battery (or accumulator);
- Power supply system (protection, DC/DC converter, connectors);
- Service interface;

- Bus connecting the microcontroller with peripherals (e.g., I2C);
- Measurement sensors (type and number selected for a given application);
- Other optional circuits (e.g., signaling, displaying information);
- EEPROM memory.

To save energy, special attachments in the form of low-loss transistor keys [67] have been proposed to turn on the peripheral circuits needed at a given time.

The EEPROM stores measurement data and configuration information.

The sensory node proposed as a true-to-life example includes the following biomedical signal sensors: body temperature, pulse and blood saturation, 3D accelerometer, 3D gyroscope and GPS, and BLE locator. This set of devices gives five data streams with different characteristics, two of which are three-dimensional. The sensor node worn by the user gives the ability to monitor vital signs and detect anomalies and most dangerous situations, including falling or fainting. Additionally, thanks to GPS and BLE location, it is possible to quickly locate the user outdoors (GPS) and indoors (BLE). The frequency and accuracy of the measurements can be set for each node separately depending on the needs and nature of the user. It is possible to transmit raw (unprocessed) data, compressed data, alarm thresholds, or only on-board recognized events.

The concentrator (hub) shown in Figure 3 acts as an intermediary to the Internet or devices such as a computer, a smartphone, etc. It receives communicates from the nodes, then processes and forwards them. Even if it is a stationary power supply device, it is also equipped with rechargeable batteries as a backup power source that maintains the operation in case of power failure.

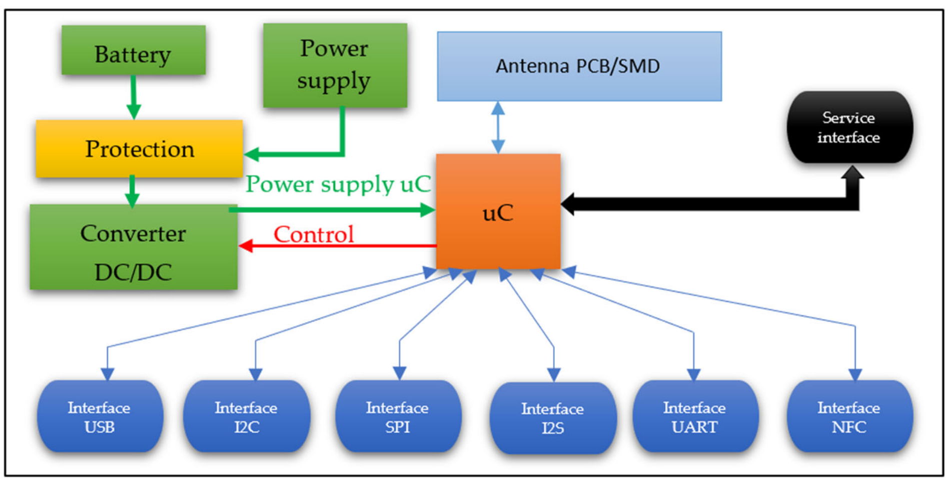

Figure 3. Diagram of the concentrator.

3.2. Software Layer

The software of the system consists of three main components:

- Management software;
- Hub software;
- Node software.

Management software is provided to configure the parameters of the whole system, collect data, process them, and share them with other external systems. With its help, the user sets all the parameters of the whole system, network parameters, individual settings of each node, and even the individual settings of each sensor.

Individual settings for each node define all operating parameters, for example:

- Operation (power) options: continuous, periodic, event-based;
- Supported requests (e.g., read on demand);

- Frequency of data sending from the node;
- Self-test procedure.

Individual settings for each sensor enable a more precise definition of data acquisition process and include:

- Frequency of reading data from the sensor;
- Frequency of sending data from the sensor;
- Data accuracy and its range;
- Alarm levels;
- Self-test.

Sensor data can be sent as raw data, i.e., without on-board processing, but from the viewpoint of data transmission economy, more interesting is to analyze sensor outcomes using a neural network and the TensorFlow Lite library.

In this case, the neural network must first be "trained" to recognize the "state" of the human or object under supervision. Since training on a low-resources platform is impractical, learning was done as a separate process implemented on external hardware beforehand, and then, the compressed neural network is "uploaded" to the node. This process is shown in detail in [74].

Instead of raw data, only recognized state identifiers are transmitted over the network, which significantly reduces the amount of information sent, the transmitter duty cycle, and necessary power.

The design of the node supports remote software upgrade via BLE. This is particularly important if the node is not easily accessible (e.g., due to its location at the patient's home). It is possible to upgrade both the communication software (system) on the node and the application that supervises the work of the node and the sensors connected to it.

