A WIRELESS SENSOR NETWORK WITH NODES BASED ON MICROCONTROLLER DEVICES

Anand Kumar Gupta, Mrs. Parul Awasthi, Madhuri Mishra

Assistant Professor ÙIET, CSJM University, Kanpur
Mail id: akgietk@rediffmail.com

Abstract: The present study presents a comprehensive evaluation of wireless sensor node platforms based on microcontroller units (MCUs) from recently published research articles. Despite extensive study in the rapidly evolving domain of wireless sensor devices, energy consumption continues to pose an issue that restricts the longevity of wireless sensor networks (WSNs). The Internet of Things (IoT) technology employs Wireless Sensor Networks (WSNs) to deliver an effective sensing and communication framework. Therefore, comparing the current wireless sensor nodes is essential. The latest advancements in MCU-based wireless sensor node platforms are noteworthy, since they have become diversified and significantly more sophisticated compared to existing commercial WSN systems. Recent wireless sensor nodes are evaluated against commercially available motes. The commercially accessible motes are chosen based on many criteria, including popularity, reported outcomes, and notable traits and features. It is essential to comprehend the developmental trajectory of these gadgets and technologies to guide research and application paths. The comparison primarily focusses on processing and memory characteristics, communication capabilities, power supply and consumption, sensor support, prospective applications, node programming, and hardware security. This work aims to delineate the advancements in the design of autonomous wireless sensor nodes to prevent redundancy in research conducted by industry and academia. This document aims to aid developers of wireless sensor nodes in creating enhanced designs that surpass current motes. This study will assist researchers and prospective users in selecting the most suitable mote for their individual application scenarios. A discourse on wireless sensor node platforms is presented, together with an enumeration of difficulties and prospective research avenues.

Keywords: Internet-of-Things (IoT); wireless sensor networks; sensor node; microcontroller unit (MCU); power consumption

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1. Introduction:

Several research efforts have been conducted in the rapidly expanding field of wireless sensor devices. The emergence of numerous Internet-of-Things (IoT) applications and scenarios is propelling the use of wireless sensor networks (WSNs) to establish an efficient sensing and communication infrastructure. A wireless sensor network is composed of distributed wireless sensor nodes, also known as motes, which are utilised for the detection of various physical and environmental phenomena. The nodes work together to transmit the collected data to a base station or sink for further analysis and decisionmaking. Examples of sensed parameters encompass temperature, pressure, moisture, motion, liquid level, and others. Wireless sensor networks are highly beneficial across various applications, including environmental monitoring, precision agriculture, IoT, water quality monitoring, and animal tracking, among others [1–4]. Throughout the years, numerous practical wireless sensor nodes, as well or motes, have been developed and introduced to the market to support the implementation of various wireless sensor network scenarios. Advancements in wireless sensor node technologies enable innovative research and practical implementation of WSNs across numerous applications worldwide.

A sensor node generally comprises the sensing, computation, communication, and power supply subsystems. The wireless sensor node platforms exhibit limitations in terms of power supply, computational resources, and storage capabilities, among other factors. [6]. The objectives of designing and developing a wireless sensor node encompass ultra-low power operation, cost efficiency per node, compact size, and the capability for software and hardware reconfiguration. The development of smaller and more cost-effective wireless sensor node platforms with ultra-low power consumption has emerged as a significant area of interest within the research community [7]. The longevity of a wireless sensor network is significantly influenced by the availability of energy to power the sensor motes. Traditionally, sensor nodes are powered by small batteries with limited capacities. In various application scenarios, a significant number of deployed sensor motes must be capable of operating unattended for an indefinite duration in remote and challenging environments. In these deployment scenarios, the challenge of battery replacement becomes significant. The energy consumption of the motes has a direct effect on the longevity of the WSNs. Consequently, ultra-low power strategies combined with energy-harvesting methods are essential for the widespread and continuous functionality of wireless sensor networks [8]. Various wireless sensor node platforms are being developed to meet the distinct requirements of different WSN applications. For example, certain applications involving tracking and monitoring within wireless sensor networks necessitate the utilisation of wearable devices.

Throughout the years, numerous wireless sensor nodes utilising microcontroller units (MCUs), field programmable gate arrays (FPGAs), system-on-chip (SoC) architectures, application-specific integrated circuits (ASICs), and various other platforms have been designed and developed [9]. The literature contains a limited number of review articles regarding wireless sensor node platforms. In 2009, a comparative review of six selected sensor motes was presented. The authors in [2] conducted a comprehensive survey on the protocols, platforms, and simulation tools associated with selected wireless sensor platforms. A comparison of the performance of two commercial motes in practical situations was conducted by [11]. In 2018, a review focused exclusively on sensor motes for IoT applications was presented by [12]. In this proposed study, the chosen wireless sensor nodes are utilised for various applications. Additionally, the authors of [9] presented a comprehensive review of wireless sensor nodes, ranging from basic MCU-based systems to advanced programmable logic devices.

