

Code: 23EC4601C

III B.Tech - II Semester - Regular Examinations – APRIL 2026**SMART AND WIRELESS INSTRUMENTATION
(ELECTRONICS & COMMUNICATION ENGINEERING)**

Duration: 3 hours

Max. Marks: 70

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- Note: 1. This question paper contains two Parts A and B.
 2. Part-A contains 10 short answer questions. Each Question carries 2 Marks.
 3. Part-B contains 5 essay questions with an internal choice from each unit. Each Question carries 10 marks.
 4. All parts of Question paper must be answered in one place.

BL – Blooms Level

CO – Course Outcome

PART – A

		BL	CO
1.a)	Differentiate between active and passive sensors.	L3	CO1
1.b)	Define self-organization of network.	L2	CO1
1.c)	List out applications of FPGA in view of node architecture.	L2	CO3
1.d)	Define communication interface.	L2	CO3
1.e)	Define data rate.	L2	CO4
1.f)	Mention two advantages of Zigbee over Wi-Fi.	L2	CO4
1.g)	Define energy management in the view of WSN.	L2	CO5
1.h)	Define thermal energy harvesting.	L2	CO5
1.i)	Define piezoelectric effect.	L2	CO2
1.j)	Define structural health monitoring.	L2	CO2

PART – B

			BL	CO	Max. Marks
UNIT-I					
2	a)	Define sensor in WSN. Explain Types of sensors and its application in detail.	L2	CO1	5 M
	b)	Discuss energy consumption concept of the different components of a sensor node.	L2	CO1	5 M
OR					
3	a)	Assess the challenges in security provisioning in WSN.	L4	CO1	5 M
	b)	Analyze the impact of energy constraints on WSN protocol design.	L4	CO1	5 M
UNIT-II					
4		Compare ASIC and FPGA in terms of performance, flexibility, power consumption and cost.	L3	CO3	10 M
OR					
5	a)	Explain the sensor node architecture with a neat block diagram.	L2	CO3	5 M
	b)	Describe the operation of XYZ node architecture and its components.	L2	CO3	5 M
UNIT-III					
6	a)	Explain the frequency spectrum used in wireless communication for WSN.	L2	CO4	5 M
	b)	Compare Zigbee, Bluetooth and Wi-Fi for WSN applications.	L3	CO4	5 M

OR					
7		Describe the hardware requirements for implementing Zigbee-based WSN.	L2	CO4	10 M
UNIT-IV					
8	a)	Illustrate the importance of energy harvesting in extending network lifetime.	L3	CO5	5 M
	b)	Explain different power sources used in WSN with advantages and limitations.	L2	CO5	5 M
OR					
9	a)	Explain battery technologies used in WSN.	L2	CO5	5 M
	b)	Explain RF energy harvesting and its working principle.	L2	CO5	5 M
UNIT-V					
10	a)	Illustrate precision agriculture using WSN.	L3	CO2	5 M
	b)	Illustrate WSN applications in traffic control and health care.	L3	CO2	5 M
OR					
11	a)	Explain pipeline monitoring using WSN.	L2	CO2	5 M
	b)	Describe the role of WSN in underground mining safety systems.	L2	CO2	5 M

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PVP SIDDHARTHA INSTITUTE OF TECHNOLOGY
(AUTONOMOUS)

III B.Tech- II Semester- Regular Examinations — APRIL 2026

SMART AND WIRELESS INSTRUMENTATION

(ELECTRONICS & COMMUNICATION ENGINEERING)