4. Results

In addition to numerous advantages, the BLE-M-LR standard has several limitations. The most relevant are those related to data transmission:

- One data segment consists of 11 bytes;
- Transmission speed ranges from 10 to 100 kbps (128–1280 bps);

These limitations significantly affect the results.

A comparison of the data transmission performance and energy consumption of the node depends on its operating mode, data sending mode, and the nature of the data. These factors are separately presented below.

The following node operating modes have been programmed:

- Continuous;
- Periodic (with different periods for multiple sensor operation);
- Event-based.

In the continuous mode, the node runs perpetually with maximum computational power and never changes the transmitted data stream. In periodic mode, the node shares time in three phases. For time T_s it reads data from sensors, for time T_t it transmits the data, and for time T_w it enters to a power shutdown state. The time T_w determines the readout update rate and can be dynamically changed as needed (not only during the initial configuration). In the event-based operation mode, the node is in the energy saving state most of the time, maintaining only the procedures necessary for event detection. When a defined event occurs, the node is woken up and performs a reading, possibly processes the data, sends them, and then returns to the energy-saving state.

The following data transmission modes have been programmed:

- Continuous data stream;
- Periodic (with different periods and duty cycles);
- Event-based.

Like a node, the sensor can be configured to read data continuously. In this case, after each reading is finished, a new read cycle begins and so forth. Periodic data transmission mode is also possible, which consists in sending data from the sensor in given time intervals. This period can be changed (even during operation, not only in the initial system configuration) and adjusted to the individual situation, capabilities or needs.

According to the nature of data transmitted we distinguish four categories and programmed respective data structures:

- Raw data (accurate sensor readings);
- Simplified data (e.g., with reduced resolution or sampling frequency);
- State labels;
- Alarms.

Sensors deliver raw data, that is, data not processed by the node. The accuracy of the raw data depends on the sensor settings made during its configuration. Alternatively, the raw data are processed (i.e., converted, scaled) by the node and the accuracy is set accordingly. The node's hardware also supports application of pre-trained neural networks to process and recognize states of the object or human supervised by a multisensory node. Consequently, the neural network aggregates information from multidimensional raw data and detects states based on specific combinations of readings from multiple sensors. Additionally, the user can set alarms. These are data thresholds or states that trigger alarm events and data relevant to the situation are sent.

The availability of data sending modes depends on the current node operating mode as shown in Table 1. The nodes send data continuously, periodically (with different periods I, II, and III) and depending on event occurrence (event-based mode).

Table 1. Table of possible configurations of operating and data sending modes.

Modes of Sending Data	Node Operating Modes				
	Continuous	**Periodic I**	**Periodic II**	**Periodic III**	**Event**
Continuous	+	-	-	-	-
Periodic I	+	+	?	?	-
Periodic II	+	?	+	?	-
Periodic III	+	?	?	+	-
Event	+	?	?	?	+

Denotations: + denotes possibility, - none, ? means a possibility on the condition of multiple of the periods. ($T_{\text{Period III}} = n^*T_{\text{Period II}}$, $T_{\text{Period II}} = m^*T_{\text{Period I}}$, where n and m are positive integers).

4.1. Current Parameters of the Node

The node may have multiple sensors. The microcontroller applied is the nRF52840 from Nordic Semiconductor (Trondheim, Norway).

Table 2 collects the time and current parameters of the transmission process.

Table 2. Current parameters of the microcontroller in the transmission process.

Transmission Process State	Duration [µs]	Current [mA]
Pre-processing	60	4.2
Crystal ramp-up	400	1.6
Standby	1072	0.5
Start radio	130	3.3
Window widening	36	6.4
Radio RX	88	6.4
Radio switch	140	3.7
Radio TX	80	6.7
Post-processing	350	2.1

From these data, the single transmission time and the average current during transmission can be calculated as 2.356 µs and 188 µA, respectively. Table 3 collects the current parameters of the microcontroller corresponding to its operating state.

Table 3. Selected current parameters of the microcontroller.

Microcontroller State	Current [µA]
Normal operation of CPU	6300
Sleep	1
Transmission (for 2.356 µs)	188

Figure 4 is a graphical visualization of the data in Table 2.

