Energy efficient embedded systems and their application in wireless sensor networks

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Abstract. Embedded systems are specialised electronic systems that perform limited number of fixed operations and are used in many application areas. Such systems are based on using microprocessors for their implementation. Embedded systems are usually part of other systems where they are embedded into some embedding systems. They have to be efficient in electrical energy consumption, size of program code, time of operation, weight and cost. Embedded systems are inexpensive and are used in almost every electronic product or other electronic systems. Many embedded systems are mobile systems supplied by batteries and the available electrical energy must be used efficiently as much as possible. Application areas where embedded systems are used and where minimal consumption of energy is required are battery powered wireless sensor networks. The methods for reduction of energy consumption and for power management in embedded systems are considered and described in this paper. The accent is given on design and application of energy efficient embedded systems in wireless sensor networks and on possibilities to reduce energy consumption in such systems. The methods for energy harvesting, that are very attractive and very useful in wireless sensor networks applications, are also considered and described. One practically implemented battery supplied wireless sensor network for application for environmental data acquisition and monitoring in agriculture is described in the paper.

1. Introduction
Development of electronic technologies enabled implementation and application of specialised electronic systems that are embedded into some other systems. Such embedded systems perform limited number of needed operations and are used in many applications [1-9]. Embedded systems are optimised and minimised in size, weight, cost, time of operation and electrical energy consumption. Such systems are used in many electronic product or other electronic systems. Many embedded systems are supplied by batteries and available electrical energy must be used efficiently. Battery powered wireless sensor networks (WSN) are areas where embedded systems are applied and where minimal consumption of energy is required [9-20].

Possibilities and methods used for power management and for reduction of energy consumption in embedded systems are considered and described in this paper. Accent is given on design of energy efficient embedded systems in wireless sensor networks and on possibilities to reduce energy consumption in such systems. Way of design and main characteristics of embedded systems and wireless sensor networks are considered and described first. Then, possibilities and methods for energy consumption reduction in embedded systems are considered and described. Also, methods for energy harvesting, that are very useful and very important in wireless sensor networks applications, are described. Finally, one practically implemented battery powered wireless sensor network is
Solar cells are used for energy harvesting and recharging of batteries in sensor nodes. The wireless sensor network is used for environmental data acquisition and monitoring in agriculture.

2. Embedded systems

Embedded systems are specialised electronic systems that realize limited number of needed and fixed tasks [1-9]. The tasks do not change during lifetime of the system. Such systems are computer based systems with strong integration of hardware and software and intended for performing of specific functions. They are embedded into some other system, for what provide better functionality and performance. The system is intended to perform a specific task. Designer can to optimize it from the aspect of speed of operation and to reduce size, energy consumption and price of the product. The term embedded indicates that such systems are integral part of some larger system that is known as embedding system. More embedded systems can coexist in one embedding system [1-9].

Embedded systems are inexpensive and used in almost all application areas and almost every electronic product. The basic purposes of a such system are: data collection and storage; data transmission and communication; data processing, monitoring and control; applications specific for users. The main areas of embedded systems application are: consumer electronics, building automation and control, automotive electronics, telecommunication systems, computer peripherals, computer networks, health care and medical systems, industrial automated systems, robotics, military applications [1-9]. Embedded systems are usually real-time systems with more inputs and outputs that respond to more independent events. Also, in many applications, the embedded systems (nodes) are connected in some type of network. Such systems are consisting of many embedded nodes that are communicating over network and perform all needed operations [9-20].

There are two main components in embedded system: hardware and software [1-9]. Hardware performs all necessary operations and should be minimal for needed application. Software defines way of hardware operation for needed application and should also be minimal. Basic subsystems or units of embedded system hardware are: processing unit or processor, memory unit, peripheral units and power supply unit. There are also other hardware components depending on the application. Such components are: reset logic, oscillator (clock generator) circuits, timers logic, interrupt logic, input logic, output logic, communication logic and application specific circuits [1-9]. Figure 1 shows general hardware structure of typical embedded system. In the most situations all this components are not used. Embedded system is always optimized and minimized and uses minimal number of hardware components needed for some concrete application.written in the style of a submission to J. Phys.: Conf. Ser., show the best layout for your paper using Microsoft Word. If you don’t wish to use the Word template provided, please use the following page setup measurements.

![Diagram of Embedded System Hardware](image)

**Figure 1.** General hardware structure of embedded system.

Processing unit or processor is computing component that executes programs and performs all needed operations in the system. It should provide processing power needed to perform the tasks within the system. There are more types of processors that are used in the embedded systems: General
Purpose Processors (GPP) (Microprocessor, Microcontroller, Digital Signal Processor, Multimedia Processor); Application Specific System Processors (ASSP); Application Specific Instruction Processors (ASIP); core(s) of GPP or ASIP processors on Application Specific Integrated Circuit (ASIC) or on Very Large Scale Integration (VLSI) circuit [1-9]. What type of processor is practically used depends of the requirements of the system application. It should be used as simple as possible and as chip as possible processor for concrete application.

Memory unit stores the software (program that the system executes) and the data that is used in the system. It consists of program memory and data memory. As program memory for software storage generally are used Read Only Memory (ROM), Electrically Programmable Read Only Memory (EPROM) and flash type memories. As data memory for data storage generally are used Random Access Memory (RAM) type memories. Such systems do not use disk.