Q.NO		Marks Distribution	Total Marks
1	a	Each Difference -1M	2
1	b	Definition	2
1	c	Each application -1M	2
1	d	Definition	2
1	e	Definition	2
1	f	Each advantage-1M	2
1	g	Definition	2
1	h	Definition	2
1	i	Definition	2
1	j	Definition	2
2	a	Definition-1M Explanation-4M	5
	b	Explanation each component-2M	5
3	a	Definition-1M Explanation-4M	5
	b	Explanation-5M	5
4		Each comparison-4M	10
5	a	Block diagram-2M Explanation-3M	5
	b	Block diagram-2M Explanation-3M	5
6	a	Explanation-5M	5
	b	Each comparison-2M	5
7		Each component Explanation-4M	10
8	a	Explanation-5M	5
	b	Each harvesting or battery Explanation-2M	5
9	a	Each Technology-2M	5
	b	diagram-2M Explanation-3M	5
10	a	Explanation each parameter -2M	5
	b	Explanation each parameter -3M	5
11	a	Explanation each parameter -3M	5
	b	Explanation each parameter -3M	5

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III B.Tech- II Semester- Regular Examinations — APRIL 2026

SMART AND WIRELESS INSTRUMENTATION

(ELECTRONICS & COMMUNICATION ENGINEERING)

SCHEME

1a Differentiate between active and passive sensors.

passive sensors do not need an external power connection, whereas in the case of active sensors it is quite the opposite - these require a source of power to operate.

Active sensors are characterized by continuous power consumption in order to perform measurements.

1b Define self-organization of network

A self-organizing system as **one where a collection of units coordinate with each other** to form a system that adapts to achieve a goal

1c List out applications of FPGA in view of node

Architecture

Any like

(i). FPGA-based wireless sensor node for a machine vibration monitoring system and fault diagnosis

(ii) Sensor Fusion: Combining data from multiple sensors (e.g., accelerometers, temperature, pressure) concurrently

1d Define communication interface

A communication interface refers to the mechanism through which two devices can exchange information and interact with each other.

1(e) Define data rate.

Data rate is the speed at which data is transmitted between devices or over a network, measured in bits per second (bps),

1(f) Mention two advantages of Zigbee over Wi-Fi.

Any of

(i)Energy savings : Extremely Low Power Consumption: Zigbee devices consume far less energy than Wi-Fi devices, allowing sensors and smart locks to run on small batteries for months or years.

(ii) Wider range

Because it uses a mesh network, the Zigbee protocol offers greater range and more stable coverage than Wi-Fi. In a mesh network, each device connects to the others without a hierarchy. This lack of hierarchy extends the reach of your connected devices, so you don't need to add repeaters like you would with Wi-Fi.

(iii) Enhanced security

Zigbee offers stronger data security — both when devices are paired with the app and during everyday use.

(iv) Simplified setup

Zigbee makes network setup and device pairing faster and easier.

1(g) Define energy management in the view of WSN

Energy management in Wireless Sensor Networks (WSNs) is the systematic process of managing, conserving, and harvesting energy to maximize the network's operational lifetime.

1(h) Define thermal energy harvesting.

Thermal energy harvesting is the process of capturing ambient or waste heat—such as from machinery, industrial pipes, or body heat—and converting it into electrical energy to power low-power electronics, including Wireless Sensor Networks (WSNs), using thermoelectric generators (TEGs). This approach eliminates the need for batteries, allowing for self-powered, sustainable, and long-lasting sensor operation.

1(i) Define piezoelectric effect

The Piezoelectric Effect can be defined as the ability of particular materials for generating an electric charge in reply toward applied mechanical pressure or stress.

1(j) Define structural health monitoring

It involves the continuous assessment of a structure's mass, stiffness, and damping characteristics to detect damage before failure occurs.

2(a) Define sensor in WSN. Explain Types of sensors and its application in detail.

A sensor is a device that detects, measures, or responds to physical, chemical, or biological stimuli—such as temperature, light, pressure, or motion—and converts this information into an electrical signal.

Classification of Sensors

The Sensor can be classified as

Based on Power Requirement

passive sensors do not need an external power connection, whereas in the case of active sensors it is quite the opposite - these require a source of power to operate.

Active sensors are characterized by continuous power consumption in order to perform measurements.

Based on the Conversion Phenomenon

This classification is based on the input and output conversion

Photoelectric: It Changes light to electrical signals.