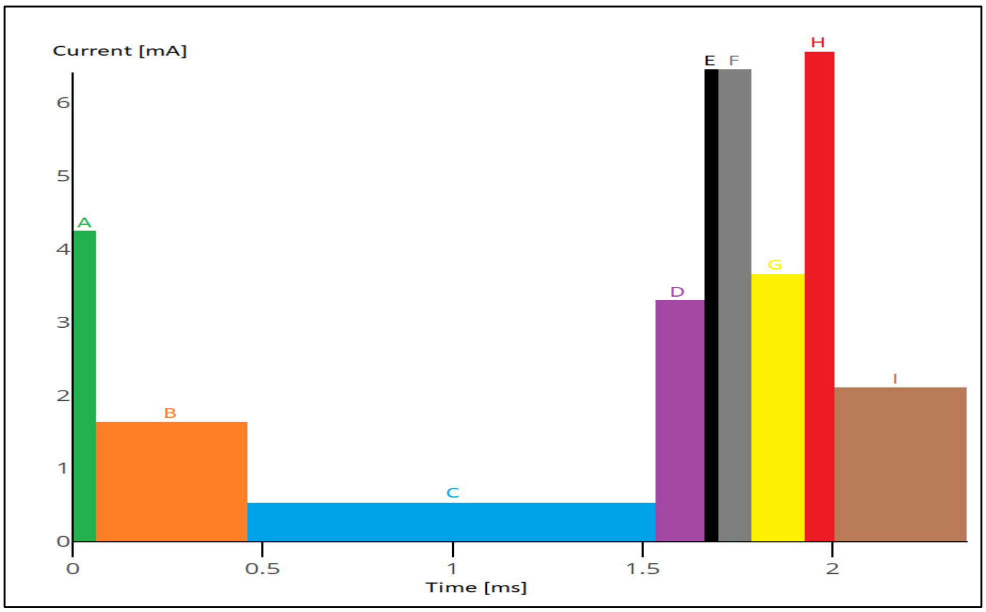

Figure 4. Transmission process state—(**A**): Pre-processing, (**B**): Crystal ramp-up, (**C**): Standby, (**D**): Start radio, (**E**): Window widening, (**F**): Radio RX, (**G**): Radio switch, (**H**): Radio TX, (**I**): Post-processing.

The full specification of the microcontroller can be found in [75,76].

4.2. Comparison of Raw Data Transmission with Transmission of Recognized States

An important part of our study was to estimate the potential benefits of applying distributed intelligence to sensor nodes. To this effect, we compare data streams as representative for wireless communication power in different operating configurations of the node (Table 4). Raw data are 2 bytes; simplified data are 1 byte, and status is 1 byte and alarm is also 1 byte.

Table 4. Table of data stream size dependence for different operating configurations.

Node Operation Mode	Data Transmission Mode	Character of Data Transmitted	Data Stream [bit/s]
Continuous	Continuous	Raw data	128
		Simplified data	64
		States	1
		Alarms	0
	Periodic I	Raw data	64
		Simplified data	32
		States	1
		Alarms	0
	Periodic II	Raw data	32
		Simplified data	16
		States	1
		Alarms	0
	Periodic III	Raw data	16
		Simplified data	8
		States	1
		Alarms	0
	Event-based	Raw data	2
		Simplified data	1
		States	1
		Alarms	0
Periodic I	Periodic I	Raw data	64
		Simplified data	32
		States	1
		Alarms	0
Periodic II	Periodic II	Raw data	32
		Simplified data	16
		States	1
		Alarms	0
Periodic III	Periodic III	Raw data	16
		Simplified data	8
		States	1
		Alarms	0
Event-based	Event-based	Raw data	2
		Simplified data	1
		States	1
		Alarms	0

As shown in Table 4, states are transmitted as infrequently as possible (once per maximum time—period), while alarms are basically unnoticed. Of course, the number of alarms depends on the system and configuration, but we assume that these are exceptional situations that very rarely occur. Consequently, they will be hardly noticeable and will have a marginal impact on the amount of transmitted data.

In addition to energy savings, an additional benefit of rare transmission of irregular data packets (such as periodic operation and transmission of state labels) is lower susceptibility to piracy.

4.3. Comparison of the Energy of the Two Transmission Types (Battery Life)

The second outcome of our study is the estimate of energy requirements in each operation and data transmission mode (Table 5).

Table 5. Table of average node current dependencies for different operating configurations.