Peripheral units are connected to embedded system and enable communication with the external environment. Input peripheral units are generally connected with the sensors that measure the environment parameters data. The system processes that data and controls the output operations. Output peripheral units are generally connected with the actuators that control the environment parameters. For interconnection of the system with sensors generally are used A/D converters and for interconnection with actuators are used D/A converters.

Software of embedded system is set of programs that define what the system performs and how it performs. The software defines way of data collection, way of interpretation of data from sensors and way of generation of control signals for actuators. The software can consist of program components such as: initialization and configuration, operating system, application software, error handling, debug and maintenance support etc. [1-9]. To be effective as much as possible, the software should be small as much as possible. That is the main reason that many embedded systems use application software only. If the operation system is used then it is Real Time Operation System (RTOS). During design of software for embedded systems it should be taken into consideration the three constraints: available memory, processor speed and need to limit power consumption.

Main characteristics of embedded system are [1-9]:
- Connectable - Connected to physical environment through sensors and actuators,
- Dependable - Reliable, maintainable, available, safe, secure,
- Heterogeneous - Contain analogue and digital parts,
- Application-specific - Application is specific and fixed in advance,
- Dedicated and single-functioned - Usually performs a specialized task repeatedly,
- Tightly constrained - Must be of minimal possible size, operate fast enough to process data in real time, consume minimum power and be inexpensive,
- Reactive - Typically must continually reacts on events and changes from its environment,
- Real time - Usually must complete needed tasks in real time without any delay,
- Microprocessors based - Mainly microprocessor or microcontroller based.
- Memory based - Have memory, since software usually is in ROM memory, but does not need secondary memories.
- Efficient - Small size, low weight, low power consumption, low cost.

Main advantages of embedded system are: easy customizable, low power consumption, low cost, enhanced performances. Main disadvantages of embedded system are: complicated and expensive development process, long time to market [1-9].

Some high demanding real-time applications, such as multimedia and network applications, have large influence on development of embedded systems with using multiprocessor systems-on-chip (MPSoC). It combines the advantages of parallel processing with the high integration levels of systems-on-chip (SoC). There is also trend of networking of embedded systems (nodes). Further development and application of embedded systems will be also positively influenced by development of Artificial Intelligence (AI), Virtual Reality (VR) and Augmented Reality (AR), machine learning, deep learning and the Internet of Things (IoT) or Internet of Everything (IoE) [1-9].
3. Wireless sensor networks

Development of wireless communication technologies and embedded electronic systems enabled their application in many areas and different physical environments. Such were created the wireless sensor networks [9-20]. Primary goal of application of such embedded systems is monitoring and control of activities and parameters in different environments. By integration of different embedded systems (nodes) and wireless communication it is possible to implement adequate automated system. Such system performs set of programmed functions for control and monitoring of many values, parameters and performances, by direct or remote access [9-20].

Wireless sensor network (WSN) is larger network of small embedded sensor nodes (SN) capable for data collection, data processing and wireless communication [9-17]. Architecture and organization of WSN is of homogenous or heterogeneous type depending on application and implementation of the network. The goal in every WSN is to establish data collection from source sensor node to destination node. Data flow can be realized by direct communication of two nodes or via intermediary nodes (multihop). Such nodes are directly or indirectly connected with WSN and belong to the WSN network. In source node data are collected from sensors, realized potential processing and transferred to external (sink) node that collects the data. Destination node can be some external device as is computer. In many cases WSN is integrated with other technologies to enable data transfer toward distant data base. It enables centralized monitoring of collected data. Architecture of WSN is analogous to the protocol stack of usual computer network. Layers of WSN protocol stack are: physical layer, data layer and service layer [10]. In every of layers are realized appropriate services.

Each of sensor nodes types has appropriate functionalities and realizes appropriate services. For queries or requests responsible is external node that processes them and transfers toward other nodes in the network. The child node is responsible for providing data, that using data layer, is forwarded back to the source.

In the physical layer can be realized sensor nodes. The sensor nodes can be: external node, cluster node, child node and parent node [9-20]. Cluster nodes have ability of data collection and forwarding (via neighbouring nodes) to the sink node (nodes). Parent nodes are integrated into more than two cluster nodes. For forwarding, processing and generation requests for data toward other nodes responsible is the data layer. Process of data forwarding to group of nodes can be toward WSN or some region of WSN depending on query (request) [10].

WSN can be implemented using direct or indirect communication. Direct communication is realized between source and destination node. In indirect communication more intermediary nodes participate in data forwarding (multihop). What type of the communications should be realized depends on needs, environment and possible constraints. To avoid eventual problems in WSN often is used indirect type of communication [10,11]. WSN use indirect communication if exist obstacles for communication and if is used larger number of sensor nodes. Using such type of WSN decreases energy consumption with realization of efficient data routing through WSN using appropriate routing algorithm.

Complex applications and networks may use very large number of sensor nodes. Such WSN can be implemented in form of cluster organized WSN. Cluster based WSN uses division of WSN into certain number of sensor nodes groups. Every group of sensor nodes has appropriate cluster sensor node. Cluster node has specific role and function of control of neighbouring nodes in the group [10,11]. In such groups all neighbouring nodes of one cluster group exchange data with their cluster node. Cluster nodes forward data to destination node. Data can be then forwarded towards centralized system or data base.

In some WSN it is necessary to enable mobility of sensor nodes. There are applications here is needed that certain types of sensor nodes (source or destination nodes) move. In such networks nodes are moving in the area where the data is collected [9-20].