Thermoelectric: It Changes temperature difference to electrical voltage.

Electrochemical: It Changes chemical reactions to electrical signals.

Electromagnetic: It Changes magnetic fields to electrical signals.

Based on Output Type

Analog Sensors: It produce an output signal which is usually in the form of voltage, current, or resistance, proportional to the measured quantity.

Digital Sensors: It provide discrete or digital data as output.

Types of Sensors

Temperature sensors: Monitoring temperature of used devices in industrial applications. it is used to measure temperature. this can be air temperature, liquid temperature or the temperature of solid. It can be analog or digital. In an Analog Temperature Sensor, the change in the Temperature correspond to change in its physical property like resistance or voltage. LM35 is a classic Analog Temperature Sensor. In Digital Temperature Sensor, the output is a discrete digital value, DS1621 is digital sensor which generates 9 bits temperature data.

Accelerometer sensors: It measures the rate of change of velocity and this sensor generate magnitude and acceleration of the acceleration. Accelerometer sensor sensor ADXL335 provides 3 axes (X,Y, and Z) values in analog voltage. it is used in car electronics, ships, and agricultural machines.

Alcohol sensors: as the name suggests it detects alcohol. Usually, alcohol sensors are used in breathalyzer devices, which determine whether the person is drunk or not. Law enforcement personnel uses breathalyzers to catch drunk-and-drive culprits.

Radiation sensors: Radiation Sensors/Detectors are electronic devices that sense the presence of alpha, beta, or gamma particles and provide signals to counters and display devices.

Radiation detectors are used for surveys and sample counting.

Position sensors: Position Sensors are electronic devices used to sense the positions of valves, doors, throttles, etc. and supply signals to the inputs of control or display devices. Key specifications include sensor type, sensor function, measurement range, and features that are specific to the sensor type. Position sensors are used wherever positional information is needed in a myriad of control applications. A common position transducer is a so-called string-pot, or string potentiometer.

Gas sensors: It measures and detects concentration of different gases which is present in the atmosphere or any other environment.

Torque sensors: This sensor is used for measuring the rotating torque and it is used to measure the speed of the rotation.

Optical sensors: it is also called photosensors which can detect light waves at different points in the light spectrum including ultraviolet light, visible light, and infrared light. it is extensively used in smartphone, robotics and Blu-ray players.

Proximity sensors: This sensor is used to detect the distance between two objects or detect the presence of an object. it is used in elevators, parking lots, automobiles, robotics, and numerous other environment.

Touch sensors: Touch sensing devices detect physical contact on a monitored surface. Touch sensors are used extensively in electronic devices to support trackpad and touchscreen technologies. They're also used in many other systems, such as elevators, robotics and soap dispensers.

Application of Types Of Sensors

Given below are the Application of Types Of Sensors

Automotive Industry: They are used in the Automotive industry for monitoring engine temperature, speed and other parameters.

Smart Homes: They are used in the Smart Homes for detecting movements, Control HVAC and other measurements.

Robotics: They are used in the Robotics for object recognition, Tracking the position and measuring force.

Transportation: Sensors such as GPS , Load, and Speed sensors are used in transportation infrastructure.

2(b) Discuss energy consumption concept of the different components of a sensor node.

Energy

The constraint most often associated with sensor network design is that sensor nodes operate with limited energy budgets. Typically, they are powered through batteries, which must be either replaced or recharged (e.g., using solar power) when depleted. For some nodes, neither option is appropriate, that is, they will simply be discarded once their energy source is depleted. Whether the battery can be recharged or not significantly affects the strategy applied to energy consumption. For nonrechargeable batteries, a sensor node should be able to operate until either its mission time has passed or the battery can be replaced. The length of the mission time depends on the type of application, for example, scientists monitoring glacial movements may need sensors that can operate for several years while a sensor in a battlefield scenario may only be needed for a few hours or days. As a consequence, the first and often most important design challenge for a WSN is energy efficiency. This requirement permeates every aspect of sensor node and network design.