Operation Mode of the Node	Mode of Data Transmission	Character of Transmitted Data	Average Current [μA]
Continuous	Continuous	Raw data	6300.05669
		Simplified data	6300.02835
		States	6300.00044
		Alarms	6300.00000
	Periodic I	Raw data	6300.02835
		Simplified data	6300.01417
		States	6300.00044
		Alarms	6300.00000
	Periodic II	Raw data	6300.01417
		Simplified data	6300.00709
		States	6300.00044
		Alarms	6300.00000
	Periodic III	Raw data	6300.00709
		Simplified data	6300.00354
		States	6300.00044
		Alarms	6300.00000
	Event-based	Raw data	6300.00089
		Simplified data	6300.00044
		States	6300.00044
		Alarms	6300.00000
Periodic I	Periodic I	Raw data	0001.02835
		Simplified data	0001.61888
		States	0001.63034
		Alarms	0001.00000
Periodic II	Periodic II	Raw data	0001.01417
		Simplified data	0001.30944
		States	0001.63034
		Alarms	0001.00000
Periodic III	Periodic III	Raw data	0001.00709
		Simplified data	0001.15472
		States	0001.63034
		Alarms	0001.00000
Event-based	Event-based	Raw data	0001.00089
		Simplified data	0001.00674
		States	0001.63034
		Alarms	0001.00000

Tables 4 and 5 show the dependencies of the amount of data transmitted and the average node current under different operating configurations, respectively. Table 5 also shows that the periodic operating mode addresses the energy saving aspect of the node. Due to the low duty cycle of the microcontroller and transmitter, in the periodic mode, current consumption drops by hundreds of times, which vastly increases the time of autonomous node operation. Sensor side state recognition does not contribute significantly to the continuous operation mode, but in the energy efficient periodic mode, additional processing decreases battery longevity by 63%.

5. Discussion

For continuous operation of the processor, the mode of data transmission and the nature of the transmitted data have little significance for current consumption. Continuous operation of the processor causes very high current consumption, and for a 3 V battery with a capacity of 3500 mAh (e.g., 2 × AA—R6 Energizer L91 Ultimate) the working time of the node will be about 23 days. The exact details of the proposed battery can be found in its specifications [77]. This autonomy time is acceptable in wearable or home care devices that are regularly maintained by health technicians. However, this scenario is not always possible in remote areas.

On the other hand, the most advantageous in terms of energy savings is sending only alarms and almost constantly putting the processor to sleep, which with the same battery will allow the node to work for about 40 years. However, such a battery will self-discharge sooner, the manufacturer determined this time to be about 20 years. The autonomy time exceeds the foreseen system usage cycle; however, the integrity of the network requires that all nodes be operated, and thus, the network is operable until the failure of the weakest energy source.

Two scenarios of data processing were considered in our studies: simplification and state recognition. In both cases, maintaining the microprocessor running costs energy that was not compensated for by savings on occasional transmission. As expected, recognizing states is not always beneficial. It depends on the size and frequency of data transfer and the compromise may only be established in particular sensing scenario. Moreover, due to limited resources of node system, states recognition always increases the risk of uncertainty, and therefore, should be applied carefully in particular when the raw signal is lost.

6. Conclusions

A very important aspect of designing a system for processing and sending biomedical signals is the choice of processor operating duty cycle and data transmission method. Both have a serious impact on energy consumption and consequently on battery life.

The proposed and analyzed system can be used to transmit various types of data from biosensors. The nature of the data, the degree of their processing, and the nature of the node's operation may determine the energy-efficient mode of data transmission. The investigation included only selected sensors and data, but the results may be easily generalized to pave the way for individual analysis of energetic aspects of sensing nodes cooperating in a wireless sensor network applied in assisted living scenarios.

There is no single best transmission method, and the optimal solution should be chosen according to specific needs, as shown in this paper.

The results of this work are planned to be applied to medical applications and to search for other possibilities of energy savings related to the optimization of data processing or transmission protocol. Moreover, it is intended to increase the security of transmitted data through the aspect of energy-efficient encryption (e.g., of states) located in the network node.

