University of Huddersfield

Evaluation of Energy Consumption in Industry 4.0

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Abstract

Wireless sensor networks (WSN) are significantly important in the advanced monitoring of applications for the Internet of Things, particularly in difficult-to-access locations where wired solutions are impractical or expensive. Critical elements and characteristics of WSNs in terms of powerconsumption are being characterized and evaluated. However, there is a gap in research in terms of selecting and structuring the most efficient (WSN) in consideration of energy sustainability and the amount of required energy by the WSN that can be supplied wirelessly. In this thesis, a systems-level approach was taken to evaluate the energy required for sensing, processing, and communication over a WSN for an industrial application. A literature review was also conducted to identify the power consumption of some transducers typically used in manufacturing, such as temperature, acceleration, and displacement transducers. Additionally,the power consumption of the commonly available local processing units used to produce "smart" sensors was compared in this work. Different data transmission protocols were also evaluated for power consumption in different operation modes for different microcontrollers. These requirements and results taken from the literature were used to identify the power consumption at each location in WSN. This was then used to create a framework for surveying the theoretical requirement (limits) to power each of these locations. Various power sources were considered as possible solutions, including energy storage (wired and wireless charging), power distribution, and power harvesting techniques. The framework can be used in one of two ways; the WSN can either be modified to reduce power consumption to meet supply (for example, changing the operational mode to a more energy-efficient one), or a different power supply can be proposed to meet demand. In this way, the framework provides a tool for the design of any industry-based WSN. Finally, a machine tool was used as a case study to show how the framework can be used, in consideration of the available energy harvesting techniques that can be used to power specific elements of the WSN. Further work should focus on investigating the possibility of using other techniques to optimize the power consumption of WSNs considering the available wireless energy sources, as well as suggest other efficient techniques.

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Abbreviations

ADC	Analogue to Digital Converter
ATC	Automatic Tool Changer
BS	Base station
BOD	Brown Out Detection
CPU	Central processing Unit
CNC	Computerized Numerical Control
CTS	Compete To Send
DC	Direct Current
DVS	Dynamic Voltage scheduling
DPM	Dynamic Power Management
DSWDT	Deep Sleep Watch Dog Timer
EHT	Energy Harvesting Techniques
IOT	Internet Of Things
IVR	Internal Voltage Reference
MCU	Microcontroller Unit
MEMs	Microelectromechanical systems
MPT	Microwaves Power Transmission
RF	Radio Frequency
RH	Relative Humidity
RX	Receiver
RTS	Request To Submit
SPI	Serial peripherals Interface
TX	Transmitter
VDS	Variable Voltage Speed
WDT	Watch Dog Timer
WPT	Wireless Power Transmission
WSN	Wireless Sensors Networks
WTT	Wireless Transmission Technology

1. Introduction

Wireless sensor networks (WSNs) are mainly composed of wireless networks of small sensor-equipped devices that are deployed to monitor physical conditions. WSNs is proposed for use in several fields, including medical, industry, military, and smart monitoring applications. Multiple compact sensor nodes are installed in the desired area to monitor, detect, and gather data of the requiredphenomena; the data is then transmitted to a base station (BS)[1] .WSNs are classified as ad hoc networks, and hence, they have the same limitations as ad hoc networks. However, they have additional unique issues, such as memory constraints, routing, connectivity, synchronization, and localization [1]. The fundamental objective of WSNs is to collect, transmit, and process the collected data. However, given that in most wireless applications, the resources are constrained, therefore, an efficient approach is needed for the transfer of the collected data to the BS.

Routing is critical in WSN applications, for example, in some Industry 4.0 applications,wireless sensors could be utilized to monitor the status of a CNC machine during machining time. Machine real-time data must be delivered consistently and within a specified time frame in such applications, otherwise, it is useless and may increase the product's uncertainty. In military applications, the required data, such as enemy tracking, battleground surveillance, or target identification must be precisely routed back to the BS. Additionally, WSN is utilized to assist rescue crews in the event of natural disasters by assisting them in finding victims trapped in avalanches[2] . Once more, efficient information routing to the base station iscritical. In civil infrastructure, WSNs are often deployed to detect cracks and structural problems. Energy-efficient technologies and real-time routing measures are needed for such applications[2] .

Consequently, continuous monitoring is a critical technical issue in WSNs and must be appropriately addressed. The limitations associated with routing in WSNs emerge from several aspects, such as the dense deployment of enormous sensor nodes, which require sufficient power to run them. However, given the power-demand nature of WSNs and the direct effect of energy consumption on network lifetime, energy consumption has become one of the most significant routing challenges [3, 4].

Commonly, sensor nodes are deployed once and are anticipated to function for an extended period. As a result, it is critical that the energy supply must be sufficient during the monitoring process [5]. This will sustain the WSNs to continue operating for the long term to perform routing and transmission of data packets. Along with minimizing nodes' residual energy, harmonizing power usage among nodes also helps to minimize the overall energy usage and this demands the deployment of an optimal approach. In this research, the structure of WSNs is summarized, followed by a review of the mostpopular microcontrollers based on their power consumption. The conventional limitations of battery-based sensor nodes and the traditional energy harvesting technologies commonly employed in WSNs to replenish nodes' batteries were also reviewed. Then, the various routing protocols developed by other developers were compared in terms of their benefits, drawbacks, and unique features. Furthermore, the energy harvesting technologies built on piezoelectric nano-generators to power WSNs were also reviewed. Again, the ultra-low-power modes used to conserve energy in the studied microcontrollers were covered. Finally, the challenges and further works were highlighted.

The rest of this dissertation was organized as follows: Chapter 2 presented the review of related works while Chapter 3 detailed the power consumption of transducers used in Industry4.0. Chapter 4 detailed the power consumption of local processors, such as Arduinos and Motenio. Chapter 5 evaluated the power consumption of WSN and highlighted the most popular communication protocols. Chapter 6 compared and discussed several techniques used to power wireless sensors and highlighted some harvesting mechanisms and wireless power transmission approaches. Chapter7 provided a case study conducted on a 3-axes machine at the lab. Finally, Chapter 8 concluded and discussed future works.

2. Literature Review

In the previous chapter, the scope of the research was identified. The chapter also explained briefly the advancements in WSNs and the significant role they play in the industry. In addition, the power requirements of these networks were briefly presented. Different types of microcontrollers were discussed as well. This chapter will focus on different topics related to power consumption in smart sensors, such as WSN structure, Microcontrollers, protocols to reduce power consumption, wireless power transmission techniques, and potential sources to harvest energy.

Following the development of the WSN paradigm, the number of current and prospective applications has been rapidly increasing. Regrettably, battery energy density did not witness the same development, and energy harvesting mechanisms can only power a limited type of devices, most of which have limited capabilities [4]. As a result, both the scientific and industrial sectors have renewed their interest in energy consumption modeling and reduction. WSNs are currently being applied in different industrial monitoring applications, such as predictive maintenance and real-time monitoring to enable wireless data collection and monitoring for the CNC machine[6]. WSN is used in the CNC machines to replace wired sensors and reduce the cost of temperature and vibration sensors[7] . WSN is used to monitor the overall performance of the machine tool and send machine data to a base station to make suitable decisions [8] . Due to the limited processing capabilities of WSN nodes, their load is usually limited to basic computations. The peripherals, particularly the radio module, consume the largest amount of energy. Thus, numerous power-saving techniques are developed based on the reduction of power consumption of the node peripherals [1].

Passive and active techniques are both feasible in this regard. Passive power conservation measures lower the power consumption of sensor nodes energy by switching off its transmitter interface module if no transmission activity is required[9] .

Furthermore, extra energy savings can be obtained by optimizing the processor's performance in the active state and altering its operating frequency[10] . Indeed, it is feasible to reduce the total power consumption of the processing unit by reducing the supplied voltage and clock frequency of the processing unit. However, this is only possible if the processing unit is equipped with variable processor speed (VPS). Utilizing the VPS, it is essential to develop a scheduling system capable of selecting an appropriate supply voltage and suitable frequency for each activity. Dynamic Voltage Scheduling (DVS) is one of the technologies capable of achieving this feature without impairing the node's overall performance[10]. Dynamic Power Management (DPM) presented by[3] is another methodology for extending the lifespan of sensor nodes. DPM performs similarly to DVS, except that instead of altering the clock frequency, it dynamically turns off and wakes up the components of the sensor node only when needed.

This state shifting is performed at the microprocessor level by several power modes that deactivate the CPU, memory, and any other internal peripherals. It is essential to consider that each state transition requires time and consumes some energy as illustrated in Figure 1. Each power mode, "commonly known as low-power-mode (LPM)", incrementally disables the un-required peripherals. Any transition from an idle state to a low-power mode incurs a fixed cost, represented by the symbol b0 in Figure 1, which is typically insignificant. However, the energy consumption for waking up the microprocessor changes proportionally with the depth of the low-power mode. Consequently, it is essential to minimize state transitions while still maintaining the balance of the scheduling mechanism without utilizing deep-power-down modes.

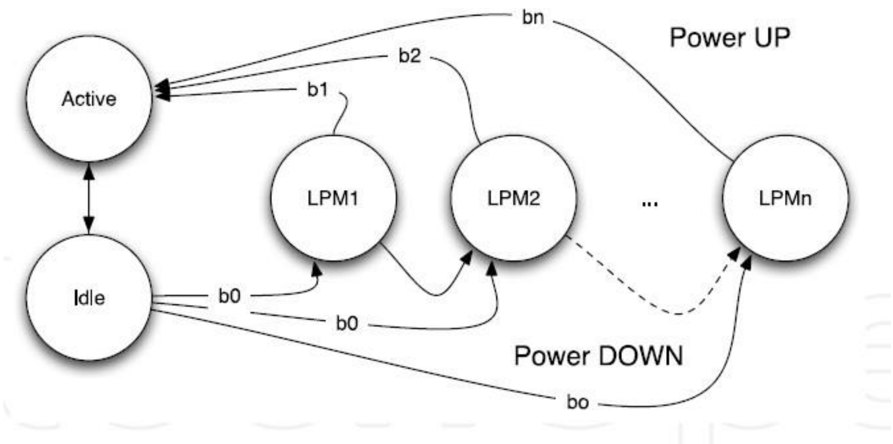

Figure 1.shows the time taken and consumed energy during the transition between states[3]

2.1 Microcontroller

The microcontroller unit (MCU) performs a pivotal role in the monitoring process and accounts for a significant portion of its total energy consumption. Though the MCU is often selected based on the computational application requirements, it could also substantially impact the power characteristics of the node. Generally, motes like the MicaZ utilize off-the-shelf processors such as the ATMega128L. Lynch, & O'Reilly [11] surveyed the computing requirements of a typical class of WSN application and found that the majority of commercially available MCUs are often over-kill. Ideally, in power-aware circumstances, the MCU should be selected based on the application scenario to obtain the highest level of correspondence between the MCU's capabilities and the application's demand. Table 1 summarized the outcome of their study.

Table 1.Presents some "Commercial Microcontrollers used In Sensor Networks[10]

	PIC16	ATMega128	MSP430
Context Switching	No special fratures	Software accessible stack	Sofrware accessible stack
Interrupt Structure	Power interrupt with priority	Power interrupt with priority	Interrupt with hardwired priority
ISA	8-bit RISC-like ISA with 30-40 instr.	8-bit RISC with up to 133 instr.	16-bit RISC with 27 instructions
Processor Architec-ture	Harvard with banked memory, 8K ROM	Harvard with 32 GPRs and 8K ROM	Von Neumann with 16 GPRs
I/O	GPIOs, UART, SPI	GPIOs, UART, SPI and JTAG for testing	GPIOs, UART, SPI
Clock Scaling	No clock scaling	Software selectable clock frequency	Software selectable clock scaling
Sleep Modes	One sleep mode (power off)	Modes ranging from idle to deep sleep	Modes ranging from idle to deep sleep
Pipeline	2-stage fetch-execute pipeline	2-stage fetch-execute pipeline	No pipeline

Power management in WSN is a well-researched topic[12]. Numerous studies have addressed the uses of microcontrollers in WSN[13]. Lynch and O'Reilly have demonstrated few commercial processors that are now being used for WSN applications[10]. The study showed a wide disparity in the features of the processors and concluded that the MSP430 processor is the best available processor in terms of power consumption. However, this claim can be easily queried significant advancements have been witnessed in this field since the time they reported their findings.

2.2 Cross-layer protocols and architectures

Sensor nodes in WSN are battery-powered devices that receive data from their environment and transmit it to a sink for processing; this process consumes energy and, consequently drains their batteries. These challenges have necessitated the development of new energy efficiency protocols for sensor nodes. In a typical system, sensor nodes perform many-to-one communication with the sinks, leading to quicker power depletion of sensor nodes located near the sink. This issue is known as the Hot Spot phenomenon. It is claimed that the sink mobility technique can optimize the sensor nodes' energy dissipation. Utilizing mobile sinks can conserve energy and balance the load on the nodes.

Numerous cross-layer protocols and architectures have been explored in the literature; the first protocol is LEACH, a low-energy adaptive clustering hierarchy that integrates application-specific data aggregation with energy-efficient cluster-based routing. Clusters are made using a distributed algorithm, and nodes can decide whether to become cluster heads or not.The rotation of cluster heads divides the loads evenly between the nodes. When TDMA is deployed for intra-cluster communication, nodes only turn on their radios when transmitting data, leading to considerable energy savings. However, these savings are used by the cluster heads that transmit directly to MS[14].

Self-Organized-TDMA-Protocol (SOTP) incorporates routing and TDMA to support the application-specific and data-centric requirements of WSN[15]. MS uses routing data to allocate time slots to nodes. At a far distance from the MS, nodes should be given a time slot at an earlier location in the TDMA frame to minimize data latency. The cross-layer combination makes node design easier while also improving energy efficiency. To adapt the network to any node/link failures, every single node sends an active-state indicatorpacket to the MS at regular intervals. As a result, nodes located far from the MS use a huge portion of their energy resources, reducing the network's total lifetime. SOTP has been shown to outperform the standard version of LEACH; however, this comparison is inaccurate as SOTP employs Multi-Hop routing, whereas vanilla LEACH communicates directly with the MS. The work of Kebkal introduced the D-MAC protocol for data transmission between multiple nodes and a master server[15]. It is a multilayer protocol that integrates media access and routing to form a data collection tree rooted on MS. To ensure uninterrupted data transmission over a multi-hop path, D-MAC staggers node schedules and enables them to wake up consecutively similar to a chain reaction. If *d* is the depth of the node in the data collection tree, the node configures its wake-up cycle *dl* ahead ofthe MS cycle and alternates between receiving, transmitting, and sleeping states on a periodic basis. So, when there is no collision, data is serially forwarded to MS without adding sleep latency, thereby reducing total data latency. Because nodes are awake only once they are required to transmit data, D-MAC significantly reduces the energy consumption of the nodes.

The disadvantage of D-MAC is that it doesn't take node fairness into account, and interference with other nodes at the same depth must be managed carefully. Additionally, the protocol does not specify how the node can acquire route and depth information. It is a route-independent protocol, and nodes outside of the routing routes consume energy resources on idle listening. FlexiTP utilizes MAC protocol awareness of a node's schedule to allow routing protocols to transmit and collect data between nodes[2].It configures the network using CSMA/CA and creates a data collection tree rooted at MS [16]. It establishes transmitting schedules that nodes adhere to during their lifetime. To prevent collisions, a token passing scheme is used, with nodes only performing procedures if they possess a token. Following network configuration, nodes execute data collection activities using their TDMA schedules.

This is accomplished through nodes transmitting data to their parents before parents become inaccessible due to energy drain or environmental conditions. Only the nodes engaged in data transmission remain awake throughout the TDMA slots, resulting in considerable energy savings. FlexiTP's loose slot structure ensures end-to-end data transmission and fault tolerance by allowing nodes to create, expand or change their schedules based on local knowledge. On the negative side, the number of child nodes that a parent may have is not limited, resulting in unequal load distribution across parent nodes. Overall, the child selection mechanism is based on a simplistic broadcast-reply method that can result in an incorrect parent–child pair, lowering the protocol's overall performance and efficiency. Energy-efficient fast-forwarding (EEFF) is an energy-efficient MAC protocol combined with dynamic minimal hop routing mode [17].

The nodes are not coordinated, and each follows its own active sleep cycle. The relay node determines whether to approve a request to submit (RTS) from the source node depending on data latency to MS and its current state active or sleep. Then, the nominee relay nodes compete to transmit clear to send (CTS) messages to the source node. The winner will remain awake to receive data. Nodes regularly broadcast their local routing details to create a minimum hop-routing schedule for data transfer to MS via multiple hops. EEFF maintains high energy savings and low data latency by a flexible routing strategy that chooses relay nodes while transmitting, and data is transmitted without obstacles. On the negative side, data latency estimation done by the relay node ignores the variable network traffic loads which can lead to incorrect relay nodes. Above all, each data transfer process needs RTS/CTS and acknowledgment (ACK), and these increase the protocol's overhead.