The energy consumption of a sensor node is primarily driven by its four main functional units: the sensing unit, the processing unit, the communication unit, and the power unit. Managing power is critical because these nodes often rely on limited battery life in remote environments.

1. Communication Unit

This is almost always the highest energy consumer in a sensor node.

Transmitting vs. Receiving: Sending data requires significant power to drive the antenna and propagate signals. However, "idle listening"—keeping the radio on to wait for incoming packets—can consume nearly as much power as active reception.

Startup Costs: Frequent switching between "sleep" and "active" modes incurs a power spike during the radio's startup phase.

2. Processing Unit

The microcontroller (MCU) manages data and controls the other components.

Operational States: Energy use depends on whether the MCU is in Active, Idle, or Sleep mode.

Data Processing: Performing local data compression or filtering can actually save energy overall by reducing the amount of data the communication unit (the bigger power hog) needs to send.

3. Sensing Unit

This unit converts physical phenomena (like heat or light) into electrical signals.

Passive vs. Active: Passive sensors (like a thermometer) use very little power. Active sensors (like sonar or radar) require their own energy source to probe the environment, leading to much higher consumption.

Analog-to-Digital Conversion (ADC): The process of converting raw signals into digital data for the MCU consumes a steady, measurable amount of power.

4. Power Unit

While this provides energy, it also experiences loss.

DC-DC Conversion: Converting battery voltage to the specific levels required by the MCU

3(a) Assess the challenges in security provisioning in WSN

Many wireless sensor networks collect sensitive information. The remote and unattended operation of sensor nodes increases their exposure to malicious intrusions and attacks. Further, wireless communications make it easy for an adversary to eavesdrop on sensor transmissions. For example, one of the most challenging security threats is a denial-of-service attack, whose goal is to disrupt the correct operation of a sensor network. This can be achieved using a variety of attacks, including a jamming attack, where high-powered wireless signals are used to prevent successful sensor communications. The consequences can be severe and depend on the type of sensor network application. While there are numerous techniques and solutions for distributed systems that prevent attacks or contain the extent and damage of such attacks, many of these incur significant computational, communication, and storage requirements, which often cannot be satisfied by resource-constrained sensor nodes. As a consequence, sensor networks require new solutions for key establishment and distribution, node authentication, and secrecy.

Security provisioning in Wireless Sensor Networks (WSNs) is primarily challenged by extreme resource constraints (limited energy, memory, and processing power), hostile deployment environments, and the inherent vulnerability of wireless communication to eavesdropping and jamming.

Key Challenges in WSN Security :

Resource Limitations: Sensor nodes possess limited battery life, computational capacity, and memory, making it difficult to implement strong, complex encryption algorithms.

Physical Vulnerability: Nodes are often deployed in unattended, hostile, or remote areas, making them susceptible to physical tampering, theft, or replacement.

Unreliable Communication: The wireless medium is susceptible to packet loss, interference, and eavesdropping, hindering secure transmission and data integrity.

Scalability and Deployment: WSNs can contain thousands of nodes, requiring automated, secure key distribution, management, and authentication mechanisms that can operate at scale.

3(b) Analyze the impact of energy constraints on WSN protocol design

Energy Constraints

Wireless sensor nodes are typically driven by finite power sources, that is, either disposable or rechargeable (e.g., via solar panels) batteries. Battery replacement can add significantly to the cost of a WSN, particularly in large-scale networks and when the nodes are in difficult-to-service locations. Therefore, time synchronization protocols should not contribute significantly to the energy consumption of wireless nodes to ensure long battery life times. Since communication among sensor nodes is typically the basis for time synchronization, an energy-efficient synchronization protocol should aim for the minimum amount of the smallest possible messages necessary to obtain synchronized nodes

Energy constraints are the primary driver of Wireless Sensor Network (WSN) protocol design because nodes typically rely on limited, non-rechargeable batteries. Unlike traditional networks that prioritize maximum throughput or low latency, WSN protocols are designed to trade off performance for network longevity. Designers implement duty cycling, where nodes remain in a "sleep" state and only wake up periodically to check for traffic. This directly addresses the main sources of energy waste:

Idle Listening: Keeping the radio on while waiting for a packet.