In large and complex WSN important is also network scalability. Scalability enables maintenance of characteristics and performance in WSN with many sensor nodes using complex protocols for efficient routing. It is important for multihop WSN where exists very large number of sensor nodes [9-17].
To achieve optimal performance of WSN used are more types of WSN topologies. Every of topologies has some advantages and disadvantages. Every topology has wide application depending of application and requirements. Topologies of WSN generally are: star, node-to-node (Peer-to-Peer), mesh and hierarchical or tree topology [9-17]. Forming and using of some topology is based on application of appropriate algorithms.

Main areas of applications of wireless sensor networks are: environmental monitoring, agriculture, civil engineering, military applications, health monitoring.

Wireless sensor node is embedded system that uses several embedded electronic components [9-17]. The components implement tasks of measurement, processing of measured values and transmission of processed information toward other sensor nodes, network coordinator or external (sink) node. Process of measurement detects value of some physical parameter in environment that is then processed. After processing the data is sent by wireless way. Wireless communication enables wireless transfer of information and interaction of sensor nodes [9-17]. Architecture of typical wireless sensor node (SN) is shown in Figure 2. The sensor node has five basic subsystems or units: computing or processing subsystem, communication subsystem, sensors subsystem, actuators subsystem and power supply subsystem. Main components of processing subsystems are microprocessor or microcontroller and memory. Communication subsystem consisting of two main components: short range radio transceiver for wireless communication and antenna. Sensors subsystem connects node to external environment and consists of sensors, sensors logic and A/D converters logic. Actuators subsystem also connects node to external environment and consists of actuators, actuators logic and D/A converters logic. Main components of power supply subsystem are battery, DC-DC converter and energy harvesting logic. Some wireless sensor nodes use two additional subsystems: localization subsystem and mobilizer subsystem. Localization subsystem is used to identify location or position of sensor node in applications where sensor nodes are randomly distributed or are mobile. Mobilizer subsystem is used to provide mobility for sensor node in applications where sensor nodes are mobile. In the most practical implementations all this components are not used. Sensor node is always optimized and minimized and uses minimal number of hardware components for some concrete application.

![Figure 2. Architecture of wireless sensor node.](image)
Wireless communication technologies and wireless standards that are most often used for interconnection of wireless sensor nodes and for implementation of wireless sensor networks are: WiFi, ZigBee, Radio Frequency Identification (RFID), Bluetooth and mobile technologies [9-20].

4. Energy efficiency in embedded systems
Embedded systems in large number of applications are realized as battery supplied devices and it is imperative to be implemented as systems with minimal energy consumption [6,21-39]. In such low-power applications available electrical energy must be used very efficiently. Typical low-power applications are: battery operated equipment, mobile communication equipments, wireless communication equipment, consumer electronics, biomedical applications. To reduce power consumption as much as possible in such applications are used CMOS circuits since CMOS is the technology with minimal energy consumption.

4.1. Reduction of energy consumption
The two main sources of total power consumption (dissipation) in digital circuits are static and dynamic power consumption [21-24]:

\[ P_{td} = P_{sd} + P_{dd}, \]  

where \( P_{td} \) is total power consumption, \( P_{sd} \) is static consumption and \( P_{dd} \) is dynamic power consumption.

Static power consumption in CMOS digital circuits consists of leakage current power dissipation (\( P_{lc} \)) and static power dissipation (\( P_{sp} \)):

\[ P_{sd} = P_{lc} + P_{sp}. \]  

Leakage current power dissipation (\( P_{lc} \)) is dominant static power consumption. Static power dissipation (\( P_{sp} \)) is minor static power consumption and practically can be neglected. Leakage current power dissipation (\( P_{lc} \)) is practically given by:

\[ P_{lc} = I_{lc}V_{dd}, \]  

were \( I_{lc} \) is leakage current and \( V_{dd} \) is power supply voltage of the circuit.

Dynamic power consumption in CMOS digital circuits consists of capacitive switching power dissipation (\( P_{cs} \)) and short circuit power dissipation (\( P_{sc} \)):

\[ P_{dd} = P_{cs} + P_{sc}. \]  

Capacitive switching power dissipation (\( P_{cs} \)) is dominant dynamic power consumption. Short circuit power dissipation (\( P_{sc} \)) is minor static power consumption but can not be neglected. Average capacitive switching power dissipation (\( P_{cs} \)) is approximately given by:

\[ P_{cs} = p_{t}C_{L}V_{dd}f_{clk}, \]  

were \( C_{L} \) is capacitive load, \( V_{dd} \) is power supply voltage and \( f_{clk} \) is clock frequency of the circuit. The product \( p_{t}C_{L} \) is called the average switched capacitance. The methods for reducing this capacitance are realized at system, architecture, circuit and technology level.

Average short circuit power dissipation (\( P_{sc} \)) is approximately given by:

\[ P_{sc} = I_{sc}V_{dd}, \]  

were \( I_{sc} \) is average short circuit current and \( V_{dd} \) is power supply voltage of the circuit.

The approximate total average power consumption (dissipation) is then given by:

\[ P_{td} = P_{lc} + P_{cs} + P_{sc} = I_{lc}V_{dd} + p_{t}C_{L}V_{dd}^{2}f_{clk} + I_{sc}V_{dd}. \]  

It can be seen from the last equation (7) that the system power consumption can be reduced by: reduction of power supply voltage \( V_{dd} \), reduction of load capacitance \( C_{L} \), reduction of switching activity \( f_{clk} \) of the circuits and reduction of leakage current \( I_{lc} \) in the embedded system.