MACRO is a combination of MAC and routing in which the next hop is chosen by the distance traveled to the final destination per transmitted energy. To reduce a node's energy demands, its radio is switched off frequently and various transmitting power rate values are used[18]. However, this means of determining the next-hop increases the number of hops taken by data to arrive at the destination, thereby increasing latency. Finally, it is assumed that the nodes are Poisson-distributed, meaning that it is highly likely to differ from a case in the actual sensor network.

The adaptive load balanced algorithm (ALBA-R) is a routing strategy and cross-layer MAC protocol that considers the node's position and traffic load when establishing routes[19] . Choosing routes with less traffic increases the protocol's energy efficiency; however, the selection procedure incurs a significant overhead when calculating the parameters that determine the node's progress toward the destination and its traffic load.

The Energy-Aware-Adaptive-Low-Power-Listening protocol (EA-ALPL) was designed based on two factors to enhance the node's efficiency. The first factor is the number of descendants in the routing tree that impacts the node's maximum load; the second factor is the duty cycle of the radio that decides the node's availability. However, the cross-layer protocol is insightful but does not introduce a practical communication protocol for implementation, rather, it validates the framework using the BMAC protocol [20]. MACROSS protocol utilizes the available routing data at the network layer for the MAC layer to extend the sleep duration of each node[21]. Moreover, it exploits Network- Allocation-Vector (NAV) data stored in RTS/CTS packets to wake up only nodes whose NAV value had already expired and are located on the routing path between the source and the MS. The remaining nodes continue to sleep even if their NAV timers have expired to conserve energy. However, the use of RTS/CTS data may increase the protocol's overhead [22].

The technique for data distribution between layers presented in [23] considers three main aspects- the energy consumption rate, the node location, and the neighbourhood data to identify the most efficient paths to the MS. The outcome confirms that the approach efficiently distributes load among forwarding nodes and decreases data latency. However, the protocol's implementation demands extensive recursions, and consumes a large amount of power for processing data.

Saleem et. al [24] presented a self-organized routing approach for choosing the relay node; this algorithm identifies the optimal p a th using decision criteria such as packet reception rate, remaining energy, and velocity. The simulated outcomes showed that for a grid- topology, the presented algorithm provided better results and less energy consumption compared to temporally-ordered-routing-algorithm (TORA) protocol [25]. ReSaF was proven to have a lower loss rate, fewer hops per packet delivery, and lower energy consumption when compared to collection-tree-protocol CTP [26] . This comparison can be argued and might be denied because neither CTP nor hop is a cross-layer protocol.

The previous section has reviewed different types of routing protocols used to transmit data packets with the lowest possible power consumption. Different routing approaches were explored in terms of their strengths and drawbacks. The next section is devoted to the review of wireless power transmission techniques.

2.3 Wireless power transmission (WPT)

Wireless power transmission (WPT) is the transfer of electric power from a source to a destination while minimizing transmission losses and deliver power wirelessly to some applications such as WSNs. Tesla is the pioneer of the WPT concept which was implemented using available technologies in 1902. Since then, several scientists have worked to expand on this concept and have obtained good results for transmitting at a short-range [27]. A research group at the Massachusetts Institute of Technology (MIT) succeeded to transmit power wirelessly over a mid-range distance using the magnetic coupling resonance technique. They lighted up a 60-watt bulb over a 2-meter distance [28]. WPT has increased the portability and offered more convenient choices. Additionally, it meets the high demand of new smart devices that currently utilize wireless technology for various operations and communications, such as Wi-Fi, which is used in laptops and smartphones for internet access. In fact, the WPT techniques have been developed more as practical applications than scientific hypotheses. This is noted in the massive number of research projects in several fields, such as industry, health, car, and environment applications.

In 1961, William C. Brown presented a pivotal research paper. The article described a systematic method for power transmission at the microwave scale. The optimal choice of such low frequencies could be attributed to the inherent benefits of wider areas being covered. However, the approach was constrained by low-level power transmission and poor efficiency. Several other challenges that developed during that time were associated with the misalignment of transmitter and receiver components, which contributed to the uncertainty in power transmission, hence decreasing the efficiency[29]. Hochmair's research remedied the aforementioned problems even though his research was largely focused on biomedical applications of power transmission; he illustrated the impact of different geometries in resolving the frequency misalignment issues in transmitter and receiver modules [30]. The work by Green and Boys on power transmission in transportation systems is another milestone for wireless power transmission. The project focused on the controlling parameters related to wireless power transmission. However, it was restricted to low power level and short distances [31]. Zhu et al in [32] paved the way for a new technological advancement in the field of WPT. The team deployed the back emf phenomena in the receiving coil. This breakthrough led to an increase in both the transmitted power and transfer distance at medium frequency ranges [32]. In 2010, Kim et al used Tesla's concepts to develop an efficient WPT system. Interestingly, they succeeded to transmit power wirelessly over a distance of two meters with a very limited efficiency of 20 %. Despite the low efficiency, the transferred power was approximately 50 W at a high radio frequency of 9.4 MHz. One of the most significant advantages of this technology was the ability to transmit power beyond physical obstacles. The technique was constrained by the increased impact of radiation and the inherent difficulties of manufacturing [33].

Haerinia & Afjei in [34] deployed the WPT feature for power transmission from one point source to multiple receivers. This approach improved the knowledge of the power distribution concept across several simultaneous receivers and receivers located at different distances. Additionally, the study inspired the concept of multiple systems and multiple charging using a single transmitting source. The system was highly unreliable, underdeveloped, and subjected to design faults.

Beh in [35] presented an enhancement to the experimental results of Kim et al in [33]. The researchers increased the efficiency of the WPT systems by employing impedance matching technologies via magnetic resonance methods. This was achieved by using a high frequency to eliminate the internal losses. The high-frequency approach was chosen due to some limitations of electromagnetic induction over short ranges and the limited efficiency of wireless transmission via microwaves. It contributed to optimizing power transferby increasing the efficiency up to 40 % across the same distances using this technique. This was performed using an impedance matching approach for different distances and air gaps.

Ho et al in [36] established a framework for power distribution and conducted a comparative assessment of two widely used approaches. The researchers compared the performance and physical characteristics of novel WiTricity with a conventional inductive-magnetic-coupling and discussed their advantages and disadvantages. While the work is comprehensive, the relationship between the techniques and history is inadequate [36]. According to research conducted by Gundogdu & Afacan, sine waves were the most efficient waveform when compared to other waveforms [37]. According to [38, 39] the efficiency of WPT is inversely related to the duty cycle once a complete duty cycle is reached.

Despite the existence of Brook's coils and multilayer coils, the utilization of magnetic cores in WPT coil design was ineffective due to core saturation phenomena [40] along with the negative impact on other neighboring wireless devices[41]. Furthermore, Soong et al. justified the use of an air-core because it is efficient and has no effecton the inductance as current increases.

2.4 Energy harvesting techniques (EHT)

The primary shortcoming of energy harvesting is that the power being harvested from ambient available power sources like radio waves is not stable and not predictable. Many researchers have aimed to enhance the efficiency of the harvested power obtained from the low ambient sources. In this section, the performance of rectifying antennas in improving the output power harvested from low potential ambient power sources, as well as the promising technologies for energy harvesting was investigated.

A sensor for the Internet of Things (IoT) is a potential application for the energy harvester. IoT applications have paved the way for other technologies, such as Radio Frequency (RF) energy harvesters to harvest energy. A clock, for instance, is a low-power traditional device that is well-suited for EHT. A research team at the University of Washington has developed a battery-free mobile phone that runs using a combination of analog and digital techniques and consumes only 3.48 μWatts. This power consumption was obtained via RF energy harvesting techniques [42].

Another research team at the same University has developed an augmented-reality-contact-lens. The study was conducted in collaboration with Google Inc and other organizations[43]. Medical applications and environment mentoring devices are other potential applications for EHT and WPT. Numerous medical and environmental applications can be found in [44]. Li & Shi in [45] presented an Intelligent- Solar-Energy-Harvesting (ISEH) technology for a long-term and steady supply of energy in WSN. A solar panel, control circuit, and a lithium battery work together to provide clean energy 24 hours a day. Solar energy is used when there is sufficient sunlight, whereas the lithium battery is used when there is insufficient sunlight. The presented system incorporates a sun tracking circuit to maximize the harvested energy and provide an efficient charging mechanism suitable for long-term conditions of the lithium battery.

HASS is a Harvesting-Aware-Speed-Selection algorithm presented in Zhang et.al, (2013) [46] to optimize the energy savings of nodes in the network without impacting the application's performance in WSN. It employs the DVS technique to conserve computation energy by simultaneously reducing the CPU voltage and frequency and uses the DMS approach to conserve communication energy by reducing the radio modulation level. The traditional EHT discussed above is inappropriate with tiny sensor nodes, such as those employed in Wireless-nano-sensor-Networks (WNSN) applications [8]. The reasons are (i) Solar energy harvesting utilizes a low-efficiency photovoltaic nano-cell that cannot be enhanced even if nano-components like carbon nanotubes are used [47]; (ii) Normally, sunlight is unavailable in all WNSN applications, and to solve this issue of the limited capacity of energy in nano-sensor nodes, some researchers have suggested the use of piezoelectric nano-generators to replenish the nano-devices energy [48].

The following section discusses several studies that have used piezoelectric nanogenerators to supply nanosensors. Pierobon et al., [49] proposed a novel routing system based on Terahertz-Band-Communication and nanoscale-EH. The framework organizes the WNSN into multiple clusters using a hierarchical cluster design. Each cluster has a capable Nano controller that coordinates and collects data from the nano-sensors.

The framework demonstrates a method for conserving the energy gathered by the nano-sensors while also increasing the throughput of data transmission between the nano-sensor and the Nano-controller. To transfer data, the nano-sensor initiates a communication with the Nano-controller by sending a request specifying the quantity of data to be transmitted. The Nano-controller then determines if the nano-sensor must transmit data in a single-or multi- hop based on the distance between the nano-sensors and based on their density. Equation (1) estimates the average energy needed to transmit one bit of data over a given distance [49].

$$E_{bit}(l) = \left(\frac{4\pi f_0}{C}\right)^2 \frac{N_0 SNR}{\log_2(1 + SNR)} l^2 \quad (1)$$

Where l represents the distance, N_0 is a constant, and F_0 is the center frequency. C represents the speed of light in a vacuum. The simulation results of the suggested technique indicate that it performed near optimally. The EHT for WSN was summarized in Table 2, along with the associated pros and cons for each approach.

Table 2. "Summary of energy harvesting mechanism WSN retrieved from [50]

Mechanism	Source	Feature	Advantages	Disadvantages	Application field
Conventional energy harvesting	Solar	Light energy is transformed into electrical energy	Established technology	High installation cost	Environment [13], agriculture [53, 100]
	Wind	Kinetic energy of wind is transformed into mechanical energy then into electrical energy		Sunshine is not available at all times	
Piezoelectric nanogenerators energy harvesting	Vibration	Energy from movement or vibration is converted into electrical energy	No limit to harvested energy limit [28]	Still an emerging technology Amount of energy is small	Biomedical, industrial and military [4]. Drug delivery systems [28]

2.5 Aim and objectives

The aim of this work is to evaluate the power consumption of wireless sensor networks used in manufacturing. The second aim is where possible to suggest a suitable methodology for energy harvesting to power wireless monitoring process in a computer numerical control (CNC) application.

The aim of this work can be achieved by implementing the following objectives.

- Experiments to measure the power consumption of temperature and vibration sensors along with the power consumption of available microprocessors were initially to be conducted in a workshop environment. Instead, a detailed review of previous works is conducted.
- The power consumption of several types of temperature sensors is theoretically evaluated based on previous research.
- The same approach is applied to selected vibration sensors.
- Different communication protocols are investigated to "identify" the most efficient power-saving protocol considering the transmission rate and data latency.
- Wireless power transmission techniques are investigated, and their advantages and disadvantages are explained.
- A 3_axis machine is used as a case study. The MEMs used for vibration measurements

and direct-to-digital temperature sensors used to monitor the conditions of the ball screw are investigated and their power consumption is evaluated. Finally, an energy harvesting technique is proposed to be used in the Case study machine.

2.6 Methodology

The methodology adopted for this thesis is to review the literature on energy consumption and apply it to a case study for machine tools. Condition monitoring of such systems is a widely researched topic, and the inclusion of wireless sensors would make practical systems more efficient to implement and maintain. This is particularly true for hard-to-reach areas of the machine (under guards) and where moving parts (machine axes) make wired sensors costly to install and susceptible to damage. The advantages of wireless data transmission are partially lost if the power supply still has to be cabled back to a central source. Similarly, the use of replaceable batteries for each element of a WSN is unlikely to be acceptable.

It had been intended to undertake a physical/practical assessment of the energy consumed at different parts of the system, but due to the shutdown in 2020/21 due to COVID-19, this was not possible. Instead, a more in-depth review of existing literature to find the relevant parametersis presented in Chapters 3, 4, and 5. Chapter 6 presents some methods that could be used to power WSN at each level. A calculation-based case study has been included in Chapter 7 to show how the concepts in this thesis could be applied.

2.7 Chapter summary

In this chapter, the focus was on different topics related to power consumption in smart sensors such as WSN structure, microcontrollers, protocols to reduce power consumption, wireless power transmission techniques, and potential sources to harvest energy. It is clear from the literature that the topic of maintaining energy in WSNs has been recognized as a significant issue, confirming its suitability for this research work. Recent advanced wireless power transmission techniques were also reviewed, with encouraging results seeing the successful wireless transfer of power to light-up bulbs. The use of sensors for condition monitoring of machine tools has also been reviewed. Many areas of a machine are difficult to access and cabling to moving parts, such as the ball screw nut, is very difficult. The next chapter will evaluate the power consumption of some transducers typically used in manufacturing applications.

3 Evaluation of Power Consumption – Transducer

In the previous chapter, different topics related to WSN were explored to identify a research gap. Many research works were reviewed, and a brief conclusion was given. This chapter focused on the evaluation of the power consumption of commonly used transducers. Some temperature, humidity, and vibrations sensors were reviewed and evaluated. At some points, they were compared with different types in terms of their structure, application, and power consumption.

3.1 Temperature

Temperature is one of the most important monitored parameters[50] . Temperature can be obtained from natural resources, such as sunlight, and can be generated electrically via the flow of current through conductive materials. Also, it can be generated mechanically by motion or friction between machine parts. Temperature significantly contributes to the increase of uncertainty in machining processes. For example, in a machine tool, some of the consumed mechanical and electrical energy during cutting, turning, or milling processes is converted to thermal energy; most of this heat is transferred to the machine body and the cutting tool [51]. This heat causes the terminal deformation issue for the machine tool. Moreover, the product surface quality and tool life will be affected [52].

3.1.1 DS18B20 Digital Thermometer

The DS18B20 is a digital thermometer that presents between 9 to 12-bit readings that represent the actual measured temperature of the process. 1-Wire interface is used to send and receive data from the DS18B20, therefore, the connection between the DS18B20 and the microprocessor is made by using one wire beside the ground. There is no need for a power source to read, write, or perform temperature conversions since the required power can be drawn from the data line directly. Many DS18B20s sensors can use the same 1-Wire bus as every DS18B20 has a specific silicon serial number. This enables the sensors to be placed in several locations. This feature is beneficial in various applications, such as HVAC environmental controls, temperature sensing around big buildings, process monitoring, and equipment or machinery[53].

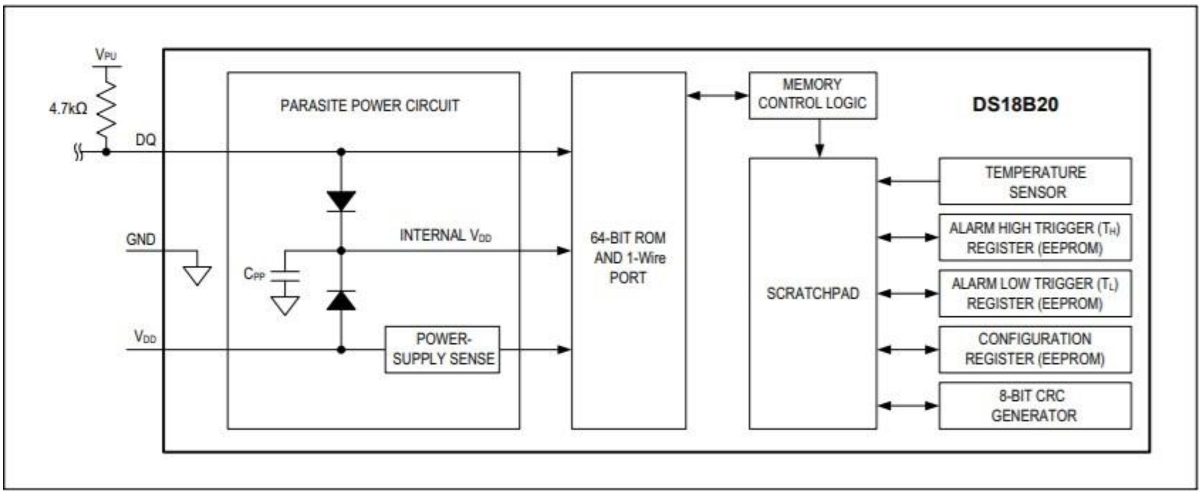

Figure 2.Block diagram of the main components of the digital thermometer [53].