Overhearing: Receiving packets meant for other nodes.

Collisions: Wasted energy due to retransmitting failed packets.

Energy constraints impose strict trade-offs that designers must balance according to the application.

4 Compare ASIC and FPGA in terms of performance, flexibility, power consumption and cost

An application-specific integrated circuit (ASIC) is an integrated circuit (IC) that can be customized for a specific application.

The ASIC architecture consists of cells and metal interconnects. A cell is an abstraction of a logical functionality that is physically implemented by active components (transistors).

When several of these cells are interconnected by the metal interconnects, they make up an application-specific integrated circuit. The manufacturing of cells has reached such a

maturity that there is a standard library of cells consisting of a collection of low-level logic functions, including basic gates (AND, OR, and INVERT), multiplexers, adders, and flipflops. As the standard cells have identical size, they can be arranged in rows to ease the process of automated digital layout. Using predefined cells from a cell library makes the ASIC design process much easier. In a fully customized IC, some (possibly all) logic cells, circuits, or layouts are custom Made.

FPGAs are programmed electrically, by modifying a packaged part. This process may take from a few milliseconds to a few minutes, depending on the programming technology Node Architecture. and the size of the part. The programming is done with the support of circuit diagrams and hardware description languages, such as VHDL and Verilog..FPGAs have a higher bandwidth compared to DSPs; they are more flexible in their application and can support parallel processing. While DSPs and microcontrollers can incorporate an internal ADC, a FPGA does not.

Performance

ASIC: Offers the highest performance, speed, and efficiency for a specific task because the circuit is custom-designed.

FPGA: Generally lower performance than ASIC due to overhead from programmable logic blocks and interconnects, though they provide high parallel processing capabilities.

Flexibility

ASIC: Zero flexibility. The design is fixed after manufacturing, and any change requires a new redesign and production run.

FPGA: Highly flexible. It can be reconfigured or updated even after deployment, enabling upgrades and bug fixes.

Power Consumption

ASIC: Lower power consumption. Components are optimized and limited to what is needed, minimizing wasted energy.

FPGA: Higher power consumption due to a massive number of unutilized logic gates and complex routing structures.

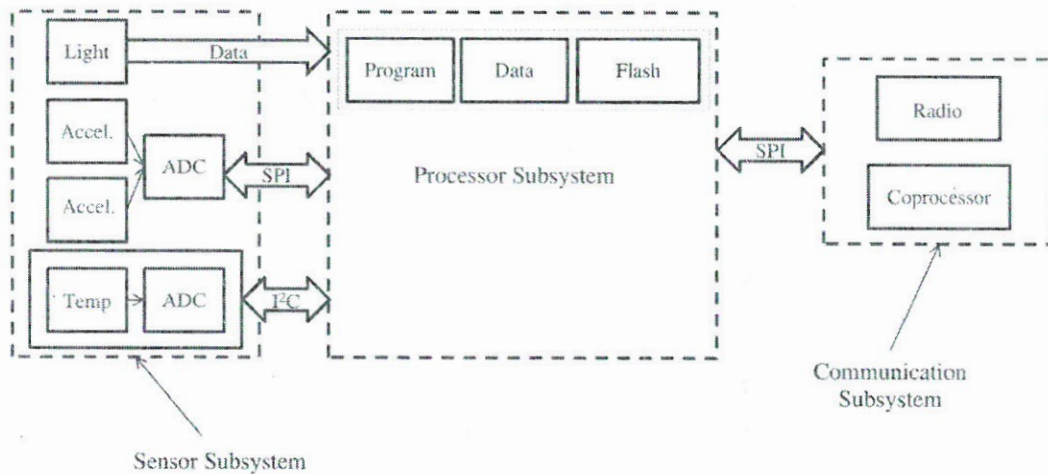
Cost

ASIC: High Non-Recurring Engineering (NRE) costs (mask sets, design, verification). Low cost per unit makes them suitable for high-volume production.