Reduction of power supply voltage \( V_{dd} \) has the greatest impact on reduction of total power consumption. It reduces all types of the power consumption. The greatest contribution is in decreasing capacitive switching power dissipation (\( P_{cs} \)) what is the biggest power consumption in many applications, especially in high speed applications. Reduction of the power supply voltage gives quadratic improvement in decreasing of that type of power consumption. But, reduction of the power supply voltage has one very negative influence what is reduction of speed of operation of the circuits and the system. The value of power supply voltage \( V_{dd} \) of every circuit, unit and all system should be
minimized as much as possible for the concrete application of the system. There are more methods for the power supply voltage management that are used in embedded systems.

Reduction of load capacitance $C_L$ decreases capacitive switching power dissipation ($P_{sc}$) what is the biggest power consumption in high speed applications. That reduction gives linear improvement in decreasing of that type of power consumption. Reduction of the load capacitance has also very positive influence on increasing of speed of operation of the circuits and the system. The value of load capacitance $C_L$ of every circuit, unit and all system should be minimized as much as possible for the concrete application of the system. There are more methods for reduction of load capacitance used at technology level, circuits level, architectural level and system level design.

Reduction of switching activity of the circuits in the embedded system reduces dynamic power consumption. Reduction of switching activity is mainly performed by decreasing the clock frequency $f_{clk}$ of the circuits and system. Decreasing of the clock frequency reduces linearly capacitive switching power dissipation ($P_{sc}$). It also reduces average short circuit current $I_{sc}$ and such reduces short circuit power dissipation ($P_{sc}$) of the system. But, reduction of the clock frequency has negative influence in reduction of speed of operation of the circuits and the system. The value of clock frequency $f_{clk}$ of every circuit, unit and all system should be minimized as much as possible for the concrete application of the system. There are more methods for the clock frequency management that are used in embedded systems.

Reduction of leakage current $I_{le}$ reduces static power consumption. Leakage current is independent of operating frequency. It depends very much on the process technology used for realization of system hardware components. Reduction of leakage current can be mainly obtained by using hardware components realized in technology with smaller leakage currents. Leakage current also decreases with decreasing the power supply voltage value $V_{dd}$ of the circuits and system. But, reduction of the power supply voltage reduces speed of operation of the circuits and the system. There are more methods for reduction of leakage current used at technology level and circuits level design. As the process technology advances the dynamic current decreases, but the static leakage current (for low-voltage submicron technology) tends to increase and such becomes more important.

There are many methods or techniques for power management and reduction of energy consumption or energy saving in embedded systems [21-39]. All the methods can be classified in two types: hardware based methods and software based methods. Hardware based methods are using appropriate design and implementation of hardware elements and complete system hardware that reduce and minimize energy consumption in concrete application. Software based methods are using appropriate design and implementation of software elements and complete system software that reduce and minimize energy consumption in concrete application.

The most often used hardware based methods for reduction of energy consumption in embedded systems are [21-39]:

- Design and implementation using as minimal hardware as possible, where only necessary hardware components should be present, for concrete application,
- Design and implementation using technology that has minimal energy consumption, using CMOS technology,
- Design and implementation using as minimal supply voltage value as possible for concrete application,
- Power gating that involves turning off the supply voltage of hardware blocks whenever is possible or when they are not active, especially blocks with high energy consumption, as are microprocessor and memory,
- Decreasing value of the supply voltage of hardware blocks whenever is possible or when they are not active, especially blocks with high energy consumption, as are microprocessor and memory,
- Using voltage islands if some blocks are slower than others and then is possible to isolate slower blocks, run them at lower frequency and turn down the supply voltage until these blocks meet needed operation speed,
Using dynamic voltage frequency scaling that is combination of voltage islands and power gating where the designer adjusts the voltage and clock frequency of each block so that it is meeting its operation speed for the current application,

Design and implementation to have as minimal load capacitances of circuits, blocks and units as possible for concrete application,

Dividing hardware components into more modules where such modules have smaller load capacitances and smaller number of accesses,

Reduction of load capacitance of buses reducing their length, using reserved buses instead of multiplexed ones, segmenting buses,

Design and implementation using as minimal clock frequency value as possible for concrete application,

Using clock gating technique for reducing dynamic power that shuts off the clock to parts of the system that are inactive and designers use clock gating at the block level to create a standby mode,

Design and implementation using hardware components realized in technology with as minimal leakage currents as possible for concrete application,

Design and implementation of the system to be as much as possible in one of inactive states, in power off, power down, idle, sleep or standby mode.

The most often used software based methods for reduction of energy consumption in embedded systems are [21-39]:

Design and implementation of the software to minimise as much as possible number of operations for concrete application,

Design and implementation of as short as possible software, with minimal number of instructions, where only necessary software components are present, that also will need minimal program memory capacity for concrete application,

Using assembler programming language for software development to obtain minimal programs and minimal number of instruction executions,

Avoiding using program loops, using as much as possible the sequential programs and using unrolling the loop style of programming what decreases number of instruction executions,

Avoiding as much as possible using program structures as procedures, subroutines, functions and modular programming and using sequential programs what decreases number of instruction executions,

Avoiding as much as possible using program branches and jumps and using the sequential programs what decreases number of instruction executions,

Minimising as much as possible using interrupts and if interrupts are used minimising interrupt processing programs what decreases number of instruction executions,

Avoiding using operating system and using only applicative program what decreases number of instruction executions and if operating system is used use specialised operating systems for embedded systems that have dynamic power management function,

Design, writing and implementation of the software as one compact and as short as possible program, application program,

Using such way of data representation and data length that will enable the greatest savings in energy consumption for concrete application,

Design and implementation of the software to put the system as much as possible in one of inactive states, in power off, power down, idle, sleep or standby mode.