Numerous published articles in the literature provide a list and comparison of various motes applicable to different IoT applications [13–17]. However, these articles do not encompass the recent motes that have been proposed and published in the literature. Additionally, the referenced articles lack comprehensive comparisons and descriptions of these motes. In contrast, this paper enumerates the latest motes published in the literature and offers more detailed comparisons, thereby enhancing its

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value for IoT application developers and solution providers.

This paper presents a comprehensive comparative review of MCU-based wireless sensor nodes, drawing from recently published research articles spanning the years 2016 to 2022. The sensor nodes discussed in recent research articles are evaluated against the most commonly utilised commercially available motes, focussing on aspects such as processing and memory specifications, communication capabilities, power supply and consumption, sensor support, potential applications, node programming, and hardware security, among others. This paper aims to present a comprehensive overview of the trend in designing energy-efficient and autonomous wireless sensor nodes, thereby minimising redundancy in research conducted by both industry and research institutions. It is essential to comprehend the developmental trajectory of these devices and technologies to guide research and application directions effectively. This review paper aims to encourage developers of wireless sensor nodes to introduce enhanced platforms that surpass the current motes. Additionally, we expect this paper to assist researchers and potential users in effectively selecting the most suitable sensor mote for their specific application scenarios. The subsequent sections of the paper are structured as outlined below. Section 2 provides an overview of the primary components of the wireless sensor node. Section 3 provides a summary of the latest MCU-based hardware platforms and highlights the popular commercial motes currently available in the market. Section 4 presents a detailed analysis of the surveyed MCU-based 2. Wireless Sensor Node: A Comprehensive Overview of Platforms. In conclusion, Section 5 summarises the findings of the paper and outlines potential avenues for future research.

2 Node with Wireless Sensors:

While numerous wireless sensor node platforms utilising the MCU have been introduced, they typically share a common fundamental architecture. Their differences lie in processing and memory specifications, communication capabilities, as well as power supply and consumption. Support for sensors, applications, and related areas. A fundamental wireless sensor node consists of sensing components (including sensor interfacing and sensors), computational elements (such as a microcontroller), communication capabilities, and power supply subsystems, as illustrated in figure 1.

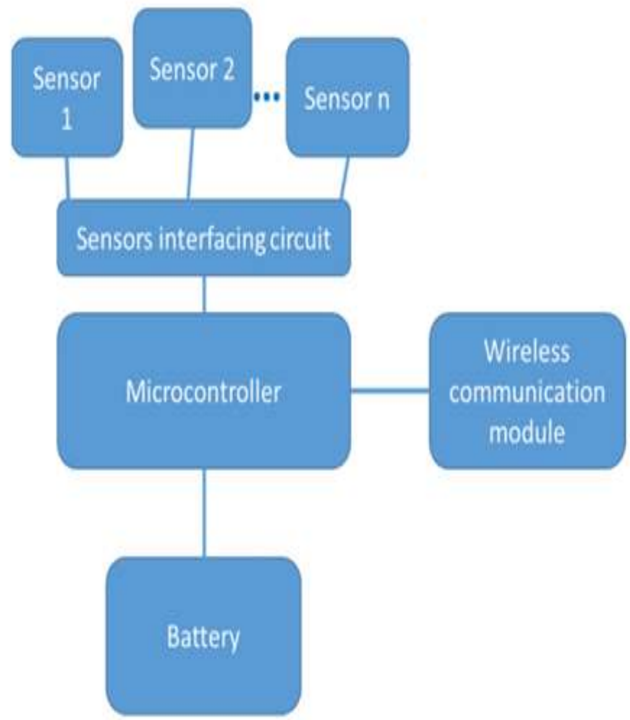

Figure 1. Basic architecture of a sensor node [13].

2.1 Sensing Sub-System

Sensors transmute physical occurrences into electrical impulses [5]. Consequently, the sensing sub-system connects the node to its surroundings. Both digital and analogue signals can be obtained from the sensors. The interface circuit of the sensors allows the microcontroller to process the detected signals. Certain existing

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node platforms possess integrated sensors, whilst others lack this feature. Numerous sensor nodes possess sockets designed to accommodate various sensors, hence ensuring versatility.