The sensing unit gets its required power from the 1-Wire communication line by saving energy on a capacitor regularly when a signal is present on the line and processes to use this source when the signal is absent in the line. Then, the capacitors are charged again when the signal becomes high. However, the DS18B20 can be supplied by an external power supply of 3-5.5 volt.

Parasite Power

The parasite powered circuit is shown in Figure (3). The circuit can derive the required power if the signal is present on DQ or VDD pins for a specific time. However, voltage requirements must be met as well to enable the circuit to perform efficiently. There are 2 main advantages of this circuit:

- External power source is not required for the remote sensing process of temperature.
- The data stored in the ROM can be manipulated even if an external power source is not existing.

Whenever a temperature conversion process is being performed, adequate power must be supplied to the DQ line to perform precise temperature conversions. Based on its datasheet, the required current to operate this sensor is 1.5 mA. That means the DQ line cannot have enough drive because of the high-value pull-up resistance “5k”. This issue is exacerbated when multiple DS18B20s are connected to the same DQ and intending to convert concurrently. There are two main methods for assuring that the DS18B20 sensor receives enough current throughout its conversion cycle. The first method is to offer a high pull-up on the DQ line during temperature conversions. This can be achieved by connecting the DQ line to the power source directly through a MOSFET as seen in Figure 3.

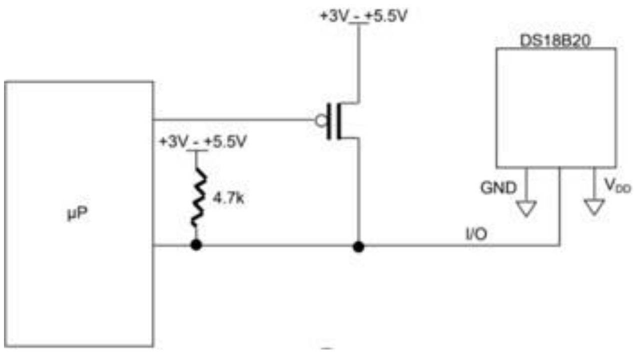

Figure 3.The circuit of a "Strong Pullup for suppling DS18B20 during temperature conversion[54]

However, the DQ line must be switched to the high pull-up within 10 µs after releasing any protocol that requires copying data to the E2 memory or start performing temperature conversions. The VDD pin must be connected to the ground whenever the parasite power mode is active[54]. Another means of powering the DS18B20 sensor is via an external power source connected to the VDD pin as seen in Figure 4.

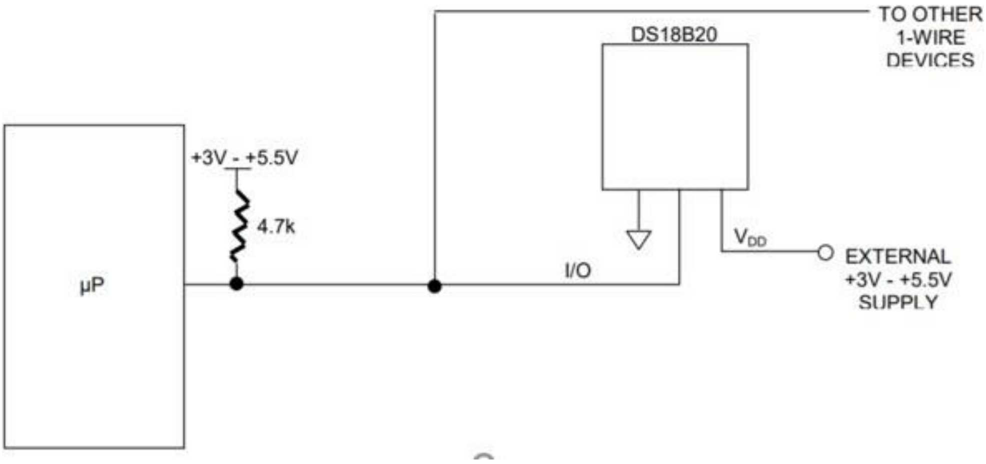

Figure 4."A block diagram shows the Using of the Vdd to supply temperature conversion current [54]

The benefit of this method is that no strong pullup is required on the DQ line; the bus master is not required to keep the line occupied during conversions of temperature. This enables additional data traffic on the 1-Wire bus while the conversion is taking place. Additionally, any amount of DS18B20s sensors can be wired to the 1-Wire bus, and if all of them are powered externally, they all may conduct conversions concurrently by executing the Skip ROM instruction, followed by the Convert T instruction. One should keep in mind that when the external power source is turned on, the GND pin won't be floating. However, it is not suggested to utilize parasite power over 100°C, as it may be unable to maintain communication due to the DS18B20's increased leakage currents at these temperatures. It is suggested that VDD be supplied to the DS18B20 in situations where high temperatures are expected.

3.1.2 BMP180 Barometric Pressure & Temperature Sensor

The BMP180 is a piezo-resistive MEMS sensor designed for applications that require high standards and robustness. The BMP180 is Bosch Sensortec's latest digital temperature, barometric pressure, and temperature sensor. It is commonly used in modern portable devices like tablets, smart phones, smart watches, and sports gadgets. It replaces the old BMP085 sensorand has several advancements, including reduced size and an extra digital interface.

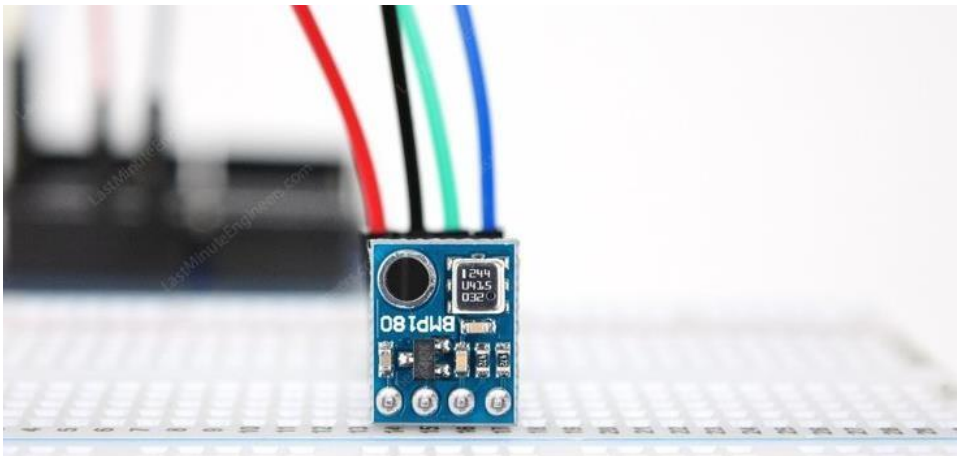

Figure 5.Shows the Bosch Sensortec BMP180 Barometric Pressure & Temperature Sensor [55]

The BMP180's ultra-low power consumption approach of less than 3μ A makes it one of the most power-efficient sensors available for portable devices. Additionally, the BMP180 is characterized by its very steady performance in terms of supply voltage independence. The BMP180 sensor is among the most dependable sensors used for precision applications, such as CNC machinery because of its high relative precision of 0.12 hPa (1m). Its compact dimension of 3.6* 3.8 mm^2 and low height of 0.93 mm makes it, in the words of the manufacturer, "ideal" for use in embedded devices[55] . Figure 5 showed the BMP180 barometricpressure & temperature sensor.

3.2 Humidity sensors

Humidity sensors are not usually required for CNC machines; however, new studies have drawn attention to the effect of relative humidity on the accuracy of the CNC machine. Excessive humidity may damage the components of the control systems and result in more failures. The study by Van in investigated the effect of relative humidity on thestopping position of the Automatic Tool Changer (ATC) in a CNC machine. CNC machines often utilize pneumatic dynamic cylinders. However ,the friction in the cylinder impacts the stopping position of the ATC. The results indicate that when the humidity level increases from 51 % to 99 %, the friction decreases. The study showed that friction is proportional to the relative humidity of the air. Accordingly, the deviation of the ATC's positioning system is reliant on the relative humidity of its ambient [56].

3.2.1 Digital Humidity Sensor SHT2x (RH/T)

The SHT2x family is humidity sensors widely used in a range of applications that require low power consumption. The SHT2x series includes a low-cost model, standard model, and high-end model with SHT20, SHT21, and SHT25 humidity sensors, respectively. The cavity mould frame that shields the microchip from the sensor head shields the capacitive sensor from external effect and ensures good long-term performance. SHT2x sensors can be found in both mini or large sizes [57]. This type of sensor i ncludes a band-gap sensor for temperature measurements, capacitive humidity sensor, and integrated analog-digital circuit combined on one CMOSens® chip. This design results in greater sensing accuracy and reliability, and most importantly, consumes less power. Additionally, the resolution of the SHT2x sensor may be modified using specific commands. With this combination of characteristics, as well as its long-term stability, the SHT2x family provides “an exceptional affordability”.

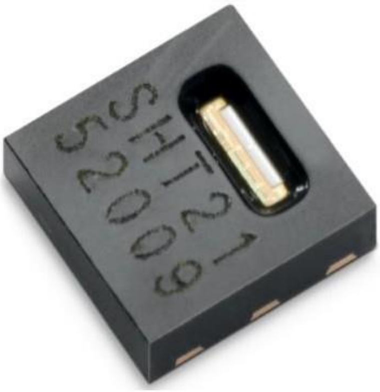

Figure 6.SHT21.Digital Humidity Sensor[57]

Table 3.SHT21.Digital Humidity Sensor from Sensirion[57]

Feature	**Characteristics**
Size	3 x 3 x 1.1 mm
Output	I²C digital, PWM, SDM
Supply voltage range	2.1 to 3.6 V
Energy consumption	3.2µW
RH operating range	0 - 100% RH
T operating range	-40 to +125°C
RH response time	8 sec

3.2.2 Digital humidity and temperature sensor SHTW2

The SHTW2 is a temperature and humidity digital sensor combined in a chip package. This type of package enables the development of a new class of ultra-compact sensors that are ideal for many applications with the strictest space limitations. The sensor can measure the temperature starting from -30°C to 100°C and measures humidity starting from 0 to 100 % RH with a standard accuracy of 0.3°C and 3% RH [57]. However, this accuracy (0.3 degrees C) might be unsuitable for a high-end application. The high-efficiency power-saving approach in the SHTW2 and its operating voltage of 1.8 V makes it highly recommended for use in wireless sensor networks with limited power resources. All these features make this type of sensor suitable in places where power source availability is not the main constraint, such as in WSNs application.

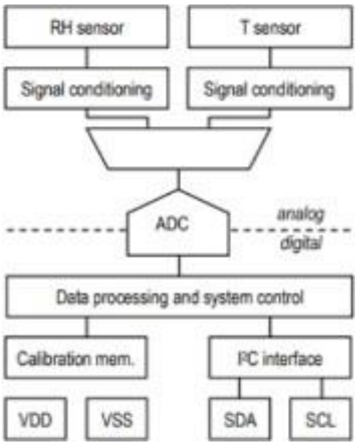

Figure 7.Block diagram of relative humidity sensor SHTW2 [57]

3.2.2.1 Power-Up and Communication Start

When the voltage on VDD reaches the operating voltage, the SHTW2 sensor enables the idle state after a cycle of CPU. In this mode, the sensor is prepared to receive and execute instructions from the microcontroller. Every transmission process starts with a START command (S) and finishes with a STOP command (P), as specified in the I 2C-bus standard. When this type of sensor is switched on but not taking a measurement or transmitting data, it enters an idle state automatically to save energy. This approach is suitable where a constant data stream is not required but would not be viable if data is constantly streamed to the data acquisition system.

3.2.2.2 Sensor Behaviour during Measurement and Clock Stretching

While measurements are performed, the sensor generally doesn't react to I 2C activities, i.e., the I2C sensor's headers for reading and writing are not recognized (NACK). Whenever the clock is enabled by executing a specific measuring command, the sensor reacts to the reading header and then starts pulling the SCL line until all the measurements are done. Once the measurements are performed, the sensor begins transmitting the results. To ensure the highest level of repeatability for temperature and humidity measurement, it is suggested to disable all I2C bus communication while the SHTW2 sensor is performing measurements. The estimated current consumption while performing measurements is shown in Table 4.

Table 4.The electrical specifications of SHTW2 Digital Humidity and temperature Sensor[57]

Parameter	Symbol	Conditions	Min	Typ.	Max	Units	Comments
Supply voltage	V_{DD}	-	1.62	1.8	1.98	V	-
Power-up/down level	V_{POR}	Static power supply	1.05	1.2	1.35	V	-
Supply current	I_{DD}	Idle state	-	0.7	1.5	µA	-
		Measurement	-	385	465	µA	Average current consumption while sensor is measuring[10]
		Average	-	4.8	-	µA	Average current consumption (continuous operation with one measurement per second)[10]
Power consumption	-	Average	-	8.6	-	µW	Average power consumption (continuous operation with one measurement per second) [10]
Low level input voltage	V_{IL}	-	-0.5	-	0.3 V_{DD}	V	-
High level input voltage	V_{IH}	-	0.7 V_{DD}	-	V_{DD}(max) + 0.5	V	-
Low level output voltage	V_{OL}	3 mA sink current	-	-	0.2 V_{DD}	-	-

3.2.2.3 Readout of Measurement Results

After issuing a measurement instruction and the measurement process has been performed by the sensor, the master will read the results by issuing a START command, followed by an I2C.The sensor will transmit 2 bytes of data at once to verify that the data has been delivered accurately; a one-byte checksum CRC command is sent after. Then, the same process is repeated until all the data is sent. To allow the sensor to continue transmitting data, every byte should be identified by the microcontroller with an ACKcommand. Otherwise, the sensor will stop transmitting data. However, this behaviour might save some energy which might be wasted while sending unrecognized data as the microcontroller will not verify the reception of the data and as a result, will not process it. On the other side, this behaviour can be challenged by the amount of energy used by the microcontroller to send the AKN command to the sensor. If the user is interested only in temperature and humidity signals and not interested in processing CRC data, it is advised to read only the first 2 bytes of the transmitted data with the CRC byte and stop the transfer of readings after reading the second 2 bytes. This technique is faster than initiating two separate measurements and terminating the read transfer process after the first 2 bytes on each occasion. This technique can be more efficient in terms of saving extra power as the actual real-time of processing can be shortened.

3.2.3 Wireless Relative Humidity (RH) Sensor

Relative humidity (RH) sensors detect the moisture content in the medium being measured for a given temperature and pressure [57]. A sensor transmits readings for relative values of temperature and humidity to the Online iMonnit Monitoring System. This system processes the received data and saves all the processed data in an online platform where it may be viewed, downloaded, or printed. In addition, notifications can be sent to smart devices to monitor or to execute any further action. However, this type of sensor might not be the best choice in cases where the power resources are the main constraint. Its power requirements are relatively highand can consume much power which reduces the lifetime of the batteries. On the other side, it has some features that might enhance its performance in terms of power consumption. This type of sensor can be powered up by solar power, which means that it can harvest energy from sunlight if it is used outdoors. It uses a rechargeable battery (Lithium Iron Phosphate) connected to a solar power cell. Other energy harvesting methods might be appropriate, such as harvesting energy from vibration or temperature. This means it can be used in industries, especially in tool machines.

Figure 8.Typical Wireless Humidity (RH) Sensor retrieved from [57]

Table 5.Technical specifications of the sensor.

Supply Voltage	**2.0 - 3.6 VDC**
Current Consumption in sleep mode	0.7 µA
Current Consumption(radio idle/off mode)	2 mA
Current Consumption (measurement mode)	2 mA
Accuracy	± 3% under normal conditions
RH Response Time	8 sec (tau 63%)
Radio RX mode	25 mA
Radio TX mode	35 mA

3.3 Vibration

Monitoring vibrations is one of the most important ways to protect the CNC machine during the machining process. The objective of vibration monitoring is to monitor machine health. The observable vibrations can be correlated with common wear-out mechanisms such as gears, belts, bearings, brushes, chains, shafts, and machine tools. These mechanisms in a typical CNC machine need to be maintained on a regular basis. When warning circumstances are observed, using real observations such as vibration signals gives an opportunity for quick response to prevent serious damages [58].

3.3.1 AMS 9420 Wireless Vibration Transmitter

The AMS 9420 is a wireless vibration sensor that provides complete vibration data in a self-organizing wireless network application. It offers comprehensive data on the health of machinery for both operations and maintenance purposes.

Figure 9.AMS 9424 vibration transmitter [59]

3.3.1.1 Cost-Effective Reliable Monitoring

The AMS 9420 expands the range of vibration monitoring applications. While it is suitable for the majority of vibration monitoring jobs, it is particularly well-suited for difficult-to-reach sites such as pumping stations, WSN application, and dangerous areas. Generally, the AMS 9420 is a good alternative for any application that would need substantial engineering, cabling, or installation expenditures [59].