It is common and recommended to use multiple and as much as possible of all these hardware and software techniques for consumption reduction in different parts of embedded system design.

Principle of operation of a typical embedded system is shown in Figure 3

After turning on, configuration and initialization, the system periodically executes the application program and collects input data from environment, processes the data and sends obtained results to environment. Then it waits some needed time or until change of the input data occurs and again
repeats all activities in the control loop. Also, usually are used interrupts and interrupt logic for detecting and processing asynchronous events from the environment. The control loop has some duration time \( T_c \) and application program execution has some duration time \( T_a \), depending on the application. Difference between this two times is the waiting time \( T_w \) of the system. Always is:

\[
T_c = T_a + T_w. \tag{8}
\]

![Diagram of embedded system](image)

**Figure 3.** Principle of operation of embedded system.

To obtain energy efficient system it is needed to design system such to be control time \( T_c \) as long as possible, application time \( T_a \) as short as possible and waiting time \( T_w \) as long as possible. The application time duration \( T_a \) will be minimal if system hardware and software (application program) are optimized and minimal for concrete application. The control loop time duration \( T_c \) should be selected to be maximal for concrete application. In such situation the waiting time \( T_w \) will be maximal possible. In the waiting time interval should be used all appropriate and most suitable hardware methods for energy consumption reduction. It should be used one of system inactive states (power off, power down, idle, sleep or standby). The best is to use method of power supply disconnection (power off) for all the hardware components if it is possible. It reduces the energy consumption to zero in the waiting time interval.

To increase energy efficiency it should be avoided using interrupts. Interrupts should be used only if it is unavoidable for concrete application of the system. In such situations it should be used minimal number of interrupts. Also, used interrupts should be occurred as rarely as possible, with the lowest possible frequency of occurrence. Programs for interrupt processing (interrupt routines) should also be as much as possible simple and short, with minimal number of instructions and minimal number of branches or jumps.
4.2. Energy harvesting

There are many embedded systems that are used in situations and applications where the sources of permanent power energy supply (AC power supply) are not existing or are not available [17,21-24,32-34,39]. Such situation is in application of wireless sensor networks and sensor nodes, where sensor nodes can be randomly placed or be movable and mobile. In such situations it has to be used batteries as sources for power energy supply of the systems. But, batteries have limited lifetime what limits lifetime of the sensors nodes and the systems. Solution for that problem is using rechargeable batteries and extracting energy from ambient sources for the batteries charging. Process of extracting and collecting energy from environmental sources is known as energy harvesting. Such way of embedded systems energy supply enables that the batteries and the system operate continuously and practically without limited lifetime. It also reduces problems of obtaining energy efficiency of embedded systems since it can provide enough energy for system correct and permanent operation [17,24,32].

Main energy environment sources for energy harvesting are:
- Mechanical energy from vibration, pressure and strain,
- Thermal energy from furnaces and other heating sources,
- Solar energy from all light sources, from lighting to the sun,
- Electromagnetic energy captured via inductors, coils and transformers,
- Wind and fluid energy from air and liquid flow,
- Human energy of human movement by foot, human skin and blood,
- Chemical energy from natural chemical processes or biological processes.

By using energy harvesting the embedded system completely alone collects and accumulates energy as it becomes available. In many cases, such energy sources provide energy in small packets. In such situation, the harvesting circuit must stay in active mode permanently, to capture harvestable energy when it becomes available, and to provide output required for the application. The power consumption of the harvester has to be as small as possible. The energy consumed by this circuit must be much smaller than the energy obtained by the ambient sources. Also important characteristic of the harvesting circuit is the capability to store obtained energy as long as possible with minimal loss. Energy harvesting circuits must have very high that capability due to the infrequency of the energy capture activity. The energy harvesting circuit must also economize the stored energy in order to provide correct operation of the supplied system for the concrete application.

Energy harvesting is most suitable for applications demanding small amounts of continuous power or having short periods of high-power consumption, what harvested and stored energy can provide. Wireless sensor nodes are typical devices for such applications. Harvesting ambient energy allows the wireless sensor nodes to operate nearly indefinitely, without their battery failure. Also, energy harvesting devices are usually small. There are sensor nodes that do not use any self-contained energy source. They only harvest energy from the environment. But, the supply of energy may be interrupted some period of time since the power obtained from the harvesting can not be guaranteed all the time.

There are more types of energy harvesting with different degrees of efficiency depending on the application [17,21-24,32-34,39]. Classification of energy harvesting can be based on the type of energy used to harvest the power. Generally, there are three main and most used types of harvesting sources from environment [17,21-24,39]:
- Mechanical vibration,
- Thermoelectric generation,
- Solar cells.

Mechanical vibration energy harvesting is based on the principle that device in movement can generate one of next types of energy: vibration, kinetic or mechanical energy. All types of this energy can be converted into electrical energy and be harvested. For such energy conversion and harvesting can be used piezoelectric, electrostatic and electromagnetic mechanisms and devices.