FPGA: Low upfront investment (no NRE), but significantly higher per-unit cost. Generally more economical for low-volume or prototyping.

5(a) Explain the sensor node architecture with a neat block diagram.

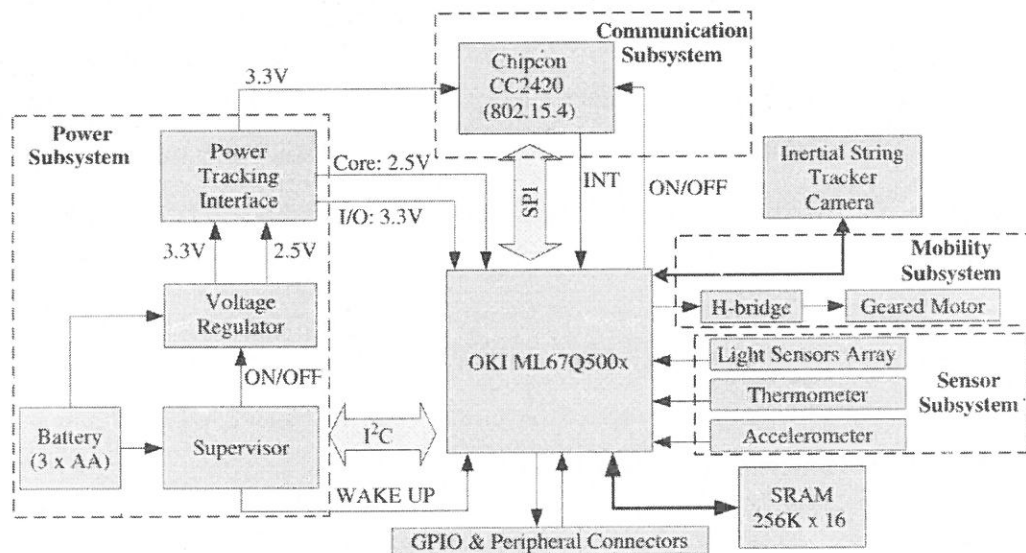
Node Architecture



The wireless sensor nodes are the central element in a wireless sensor network (WSN). It is through a node that sensing, processing, and communication take place. It stores and executes the communication protocols and the data-processing algorithms. The quality, size, and frequency of the sensed data that can be extracted from the network are influenced by the physical resources available to the node. Therefore, the design and implementation of a wireless sensor node is a critical step. The node consists of sensing, processing, communication, and power subsystems. The designer has a plethora of options in deciding how to build and put together these subsystems into a unified, programmable node. The processor subsystem is the central element of the node and the choice of a processor determines the tradeoff between flexibility and efficiency – in terms of both energy and performance. There are several processors as options: microcontrollers, digital signal processors, application-specific integrated circuits, and field programmable gate arrays.

There are a number of ways to connect the sensing subsystem with the processor. Connecting two or more analog sensors with a multichannel ADC system that integrates multiple high-speed ADCs into a single IC design is one way. Likewise, the communication subsystem can be interfaced with the processor subsystem in different ways. One way is to use the SPI serial bus. Some transceivers have their own processor board to perform low-level signal processing pertaining to the physical and the data link layer, thereby relieving the main processor from these concerns. The communication subsystem is the most energy intensive subsystem and its power consumption should be regulated. Almost all commercially available transceivers provide a controlling functionality to switch the transceiver between various active operation levels; idle and sleep state. The power subsystem provides DC power to all the other subsystems to bias their active components such as crystal oscillators, amplifiers, registers, and counters.

5(b) Describe the operation of XYZ node architecture and its components.