2.2 Computation Sub-System

The microcontroller's responsibilities encompass the processing of signals originating from section 2.2, Computation. Sub-system for detecting and transceiving, while coordinating the functions of additional sensor mote components [14]. The primary objective of the central processor unit (CPU) core is to guarantee accurate program execution. Consequently, the CPU must possess the capability to access memory, execute computations, coordinate external devices, and manage interrupts. Processors in sensor motes can operate in several modes, including active, idle, and sleep, to minimise excessive power use. The storage component of the mote often includes flash memory and a digital (SD) card interface, enabling the mote to possess non-volatile memory for data that requires offline acquisition. Nonetheless, the procedure of writing to the SD card requires significant power. Random Access Memory (RAM) Figure: 1(a). The flash memory retains the program code for the sensor mote, enabling rapid sampling and adaptable program updates, while the RAM is employed for storing sensed data and any information necessary for computations [15]. The electrically erasable programmable read-only memory (EEPROM) serves to store information for identifying registered sensor motes within the network [16]. Certain motes feature an integrated micro-secure digital (SD) card interface, enabling non-volatile memory for offline data collection. Nevertheless, the procedure of writing to the SD card requires significant amounts of power.

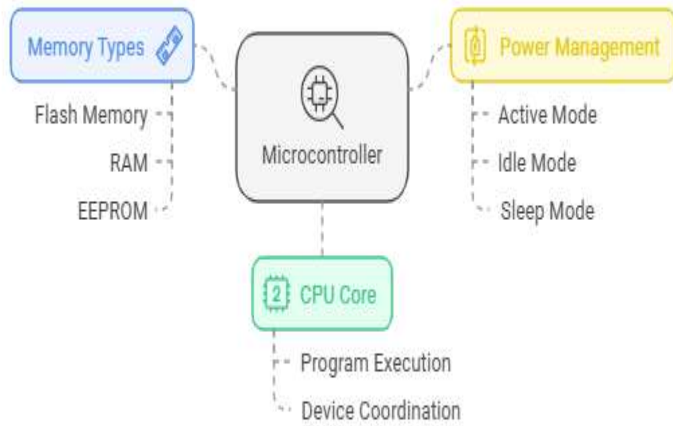

Figure: 1(a) Basic structure of Microcontroller

2.3 Communication Sub-System

The communications subsystem includes a radio module or transceiver for enabling the reception and transmission of signals to and from the wireless sensor motes, as well as to a base station or sink [14]. Radio frequency (RF) communication is appropriate for wireless sensor networks (WSNs) as it is not constrained by line-of-sight (LOS) requirements, and recent advancements enable the use of low-power radio modules with customisable data rates and communication ranges tailored to specific application scenarios.

2.4 Power Supply Sub-System

The power supply subsystem typically comprises a battery and/or a supercapacitor for energy storage and powering the sensor node. In many application scenarios of wireless sensor networks, the anticipated lifespan of sensor nodes may extend to several years, and the replenishment or replacement of batteries might be expensive, impractical, or even unfeasible, particularly in extensive, remote, and hazardous settings. Consequently, designers implement ultra-low-power and energy-efficient sensor nodes, together with the corresponding communication protocols and the motes' sleep/awake mode schedules. Energy harvesting from potential sources, including RF signals,

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solar energy, and vibrations, may also be utilised to replenish batteries [17].

3. MCU-based platforms for hardware for wireless sensor nodes.

The following article analyses wireless sensor nodes from recent research articles and popular commercially accessible motes, focussing on their potential applications, processor and memory specifications, communication capabilities, sensor support, power supply, and power consumption. The sensor nodes from recent studies were sourced from globally acknowledged databases. This study chose commercially accessible motes (MICAz, IRIS, LOTUS, WiSense, and Waspmote Plug & Sense!) for comparison based on factors such as popularity, published results, and notable traits and features. The well-known MiCAz mote from CrossBow Technology, albeit not recent, was selected as a reference mote for comparison purposes. Figure 2 illustrates a representation of standard wireless sensor nodes from a recently published research publication.

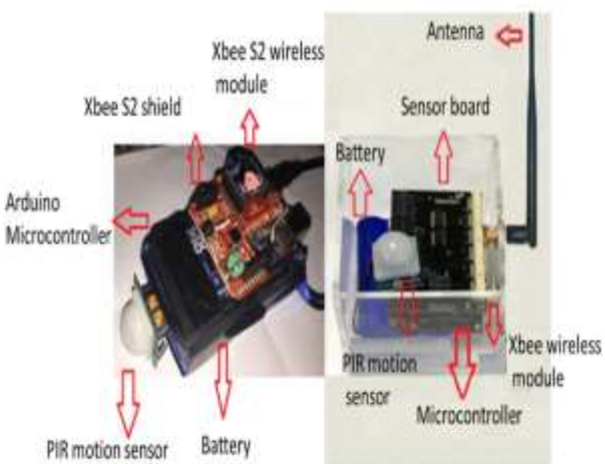

Figure: 2 Illustration of two common wireless sensor nodes based on MCUs

This document presents a debate on the recently announced wireless sensor nodes published between 2016 and 2023, as well as commercially available wireless sensor nodes. The nodes are classified based on their prospective programs, including human monitoring and tracking, environmental monitoring and smart agriculture, smart cities, automotive uses, general IoT applications, and seismic monitoring. The discourse centres on the applications of wireless sensor nodes, their processor and memory specifications, communication capabilities, sensor compatibility, power supply the requirements, and the use of energy.