3.3.1.2 Power requirements

The AMS 9420 offers flexible power options; for a wireless application, the Blue SmartPower(TM) module provides extended operating life in excess of 5 years (actual operating life depends on the device configuration). An optional power adapter is also available that allows the device to be powered by external DC voltage. An AMS 9420 unit can be easily converted from battery operation to line power. It consumes almost 18 mA, and this amount of power will prevent its usage in WSN applications.

3.3.2 Analog devises ADXL354 and ADXL355 MEMS

The ADXL354 and the ADXL355 are used to measure vibrations; they have been used in different applications[60]. They are used in CNC applications, such as in the reported case study in chapter 7. They consume relatively low power and consume 150 µA and 200 µA respectively in the measuring mode but in the standby mode, both consume only 21 µA. The low power consumption of ADXL355 allows it to be used in IoT applications.

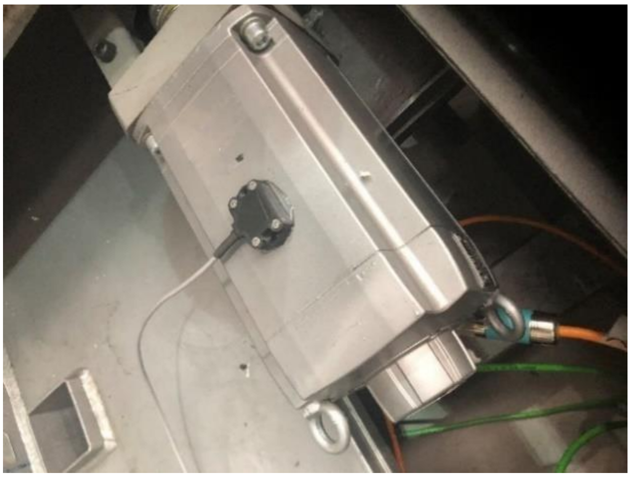

Figure 10.ADXL355 MEMS used to measure the vibration [60]

3.4 Summary

In this chapter, different types of transducers were reviewed, and their electrical capabilities were evaluated. In addition, some issues related to their power consumption and data transmission were critically appraised. This work will be used in Chapter 7 as part of the case study. The next chapter will evaluate and review the commonly used Arduinos and Moteino processors as examples of processors that might be used for local data processing in "intelligent" or "smart"sensors.

4 Evaluation of Power Consumption - Local Processing

In this chapter, the focus is on the evaluation of the power consumption of commonly used processors. Different models of Arduino are reviewed and compared in terms of their power consumption. However, their overall performance is not the constrain in this research. In addition, the Moteino microcontroller is explored, followed by an evaluation of the ATmegaXX microprocessors family and their comparison with the other models.

4.1 Arduino

Arduino controller is an open-source microprocessor that can be programmed and reprogrammed at any time. Launched in 2005, the Arduino platform was developed to enable users, students, and developers to easily design devices that interface with their surroundings via sensors and actuators. It is used to control different applications. Additionally, it is capable of functioning as a minicomputer by processing inputs and manipulating the outputs of a range of electrical devices [61].

4.1.1 Arduino Pro Mini with the ATmega328P

A 9V battery can run an Arduino Uno for almost a day due to its relatively high current consumption of roughly 45 mA. But when using Arduino Pro Mini with a minor adjustment, the power consumption can be significantly optimized and reduced to 54µ A for the 3.3 V batteries and to 23µ A for the 5 V batteries in power-down sleep. That means it can run for almost four years using a 9 V battery with a 1,200 mAh capacity; this is more efficient by 2,000 times than Arduino Uno. In case of disabling the voltage regulator, the Arduino pro mini only consumes 4.5 µA when using a 3.3 V battery and draws 5.8µA with a 5 V battery in power-down sleep. One more feature in favour of the Arduino Pro Mini with an ATmega328P processor is its cost-effectiveness since it can be obtained only for £2.

This section discusses the major characteristics of the Pro Mini in terms of how to put it into the low-power mode, how to deactivate the unnecessary LEDS such as power LED, how to disconnect the VR, and determine how much current can be saved during each step whether using the 3.3 V or 5 V version [61]. The Pro Mini normally uses the Atmel ATMega328P microprocessor as the Uno. Because they both use the same MCU, the memory size and the speed are the same as well. Additionally, the I/O pins are the same in both versions [62]. The essential difference between them is their physical dimensions as shown in Figure 8. Additionally, the Pro Mini has no USB port connection. As previously mentioned, Pro Mini

Arduino is available in both 3.3V and 5V versions. The 5 V version operates at a maximum of 16 MHz, whereas the 3.3 V type operates at just 8 MHz.

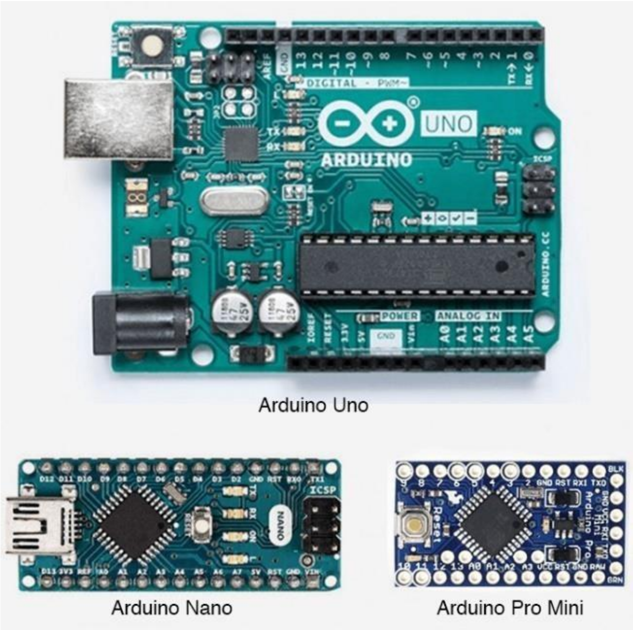

Figure 11.Shows the differences between Pro Mini &Uno [62].

There is a third version that can support 3.3 v or 5.0 v using an adjustable regulator through setting a jumper fitted in the Arduino. However, this version is not recommended in an applicationwhere the power sources are limited because the adjustable regulator consumes extra power in power-down sleep mode. Whichever version you pick (3.3 V or 5 V) is likely to be determined by the sensor's power requirements or other modules intended to be connected. If all modules run at 3.3 V, the 3.3 V version is the preferable option. If some components run at 5 V, the 5 V version may be the best option [61]. One-third comment about the power source; the RAW pin can be used to supply unregulated voltage to the Pro Mini. For instance, a 9 V battery can be used, however, in all scenarios, the input voltage must be greater than the output voltage by 0.4V in minimum because some voltage will drop on the regulator. The regulator will dissipate the voltage difference as heat[61] . This point should be considered when designing a wireless system. This extra heat might influence the performance of the Arduino which might result in more power consumption . According to the MIC5205 datasheet, the overheating issues can be reduced by using 6.3 V input voltage for 3.3 V output at a maximum load of 150 mA. Alternatively, the Arduino can be powered directly through the VCC pin. The voltage applied to the VCC pin is the actual voltage on the MCU and all other pins on the board.

4.1.1.1 Power down sleep to save energy

Whenever the ATmega328P processor is in active mode, millions of instructions are executed continually per second. Additionally, all the peripherals consume power such as the Analog-Digital Converter (ADC), the Timers, the Serial Peripheral Interface (SPI), the Brown-out Detection (BOD), and others. All these peripherals are essential for the processor to perform efficiently, however, they will apply extra load and drain the battery faster. To conserve more power and extend the battery life, the ATmega328P MCU offers a variety of sleep modes and disables all unwanted peripherals. The sleep modes vary in terms of which peripherals stay active, sleep duration, and the required time to wake up which is commonly known as a wake-up period. The sleep modes and peripherals are configured by using the AVR Sleep and Power libraries, more specifically by using Rocket scream's Low-Power library. This library is very easy to use, yet, it is an extremely powerful library. The Low-Power-Power- Down (SLEEP 8S, ADC OFF, BOD OFF) command places the processor in the Sleep Mode Pwr-Down mode for an estimated period ranging between 16 ms to 8 seconds based on the first argument [61].

It deactivates the BOD and Analogue Digital Converter. Power-down sleep mode disables all microchip functions until the next interrupt occurs. Additionally, the auxiliary oscillator is deactivated. The processor can only wake up by WDT, pin change interrupts, INT1 and INT2, if all or one of them is enabled. Thus, with just one statement, energy consumption might be significantly reduced. By disenabling the voltage regulator, and disconnecting the power LED, the energy consumption of the Arduino pro mini can be brought down to 4.5µA for a 3.3 Version. That is quite close to the 4.2µA for power-down sleep mode with WDT-enabled as specified in the datasheet of ATmega328P microchip. As a result, it is certain that the power-down function disables everything reasonably conceivable and plays a massive role to save extra power. Therefore, it can be highly recommended to be used in wireless-powered applications due to its low power consumption [61].

Table 6. Result Overview of ATmega328P Pro Mini Version with 5 &3.3 V retrieved from [61].

ATmega328P Pro Mini Version	PWR Source	State	5.0 V @ 16 MHz	3.3 V @ 8 MHz
Unmodified	RAW Pin	ACT	19.9 mA	4.74 mA
Unmodified	RAW Pin	PDS	3.14 mA	0.90 mA
No Power LED	RAW Pin	ACT	16.9 mA	3.90 mA
No Power LED	RAW Pin	PDS	0.0232 mA*	0.0541 mA*
No Power LED, no Regulator	VCC Pin	ACT	12.7 mA	3.58 mA
No Power LED, no Regulator	VCC Pin	PDS	0.0058 mA	0.0045 mA

4.1.1.2 Disable the power LED

In case of canceling the power LED, the Arduino Pro Mini 3.3 V consumes around 0.85 mA less, while the 5 V version consumes even less than that, to be more specifically 3 mA less. However, the power LED cannot be disabled by the ATmega328P chip. Thus, to deactivate the LED, a little hardware change is required by disconnecting one of the 2 tiny traces that connect the LED to the board as shown in Figure (12&13) [63].

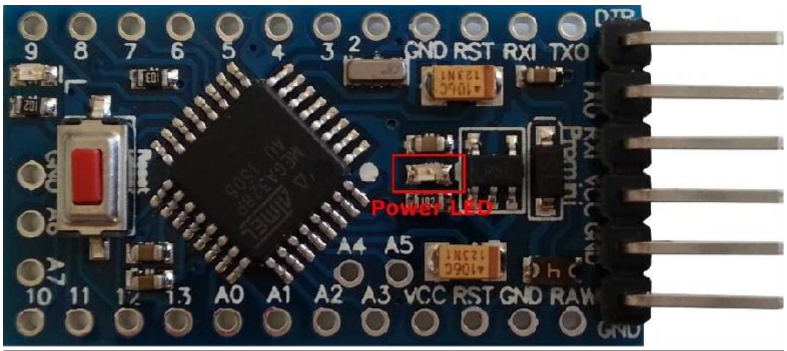

Figure 12.Shows the Power LED location on Arduino Mini Pro [63]

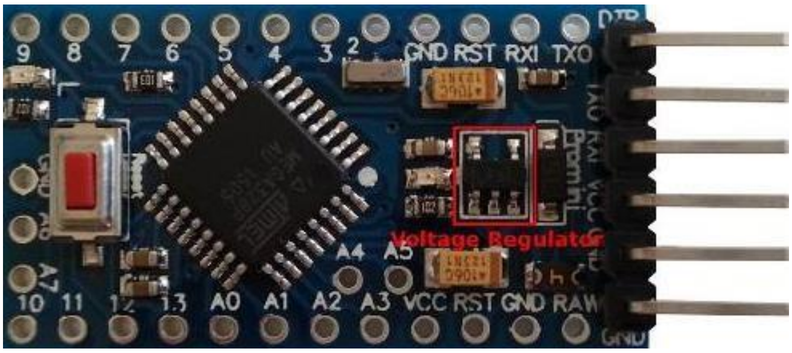

Figure 13.Shows the "voltage regulator" location on Arduino Mini Pro[63]

Now, the LED's power share is saved, and the Arduino should consume around 54µ with 3.3V version and around 23 µA with 5V version.

4.1.2 Previous experiments compared the power consumption of pro mini with a Custom Circuit board (codename OLGA).

4.1.2.1 Setup the Arduino Uno Board

For configuration, a wire was soldered to the fuse just underneath the USB port and connected to a Multimeter (a reasonably priced Digital Multimeter). Then, the other terminal from the Multimeter was connected to the USB port of a computer system to provide a 5V Dc supply to the Arduino [64].

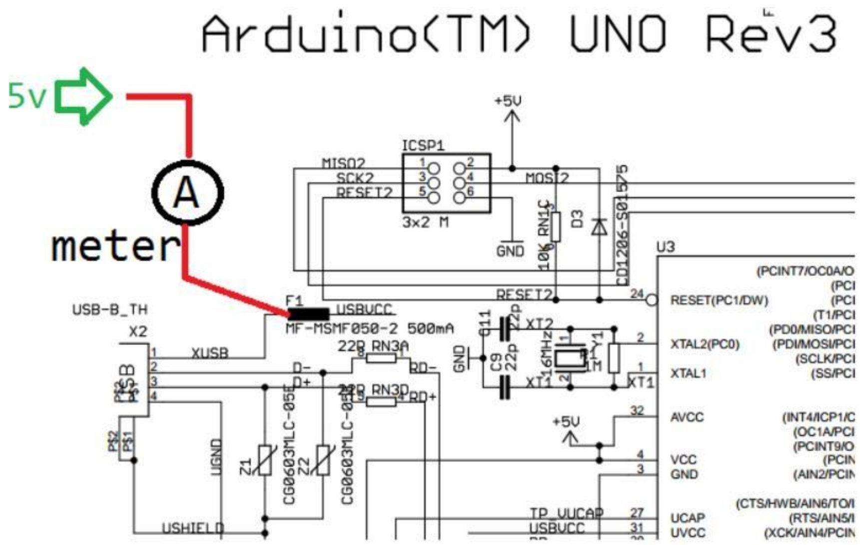

Figure 14.Shows the layout of the Boars configurations[64]

4.1.2.2 Measuring the current consumption

The measured current was 46.5mA when using Arduino Uno 5V version with no load code.

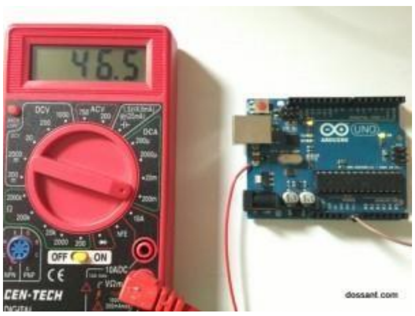

Figure 15.A Multimeter displays the actual measured current consumption [64]

4.1.2.3 . Calculating the Power Consumption of Arduino UNO

The power consumption can be calculated using the following equation [64] :

P = V x I

P = 5v * 46.5mA = 232.5mW

4.1.2.4 Putting the Arduino to sleep mode

The code was dedicated to waking up the Arduino every few seconds based on the watchdog timers and INT1 and INT2. The results were promising as can be seen from the pictures; the power consumption reduced from 46.5mA to 34.4mA which is about 26 % of the total consumption [64].

Figure 16.A Multimeter displays the actual measured current consumption when the Sleep Code is activated and Power LED is on [64].

Figure 17.A Multimeter displays the actual measured current consumption when the Sleep Code is deactivated and Power LED is off [64].

When the power LED was disconnected, the drawn current was reduced to 32 mA, saving an extra 2.2 mA. However, the consumption of Arduino Uno is relatively high compared to Pro Miniand it can be said that it cannot be used with constrained power applications [64].

4.1.2.5 Custom Circuit board (codename OLGA)

OLGA is a board that uses the same processor as in Arduino, running at 8M Hz 3.3v, but it was opposed to Arduino UNO as it runs on 5V 16 MHz. This method might be used to decrease the power consumption of the board. This technique can be complimented in terms of the processing speed of the board[64]. The processor speed will be enhanced, which means that the processor will be in active mode for less duration, thereby lowering the power consumption for the same amount of processed data. However, it can be criticized in terms of the voltage applied on the microchip and related peripherals. The applied voltage is 5V which is higher than the supposed voltage (3.3V). The extra voltage will cause extra heat on the controller and may affect the overall performance[64].

4.1.2.6 Result Comparison

The experimental results showed that the power consumption in this customized board is 1.456 mA. The drawn current dropped from 32 mA to just 1.456 mA. The power consumption can be enhanced by turning the Power LED off and the result was 495 uA.

Figure 18.A Multimeter displays the total current consumption of the customized board[64]

Figure 19.A Multimeter displays the actual measured current consumption of the customized board when the Power LED is off[64] .

Figure 20.Comparison of the results between Arduino pro mini and the customized board[64].