Author Contributions: Conceptualization, M.S. and P.A.; methodology, M.S..; software, M.S.; validation, M.S. and P.A.; formal analysis, M.S..; investigation, M.S.; resources, M.S.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing, P.A.; visualization, M.S.; supervision, P.A.; project administration, P.A.; funding acquisition, M.S. and P.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AGH University of Science and Technology in 2022 as research project No. 16.16.120.773.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Zeng, D.; Li, P.; Guo, S.; Miyazaki, T.; Hu, J.; Xiang, Y. Energy Minimization in Multi-Task Software-Defined Sensor Networks. *IEEE Trans. Comput.* **2015**, *64*, 3128–3139. https://doi.org/10.1109/tc.2015.2389802.
2. Fateh, B.; Govindarasu, M. Energy minimization by exploiting data redundancy in real-time wireless sensor networks. *Ad Hoc Netw.* **2013**, *11*, 1715–1731. https://doi.org/10.1016/j.adhoc.2013.03.009.
3. Fateh, B.; Govindarasu, M. Joint Scheduling of Tasks and Messages for Energy Minimization in Interference-Aware Real-Time Sensor Networks. *IEEE Trans. Mob. Comput.* **2015**, *14*, 86–98. https://doi.org/10.1109/tmc.2013.81.
4. Ammar, A.B.; Dziri, A.; Terre, M.; Youssef, H. Cross-Layer Approach Based Energy Minimization for Wireless Sensor Networks. *Wirel. Pers. Commun.* **2018**, *98*, 2211–2221.
5. Abdolmaleki, H.; Kidmose, P.; Agarwala, S. Droplet-Based Techniques for Printing of Functional Inks for Flexible Physical Sensors. *Adv. Mater.* **2021**, *33*, 2006792. https://doi.org/10.1002/adma.202006792.
6. Phaneuf, A. 5 Examples of Popular Wearable Devices in Healthcare. Available online: https://www.businessinsider.com/5-examples-wearable-healthcare-devices-2021-5?IR=T (accessed on 19 September 2021).
7. Ding, X.-R.; Clifton, D.; Ji, N.; Lovell, N.H.; Bonato, P.; Chen, W.; Yu, X.; Xue, J.; Xiang, T.; Long, X.; et al. Wearable Sensing and Telehealth Technology with Potential Applications in the Coronavirus Pandemic. *IEEE Rev. Biomed. Eng.* **2020**, *14*, 48–70. https://doi.org/10.1109/rbme.2020.2992838.
8. Kruglyak, I. 20 Examples of Wearables and IoT Disrupting Healthcare. Available online: https://www.avenga.com/magazine/wearables-iot-healthcare/ (accessed on 19 September 2021).
9. Bokolo, A., Jr. Application of telemedicine and eHealth technology for clinical services in response to COVID-19 pandemic. *Health Technol.* **2021**, *11*, 359–336.
10. Obika, B.D.; Dolezova, N.; Ponzo, S.; Valentine, S.; Shah, S.; Gledhill, J.; Plans, D.; Nicholson, C.; Walters, C.; Stephen, L.; et al. Implementation of a mHealth solution to remotely monitor patients on a cardiac surgical waiting list: Service evaluation. *JAMIA Open* **2021**, *4*, ooab053.
11. Atilgan, K.; Onuk, B.E.; Coskun, P.K.; Yesïl, F.G.; Aslan, C.; Çolak, A.; Celebï, A.S.; Bozbas, H. Remote Patient Monitoring after Cardiac Surgery: The Utility of a Novel Telemedicine System. *J. Card. Surg.* **2021**, *36*, 4226–4234. https://doi.org/10.1111/jocs.15962.
12. Islam, M.; Mahmud, S.; Muhammad, L.J.; Nooruddin, S.; Ayon, S.I. Wearable Technology to Assist the Patients Infected with Novel Coronavirus (COVID-19). *SN Comput. Sci.* **2020**, *1*, 320. https://doi.org/10.1007/s42979-020-00335-4.
13. Addo, E.; Kommey, B.; Agbemenu, A. Wearable Networks: Requirements, Technologies, and Research Trends. *J. Appl. Inf. Syst.* **2019**, *12*. https://doi.org/10.5120/ijais2019451789.
14. Magno, M.; Brunelli, D.; Sigrist, L.; Andri, R.; Cavigelli, L.; Gomez, A.; Benini, L. InfiniTime: Multi-sensor wearable bracelet with human body harvesting. *Sustain. Comput. Inform. Syst.* **2016**, *11*, 38–49. https://doi.org/10.1016/j.suscom.2016.05.003.
15. Kansal, A.; Hsu, J.; Zahedi, S.; Srivastava, M. Power management in energy harvesting sensor networks. *ACM Trans. Embed. Comput. Syst.* **2007**, *6*, 32. https://doi.org/10.1145/1274858.1274870.
16. Hsu, J.; Zahedi, S.; Kansal, A.; Srivastava, M.; Raghunathan, V. Adaptive duty cycling for energy harvesting systems. In Proceedings of the 2006 International Symposium on Low Power Electronics and Design, Tegernsee, Germany, 4–6 October 2006; pp. 180–185.
17. Vigorito, C.; Ganesan, D.; Barto, A. Adaptive control of duty cycling in energy-harvesting wireless sensor networks. In Proceedings of the Fourth Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON 2007, San Diego, CA, USA, June 18-21, 2007; pp. 21–30.
18. Gu, Y.; Zhu, T.; He, T. ESC: Energy synchronized communication in sustainable sensor networks. In Proceedings of the 17th IEEE International Conference on Network Protocols (ICNP 2009), Plainsboro, NJ, USA, 13–16 October 2009; pp. 52–62.
19. Zhu, T.; Zhong, Z.; Gu, Y.; He, T.; Zhang, Z.-L. Leakage-aware energy synchronization for wireless sensor networks. In Proceedings of the Mobisys '09: The 7th International Conference on Mobile Systems, Applications, and Services, Kraków, Poland, 22–25 June 2009; pp. 319–332.
20. Sharma, V.; Mukherji, U.; Joseph, V.; Gupta, S. Optimal energy management policies for energy harvesting sensor nodes. *IEEE Trans. Wirel. Commun.* **2010**, *9*, 1326–1336.
21. Moser, C.; Chen, J.-J.; Thiele, L. An energy management framework for energy harvesting embedded systems. *ACM J. Emerg. Technol. Comput. Syst.* **2010**, *6*, 1–21. https://doi.org/10.1145/1773814.1773818.
22. Shah, I.K.; Maity, T.; Dohare, Y.S. Algorithm for energy consumption minimisation in wireless sensor network. *IET Commun.* **2020**, *14*, 1301–1310. https://doi.org/10.1049/iet-com.2019.0465.