3.1 Human Surveillance and Following

3.1.1 Infinitime.

InfiniTime [18] is a wrist-mounted sensor node designed to capture photos, audio, video, accelerometer data, and temperature for monitoring purposes. It employs a near-field communication/radio frequency identification (NFC/RFID) tag-integrated circuit (IC) featuring 16 kB of electrically erasable programmable read-only memory (EEPROM) and an inter-integrated circuit (I2C) bus interface. The node's communication capabilities are enabled by the M24LR16E-R transceiver produced by ST Microelectronics for wireless communication. The data rate ranges from 6.6 kbps to 26 kbps. Additionally, the node is equipped with an integrated ultra-low-power 3-axis accelerometer (ADXL362) from Analogue Devices, a temperature sensor, an INMP801 MEMS analogue microphone, and an external 112 × 112 pixel analogue camera.

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The node is powered by sunlight and heating energy harvesters. The solar panel has a parallel configuration of eight tiny amorphous silicon solar cells (AM-1417CA) manufactured by Sanyo Energy. The thermal energy collection is enabled by seven thermoelectric generator (TEG) modules. A solitary 40 mAh, 3.7 V lithium-polymer (LiPo) rechargeable battery is utilised for energy storage. Concerning the node's power consumption, at an 8 MHz MCU clock frequency, the current draw during ultra The current consumption in sleep, idle, display update, and data transmitting modes (with radio active) is 1.225 µA, 859 µA, 4278 µA, and 0.442 µA, respectively.

3.1.2 Electronics for Wireless Sensor Networks in Automotive Industries

The suggested economical sensors node is applicable in sports for monitoring athletic capabilities, including reflexes and response times [19]. The nodes can be customized for alternative purposes. The Arduino Pro Mini 3.3 V is utilized for processing detected data. The board features an Atmel ATmega328P microcontroller with 32 kB of flash memory and an 8 MHz quartz crystal. The ultra-low power nRF24L01 transceiver is utilized for communication purposes. It functions at 2.4 GHz with data rates of 250 kbps, 1 Mbps, and 2 Mbps. The transmission power can be configured to −18 dBm, −12 dBm, −16 dBm, or 0 dBm. The transceiver may get coverage of up to 250 meters at a data rate of 250 kbps with 0 dB transmission power.

The node is provided with a connecting interface that includes fourteen pins for digital in/output and 6 analog inputs to facilitate sensor connectivity. The node can be powered by battery voltages between 3.35 V to 12 V, facilitated by the Arduino Pro Mini 3.3 V voltage regulator. A 3.7 V lithium-ion (Li-ion) rechargeable battery, a 5 V rechargeable power bank, or a 5 V, 5500 mAh lithium polymer (Li-Po) rechargeable battery may be employed for power delivery. The mean consumption of current in transmission and power-down modes is 5.4 mA. 0.5 milliamperes, respectively.

3.2 Monitoring the environment as well as Innovative Farming

3.2.1 MoleNet

The MoleNet [20] node for sensors enables subterranean-to-underground (UG2UG) and subterranean-to-aboveground (UG2AG) communication for underground soil monitoring. The Wattuino Pro Mini, powered by the At-mega328p microcontroller, served as the foundation for development. The authors used an RV8523 real-time clock (RTC) to maintain local time and switch the MCU out of deep sleep mode. It has six sleep patterns.

For UG2UG and UG2AG communications on the MoleNet, a HopeRF RFM69CW transceiver was used. At 433 MHz transmission frequency, the UG2AG range for transmission was 80 m, while the 868 MHz transceiver had a line of sight range of 20 m. The radio that operates at 433 MHz allows for a UG2UG communication range of 7.5 m. The suggested node includes on-board volumetric water content and temperature monitoring for subsurface insertion.

The authors report a battery life of over five years. The power supply is regulated using a power-efficient MCP1703 regulator. The power usage is around 19 mA when sensing, 56 mA during transmitting, and 5 mA in idle periods.