Piezoelectric materials convert mechanical energy from vibrations, pressure or force into electricity. The advantage of such harvesters is direct generation of needed voltage. They do not need separate voltage source and additional components. But, they have some disadvantages since
characteristics of piezoelectric materials are changing with age, pressure and temperature, such materials are breakable and may have leakage of charge.

Electrostatic principle of harvesting is based on changing the capacitance of vibration-dependent varactors. Vibrations separate the planes of initially charged varactor. The mechanical energy is converted into electrical energy. The main advantage of electrostatic converters is ability to integrate into microelectronic devices without added components. Disadvantage of such converters is that they need an additional voltage source for initial charging of the capacitor.

Electromagnetic energy harvesting is based on using electromagnetic induction. The most effective ways of electromagnetic energy harvesting are with using permanent magnets, coil and resonating cantilever beam. Such harvesting has advantage of improved reliability, there is not mechanical contact of any parts and separate voltage source is not needed. The main disadvantage of this type of harvesting is that electromagnetic materials are large in size and complicated to integrate with embedded systems.

Thermoelectric generation energy harvesting use the principle of creating electric potential based on a temperature difference. Voltage is generated when there is temperature difference between two junctions of conducting materials. Thermal energy harvesting uses temperature differences or gradients to generate electricity.

Solar cells or photovoltaic cells energy harvesting is the best known and the most practically used way of harvesting. It uses devices that convert light energy into electrical energy. Typically used is light energy obtained from sunlight. For locations where there is available light and where usage of other types of power supply are not possible or are expensive, usage of solar cells is very convenient solution. In designing sources which harvest solar energy it must have in mind such factors as availability of day light, characteristics of used solar cells and the intensity of the incident light. However, the supply of solar energy is interrupted at some period of time and the power obtained can not be guaranteed all the time.

5. Energy efficient embedded wireless sensor network system

As example of application of energy efficient embedded systems here is described implementation of one simpler on ZigBee wireless technology based wireless sensor network. The network was realized for measurement and monitoring of some values from environment. Such systems were described in papers given in references [18-20]. The network is flexible, modular and can be used for different applications. It is possible to realize measurement and monitoring of environment parameters values obtained from sensors in sensor nodes. There are two types of sensor nodes in the network: end or field sensor node and coordinator sensor node. Data read from sensors of end sensor nodes are wirelessly transmitted to coordinator node. Coordinator node is connected with personal computer of PC type. Personal computer is connected with the Internet. Data from coordinator node is transferred to personal computer and stored in appropriate file. Then the data from the file is stored in the local data base. It is also realized Web based application that enables presenting and monitoring of results from sensors in the network, using graphics and diagrams, via Internet and from distance. The measurement, collection and transmission of data from sensors are realized periodically. The network was designed and used for environmental data acquisition and monitoring in agriculture applications. It monitors environment temperature, environment humidity and soil humidity.

The system is based on application of the Arduino Uno boards, sensors and wireless communication modules [40-42]. End sensor node uses Arduino board, wireless module and sensors connected to board that measure temperature and humidity of environment and soil humidity. Coordinator sensor node does not use sensors and does not measure environmental parameters. It coordinates and controls operation of the network. For realization of coordinator sensor node used are Arduino board and wireless module. Hardware components used for implementation of the network are: Arduino Uno boards, wireless modules Digi Xbee S2 based on ZigBee protocol and sensors for measurement of air temperature, air humidity and soil humidity. For measurement of environmental values used is DHT11 sensor for environment temperature and humidity, and sensor for soil humidity. Sensor DHT11 is of digital type and has integrated components for measurement.
humidity is also of digital type. It gives high logical level on the output if soil is dry and low logical level if soil is wet. The block-scheme of the implemented end sensor nodes is shown in Figure 4.

![Figure 4. Block-scheme of implemented end sensor node.](image)

The end sensor nodes measure and collect measured environment data, aggregate the data and transmit the data to the coordinator node. The coordinator node is connected to computer of PC type that stores the data in the data base, presents the data to the user and statistically processes the data. During the process of measurement and collection of parameters data from sensors it is possible to remotely monitor the data in real time by the Web based application. The block-scheme of the implemented coordinator sensor node is shown in Figure 5.

![Figure 5. Block-scheme of implemented coordinator sensor node.](image)

In order to reduce energy consumption, to increase energy efficiency and to obtain practically unlimited lifetime of the system there were used appropriate methods for decreasing of energy consumption. According to the application the system measures, collects, aggregates and transmits data periodically in appropriate time period. Since are monitored very slow changing processes that time period could be very long, represented in minutes. Also, time of active operation (measurement, collection, aggregation and transmission of data) is very short, less than second. The system is designed and configured such that in active mode is very short time, during collection and transmission of data. All other time the system, including wireless module, is in sleep mode. Also, transmission of data is not occurred after every data collection. Data is collected in the end sensor nodes and transmitted after its aggregation. Period of data transmission is much longer (several minutes) than interval of data collection (less than second). Wireless module is in active mode only during data transmission. All that very much reduces average and total energy consumption of the system. Also, all the sensor nodes use rechargeable battery to power the wireless module, the sensors
and the Arduino board. Lithium–ion rechargeable batteries of type 18650 are used. In order to achieve the sensor nodes autonomous operation and extend the lifetime to practically unlimited interval, the batteries are charged using solar cells panel and DC-DC converter with protection circuit.