23. Gopalan, S.A.; Park, J.-T. Energy-efficient MAC protocols for wireless body area networks: Survey. In Proceedings of the International Congress on Ultra Modern Telecommunications and Control Systems, Moscow, Russia, 18–20 October 2010. https://doi.org/10.1109/ICUMT.2010.5676554.
24. Kutty, S.; Laxminarayan, J. Towards energy efficient protocols for wireless body area networks. In Proceedings of the 2010 5th International Conference on Industrial and Information Systems, Mangalore, India, 29 July–1 August 2010. https://doi.org/10.1109/ICIINFS.2010.5578739.
25. Park, Y.-G.; Lee, S.; Park, J.-U. Recent Progress in Wireless Sensors for Wearable Electronics. *Sensors* **2019**, *19*, 4353. https://doi.org/10.3390/s19204353.
26. Augustyniak, P. Remotely programmable architecture of a multi-purpose physiological recorder. *Microprocess. Microsyst.* **2016**, *46*, 55–66. https://doi.org/10.1016/j.micpro.2016.07.007.
27. Kar, H.; Willig, A. *Protocols and Architectures for Wireless Sensor Networks*; John Wiley & Sons Ltd: Hoboken, NJ, USA, 2005.
28. Alkhayyat, A.; Jawad, S.F.; Sadkhan, S. Cooperative Communication based: Efficient Power Allocation for Wireless body Area Networks. In Proceedings of the 2019 1st AL-Noor International Conference for Science and Technology (NICST), Sulaymaniyah, Iraq, 25–29 October 2019.
29. White, E. *Making Embedded Systems: Design Patterns for Great Software*, 1st ed.; O'Reilly Media: Sebastopol, CA, USA, 2012.
30. Lacamera, D. *Embedded Systems Architecture: Explore Architectural Concepts, Pragmatic Design Patterns, and Best Practices to Produce Robust Systems*, 1st ed.; Packt Publishing: Birmingham, UK, 2018.
31. Burns, B. *Designing Distributed Systems: Patterns and Paradigms for Scalable, Reliable Services*, 1st ed.; O'Reilly Media: Sebastopol, CA, USA, 2018.
32. Latré, B.; Braem, B.; Moerman, I.; Blondia, C.; Demeester, P. A survey on wireless body area networks. *Wirel. Netw.* **2011**, *17*, 1–18. https://doi.org/10.1007/s11276-010-0252-4.
33. Vyas, A.; Pal, S.; Saha, B.K. Relay-based Communication in WBANs: A Comprehensive Survey. *ACM Comput. Surv.* **2022**, *54*, 2.
34. Min, R.; Bhardwaj, M.; Cho, S.-H.; Shih, E.; Sinha, A.; Wang, A.; Chandrakasan, A. Low-Power Wireless Sensor Networks. In Proceedings of the Fourteenth International Conference on VLSI Design, Bangalore, India, 7 January 2001; pp. 205–210.
35. Ullah, F.; Khan, M.Z.; Mehmood, G.; Qureshi, M.S.; Fayaz, M. Energy Efficiency and Reliability Considerations in Wireless Body Area Networks: A Survey. *Comput. Math. Methods Med.* **2022**, *2022*, 1090131. https://doi.org/10.1155/2022/1090131.
36. Movassaghi, S.; Abolhasan, M.; Lipman, J.; Smith, D.; Jamalipour, A. Wireless Body Area Networks: A Survey. Computer Science *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1658–1686.
37. Chen, C.; Knoll, A.; Wichmann, H.-E.; Horsch, A. A Review of Three-Layer Wireless Body Sensor Network Systems in Healthcare for Continuous Monitoring. *J. Mod. Internet Things* **2013**, *2*, 24–34.