To conclude, an Arduino Uno R3 consumes 46.5 mA at a no-load situation, which may not be useful in battery-powered applications. When the sleep mode was activated, the consumption was significantly improved (32.4 mA). Finally, the customized board (OLGA board) made a noticeable difference and brought the consumption down by almost 97 %, meaning that battery life can be extended and might be used in battery-powered applications.

4.2 Moteino

Moteino was launched as a low-power wireless Arduino-enhanced network based on the ATmega328p processor found in the Arduino UNO. Currently, different Moteino boards are available; they use different microchips, such as MoteinoMEGA, which uses the

Atmega1284P, and MoteinoM0, which uses other types of processors (the SAMD21G18 CortexM0+). An external FTDI-Adapter will be required to load codes, which results in reduced size and less cost. They are interoperable and can be connected with other versions of Arduinos or programming platforms that utilize the common transceivers, such as LoRa, RFM12B, and HopeRF RFM69. Additionally, Moteino includes an SPI memory chip that may be used either for wireless coding or data acquisition. They are well-suited for the Internet of Things (IoT) and long-range wireless applications. The following are some of Moteino's features [63].

- Its compact and lightweight design fits into even the tiniest enclosures.
- Flexible settings enable the use of multiple transceivers.
- Provides ultra-low power consumption, with 200 nA in deep sleep status, and enables battery-powered applications, such as wireless sensors to run for many years while in watchdog sleep mode, it consumes less than 6 uA.
- The latest version, 8Mhz Moteino enables the lowest possible consumption with almost 100 nA.

Table 6.Comparison of the specifications of different types of Moteino

Parameters	**Moteino**	**MoteinoMEGA**
Transceiver	RFM69, RFM95/RFM96 LoRa, RFM12b	RFM69, RFM95/RFM96 LoRa
Microchips	ATmega328p	ATmega1284p
Frequencies	433MHZ,868MHZ,915MHZ	433MHZ,868MHZ,915MHZ
Input voltage	3.6 to 16V	3.6 to 16V
Digital I/O Pins	14+6	24+8
Current per pin	10mA	10mA
Memory	32 KB	128KB
Power usage	~8mA active mode	~8mA active mode
Lowest power	6.5uA	6.5uA

4.2.1 Moteino 8Mhz variant

There is no low dropout (LDO) in the Moteino 8Mhz variant, which enables activating the lowest possible power-saving modes of the MCU (ATmega328p). It differs from the standard Moteinos in the following features:

- The Moteino 8Mhz variant has no low-dropout linear regulator.

- Whenever an RFM radio or FLASH-MEM is used with it, the microcontroller must bepowered by a 3.6 V source or less, otherwise, it might be damaged.
- Low power consumption as it consumes 2 uA less than the standard Moteino.

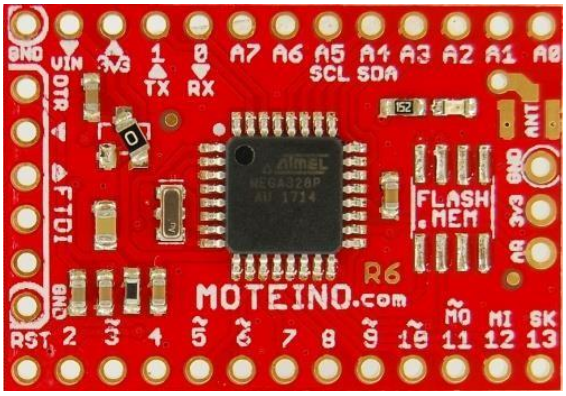

Figure 21.Typical Moteino 8MHz variant board [63]

This version is ideal for ultra-low-power applications based on coin-cell and some other micro-power node networks. They require only 3.6 V or less to be powered on and perform tasks. Obviously, with such small power supplies, transceivers must be selected properly in terms oftheir power requirements as it is almost certainly impossible to transfer data at full 20 dBm from a coin cell. It is recommended to use Auto Power Dial RFM69_ATC library in WSN applications in real-time monitoring in CNC machines. MoteinoM0 is a low-power controller and uses an ultra-low-power SAMD21 Cortex microchip.

- Input voltage of 3.6-6V.
- Supports FM69HCW, RFM95, and RFM96 transceivers.
- Low power consumption of around 8 uA in standby mode.
- Long-distance wireless communications.

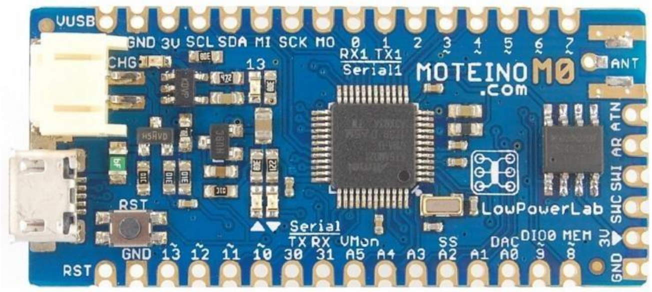

Figure 22.Typical Moteino M0 board [63]

4.3 Examples of Microcontrollers and their Operating Modes

4.3.1 The ATmegaXX family

The ATmegaXX series of microprocessors is a low-power design built on the AVR improved RISC architecture. By performing robust commands in a duty cycle, the ATmega1 accomplishes outputs close to 1MIPS per 1 MHz. This enables the designer to balance power consumption and computing performance on the microchip. The AVR® core from Atmel includes a comprehensive command set with 32 general-purpose registers. All the registers have been linked directly to the Arithmetic Logic Unit (ALU), enabling access to 2 separate registers by one instruction in a single clock cycle. The resultant design seems to be more efficient in terms of coding whilst reaching outputs 10 times quicker than the standard CISC microcontrollers. The ATmega series offers six different power-saving modes. Idle mode forces the CPU to stop while allowing the other peripherals such as Timer/Counters and interrupters to keep functioning. The Power-down mode holds the values of the registers but pauses the Oscillator, deactivating all other microchip operations until the occurrence of the next internal or external interrupt.

The timers continue working in Power-save mode, enabling users to keep a timer base whereas the other peripherals of the microchip are put into sleep. To decrease switching noise while processing ADC conversions, the ADC Noise Reduction Mode disables the CPU as well as all I/Ocomponents apart from the timer and ADC. Standby mode in this mode keeps only the oscillator running whereas the other sinks of the microprocessor are put to sleep. This enables extremely rapid start-up while maintaining low power usage. In Extended Standby mode, the timer and the oscillator continue to function normally. The Atmel ATmegaXX series of microcontrollers is powerful and flexible. It is a cost-effective option for a wide variety of embedded control systems.

Table 7.Compares the features of different microcontrollers.

Microcontroller	**Active mode**	**Power down mode**	**Power save mode**
ATMega644P	240µA at 1.8V,1MHz	0.1µA @ 1.8V	N/A
ATmega328P	1.5mA at 3V -4MHZ	1µA at 3V	N/A

ATMega1284P	1MHz, 1.8V, 0.4mA	0.1µA	0.6µA
ATmega48P\V	At 1MHZ 1.8v0.3mA	0.1µA	0.8µA
ATmega168P\V	At 1MHZ 1.8v0.3mA	0.1µA	0.8µA
ATmega88P\V	At 1MHZ 1.8v0.3mA	0.1µA	0.8µA
ATmega168	4MHz, 3.0V: 1.8mA	5µA at 3.0V	N/A
ATmega88	4MHz, 3.0V: 1.8mA	5µA at 3.0V	N/A
ATmega2560	1MHZ,1.8V 500µA	0.1µA at 1.8V	N/A

4.3.2 The ATmega128RFA1

The ATmega128RFA1 is a low-power 8-bit microprocessor with a high-speed ZigBee transmitter and IEEE 802.15.4 that support the 2.4 GHz ISM band. The radio transmitter offers high-speed data transmission rates, maintains robust communications, and requires the fewest external components possible. It integrates great radio frequency performance at affordable prices; it is small-sized and demands less current. To enhance energy consumption, the sensor nodes are powered on only during the data collection process. Once the process has been completed, it will enter a deep sleep mode till the next cycle of data collection. A low-cost approach was chosen to design a microstrip antenna rather than using traditional antennas or commercial parts, which would increase the cost of the device [65].

4.4 Power Management and Some Sleep Modes

Sleep modes enable microcontrollers to turn off un-needed MCU modules, thereby conserving extra energy. The device offers a variety of sleep modes, allowing the developer and system to customize the device's power usage to the specific needs of the application. When activated, the BOD constantly monitors the voltage of the power source during sleep periods. To save extra power, the BOD can be deactivated in certain sleep modes [61].

4.4.1 BOD Disable

As previously mentioned, the DOB monitors the voltage supply. The consumption in sleep mode will thus be the same as when BOD is deactivated through fuses. If the BOD is deactivated in software, its function is deactivated instantly upon entering sleep mode. BOD is enabled automatically upon waking up from sleep mode. This assures safe functionality if the VCC has dropped during the sleeping duration. Once the BOD is activated, the MCU wakes up from sleep mode after around 60 µs to assure that the BOD is running normally before continuing to execute the code[65].

4.4.2 Idle Mode

The idle mode stops the CPU and allows other peripherals to work. Basically, this mode stops clkCPU and clkFLASH, but keeps the other clocks running. In this mode, the MCU is waked-up by both external and internal interrupts like Timer Overflow. If the Analog Comparator is not used to woke-up the MCU, then, it is highly recommended to power it down by configuring its register. Following this approach can save more power and extend the battery lifetime.

4.4.3 ADC Noise Reduction Mode

This is almost the same as the Idle mode, but it reduces the ADC's noise during the conversion process, resulting in greater resolution measurements. Serval Interrupts wake up the MCU from this mode, such as:

- External Reset and Watchdog System Reset.
- Watchdog Interrupt and Brown-out Reset.
- Timer/Counter interrupt.

Other sleep modes are already briefly explained above.

4.4.4 Power Reduction Registers

The PRR1 and PRR0 are Power Reduction Registers; they provide a mechanism for powering down particular peripherals individually. This mechanism can be utilized in both Idle and Active modes to greatly decrease the total power usage.

4.5 Minimizing Power Consumption

When attempting to decrease power usage in a micro-controlled system, there are numerous things to consider. Generally, sleep modes should always be utilized whenever possible. Sleep modes must be configured in such a way that the device's functions are minimized. All unnecessary functions must be deactivated. The next modules may require special consideration while attempting to accomplish the lowest power usage.

4.5.1 Analog to Digital Converter

When activated, the ADC will be activated in all sleep modes. To conserve power, deactivate the ADC before going into any sleep mode. Whenever the ADC is reset, the following conversion will become an extended conversion.

4.5.2 Analog Comparator

The Analog Comparator is already deactivated by default almost in all modes. However, it must be disabled manually "If not required" when entering both Idle and ADC Noise Reduction modes. In case the Analog Comparator is configured to utilize the internal voltage as its input supply, it must be deactivated in all modes, otherwise, the reference voltage will be activated independently of all modes, resulting in extra power consumption, and reducing the battery life.

4.5.3 Brown-Out Detector and watchdog Timer

If the implemented process does not require the (BOD) and the Watchdog Timer, then, it is highly recommended to turn them off. If these modules are activated via BODLEVEL Fuses, they will be activated in all modes and thus consume power continuously. However, this will greatly contribute to the overall consumed current in deeper sleep modes, limiting its usage in restricted power consumption applications.

4.5.4 Internal Voltage Reference

Automatically, the IVR will be activated if required by either the BOD, the Analog Comparator, or ADC. When these modules are deactivated as explained in the previous sections, the IVR is turned off automatically and does not consume any power.

4.5.5 Port Pins

Before initiating the sleep mode, port pins must be set up to consume the least amount of power possible. The critical point is to assure that no pins are driving resistive loads. In the sleep mode where both the I/O clock and the ADC are deactivated, the device's input buffers are already deactivated by default. This may guarantee that the input logic doesn’t consume any power when it is not required to perform any logical process.

4.5.6 On-chip Debug System

It is not recommended to activate the on-chip debug system during sleep mode because the primary clock source will be enabled as well and hence, constantly drains the power source. This will greatly contribute to the overall current consumption in the deeper sleep modes.

4.6 PIC Microcontrollers

PIC® microcontrollers based on flash memory are utilized in a variety of daily applications, including monitoring systems, industrial projects, automotive machinery, and medical goods. PIC microcontrollers use the nanoWatt technology to provide a number of critical features that become industry standards for PIC microcontrollers. Since the launch of nanoWatt technologies, the performance of the MCU has greatly enhanced, leading to new and fewer power demands. It plays a major role in developing advanced wireless applications. PIC MCUs which use "nanoWatt eXtreme Low Power (nanoWatt XLPTM)" technology is more power-efficient than nanoWatt technology because it lowers the static power usage and adds flexibility to power management. The Next strategies can be used in a variety of applications to maximize the performance of PIC MCU that use the nanoWatt and nanoWatt XLP technologies. These strategies are applicable to all PIC MCUs and may be used to significantly lower the power consumption of practically any application [66].

4.6.1 Turning Off External Circuits/Duty Cycle

All the low-power modes can help to reduce power consumption to a certain point; however, in many applications, they will not be enough to secure extra power savings if we cannot regulate the power consumed by external circuits. Power consumed to light an LED is almost equivalentto run a PIC at 5V_20MHz. When designing circuits, it is advised to use only the essential and required physical peripherals and split the electronics to disable unnecessary circuitry when they are not needed [61].

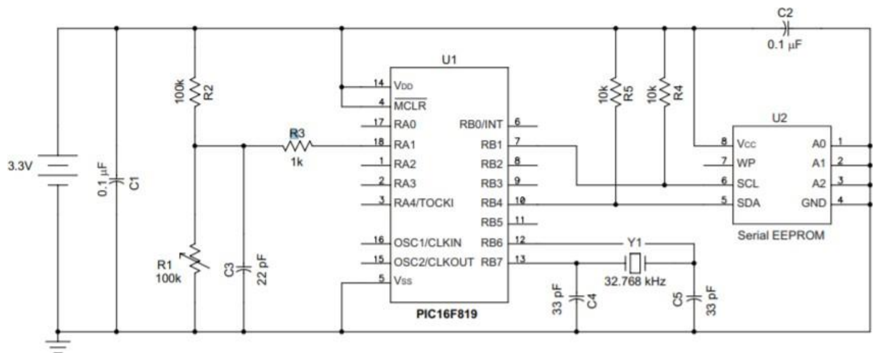

Figure 23.Show a layout of an external circuit used with microcontrollers [66]

The system presented above is simple and all the components are clearly identified in terms of their power requirements. However, it has several weaknesses in that the sensor, EEPROM, and the bias circuit are always energized, resulting in continuous power consumption. To get the lowest possible current consumption for this system, it would be a benefit to turn off these circuits while they are not in use.

Example:

This application is a long-term data recorder that uses a sensor, a battery, an EEPROM, and a microcontroller. It acquires the sensor's reading every 2 sec, then, scales and saves the readings in the EEPROM before entering a standby mode waiting for the next batch of data.

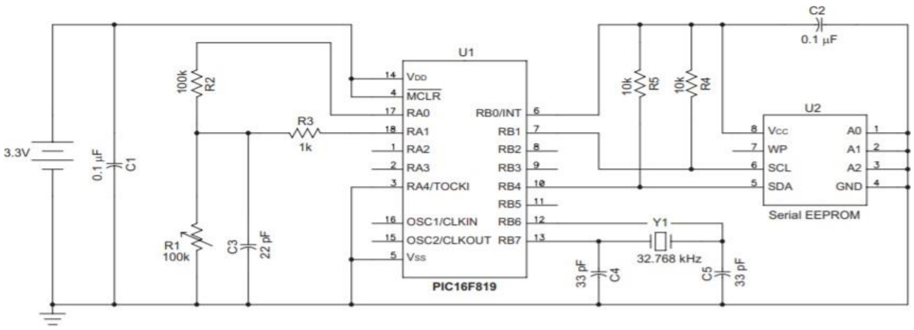

Figure 24.External circuit used with PIC microcontrollers[66]

I/O pins are utilized to supply the sensor and the EEPROM as shown in Figure 1-2. Most PIC MCU devices can provide up to 20 mA from each I/O, eliminating the need for extra power switching components. If the supplied current by the PIC is not enough to complete the task, then, the PIC can activate or deactivate a MOSFET to run the circuit [67].

4.6.2 Power budgeting

Power budgeting is a powerful approach used to estimate current usage and predicate battery life. It is conducted by calculating how much charge is consumed by each mode. Practically, this might be achieved by multiplying the consumed current of each mode by the time spent in that mode. To obtain the average current, the charge of all modes is summed and then averaged by the entire loop duration. The power budget in Table 9 is calculated using the same application in Strategy 1 where a typical nanoWatt XLP device was used.