3.2.2 Sensors Nodes for Agricultural and Rural Surveillance.

The data collection systems developed by [21] are intended for rural monitoring and agricultural applications. The sensor modules used the STM32L152 MCU, which has 128 kB Flash, 16 kB static random-access memory (SRAM), and 4 kB electrically erasable programmable read-only memory (EEPROM). However, the MCU's specifications have altered. The ultra-low-power 32-bit MCU Arm®-based Cortex®-M3 (32 MHz) now has 512 kB flash memory, 80 kB SRAM, and 16 kB EEPROM. The

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modules have IEEE Std. 802.15.4™-compliant RF transceiver wireless modules (MRF24J40) that can span distances up to 120 m in outdoor conditions. The transceivers operate in the unlicensed ISM Band (2.405 GHz-2.475 GHz) and can reach data speeds of up to 500 kbps. The receiver sensitivity of the modules is around -94 dBm.

The detection modules are equipped with SHT11 (air temperature and humidity) and 5TM (soil temperature and moisture content) sensors. The node can accommodate several sorts of commercial sensors. The modules require a power supply between 2.7 and 3.3 volts. The device consumes 20.2 mA during receiving mode and 19.7 mA during transmission mode at 0 dBm power.

3.2.3 FROG Node

The Fog-computing platform "FROG" [22] was created for applications in smart cities and precision agriculture. The FROG node is constructed on the Arduino Fio V3, utilizing the energy-efficient ATmega32U4 microcontroller, which features 32 kB of flash program memory, 2.5 kB of SRAM, and 1 kB of EEPROM. A throughput of 16 million instructions per second (MIPS) @ 16 MHz can be achieved to optimize power consumption relative to processing speed. A communication system utilizing an XBee-PRO XSC radio operating within the 902–928 MHz frequency band was selected. The radio system can achieve a software-selectable transmit power output of 24 dBm. The receiver sensitivity is −109 dBm in the 9600 band. The optimal line-of-sight communication range can extend to 45 kilometers.

The node is outfitted with multiple on-board gas sensors, including CO2 sensors. A 12 V lithium polymer battery with a capacity of 6400 mAh is employed to power the sensor node. The FROG node's processor and sensors collectively consume 741.98 mA of current. The XBee-PRO XSC radio module presently consumes around 266.5 mA.

3.2.4 Sensor Node Architecture for Agriculture Surveillance.

The node suggested by [23] was specifically engineered for agricultural monitoring applications. The module features an ATmega328P-PU microcontroller, equipped with 2 kB of RAM, 1 kB of EEPROM, and 32 kB of in-system self-programmable flash memory. It can attain 16 MIPS with a clock frequency of 16 MHz. The planned node utilized the CC1101 transceiver from Texas Instruments for communication, functioning within the 300–348 MHz, 387–464 MHz, and 779–928 MHz frequency bands. It is capable of transmitting in the 868/915 MHz frequency. at a peak power of 12 dBm. The data rate can be modified between 0.6 and 600 kbps. The node may achieve communication ranges exceeding 400 meters. The hardware was designed utilizing a panStamp NRG2 module.

A Bosch Sensortec BME280 environmental sensor is employed to measure temperature, humidity, and air pressure. The proposed mote can support supplementary sensors for agricultural monitoring. The node is powered by a series connection of two common AAA alkaline batteries, providing 3 V. Energy harvesting technologies can be seamlessly integrated into the mote. The sensor mote uses 1.1 µA in sleep mode. The mean current usage during communication is roughly 17.5 mA at 0 dBm and approximately 30.1 mA at 12 dBm.

3.2.5 WiFi Sensor Networks for Critical Incident Surveillance

The sensor node introduced by [24] was designed for environmental monitoring and fire detection. The design is based on Libelium's Waspmote microcontrollers (ATmega1281), functioning at 8 MHz, equipped with 8 kB SRAM, 4 kB EEPROM, 128 kB FLASH, and 2 GB of SD card storage. A combination of communication modules was employed. The authors selected the restricted range XBee S1 Pro, which operates at the 2.4 GHz frequency, and the wide range

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XBee 900LP, which operates at the 900 MHz band. Moreover, the writers utilized the humidity, carbon monoxide, temperature, and pressure sensors. The node depends on a rechargeable battery for its power source. A solar panel is available for energy harvesting. The authors did not specify the power utilization of the node.

3.2.6 The Shorter the Better: Sensor Node

The node suggested by [25] was engineered for the extensive surveillance of environmental variables, including temperature and humidity. The authors employed the CMWX1ZZABZ-078 semiconductor by ABZ Murata, which integrates a microcontroller (STM32L082CZ), a low-power long-range (LoRa) module (SX1276), and a resistance matching line within a single system-on-chip. The STM32 microcontroller is of the Cortex M0+ architecture, featuring 192 kB of flash memory, 20 kB of SRAM, and 6 kB of EEPROM.