38. Yessad, N.; Omar, M.; Tari, A.K.; Bouabdallah, A. QoS-based Routing in Wireless Body Area Networks: A Survey and Taxonomy. *Computing* **2018**, *100*, 245–275.
39. Sangwan, A.; Bhattacharya, P.P. Wireless Body Sensor Networks: A Review. *Int. J. Hybrid Inf. Technol.* **2015**, *8*, 105–120.
40. Guan, Q.; Yu, F.R.; Jiang, S.; Leung, V.C.M. Capacity-Optimized Topology Control for MANETs with Cooperative Communications. *IEEE Trans. Wireless Comm.* **2011**, *10*, 2162–2170.
41. Guan, Q.; Yu, F.R.; Jiang, S.; Leung, V.C.; Mehrvar, H. Topology control in mobile Ad Hoc networks with cooperative communications. *IEEE Wirel. Commun.* **2012**, *19*, 74–79. https://doi.org/10.1109/MWC.2012.6189416.
42. Deshpande, A.; Montiel, C.; McLauchlan, L. Wireless Sensor Networks—A Comparative Study for Energy Minimization Using Topology Control. In Proceedings of the 2014 Sixth Annual IEEE Green Technologies Conference, Corpus Christi, TX, USA, 3–4 April 2014; pp. 44–48.
43. Xu, M.; Zhu, H.; Wang, J.; Xu, H.; Li, C. Low-Cost Topology Control for Data Collecting in Duty-Cycle Wireless Sensor Networks. In Proceedings of the 2020 IEEE 18th International Conference on Industrial Informatics, (INDIN), Warwick, UK, 20–23 July 2020; pp. 828–832.
44. Xiao, S.; Dhamdhere, A.; Sivaraman, V.; Burdett, A. Transmission Power Control in Body Area Sensor Networks for Healthcare Monitoring. *IEEE J. Sel. Areas Commun.* **2009**, *27*, 37–48. https://doi.org/10.1109/jsac.2009.090105.
45. Smith, D.B.; Hanlen, L.W.; Miniutti, D. Transmit power control for wireless body area networks using novel channel prediction. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Paris, France, 1–4 April 2012; pp. 684–688.
46. Newell, G.; Vejarano, G. Human-motion based transmission power control in wireless body area networks. In Proceedings of the IEEE 3rd World Forum on Internet of Things (WF-IoT), Reston, VA, USA, 12–14 December 2016; pp. 277–282.
47. Wang, Z.; Zhou, J. Power control mechanism in software defined wireless networking. In Proceedings of the 2016 8th IEEE International Conference on Communication Software and Networks (ICCSN), Beijing, China, 4–6 June 2016; pp. 428–431.
48. Priyesh, P.P.; Kar, S. Dynamic Transmission Power Control in Wireless Sensor Networks Using P-I-D Feedback Control Technique. In Proceedings of the 2017 9th International Conference on Communication Systems and Networks (COMSNETS), Bengaluru, India, 4–8 January 2017.
49. Fernandes, D.; Ferreira, A.G.; Abrishambaf, R.; Mendes, J.; Cabral, J. A Low Traffic Overhead Transmission Power Control for Wireless Body Area Networks. *IEEE Sens. J.* **2018**, *18*, 1301–1313. https://doi.org/10.1109/jsen.2017.2778802.
50. Newell, G.; Vejarano, G. Motion-Based Routing and Transmission Power Control in Wireless Body Area Networks. *IEEE Open J. Commun. Soc.* **2020**, *1*, 444–461. https://doi.org/10.1109/ojcoms.2020.2986396.