Mode	Time in Mode (mS)	Current (mA)		Charge Current * Time (mA * Sec)
		By Device	Mode Total	
Sleep MCU Sleep Sensor Off EEPROM Off	1989	0.00005 0 0	5.00E-05	9.95E-05
Initialize MCU Sleep Sensor On EEPROM Off	1	0.00005 0.0165 0	1.66E-02	1.66E-05
Sample Sensor MCU Run Sensor On EEPROM Off	1	0.048 0.0165 0	6.45E-02	6.45E-05
Scaling MCU Run Sensor Off EEPROM Off	1	0.048 0 0	4.80E-02	4.80E-05
Storing MCU Run Sensor Off EEPROM On	8	0.048 0 1	1.05E+00	8.38E-03

Table 8.Presents the results of the power budgeting strategy of the used application [67]

4.6.3 Computing Battery Life

By calculating the average current required to run an application from the computed power budget, it is possible to estimate how long a battery can run the application. The lifetimes of the most popular batteries are shown in Table 2 using the average power from Table 10.

Table 9.shows the estimated lifetimes of the most popular batteries [67]

Battery	Capacity (mAh)	Life			
		Hours	Days	Months	Years
CR1212	18	4180	174	5.8	.48
CR1620	75	17417	726	24.2	1.99
CR2032	220	51089	2129	71.0	5.83
Alkaline AAA	1250	290276	12095	403.2	33.14
Alkaline AA	2890	671118	27963	932.1	76.61
Li-ion*	850	197388	8224	274.1	22.53
NOTE: Calculations are based on average current draw only and do not include battery self-discharge. *Varies by size; value used is typical.					

When power budget calculations are achieved, it is possible to select the battery size needed to meet the project's requirements. If extra power is utilized, it is straightforward to understand where further effort should be made to minimize consumption.

4.6.4 Configuring Port Pins

All PIC microcontrollers provide bidirectional I/O pins. Most of them support analogue inputs. It is critical to monitor the signals type applied to these ports to ensure that the lowest amount of power is utilized.

Digital Inputs

Once the input voltage is around Vdd or Vss, the digital input port uses the lowest possible power. However, it is highly recommended to ensure that the input voltage is always equal to or near the VDD, otherwise, the transistors in the digital buffer will be biased in the linear region, resulting in high current consumption, and reducing the lifetime of the used battery. If this port can be set as an analogue input, the digital buffer is deactivated which reduces the drawncurrent by the pin and the controller's overall current.

Analog Inputs

Due to the high impedance of analogue inputs, they draw relatively little current. They use less current compared to digital input once the applied voltage is typically between Vdd and Vss. Therefore, it will be much efficient to apply analogue signals whenever possible.

Use High-Value Pull-Up Resistors

Using higher pull-up resistors on I/O pins like I2C™ signals is much more power-efficient. For instance, a standard I2C pull-up resistor is 4.7k. When the I2C transmits and pulls a line low, it uses roughly 700 uA for every bus at 3.3V. This current consumption can be brought to half by increasing the I 2C pull-ups to 10k. This approach reduces the maximum speed of the I2Cbus, although this might be beneficial for other low-power applications where the speed is not a constraint. This approach is particularly effective when the pull-up resistance can be pushed to a very high value, like 100k or even 1M.

4.6.5 Reduce Operating Voltage

Minimizing the device's operating voltage (Vdd) is an effective way to reduce total power usage. When a microcontroller is running, the clock speed has the greatest effect on power demands. While in sleeping modes, the most critical factor is transistor current leakage. Low operating voltages demand less charge to run the system clocks and less current will be leaked via transistors. However, it is critical to note how lowering the operating voltage lowers the maximum operating frequency otherwise, the speed will significantly drop and then influence the efficiency of the system, especially if continuous and real-time monitoring is essential to keep the system working safely and effectively. Therefore, the optimum voltage must be selected to allow the microcontroller to perform tasks at its highest speed.

4.6.6 Battery Backup for PIC MCUs

It is vital for applications that can be operated from an external power source or a battery backup to be able to switch between the two modes without user involvement. This can be performed using battery backup integrated circuits; it may also be achieved with a diode or circuit as seen in Figure 7-1. Whenever an external power supply is provided, diode D1 cuts the flow of current towards the battery from VEXT. When VEXT is removed, D2 cuts the flow of current towards any external components. While an external supply with a greater voltage than the battery is available, no current will be drawn from the battery. Once VEXT is disconnected and voltage falls below VBAT, the battery starts to operate the MCU.

Schottky diodes that run on very low voltages at forwarding biases ranging between. 0.1V and 0.46V can be utilized instead of standard diodes to decrease the diode's voltage dropout. Furthermore, inputs may be addressed to VEXT and VBAT to detect the battery and external power supply voltage levels. This enables the microcontroller to adopt low-power modes when the external power supply is disconnected, or the battery is drained.

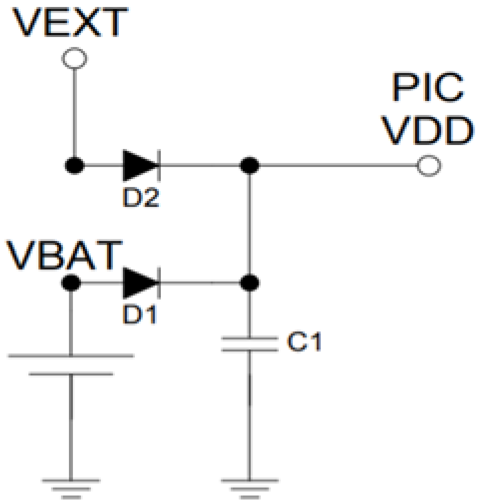

Figure 25.Show a battery backup integrated circuits [67]

4.7 Dynamic Operation Techniques

The following strategies are used to optimize the dynamic operational current usage of an application. This helps an application to complete processing faster, allowing it to sleep longer and consuming less current during processing. These techniques may play an important role in reducing the total power consumption of some particular applications, such as wireless smart sensors in harsh environments or limited power sources because in this kind of monitoring or controlling applications, sensed data should be sent regularly at specific times; so, no need to keep the sensor or the micro on all the time. However, it is not useful when real-time monitoring is required.

4.7.1 Enhanced PIC16 Mid-Range Core

The optimized PIC16 mid-range core includes many features that increase power efficiency. New advanced commands empower the chip to execute several applications within less time. As a result, it increases the sleeping time and reduces the power consumption in each cycle. Newadvanced instructions empower the chip to execute several applications within less time. As aresult, it increases the sleeping time and reduces power consumption in each cycle[44].

4.7.2 Two-Speed Start-Up

"Two-speed start-up" is an auxiliary function on certain nanoWatt and all nanoWatt XLP systems that helps to save power by enabling applications to wake up and sleep faster. Users can run codes whilst waiting for the OST timer to end by using the internal oscillator.

4.7.3 Clock Switching

NanoWatt and nanoWatt XLP systems include various clock sources and have a logic circuit that enables the system clock to be switched between the various available clock sources [44]. This affords huge power savings by setting different clocks to different sections of an executed code. For instance, an application may utilize a slower internal oscillator to execute a non-critical piece of code and change to a faster oscillator to execute time- or frequency-critical codes.

4.7.4 Use Internal RC Oscillators

It is recommended that all nanoWatt (XLP) devices use their in-built RC oscillators. An in-built oscillator provides higher frequency stability and consumes less current versus external oscillators.

4.7.5 Idle Mode

Idle mode is available on nanoWatt(XLP) systems where the clock is not connected to the CPU. Only peripherals are clocked. Idle mode is optimal for situations when the CPU must wait for an external event from a peripheral which cannot work in Sleep mode. In several systems, the idle mode may minimize power consumption by up to 96% [44].

4.7.6 Peripheral Module Disable (PMD) Bits

Some applications based on PIC microcontrollers such as PIC24, PIC32, and others have PMD bits that might be utilized to deactivate the unused peripherals in the application. By configuring these bits, the module power is disconnected. Due to the total cut-off of power, the PMD bits provide extra power savings versus deactivating the module by switching off its enable bit. The PMD bits perform optimally at maximum clock frequencies and maximum speed, allowing for considerable reductions in average current consumption[44].

4.8 Static Power Reduction Tips

The following ideas will enhance the device's power consumption during sleep modes.

4.8.1 Deep Sleep Mode

Deep sleep mode disables all peripherals apart from the RTCC, DSWDT, and LCD. Furthermore, it deactivates the CPU, Flash, and voltage supervision circuitry. This enables the microchip to consume less power than when it runs in other modes. In most cases, the average Deep Sleep current would be below 50 nA. The DSGPRx register holds 4 bytes of data that might be utilized to store certain essential data needed for the application. When the device is woken up, it restarts operating at the reset vector. Deep Sleep enables devices to operate at the lowest possible static power. The only trade-off is that following its waking-up, the firmware must also be re-initialized. To conclude, Deep Sleep is suitable for applications that demand extended battery life and sleep durations.

4.8.2 Extended WDT and Deep Sleep WDT

The WDT or DSWDT are frequently used to wake up the PIC from sleep modes. The PIC MCU consumes less power when it is in sleep mode. Therefore, it is advisable to utilize the longest timeout period permitted by the application for the WDT. The WDT can operate in all modes excluding Deep Sleep, while the DSWDT is employed in Deep Sleep. The DSWDT consumes less power than the WDT and has a greater timeout duration. The WDT timeout period varies by device but commonly ranges between milliseconds and two minutes.

4.8.3 Low Power Timer1 Oscillator and RTCC

All nanoWatt XLP microprocessors include a reliable T1 oscillator that consumes less than 800 nA. The nanoWatt devices have a low-power T1 oscillator that consumes around 2-3 uA. Certain devices include a selectable oscillator that can run in low-power or high-drive strength modes, allowing them to be used in low-power or high-noise applications. Waking up periods can be configured from a second to years. T1 can be used as the main system clock source instead of the oscillator. By decreasing execution speed, the overall consumed current can be decreased. However, this point can be defeated as reducing the speed increases the real working time, which means other sinks or peripheral will continue to work as well, resulting in extra power consumption.

4.8.4 Low Power Timer1 Oscillator Layout

Applications that use low-power T1 oscillators on nanoWatt (XLP) devices must consider the PCB layout. T1 consumes a very low current, which makes the oscillator susceptible to interferences from neighboring circuits. The oscillator circuit must be as near to the microcontroller as possible.

4.8.5 Use Peripheral FIFO and DMA

Certain devices include peripherals equipped with DMA or FIFO buffers. These functions are not only beneficial for performance enhancement; they could also be utilized to reduce power consumption. Peripherals with only a single buffer register demand the CPU to remain active to acquire data from the buffer and prevent it from overflowing. However, the CPU goes to either sleep or idle mode once the DMA transfer is completed. This results in the device consuming significantly less current during the lifetime of the application.

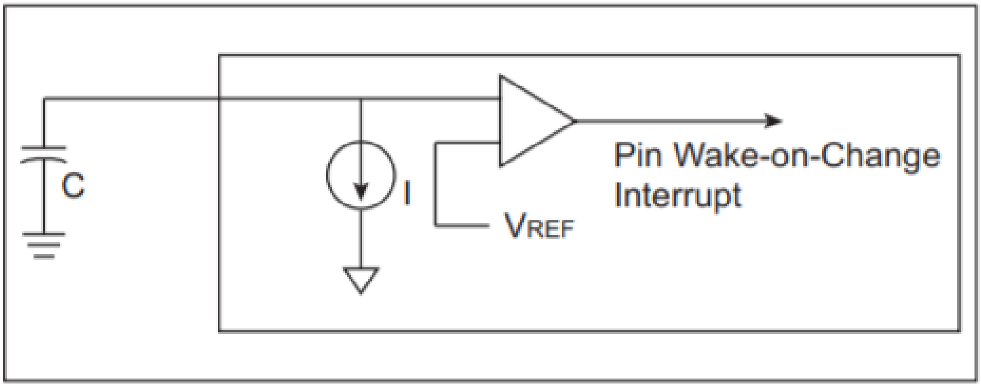

Figure 26.Shows the layout of the Ultra-Low-Power Wake-Up Peripheral [44].

4.9 Summary

This chapter focused on the evaluation of the power consumption of commonly used processors. Different models of Arduino were reviewed and compared in terms of their power consumption. However, their overall performance was not the constrain in this research. Moteino microcontroller was also explored. Finally, the ATmegaXX microprocessors family was investigated and compared with the other models.

5 Evaluation of Power Consumption - Wireless Network

Wireless sensor networks (WSNs) are a rapidly developing technology with a diverse set of possible applications. WSNs are constructed using a large number of nodes equipped with wireless detection and communication features and are distributed in an area of interest. Due to advancements in MEMS, it is now possible to manufacture compact, low-cost wireless communication equipment. WSNs are distinguished from other wireless networks by a set of unique requirements and characteristics, including node density, power requirements, and computational capability [68]. The IEEE classified network technologies based on such features. Typically, WSNs have a data rate of 1Mbps and a wireless coverage range of 1 km. The precise limit on these variables is determined by the technology used and the constraints imposed by the implemented application.

An essential parameter is the lifetime of the WSN, which is highly dependent on the balance between energy requirements and energy storage. WSNs are characterized by their inadequate energy storage, which might be mitigated through the use of potential energy harvesting techniques. However, power efficiency is a critical challenge that must be addressed at both the node and the network levels. Well-known assumptions claim that the radio interface is mostly responsible for power consumption in WSN applications. Therefore, considerable attention has been paid to data transmission protocols optimization with the aim to reduce the quantity of transmitted data and increase node low-power duration. However, developing a sustainable WSN based on power harvesting techniques would need additional and careful modelling because of the restricted and unreliable power supplies available via harvesting techniques. In this case, modelling and precise measuring of power usage related to the operation of other node functional blocks may be required in addition to the RF interface[69].

5.1 Typical Wireless Sensor Node and Network Architecture

Every node of the WSN is composed of many units as seen in Figure 27. The CPU, which is often a Microcontroller with a restricted size of memory, is at the main core of the WSNs. The CPU is connected to the transducers via ADC. The sensing unit collects data, then condition and eventually transfer the data via a transceiver unit. Although transmitters are typically bidirectional, however, certain applications require either transmission (TX) or receiving (RX) capabilities. Some nodes include a location-finding mechanism that assists the node in recognizing its position, either relative to its neighbors or global. This unit is frequently integrated into the transmitter unit and needs the use of certain algorithms based on the localization methods used [69].

The power unit (usually a battery) and power generator (usually protentional sources to harvest or generate power) are essential parts of the sensor node architecture. The power unit is responsible for supplying the electrical power required by the whole system. Additionally, smart power units can provide real-time data on the remaining available energy to make energy-conscious decisions and empower the CPU to perform its tasks. Because the power units are often comprised of batteries, such devices have a finite quantity of energy accessible, hence restricting the node's lifetime. Currently, significant efforts are made to develop alternate methods for powering such nodes using the potentially available energy sources at the node surroundings.

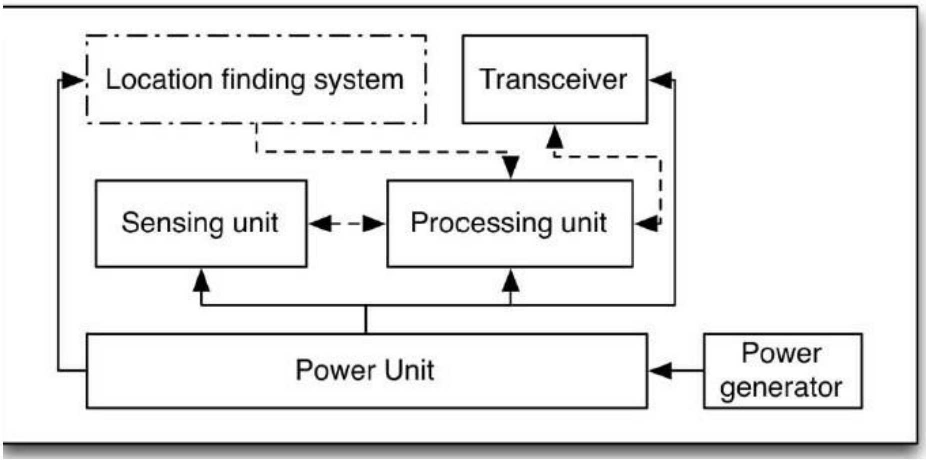

Figure 27.Typical wireless sensor node and network architecture [69]

5.2 Hardware

WSN typically consists of wireless sensor nodes, also known as motes, and a sink node,also known as a coordinator. Sensors connected to the mote can measure surrounding variables, while data processing is performed by a microprocessor. A wireless connection is used to send the acquired data to the coordinator. Usually, the radio interface deploys energy-efficient communication mechanisms to increase the battery's life. Generally, the coordinating node is not constrained in terms of power usage because normally it is in a central monitoring station. WSNs are classified as wireless personal area networks (WPANs).

Their rapid development is associated with the high advancement of the integrated electronics industry, which provides compact, low-power sensor nodes. Options such as Bluetooth, ZigBee, 802.11, UWB, and IEEE 802.15.4 are evaluated based on the intended application. Within such a range of possibilities, the IEEE 802.15.4 standard is claimed to be a benchmark for low-data-rate, energy-efficient wireless applications, and is predicted to be widely employed in the present and future WSN devices. However, in this research, the aim is to evaluate this claim and compare this technology with other technologies.