The selected LoRa module operates at transmission frequencies of 868 MHz and 915 MHz. The module produces an output power of around 14 dBm. Additionally, the nodes are outfitted with an integrated temperature sensor, humidity sensor, and pluviometer for quantifying rainfall precipitation. Energy is provided by harvesters such as solar panels and Peltier modules. The captured energy is stored in a supercapacitor and/or a battery. The nodes also feature an energy manager chip (SPV1050) and a chip for monitoring battery current and voltage. The LoRa transceiver draws 0.5 µA in sleep mode and 41 mA at 14 dBm transmission power, whereas the MCU consumes 2.8 µA in sleep mode and 9.5 mA in active mode.

3.2.7 wireless connectivity Multisensor Node

The multi-sensor node [26] was developed for the purpose of monitoring environmental factors. The node was engineered utilising the STM32F103ZET6 microcontroller, which is founded on the ARM® Cortex®-M3 architecture working at a frequency of 72 MHz. It comprises up to 512 kB of Flash memory and up to 64 kB of SRAM. The authors employed wireless fidelity (Wi-Fi) to connect a gateway with the sensor motes at 2.4 GHz. The ESP8266 transceiver module is utilised for communication. The node integrates UV light (GT-302), raindrop, noise, and SM300D2 seven-in-one sensors to assess environmental factors, including temperature, humidity, PM2.5, PM10, formaldehyde focused attention, amount of carbon dioxide, and TVOC concentrations.

The node is energised by a battery and a solar panel linked to a solar tracking device. The mote's power usage is around 0.65 W during sensing. The Wi-Fi's current usage in transmission mode is roughly 100 mA. The sensor node utilises around 0.8 W of power during gearbox mode. In the sleep state, the current consumption is around 50 mA from the STM32 core, in addition to 10 mA. due to additional standby circuits. The mote consumes around 0.3 W of electricity while in the sleep state.

3.2.8 Atmospheric Sensor Nodes

The airborne sensors motes were specifically designed for atmospheric sensing applications. The nodes are equipped with a Texas Instruments microcontroller (CC430F5137), featuring 32 kB of programmable flash memory and 4 kB of RAM. The microcontroller integrates the benefits of the CC1101 sub-1 GHz RF radio module with the MSP430 CPUXV2. The MSP430 CPU features a 16-bit reduced instruction set computer (RISC) architecture, operating at a clock frequency of up to 20 MHz.

The suggested nodes can interact over 130 distinct channels, each including 16 time slots per second, utilising transceivers operating in the industrial, scientific, and medical (ISM) band at 915 MHz. A u-Blox Max M8 GPS receiver was employed for communication. The multiple frequency time-division multiple access (MF-TDMA) technology enables simultaneous data receiving from many eMotes. The node achieves

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a communication range of approximately 50 kilometres. Additionally, the temperature and air pressure sensor (MS5803) and the Sensirion humidity and temperature sensor (SHT25) can be integrated into the proposed nodes. The writers did not specify the details of power supply and power usage.

3.2.9 Biodiversity Observation Sensor Node

The node given by [28] was primarily designed for wildlife (chimpanzee) monitoring. The authors used a Cypress CY8C4248LQI-BL583 module with a 32-Bit Arm Cortex-M0 CPU, 256 kB of flash, and 32 kB of SRAM for their processor and memory requirements. The module can be connected to a 32 GB SD card module, giving additional memory for measured data. Cypress' CY8C4248LQI-BL583 module, which includes a Bluetooth low-energy (BLE) module, was chosen for 2.4 GHz communication. The RF output power ranges from -18 to +3 dBm. The node had no sensors. Instead, it computes the distance between the animals using the received signal strength indicator (RSSI) value. A 2600 mAh, 3.6 V lithium thionyl chloride battery is used to power the node. At peak performance, the BLE module draws 1.9 mA and uses 4.99 mW of power. At 46 MHz, the CPU draws 27.7 milliamperes. The processor drains 1.7 mA when inactive and 1.5 µA during prolonged slumber mode.