The designed wireless sensor nodes, the network and all the system are suitable for measurement of ambient temperature, ambient humidity and soil-humidity level for applications in agriculture. For example can be used in some type of vegetable production, grin production or flower production.

Practically obtained results of monitoring by developed and implemented sensor nodes and sensor network placed in environment are shown in Figure 6, Figure 7 and Figure 8. The obtained monitoring results are given in % and °C, for one time interval of monitoring. Figure 6 shows results of ambient temperature monitoring. Figure 7 shows results of ambient humidity monitoring. Results of soil humidity monitoring are shown in Figure 8.

![Temperature Monitoring](image1.png)  
**Figure 6.** Results of environment temperature data monitoring.

![Humidity Monitoring](image2.png)  
**Figure 7.** Results of environment humidity data monitoring.

Given results were obtained during testing of operation of the sensor nodes, sensor network and the implemented system. It can be seen that the temperature and humidity were constant in the beginning of the testing time interval. Then it was created and generated external heating of the environment of
the sensor nodes. That caused increasing of the measured temperature and decreasing of measured humidity. After some specific time the environment heating was stopped and measured temperature and humidity naturally and gradually returned to the initial values. It all can be seen in the Figure 6 and Figure 7. The soil humidity sensor monitors the soil humidity state with the soil humidity threshold. Initially, the humidity level in the soil was low and output state was high (1). After some specific time, it was filled in some amount of water in the soil around the soil humidity sensor. Such, it was achieved appropriate level of soil humidity, greater than the humidity threshold, and sensor output changed to low (0) state. It all can be seen in the Figure 8.

![Soil-humidity monitoring](image)

**Figure 8.** Results of soil humidity data monitoring.

6. Conclusion
Advancement of electronic technologies enabled application of specialised embedded systems in very many applications. Good characteristics of such systems enable their application in almost all areas where they are embedded in some other embedding systems improving their possibilities and operation. Embedded systems perform only needed operations and are minimised in cost, weight, size, time of operation and energy consumption. Many embedded systems are powered by batteries and must be as much as possible efficient in consumption of electrical energy.

Battery supplied wireless sensor networks are based on application of embedded systems and require minimal consumption of energy. Sensor nodes of such network are embedded systems specialized for application where the network is used and interconnected in appropriate network. Optimization of sensor nodes and optimization of network topology enable realization of very effective wireless sensor networks for almost all possible applications. It is especially interesting for applications in the Internet of Things (IoT) or Internet of Everything (IoE) areas.

There are many methods for reduction of energy consumption in embedded systems. What methods should be used in some situation depends the most on the concrete application of the system. The general and the main recommendation for decreasing energy consumption in embedded systems is to design and implement system with minimal possible hardware and minimal possible software used. All other hardware and software methods for energy consumption reduction contribute to further decreasing of energy consumption of the system. That methods should be selected and applied according to needs and possibilities of the system in the concrete application. For battery supplied embedded systems it is very important to use energy harvesting from the system environment. There are many such possibilities convenient for different applications. One of the most suitable and the most practically used energy harvesting method is using solar energy and solar cells.

Practically designed and implemented battery powered wireless sensor network is based on ZigBee wireless communication technology. It is used for environmental data acquisition and monitoring in agriculture. The ZigBee communication technology is used since it is very suitable wireless technology for such type of applications. Appropriate methods for reduction of energy consumption in
the sensor nodes and in the complete wireless sensor network are used. The wireless sensor nodes and the complete sensor network are optimized and maximally adopted to the application. Also, the application enables to collect and transmit sensors data periodically, in long time periods. But, time interval of data collection and transmission is very short. Such, the system is the most of time in waiting state, between that two activities. During the waiting state the system is in the sleep mode. That very much reduces energy consumption of the system. Some other hardware and software methods are also used to reduce energy consumption in the active system state. All that is reducing total energy consumption of the system. Application of rechargeable battery and solar energy harvesting in the sensor nodes enable autonomous operation and practically unlimited the lifetime interval of the nodes and the complete system. The system is simple, modular, very flexible and inexpensive. It is very easy to increase number of sensor nodes to necessary number, to program sensor nodes for use of different sensors, and to program needed data aggregation and processing for concrete application. The system could be very easy, with small modifications, adopted also for other similar applications that require and use simple battery powered wireless sensor nodes and networks.