5.3 Power Consumption of typical wireless transmission technologies

Recently, wireless transmission technologies (WTTs) have witnessed a significant advancement in line with the high industrial demand for efficient wireless monitoring systems. Bluetooth low energy (BLE), ZigBee, Wi-Fi, high radio frequency (RF), LoRaWAN are the most widely used standardized WTTs. EnOcean, Z-wave, and ANT are also WTTs. As summarized in Table 11, these low-power WTTs provide the foundations for self-powering mechanisms via the EHT from its ambient, such as light, temperature differences, or motion.

Table 10.presents the Low-power WTTs specifications

Technology	Rate (bps)	Distance	Sleep (µW)	Transmit (µW)	Receiver (µW)	Features
Wi-Fi	54M	1Km	300	350	270	High transmission rate High power consumer Reliable
BLE 5.0	2M	300m	9	80	62	High transmission rate Ultra-low power Wide bandwidth Long-distance
BLE4.2	1M	Up to 100 m.	8	60	53	Low power Consumption Low latency.

EnOcean	125K	30m	0.6	99	72	Ultra-low power based on EHT .
Z-wave	40K	Up to 100	3	70	65	RF-based low power Consumption, Low cost.
ANT	60K	30 m at 0dBm	3	110	75	Ultra-low power
ZigBee	250K	10m to 100 m	4	72	84	Self-organization Low power consumption, low cost

Currently, a variety of popular modules for building WSN applications are available. These modules are manufactured in accordance with the WTTs described in Table 11. However, due to the variations of WSN applications and advancements in manufacturing techniques, they consume different amounts of energy even when they employ the same technology for communication. It displays that the energy consumption is often estimated in milliwatts or watts. It shows that the BLE and WI-Fi are the most energy-efficient transmitting techniques in terms of data rateand power usage and have the potential to compete with other WTT for wireless real-time machine condition monitoring due to their relatively long transmitting distance and high data transmitting rate.

The consumed power by the sensing nodes and the processors is used to collect and process the data. In fact, the cost of power consumed by a microprocessor varies according to the number of instructions executed. In other words, executing massively complicated algorithms significantly increases the power usage of the processor. In comparison, the detecting unit consumes the least power, often in the microwatt or milliwatt range as confirmed by the sensor module specifications listed in Table 11. Additionally, it isconcluding that the transmission unit uses the most energy, leading to an increase in the overall node power consumption to milliwatts and some applications, to watts [69].

5.3.1 ZigBee Wireless Technology Architecture and Applications

Most of the introduced technologies cannot fulfill the communication requirements of most sensors and control devices. These kinds of applications require low power consumption and low latency even at low bandwidths. It is claimed that Zigbee technology is the best-suited approach for applications, medical applications, industrial control, and so on. Zigbee is based on the IEEE 802.15.4 specifications for wireless personal area networks (WPANs) and is specially designed for control and sensor networks [69]. Zigbee is a low-power mesh network that is commonly used for monitoring and controlling purposes. Its range is between 10 and 100 m. This system is cost-effective and simpler than the other short-range networks such as Bluetooth or Wi-Fi. Zigbee is an extendable network andcan be operated in various modes, hence, battery life is extended.

5.3.2 Low-Power Long-Rang protocol (LoRaWAN)

Many IoT applications benefit from LoRaWAN connectivity; LoRaWAN offers three different classes (A, B, and C) which offer a trade-off between performance and energy usage. However, other protocols for low power and long-range communication are already available, such as Sigfox, Ingenu, and DASH7 which can perform similarly to LoRaWAN. The main advantage of LoRaWAN on the other protocols is its flexibility [70]. It supports many spreading factors and device classes. Classes A and B are often battery-powered, while Class C is mains-powered. The main difference in the three classes of operation is in the packets receiving approach. Class A only has two short receiving slots after sending a packet. After that, the class A devices go to sleep to save energy. Class B devices provide additional windows at scheduled intervals. Class C devices, as they are mains-powered, may hold in receiving mode (as long as they are not in transmission mode), allowing for immediate transmission of data without having to wait for a receive window to open. The power consumption of the LoRaWAN protocol depends on classes A, B, or C; it also depends on the operation mode. Table 12 showed the power consumption of LoRaWAN[71].

Table 11.Shows LoRaWAN power consumption[68]

Operating mode	Standby mode	XT mode	Sleep mode	Deep sleep mode
Power consumption	1.6 mA	117 mA	1.8 µA	1.8 µA

Class A and B can be used in applications where real-time data monitoring is not critical because the transceiver offers limited windows to receive data, and during that waiting time, critical data might lose its importance. Class C can be used for real-time monitoring applicationsbecause it is in receiving mode most of the time. However, this class is power-consuming if it is powered by a battery [70].

5.4 Existing Power Management Techniques in WSNs

This section briefly describes multiple existing power management strategies. Additionally, the drawbacks of employing these energy-saving measures are briefly discussed.

5.4.1 Duty Cycling

Cycling is a strategy for decreasing the energy consumption in a wireless sensor network by periodically turning on and off sensor node transceivers. The term "duty cycle" refers to "the ratio between the duration of the sensor node being on and the total sleeping times of the node [71]. The transceivers run in three statuses - active, listen, or sleep mode. The idle listening mode uses a considerable amount of energy. The main purpose of duty cycling is to reduce energy consumption caused by idle listening. By turning off its radio, the inactive node is put into sleep mode. However, duty cycling has a number of drawbacks; occasionally, some messages are blocked in sleep mode because the receiver is turned off. Additionally, messages are subjected to an end-to-end delay. The length of the queued packets might increase in the listening mode. This increases the likelihood of packet loss. Sleeping nodes can partially or fully hinder the WSN's functionality. It uses a control traffic technique that uses extra power. Finally, an ultra-low duty cycle may save sufficient energy, however, they are incompatible with applications that demand real-time monitoring.

5.4.2 Data Aggregation

Data Aggregation is an information reduction technique used to minimize transmission overhead. It is a technique that eliminates duplicated data to minimize energy consumption and extend the life of wireless sensor networks [69]. Neighbouring nodes can collect correlated data, which is particularly useful in dense sensor networks. As a result, data aggregation conserves energy by eliminating numerous nodes transmitting the same data through various channels. Figure 28 illustrates an example of a data aggregation tree presented by [72]. he "aggregator node" is highlighted in red, whereas the "source nodes" are highlighted in blue. Data aggregation has several disadvantages, but the greatest is that all the aggregated data might be lost at once.

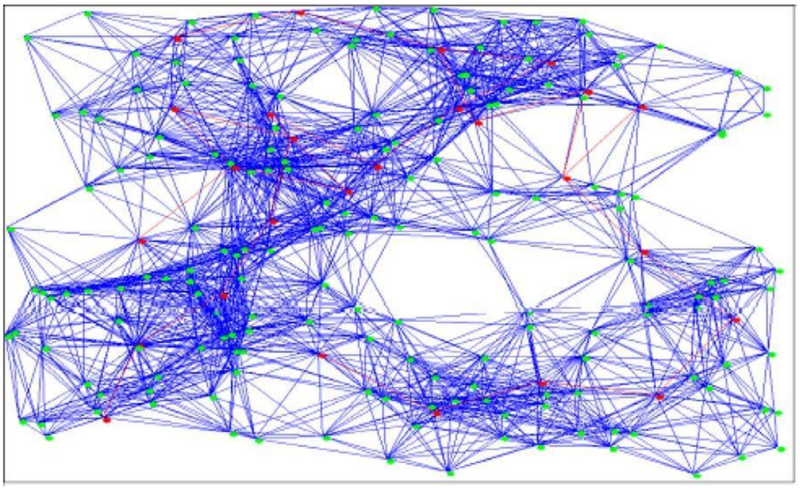

Figure 28.Example of data aggregation tree as presented by [69].

Many sensor nodes may transmit multiple versions of the same data to the aggregating node [69]. Additionally, this approach is incompatible with applications that need great precision as retrieving the original data transmitted to the BS is a time-consuming process.

5.4.3 Data Compression

The amount of energy spent by a transceiver in a WSN is highly dependent on the size and transmission distance of the data packets. Data compression techniques focus on decreasing the amount of transmitted data. This method encrypts data at the source nodes and decrypts it at the base station. Actually, communication energy is conserved at the cost of higher computing energy. However, energy savings come at the expense of data transfer delay, which is critical and not suitable for real-time monitoring applications.

5.4.4 Data Prediction

Data prediction is an approach for conserving energy in wireless sensor networks (WSNs) by minimizing the number of transmissions [73]. Algorithms are used in this technique to estimate the size of the next upcoming data based on historic parameters and values of data. Energy saving is obtained by allowing only sensor nodes whose measured data values significantly deviate from the expected values to transmit their data. Prediction techniques allow only specific assumptions to be made during data observation. This increases the technique's accuracy. However, decreasing the number of transmissions can impact the quality of the acquired data. Additionally, prediction methods incur additional computational costs. This approach can be used to send non-critical data periodically, for example, the lubrication system level and temperature.

6 Overview of Wireless Power Transmission Technologies

Wireless power transmission is a promising and noble concept. Several wireless power transmission techniques are discussed and evaluated in this section. Different natural phenomena and equipment that govern the WPT will be investigated. The advantages and uses will also be discussed in detail. WPT improves the mobility of power systems and combines communication and electric power technologies on a single platform. However, several obstacles must be overcome for WPT to sustain a constant power level. For example, electromagnetic waves distribute in space during its transmission, resulting in a substantial power loss. This section provides a comprehensive evaluation of different commonly used wireless power transmission techniques [35]. The feasibility, applications, operations, and outcomes of several approaches have been discussed to suggest the most advantageous and affordable way for low power and short-distance applications. Electric power can be transmitted using two major techniques; the first method is near-field techniques and the second one is far-field techniques.

6.1 Near field techniques

Near field energy transfer technique is dependent on mutual induction; this is solely for short distances. There are basically four common methods for WPT of near field transfer as can be seen in the next section .

6.1.1 Wireless power transmission by magnetic resonance

According to the mutual induction phenomenon, when a continuous alternative current flows through a coil, it generates a magnetic field in the region surrounding the primary coil. Due to the interaction of this variable magnetic field with the secondary coil, an induced current is generated in the secondary winding[35]. Due to the absence of mechanical energy in this approach, the losses will be reduced to the lowest possible values. However, this magnetic field might impact the nearby sensitive sensors used to monitor the conditions of the CNC machine.

6.1.2 Inductive Coupling

When two windings are designed in such a way that any change in current flowing through one wire generates a voltage across the terminals of the other wire via electromagnetic induction, then, it is said they are magnetically connected. This occurs because of mutual inductance. In some charging applications, the received power is between 5 W up to 120 W [74]. Electrical transformers and electrical generators are the most common applications of inductive coupling. This technique is limited to short distances, and this is why it is commonly used in wireless charging systems such as mobiles or smartwatches. In addition, the output power of this approach is dependent on the position of the two coils. Therefore, to get the highest possible output, the coils must be opposite to each other. This character seems to be a drawback of this technique. However, this behaviour can be beneficial in some applications such as CNC machines where it can be applied to increase the alignment robustness by using two coils (sender and receiver). The value of the received power will represent the alignment degree.

6.1.3 Resonance Inductive Coupling (RIC)

Resonance Inductive Coupling (RIC) refers to the combination of resonance and inductive coupling resonance. Using the theory of resonance, it is possible to create a very powerful interaction between the two objects. Inductance generates an electrical current in a circuit. As shown in Figure 29, the capacitor and the coil are parallelly connected and the coil generates the inductance. Prof Saljacic's research group at MIT implemented this technique to light up a bulb from two meters[37].

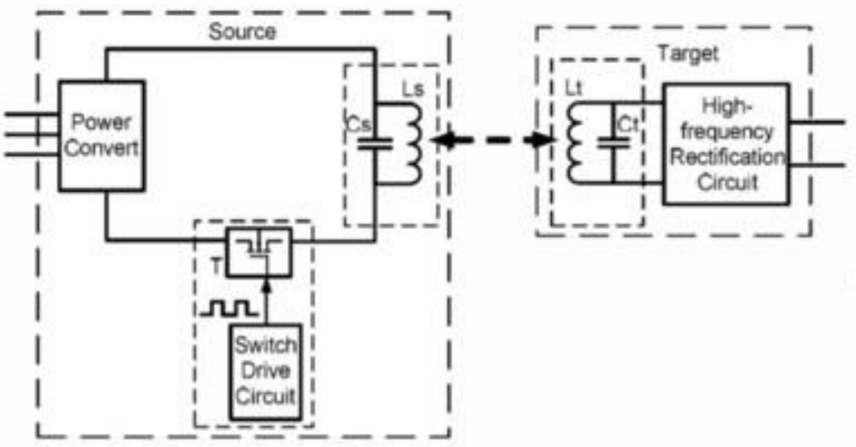

Figure 29.block diagram representation of resonance Inductive Coupling [37]

Comparison between RIC and Inductive Coupling

- RIC is quite efficient than inductive coupling.
- RIC technique has a greater range.
- RIC can be one-to-many while the inductive coupling is only one-to-one.

6.1.4 Air Ionization

The principle is the ionization of air caused by the produced field. Although this phenomenon exists in nature, its execution is highly improbable due to the high field required. Richard E. Vollrath, a California scientist, developed a sand-stormgenerator that generates energy by blasting dust-laden air via copper tubes and storing it in a sphere for later use. This technique would not be recommended in a CNC machine application because it requires a high field and that might impact the electric components of the CNC machine and increase the noise. As a consequence, the data acquisition systems might be affected as well.

6.1.5 Advantage and Disadvantage of Near Field Techniques

Table 12.Compares the advantages and disadvantages on near field techniques

Advantages	**Disadvantages**
No wires used No e-waste. Efficient energy transfer Low Maintenance cost.	Short distance. In some cases, the field strength is strong and dangerous. High Initial cost. Requires high-frequency signals.

6.2 Far-Field Energy Transfer Techniques

This approach is used to transfer power wirelessly for relatively long distances. Basically, two main techniques have been developed based on this approach, but microwaves and lasers are mostly used in this approach[34].

6.2.1 Microwaves power transmission MPT

MPT is a long-range technique that enables the transmission of electric power over long distances. This method uses a microwave voltage source to generate microwaves. The source works as a sending antenna, whereas the microwave receiver works as a receiving antenna [34]. This approach can be used to power wireless sensor networks as the microwave source can be located in a central location and the receiver can be located on the object being monitored. In addition, it can transfer sufficient power to supply low-power sinks. This approach can be used to power the MEMS explained in Chapter 7.

6.2.2 Wireless power transmission using laser

The second technique used for wireless power transmission is based on a laser beam which actsas a source. The laser beam of high intensity is thrown from some specific distances to the loadend. Depending on the range and intensity of the beam, this method is used for small-distance applications. This process is similar to the solar cells photovoltaic generation which uses the solar energy of the sunlight and converts it to electricity. At the load end, highly efficient photovoltaic cells are used to receive the laser beam, energize laser light, and finally convert lightenergy into electrical energy.

6.2.3 Comparison between LASER and MPT

Table 13.Comparison between Laser and MPT [75].

Magnetic Resonance Method	Microwaves Method	Lasers Method
It is economical as theequipment used is cheap and easily available[75].	Relatively expensive compared to other methods.	Implies same economic conditions of mutual Induction.
Useful for implementation of small distance applications.	This method is ideal for long-distance applications.	Used for small distances but could be used for longer distances (high intensity).
It is safe from the biological point of view.	Injurious to health because of high-frequency rays.	The laser method is also injurious to human health.

6.2.4 Advantages and disadvantages of wireless power transmission

The WPT would eliminate the high-tension power transmitting line cables, towers, and substations, which are seen as inefficient ways of energy transmission. This will easily lead to the global scale connectivity of power systems. Thus, the cost of transmitting and receiving the energy becomes less expensive, thereby reducing the tariff rate. Since cables are not used here, electricity can reach any place irrespective of the geographical location. Power loss through transmission is negligible, hence, this method is more efficient. Natural hazards like earthquakes, landslides, floods, and others cannot cut power as long as the WPT system operates, so reliability is higher compared to the wired energy transmission method. The power cut due to a short circuit in the cable would never occur. The rate of e-waste generation is decreased; thus, it is more environmentally friendly. The receiver can be embedded into any electrical device and appliance that it needs no battery. The portability of electrical devices increases. However, WPT has some serious disadvantages as well; the initial cost is very high, and efficiency is relatively low. In addition, wireless power transmission needs extra processing devices to obtain the final electric output.

7 Case Study for Machine Tool Monitoring

7.1 Case study – 3-axis machine tool

A 3-axis horizontal machining center was used to carry out this research. The machine was chosen because it is used as part of a collaborative research project between the University of Huddersfield and Machine Tool Technologies Ltd. The machine used in this research has 3 axes, X, Y, and Z. The temperature generated on those axes by internal and external heat sources is investigated to develop a model to measure the wasted energy in the form of heat loss, as well as to evaluate the potential energy harvesting techniques that might be used to harvest energy to supply some MEMS wirelessly instead of using the conventional wired ones, especially those used to monitor moving parts.