51. Khalily-Dermany, M.; Nadjafi-Arani, M.J. Mathematical Aspects in Combining Network Coding with Transmission Range Adjustment. *IEEE Commun. Lett.* **2019**, *23*, 1568–1571. https://doi.org/10.1109/lcomm.2019.2924625.
52. Heybon, R. *Bluetooth Low Energy: The Developer's Handbook*, 1st ed.; Pearson: London, UK, 2012.
53. Townsed, K.; Cifi, C.; Davidson, R.; Akiba. *Getting Started with Bluetooth Low Energy: Tools and Techniques for Low-Power Networking*, 1st ed.; O'Reilly Media: Sebastopol, CA, USA, 2014.
54. Bhardgava, M. *IoT Projects with Bluetooth Low Energy: Harness the Power of Connected Things*, 1st ed.; Packt Publishing: Birmingham, UK, 2017.
55. Gaitatzis, T. *Bluetooth Low Energy: A Technical Primer: Learn the Mechanics Behind: Sensors, Remote Controls, Beacons, Transmitters Using*; BackupBrain Publishing: Wroclaw, Poland, 2017.
56. Aftab, M. *Building Bluetooth Low Energy Systems*, 1st ed.; Packt Publishing: Birmingham, UK, 2017.
57. Gupta, N. *Inside Bluetooth Low Energy*, 2nd ed.; Artech House: Norwood, MA, USA, 2016.
58. Allan, A.; Coleman, D.; Mistry, S. *Make: Bluetooth: Bluetooth LE Projects for Arduino, Raspberry Pi, and Smartphones*, 1st ed.; Maker Media: San Francisco, CA, USA, 2015.
59. Bluetooth Mesh. Available online: https://www.nordicsemi.com/Products/Bluetooth-mesh (accessed on 9 September 2021).
60. Rydosz, A.; Marszałek, K.; Putynkowski, G. A novel approach for device dedicated to non-invasive diabetes control. *J. Diabetes Treat.* **2020**, *5*, 1077.
61. Nordic Semiconductor Makes AI and Machine Learning Easily Accessible on Resource Constrained Wireless IoT Chips for the Very First Time. Available online: https://www.nordicsemi.com/News/2021/01/Edge-Inpulse-and-Nordic-partnership (accessed on 9 September 2021).
62. Getting Started with the Arduino Nano 33 BLE. Available online: https://www.arduino.cc/en/Guide/NANO33BLE (accessed on 9 September 2021).
63. Cloud AI, Edge AI, Endpoint AI. What's the Difference? Available online: https://www.arm.com/blogs/blueprint/cloud-edge-endpoint-ai (accessed on 9 September 2021).
64. Embedded Artificial Intelligence: Reconfigurable Processing Accelerates AI in Endpoint Systems for the OT Market. Available online: https://info.renesas.com/recn-e-ai-white-paper (accessed on 9 September 2021).
65. Siewert, S. *Real-Time Embedded Components and Systems: With Linux and RTOS*; Mercury Learning and Information: Herndon, VA, USA, 2016.
66. Tsiatsis, V.; Fikouras, I.; Avesand, S.; Karnouskos, S.; Mulligan, C.; Boyle, D.; Holler, J. *From Machine-to-Machine to the Internet of Things: Introduction to a New Age of Intelligence: Technologies and Applications for a New Age of Intelligence*; Academic Press Inc.: Cambridge, MA, USA, 2014.
67. Szymczyk, P.; Szymczyk, M. Enerdooszczędne algorytmy w systemach wbudowanych (Energy-saving algorithms in embedded systems). *Automatyka* **2011**, *15*, 451–458 (In Polish).
68. Gunnar, J. Improve Battery Life in Ultra Low Power Wireless Applications. Available online: https://blog.nordicsemi.com/getconnected/improve-battery-life-in-ultra-low-power-wireless-applications (accessed on 9 September 2021).
69. Amini, K. *Extreme C: Taking You to the Limit in Concurrency, OOP, and the Most Advanced Capabilities of C*, 1st ed.; Packt Publishing: Birmingham, UK, 2019.
70. Linden, P. *Expert C Programming: Deep Secrets*, 1st ed.; Pearson: London, UK, 1994.
71. Guntheroth, K. *Optimized C++: Proven Techniques for Heightened Performance*, 1st ed.; O'Reilly Media: Sebastopol, CA, USA, 2016.
72. Meyers, S. *Effective C++: 55 Specific Ways to Improve Your Programs and Designs*, 3rd ed.; Addison-Wesley Professional: Boston, MA, USA, 2019.
73. Szymczyk, P.; Szymczyk, M. Minimalizacja poboru energii zasilania systemu wbudowanego (Minimizing the power consumption of an embedded system). In *Projektowanie, Analiza i Implementacja Systemów Czasu Rzeczywistego*; WKL: Warsaw, Poland, 2011; pp. 505–512 (In Polish).
74. STM32 Solutions for Artificial Neural Networks. Available online: https://www.st.com/content/st_com/en/ecosystems/stm32-ann.html#stm32sann-overview (accessed on 10 September 2021).
75. nRF52840 Product Specification v1.2. Available online: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.2.pdf (accessed on 10 September 2021).
76. Online Power Profiler for BLE. Available online: https://devzone.nordicsemi.com/nordic/power/w/opp/2/online-power-profiler-for-ble (accessed on 10 September 2021).
77. L91 Product Datasheet. Available online: https://data.energizer.com/PDFs/L91.pdf (accessed on 10 September 2021).