References
[1] Gajski D, Abdi S, Gerstlauer A and Schirner G 2009 Embedded System Design: Modeling, Synthesis and Verification. Springer
[2] Wolf W 2007 High-Performance Embedded Computing: Architectures, Applications, and Methodologies. Morgan Kaufmann
[3] Valvano J 2011 Embedded Microcomputer Systems: Real-Time Interfacing. Cengage Learning
[4] White E 2011 Making Embedded Systems: Design Patterns for Great Software. O'Reilly Media
[5] Stringham G 2010 Hardware/Firmware Interface Design: Best Practices for Improving Embedded Systems Development. Newnes
[6] Schmitz M, Al-Hashimi B and Eles P 2010 System-Level Design Techniques for Energy-Efficient Embedded Systems. Springer
[7] Marwedel P 2020 Embedded System Design: Embedded Systems Foundations of Cyber-Physical Systems, and the Internet of Things. Springer
[8] Hobbs C 2019 Embedded Software Development for Safety-Critical Systems. CRC Press
[9] Agrawal D 2017 Embedded Sensor Systems. Springer
[10] Mahalik N 2007 Sensor Networks and Configuration: Fundamentals, Standards, Platforms and Applications. Springer
[11] Sohraby C, Minoli D and Znati T 2007 Wireless Sensor Networks: Technologies, Protocols and Applications. John Wiley & Sons
[12] Nayak A, Stojmenovic I 2010 Wireless Sensor and Actuator Networks: Algorithms and Protocols for Scalable Coordination and Data Communication. John Wiley and Sons
[13] Farahani S 2008 ZigBee Wireless Networks and Transceivers. Elsevier
[14] Chai S, Wang Z, Zhang B, Cui L and Chai R 2020 Wireless Sensor Networks. Springer
[15] Elhoseny M and Hassanien A 2019 Dynamic Wireless Sensor Networks. Springer
[16] Sharma V and Pughat A 2017 Energy-efficient wireless sensor networks. CRC Press
[17] Kanoun O 2019 Energy Harvesting for Wireless Sensor Networks. De Gruyter
[18] Pasalic D, Bundalo Z, Bundalo D and Cvijic B 2015 ZigBee-based data transmission and monitoring wireless smart sensor network integrated with the Internet Proceedings of Conference MECO2015 pp.240-243.
[19] Pasalic D, Bundalo Z, Bundalo D, Softic F and Cvijic B 2015 Environment data acquisition using energy efficient wireless sensor network Proceedings of Conference ERK2015 pp. B:31-34
[20] Pasalic D, Bundalo Z, Bundalo D, Softic F and Cvijic B 2016 Environmental data monitoring using wireless sensor networks. Annals of Faculty Engineering Hunedoara-International Journal of Engineering vol. 14 no. 2 pp. 99-102
[21] Pistoia F 2008 Battery operated devices and systems: From portable electronics to industrial products. Elsevier
[22] Chedid W and Yu C 2002 Survey on Power Management Techniques for Energy Efficient Computer Systems. Mobile Computing Research Lab. Cleveland State University Cleveland
[23] Zomaya Y and Lee Y 2012 Energy Efficient Distributed Computing Systems. John Wiley and Sons

[24] Stojcev M, Kosanovic M and Golubovic Lj 2009 Power management and energy harvesting techniques for wireless sensor nodes. Proceedings of Conference TELSIKS2009 pp. 65-72

[25] Wu H, Chen C and Weng K 2021 An Energy-Efficient Strategy for Microcontrollers. Applied Sciences 11 2581

[26] Thakkar A, Chaudhari K and Shah M 2020 A Comprehensive Survey on Energy-Efficient Power Management Techniques. Procedia Computer Science 167 1189–1199

[27] Salami B, et al. 2020 An Experimental Study of Reduced-Voltage Operation in Modern FPGAs for Neural Network Acceleration. International Conference on Dependable Systems and Networks (DSN) 138-149

[28] Papadimitriou G, et al. 2019 Adaptive Voltage/Frequency Scaling and Core Allocation for Balanced Energy and Performance on Multicore CPUs International Symposium on High-Performance Computer Architecture (HPCA) 133–146

[29] Rodriguez-Zurrunero R and Araujo A 2021 Adaptive frequency scaling strategy to improve energy efficiency in a tick-less Operating System for resource-constrained embedded device Future Generation Computer Systems 124 230–242

[30] Fan K, Cosenza B and Juurlink B 2019 Predictable GPUs frequency scaling for energy and performance. International Conference on Parallel Processing (ICPP) pp. 1–10

[31] Rodriguez-Zurrunero R, Araujo A and Lowery M 2021 Methods for lowering the power consumption of OS-based adaptive deep brain stimulation controllers Sensors 21 2349

[32] Raghunathan V, Ganerival S and Srivastava M 2006 Emerging techniques for long lived wireless sensor networks IEEE Communication Magazine vol. 44 no. 4 pp. 108-114

[33] Alippi C, Anastasi G, Di Francesco M and Roveri M 2009 Energy management in wireless sensor networks with energy-hugry sensors IEEE Instrumentation and Measurement Magazine vol. 12 no. 2 pp. 16- 23

[34] Pasalic D, Bundalo Z, Bundalo D, Softic F and Cvijic B 2015 Methods for energy consumption management in wireless sensor networks Proceedings of Conference RIM2015 pp. 231-236

[35] Touati Y, Ali-Cherif A and Daachi B 2017 Energy Management in Wireless Sensor Networks. Elevier

[36] Lopez-Ardao J, Rodriguez-Rubio R, Suárez-González A, Rodríguez-Pérez M and Sousa-Vieira M 2021 Current Trends on Green Wireless Sensor Networks Sensors 21 4281

[37] Chowdhury S and Hossain A 2020 Different Energy Saving Schemes in Wireless Sensor Networks: A Survey Wireless Personal Communications 114 2043-2062

[38] Singh J, Kaur R and Singh D 2020 A survey and taxonomy on energy management schemes in wireless sensor networks. Journal of Systems Architecture 111

[39] Singh J, Kaur R and Singh D 2021 Energy harvesting in wireless sensor networks: A taxonomic survey. International Journal of Energy Research 45 118–140

[40] Atmel Corporation Datasheets. www.atmel.com/products/

[41] Arduino Datasheets. www.arduino.cc/

[42] XBee®/XBee-PRO® ZB RF Modules-ZigBee-v1.x4x 2013 Digi International