Figure 30 showed the 3-axis machine used in this case study. The machine table and ball screw were mounted on the X-axis, the headstock was mounted on the Y-axis, while the Z-axis moves in a vertical direction. AC servo motors were used to drive the axes. The machine's maximum speed along the x-axis was approximately 400 cm/min, and the x-axis travel distance was 80 cm. The table moves along the x-axis with a heatstroke of 60 cm. To monitor the machine condition, multiple sensors were used and located on different parts of the machine. In total, 26 sensors were used in this machine. To be more specific, every axis has 5 temperature sensors plus eight sensors located on the head and three ambient sensors. Ambient temperature was recorded only to eliminate the environmental variation effect. The environmental variation is not predictable and usually produces a low-temperature difference which can be neglected when it comes to energy harvesting.

In this case study, the focus was to measure the temperature produced on the ball screw using MAXIM DS18B20 direct-to-digital temperature sensors as shown in Figure 30. The friction generated in the rotating bearings and moving ball nut are the most significant heat sources on the ball screw. Additionally, vibration sensors (Analog Devices ADXL355 MEMS) were used to monitor any change in vibration signature on the bearings and nut.

Figure 30.MTT test rig used to perform some experiments at the lab[60]

To monitor the vibration of a ball screw for long-term movement of the nut, the vibration was measured at four points as shown in Figures 31, 32, 33, and 34. Two ADXL355 MEMS as shown in Figures 31 & 32 were located on the primary and secondary bearing surfaces. They were used to measure the vibration on those bearings.

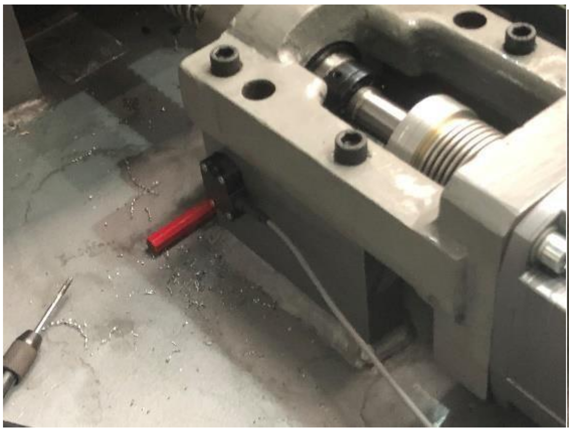

Figure 31.MEMS on Secondary bearing [60]

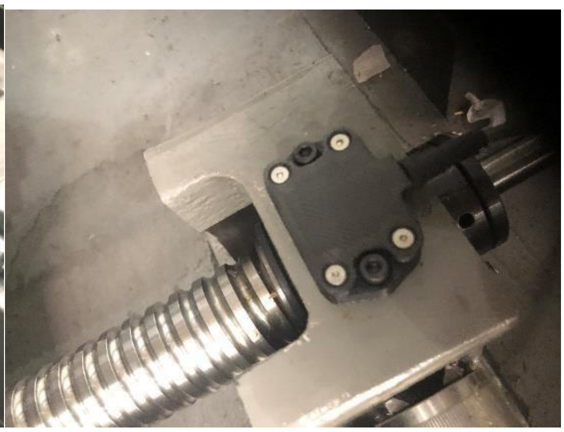

Figure 32.MEMS on Primary bearing[60]

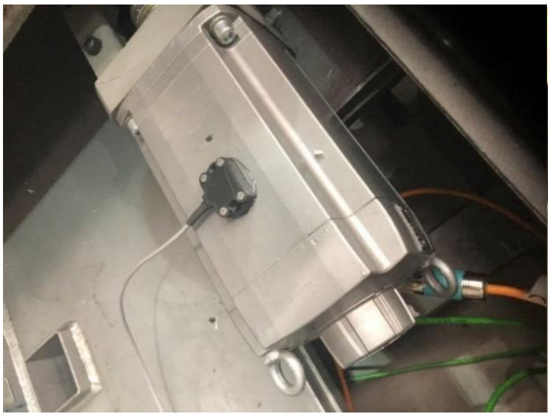

Figure 34.MEMS on Motor housing [60]

Figure 33.MEMS on ball nut[60]

The third one was used to measure motor housing vibration (Figure 33). While the most challenging one from a cabling point of view is located on the ball nut to measure its vibration while it moves. All these four MEMS were used for continuous data acquisition under machining conditions. The other DS18B20s sensors were used to measure the temperatures at other parts of the machine.

Power requirements for a monitoring system in this case study

This vibration monitoring system is wired; all the sensors were connected to raspberry pi processors. In this case, power consumption is not a constrain. However, wiredmonitoring systems might face some obstacles when measuring the vibration of moving parts, such as the nut. Therefore, it is better to go wireless whenever possible. To go wirelessly, the power consumption of all the networks should be considered. In this machine, 4 Raspberry Pis were used to acquire and process the data coming from the MEMS allocated to monitor ball screw vibration. Then, it was plugged into a computer to monitor and further process the data. To determine the consumed power for this subsystem, three scenarios can be considered.

First scenario; Using a raspberry pi for each MEMs sensor individually.

There are different models from raspberry pi. Based on the specifications collected from datasheets and other studies, the power consumption of the Raspberry Pis is relatively high as seen in the following table.

Table 14.Comparison of the power consumption of Raspberry Pis[65]

Pi Model	Pi state	Power consumption(mA)
3 B+	HDMI off, LEDs off	350
3 B+	HDMI off, LEDs off,onboard Wifi	400
3 B	HDMI off, LEDs off	230
3 B	HDMI off, LEDs off,onboard Wifi	250
2 B	HDMI off, LEDs off	200
2 B	HDMI off, LEDs off,onboard Wifi	240
Zero	HDMI off, LEDs off	80
Zero	HDMI off, LEDs off, USB Wifi	120
B +	HDMI off, LEDs off	180
B+	HDMI off, LEDs off,onboard Wifi	220
A+	HDMI off, LEDs off	80
A+	HDMI off, LEDs off,onboard Wifi	160

As shown, the lowest power consumption is model A+ with 80 mA and the highest is 3 B + with400 mA.

In the first scenario, four B 3 models were used with four sensors, each one consuming 220 mA at operating time when transmitting data via USB cable and consumes 250 mA when transmitting data wirelessly. The total power consumption of this subsystem when transmitting via USB cable for each Pi can be calculated using the Equation 2.

$$P = V * I \quad (2)$$

Where V is the supplied voltage and I is the consumed current.

$$P = 5\,V * 220mA \quad (3)$$

$$P = 1.1\,W \quad (4)$$

Total power consumption for all Pis while transmitting via USB.

$$P_t = n * P \quad (5)$$

$$P_t = 4 * 1.1W \quad (6)$$

$$P_t = 4.4W \quad (7)$$

Where n is the number of raspberry Pis and P is the power consumption when transmitting wirelessly for each Pi

$$P = 5\,V * 250mA \quad (8)$$

$$P = 1.25\,W \quad (9)$$

Total power consumption P_t for all Pis when transmitting wirelessly can be calculated using equation 10.

$$P_t = n * P \qquad 10$$

$$\text{Pt} = 4 * 1.25\text{W} \qquad 11$$

$$P_t = 5W \qquad 12$$

The calculations show that the system consumes extra power when transmitting wirelessly; that would be expectable because, during wireless transmission, extra sinks are used, such as transmitters which normally use most of the total consumed power. However, this consumption is relatively high for a monitoring system.

Second scenario; using one raspberry pi for all four MEME.

In the second scenario, two B 3 models were used with four sensors. Three sensors were geometrically close so they might be connected to one Pi, while the nut MEME was relatively far so that another Pi can be used with it. Each pi consumes 220 mA at operating time when transmitting data from one MEME via a USB cable and consumes 250 mA when transmitting data wirelessly. The total power consumption of this subsystem will be slightly different and can be calculated using equation 13.

$$P_1 = (V * I) + (V * 2I_M) \qquad 13$$

$$P_1 = (5V * 220mA) + (V * 2I_M)$$

$$P_1 = (5V * 220mA) + (5 * 2I_M)$$

$$P_1 = (1.1W) + (5 * 2I_M)$$

Where P_1 is the power consumption of the Pi connected to three MEMEs, $2I_M$ is the current consumed by the other 2 sensors. Note, 220 mA includes the pi current consumption plus one

MEME current consumption. That is why only 2 MEMEs were added to the equation. The power consumption of the nut sensor connected to one Pi is calculated as:

$$P_2 = (V * I) \quad 14$$

$$P_2 = (5V * 220mA) \quad 15$$

$$P_2 = 1.1W$$

Where P_2 is the power consumption of the Pi connected to nut MEME. The total power consumption in this scenario when transmitting via USB is:

$$P_T = P_1 + P_2 \quad 16$$

$$P_T = [(1.1W) + (5V * 2I_M)] + (1.1W) \quad 17$$

The power consumption when transmitting data wirelessly in the second scenario (three MEMEs connected on Pi and nut MEME connected on other Pi) can be calculated as follows to show the consumption of the three sensors on a Pi:

$$P_1 = (V * I) + (V * 2I_M) \quad 18$$

$$P_1 = (5V * 250mA) + (V * 2I_M)$$

$$P_1 = (5V * 250mA) + (5 * 2I_M)$$

$$P_1 = (1.25W) + (5 * 2I_M)$$

Where $(V * 2I_M)$ is the power consumption of the added two sensors connected with the Pi. The following calculations show the power consumption of the nut sensor connected to a Pi when transmitting data wirelessly:

$$P_2 = (V * I)$$

$$P_2 = (5V * 250mA)$$

$$P_2 = 1.25W$$

The total power consumption in this scenario when transmitting measured data wirelessly is:

$$P_T = P_1 + P_2 \quad 19$$

$$P_T = [(1.25W) + (5V * 2I_M)] + (1.25W) \quad 20$$

The calculations in the second scenario show that the system consumed extra power when transmitting wirelessly and this would be expectable because, during wireless transmission, extra sinks are used, such as transmitters which normally use most of the total consumed power. If the first scenario is compared with the second scenario in terms of their power consumption, it would be obvious that the second scenario consumed less power than the first one because it uses fewer processors (almost 50% less). However, this consumption is still relatively high for a monitoring system when it comes to battery-powered applications.

Third scenario: using Auridon instead of Raspberry Pi

The results in Chapter 4 clearly showed that the power consumption of the Arduino based on the ATmega family is than that of Raspberry Pi.

Table 15.Displays the power consumption of Arduinos based on ATmega microcontroller family "Data collected from Datasheets"

Microcontroller	Active mode	Power down mode	Power save mode
ATMega644P	240µA at 1.8V,1MHz	0.1µA @ 1.8V	N/A
ATmega328P	1.5mA at 3V -MHZ	1µA at 3V	N/A
ATMega1284P	1MHz, 1.8V, 0.4mA	0.1µA	0.6µA
ATmega48P\V	At 1MHZ 1.8v.3mA	0.1µA	0.8µA

ATmega168P\V	At 1MHZ 1.8v 0.3mA	0.1µA	0.8µA
ATmega88P\V	At 1MHZ 1.8v3mA	0.1µA	0.8µA
ATmega168	4MHz, 3.0V:1.8mA	5µA at 3.0V	N/A
ATmega8 8	4MHz, 3.0V:1.8mA	5µA at 3.0V	N/A
ATmega2560	1MHZ,1.8V 500µA	0.1µA at 1.8V	N/A

It would be useful and power-saving to use an Arduino instead of the Pis only if the constrain in the application is the power consumption. If the processing speed and data transmitting rate are flexible, then, it will be highly recommended to use Arduino pro mini in this case study to go wireless.

7.2 Opportunities for Energy Harvesting from the Machine

The choice of any energy harvesting technique depends on multiple aspects, such as the overall thermal situation of the machine, accessibility of transducer to the required location, dynamicsof the situation, required accuracy, cost of the applied technique, data collection, and processing [6]. Thermocouples offer many advantages such as simplicity, low cost, and remotesignal measurement which might be useful with high-speed rotating parts. However, their size is relatively big compared to other techniques. Many research works have been carried out on thermoelectric micro-generators and some of the findings are presented in the following section.

8 Conclusion and Further Work

This chapter concludes the research and recommends future work in this field.

8.1 Conclusion

As mentioned in Chapter 1, the purpose of this research is to evaluate the energy consumption of WSNs in an industrial application. In this chapter, a summary of the progress toward this goal was provided, followed by suggestions for future studies. The focus of this work is to evaluate the power consumption of wireless sensor networks used in manufacturing and where possible, to suggest a suitable methodology for energy harvesting to power wireless monitoring process in a computer numerical control (CNC). Experiments to measure the power consumption of temperature and vibration sensors, along with the power consumption of the available microprocessors were supposed to be conducted at the lab. Instead, a detailed review of previous works was conducted because of the COVID-19 pandemic and the lockdown restrictions. The dissertation has made three major contributions as follows:

In Chapters 2 and 3, a detailed literature review was conducted. Several types of low-power routing protocols were investigated in terms of their power consumption. It was clear that the performance of the routing protocols significantly contributes to the total power consumption of the WSN. In addition, the electrical characteristics of the temperature, vibrations, and humidity wireless sensors were evaluated and compared to determine the most efficient type in terms of powerconsumption. However, it was complicated to determine the most efficient type because each IoT application has special requirements and restrictions. Therefore, this research is not suggesting any particular type of the examined sensors.

In Chapters 4 and 5, the power consumption of local processers and communication protocols was evaluated. Some of the most popular controllers, such as Arduinos and Moetion were explored and compared. The observations showed that the operating mode can substantially impact the overall power consumption. Using the right mode can reduce the power consumptions from few micros to a hundred nanos. Additionally, the choice of a communication protocol, such as Wi-Fi, Zigbee, or LoRaWAN is a critical factor when designing a low power wireless network monitoring system. Next, the previous studies showed that the main contributors to battery drainage are the transmitter and the receiver. Again , the best choice can only be taken based on the application requirements and constraints. However, if the power consumption is the only constrain without considering the processing time and data transmission rate, then the Arduino pro mini controller and Zigbee protocol will be highly recommended in low power WSN applications.

In Chapter 6, wireless power transmission was discussed as a vital solution for low power WSNapplications. The near and far fields were explained, and the main features of each were indicated.The near field approach is a sensitive approach as it is mostly based on mutual induction and requires precise setup to sustain the efficiency. However, only few watts have so far been transferred using this approach in IoT applications, whereas the far field approach might have some benefits if used to transmit wireless power to devices located at difficult-to-access locations, such as sensors used to monitor the conditions of the rotating parts in a CNC machine. Energy harvesting techniques are a promising field as well; however, in a CNC machine application, it cannot be obtained because the stability of the available sources is not secure. Although the thermal energy generated from mechanical energy might be enough to generate few micro watts, this heat is one of the main concerns that must be avoided or reduced, else, it will impact the accuracy of the machine. Therefore, this research cannot recommend this approach in the meantime.

In Chapter 7, a case study based on a 3-Axis machine was carried out; all the aforementioned observations were performed. Three different scenarios were explained and theoretically simulated. Although each scenario consumed different amounts of power, the third scenario will be the most efficient in terms of power consumption.

8.2 Future work

Due to COVID-19 pandemic, this work was conducted based on theoretical studies; therefore, it would be interesting to conduct some laboratory experiments to obtain more accurate results. Energy harvesting is a promising field to investigate, therefore, it would be interesting to examine energy harvesting from available sources in a CNC machine, such as using the coolantliquid cycle. Normally the coolant liquid flow rate is relatively high, therefore, some micro or nano watts might be harvested using an appropriate technique. In addition , this liquid will gain some heat during the cooling cycle, so, it might be interesting to conduct some future studies in this aspect.

7.3 Thermoelectric micro-generators

Thermoelectric-micro generators are used to convert heat energy into electrical energy. They are commonly used to recycle heat losses and generate few microwatts. They have been embedded in some electronic devices to provide some additional power. MEMS technology is used to fabricate this kind of harvester. This technology provides small volumes and relatively high efficiency. Glatz et al. developed thermoelectric-micro generators via a microfabrication process; the harvested output power factor was 0.29 μW cm−2 K−2. Lee and Xie manufactured a thermoelectric generator using another technology known as solder-based. The generated power in this design was higher than Glatz's design with 68.6 μW/cm2 at 6K temperature difference. Huesgen et al. proposed another design using a combination of surface and bulk micromachining processes. Only 0.00814 μW was harvested at a temperature difference of 2 K in this design. Wang et al. used bulk micromachining only to design a thermoelectric-generator and the result was a power factor of 0.00173μW cm−2 K−2. Su et. al. presented a thermoelectric power generator using 6 silicon-germanium thermocouples. The output power was 0.4 μW at a 3.5 K temperature difference. The bulk-Si wet etching technique was proposed by Nishibori et al for the development of a micromachined thermoelectric generator; this was the most efficient technique among the techniques reviewed in this research with a total output power of 0.26 μW.

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