3.3 Intelligent cities and automotive uses

3.3.1 Sensors Nodes for Smart Cities

The sensors and nodes presented in [13] were designed for smart city and distant sensing applications. The nodes were engineered with the 8 MHz Waspmote microcontroller (ATmega1281), with 8 kB SRAM, 4 kB EEPROM, 128 kB FLASH, and 2 GB SD card memory. Two ZigBee radio modules are employed to facilitate communication among the sensor motes. A 2.4 GHz ZigBee module (XBee-PRO version) is selected for communication between ground nodes, while an 868 MHz ZigBee module is utilised for connectivity with the UAV node. A radio extension interface enables a node to concurrently connect to two distinct ZigBee transceivers. The 2.4 GHz XBee-PRO operates at a transmission power of 18 dBm and has a sensitivity of 100 dBm, achieving a communication range of 1500 m. The 2.4 GHz XBee S2 variant can broadcast at 3 dBm power, with a receiver sensitivity of around −97 dBm, achieving a range of up to 120 meters. The sensor nodes employ external sensor boards equipped with sockets for the HC ultrasonic sensor, DHT11 sensor (temperature and humidity), Grove-Gas Sensor (MQ2) (for detecting gas leaks including hydrogen, liquefied petroleum gas (LPG), methane, carbon monoxide, alcohol, smoke or propane), and the D-Sun Hc-Sr501 pyroelectric infrared (PIR) motion sensor. Moreover, external sockets are provided for the integration of novel sensor kinds. The authors employed batteries to energise the nodes in the initial deployment of a wireless sensor network (WSN). In the second implementation, the Waspmote board capable of supporting a solar panel was employed. The minimal power usage during data transmission was achieved by the utilisation of ZigBee modules.

3.3.2 Infrastructure for Wireless Sensor Networks in Automotive Industries

The WSN node that [31] suggested was created for intelligent car applications aimed at public transit. It focusses on keeping an eye on the environmental and mechanical strains that a travelling bus and its occupants endure. The Raspberry Pi 3 Bi+, the platform on which the node was built, has a 64-bit Cortex-A53 processor running at 1.4 GHz, 1 GB of RAM, and up to 64 GB of disc storage.

The Huawei E3372 Megafon dongle was chosen as the communication module in order to enhance the node's communication capabilities. It uses frequencies in the universal mobile telecommunications system (UMTS) (3G, 900, and 2100 MHz), long-term evolution (LTE) (4G,

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800, 1800, 2100, and 2600 MHz), and global system for mobile (GSM) communication (2G, 900, and 1900 MHz). It can function at data speeds ranging from roughly 236.8 kbps to 150 Mbps. Additionally, the node has temperature, relative humidity, and accelerometric sensors built in. With a precision of roughly ±5%, the capacitive sensor (SNS-DH11) was selected to track relative humidity data that ranged from about 1% to 90%. To measure temperature measurements, the Ad-001 Ds18b20 temperature sensor was chosen. To identify mechanical stresses, a 3-axis accelerometer ADXL-345 (SparqEE LLC, Placentia, CA, USA) based on the MMA7361 device is used.

Regarding the node's power source, the 24 V provided by the car battery is down-converted to the 5 V required to power the Raspberry Pi using a B1700526EU (Yeeco, Germany) DC-DC converter. To provide 12 V to a monitor, a second DC-DC converter (ZC104300 CPT) is also included. At its peak, the suggested node uses about 0.08 kWh. The node's energy efficiency is not a crucial consideration because it draws power from the vehicle's batteries (around 243 kWh).

3.3.3 Plants Microbial Fuel Cell-Based Wireless Sensing Node

The self-sustaining plant microbial fuel cell (PMFC)-based wireless sensor node [32] is designed for environmental monitoring in smart cities. The 16-bit RISC ultra-low-power MCU (MSP430FR5969) created by Texas Instruments features 64 kB of ferroelectric memory with random access (FRAM) and achieves a clock speed of 16 MHz.

The authors adopted the LoRa radio module (RFM95W), which employs the SX1276 LoRa transceiver with a serial peripheral interface (SPI). The transceiver functions within the 868.1 MHz frequency band, providing a coverage range of 2 km under line-of-sight conditions or around 20 km when utilising directional antennas. The gearbox power is adjustable between approximately +5 and +20 dBm. Additionally, the MQ-131 and MQ-135 sensors are utilised for the detection of ozone and carbon dioxide concentrations, respectively.

The node is energised using energy harvesting with PMFCs. The PMFCs may provide 1.25 mW/cm2 to the energy-scavenging circuit (BQ25570), which delivers a voltage of around 3.3 V. A supercapacitor serves as an energy storage device. The MCU (MSP430FR5969) functions in standby low-power mode (LPM3) and real-time clock mode (LPM3.5), with typical current consumptions of roughly 400 nA and 250 nA, respectively. The maximum power output (20 dBm) corresponds to a peak current of roughly 30 mA when the transceiver is in the active-listening mode. The mean power consumption of the mote is 2.92 mW.

3.4 *General IoT Applications*

3.4.1 MEGAN

MEGAN [14] is a sensor node utilised for several IoT applications. The sophisticated, low-power RISC-based ATmega324PA microprocessor was employed. The microcontroller comprises 32 kB of flash memory, 2.5 kB of static RAM, and 1 kB of EEPROM. The authors employed a clocking frequency of 8 MHz, which can be elevated to 16 MHz. The mote provides the benefit of selecting a communication module tailored for a certain application. The authors employed ZigBee (XBee series 1) and Bluetooth (HC-05) modules for communication in their demonstration. According to the authors, the node can accommodate additional communication technologies, including General Packet Radio Service (GPRS), Wi-Fi, and GSM. Additionally, the node comprises 32 general-purpose input/output (GPIO) pins that facilitate the connection of various sensors and actuators. A 3.7 V, 800 mAh lithium-ion battery is employed to energise the node. The battery is replenished using a recharging circuit integrated within the sensor mote. The present consumption of the

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node in sleep and active phases is 10.1 µA and 7.95 mA, respectively.

The utilisation current consumption in the active state is 16.44 mA for the Bluetooth module and 59.65 mA for the Zigbee module.

4.2 Constraints and Future Trends.

IoT technology makes use of WSNs to create a smart and effective sensing and communication setup. Even with all the research done on WSNs, energy consumption is still a big issue that shortens their lifespan. When designers are working on wireless sensor nodes, there are a few key features and characteristics they really need to keep in mind. These include ultra-low power consumption, affordability, a compact physical size, and the ability to configure both software and hardware. Sensor motes that use microcontroller units are great because they consume little power, are affordable, offer programming flexibility, and can be brought to market quickly. The nodes are mainly used for basic embedded systems that have tight budget constraints.

These days, the focus is on creating ultra-low power MCUs that really minimise power usage while they're in sleep mode. This is important because, in many applications, sensor nodes spend most of their time in that sleep state. We really need to cut down the wakeup time of the motes as much as we can. So, improving microprocessors and using ultra-low power management techniques are really important to cut down on power consumption and make sure WSNs can last a long time.

Low power MCUs work really well for applications that don't need a lot of heavy computation. It looks like the latest wireless sensor nodes are now using ARM Cortex-based processors for applications that need more computational power. We should definitely look into using energy-harvesting techniques to power the wireless sensor node and help extend the network's lifetime. To get better energy efficiency and long-range coverage, we can use some of the new LPWAN technologies like LoRa, NarrowBand IoT (NB-IoT), and Sigfox. We should definitely look into the benefits of these new and exciting communication technologies together.

It turns out that many of the newer sensor nodes are leaning towards an open source approach, whereas the older platforms are sticking with a closed source approach. It's likely that using compatible open platforms and off-the-shelf components lets researchers quickly create better sensor nodes, especially when it comes to power use, communication, and processing abilities, compared to those specially designed platforms. Also, it's simpler to handle software upgrades and hardware changes. But, using an open-source hardware setup doesn't really lead to a smaller size for the sensor node.

It's important to keep in mind that if we overlook the security issues and vulnerabilities of the sensor node during the design phase, it can really compromise how well the entire WSN functions. Security threats are always changing, which means we need to keep coming up with new ways to tackle them and ensure that we have solid protection throughout WSNs. So, There's a real need for secure protocols that are both computationally efficient and energy effective to fit the limited resources of the motes. We really need to focus on creating motes that provide consistent measurements and have a low failure rate. These motes need to be tough enough to handle changes in the environment, working well under various temperatures, pressures, moisture levels, and weather conditions without losing their accuracy. The cost-effectiveness and portability of the motes are really important for making it easy to deploy and use them in various IoT applications.

It's really interesting to look into various ways of harvesting energy, like wireless charging methods that are efficient and budget-friendly. This is still a field that researchers are diving into. Managing IoT motes from a distance and updating their firmware with technologies like over-the-air programming (OTA) is something that's still being explored. We really need to dive deeper into the energy efficiency challenges that come up when using UAVs or drones in mobile applications.

5.0 Conclusion and Prospective Projects

A comprehensive comparative analysis of MCU-based wireless sensor nodes from recently published research articles (2016–2022) has been provided. The sensor nodes from recent research articles are evaluated against the most prevalent commercially available motes, considering processing and memory specifications, communication capabilities, power supply and consumption, sensor support, potential applications, node programming, and hardware security. This work aims to elucidate the advancements in the design of energy-efficient and autonomous wireless sensor nodes to prevent redundancy in research conducted by industry and academic institutions. We expect this study to aid wireless sensor node developers in creating superior designs that surpass current motes. Furthermore, this study assists researchers and prospective users in selecting the most suitable mote for particular application scenarios. A discourse on wireless sensor node platforms is presented. The challenges and prospective research avenues are also defined. The lack of actual power consumption statistics for several sensor nodes examined in this study constitutes a limitation of this research. Exploration of ultra-low power approaches in wireless sensor nodes should persist. The miniaturisation of sensor nodes is a prospective avenue for future study. Security concerns in sensor nodes must not be overlooked. We additionally advocate for rigorous experimental performance assessments of the sensor nodes.

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