The XYZ architecture consists of four subsystems. Figure 3.10 shows the schematic diagram of the node architecture. The processor subsystem is based on the ARM7TDMI core microcontroller, which is capable of operating at a maximum frequency of 58 MHz.

The microcontroller can operate at two different modes, depending on the application requirement: at 32 bits and 16 bits. The processing subsystem provides an on-chip memory of 4 KB boot ROM and a 32 KB RAM, which can be extended by up to 512 KB of flash memory. The peripheral components that interface the processing subsystem with the remaining subsystem include an embedded DMA controller, four 10-bit ADC inputs, serial ports (RS232, SPI, I2C, SIO), and 42 multiplexed general-purpose I/O pins. Most of the multiplexed GPIO pins are available on two 30-pin headers together with the DC voltage provided by the power subsystem or directly by an on-board voltage regulator. The communication subsystem is based on the Chipcon CC2420 radio, which is connected to the processing subsystem through a SPI interface.

6(a) Explain the frequency spectrum used in wireless communication for WSN.

IEEE 802.15.4 and ZigBee

The IEEE 802.15.4 standard (Gutierrez et al. 2001) was created for low-power devices that operate in the 868 MHz, 915 MHz, and 2.45 GHz frequency bands. The data rates supported by this standard are 20, 40, and 250 kbps; rather modest compared to other protocols such as IEEE 802.11 (e.g., IEEE 802.11a offers data rates of up to 54 Mbps). Before this standard was developed, the ZigBee Alliance worked on a low-cost communication technology for low data rates and low power consumption. The IEEE and the ZigBee Alliance ultimately joined forces and ZigBee has become the commercial name for the IEEE 802.15.4 technology.

The IEEE 802.15.4 PHY adopted by ZigBee has been designed for the 868 MHz band in Europe, the 915 MHz band in N America, Australia, etc; and the 2.4 GHz band is now recognized to be a global band accepted in almost all countries.

Data rates: 250 kb/s (2450 MHz band), 40 kb/s (915 MHz),
20 kb/s (868 MHz).

IEEE 802.15.4 defines operation in three license-free industrial scientific medical (ISM) frequency bands. Below is a table that summarizes the properties of IEEE 802.15.4 in two of the ISM frequency bands: 915 MHz and 2.4 GHz.

Property Description	Prescribed Values	
	915 MHz	2.4 GHz
Raw data bit rate	40 kbps	250 kbps
Transmitter output power	1 mW = 0 dBm	
Receiver sensitivity (<1% packet error rate)	-92 dBm	-85 dBm
Transmission range	Indoors: up to 30 m; Outdoors: up to 100 m	

6(b) Compare Zigbee, Bluetooth and Wi-Fi for WSN applications

ZigBee is poised to become the global control/sensor network standard. It has been designed to provide the following features:

- Low power consumption, simply implemented
 - Users expect batteries to last many months to years
- ZigBee/IEEE 802.15.4 has active (transmit/receive) or sleep
- Even mains powered equipment needs to be conscious of energy.

ZigBee devices will be more ecological than its predecessors saving megawatts at it full deployment.

Low cost (device, installation, maintenance)

Low cost to the users means low device cost, low installation cost and low maintenance. ZigBee devices allow batteries to last up to years using primary cells (low cost) without any chargers (low cost and easy installation). ZigBee's simplicity allows for inherent configuration and redundancy of network devices provides low maintenance.

Comparison of Wireless Standards			
Wireless Parameter	Bluetooth	Wi-Fi	ZigBee
Frequency band	2.4 GHz	2.4 GHz	2.4 GHz
Physical/MAC layers	IEEE 802.15.1	IEEE 802.11b	IEEE 802.15.4
Range	9 m	75 to 90 m	Indoors: up to 30 m Outdoors (line of sight): up to 100 m
Current consumption	60 mA (Tx mode)	400 mA (Tx mode) 20 mA (Standby mode)	25-35 mA (Tx mode) 3 μ A (Standby mode)
Raw data rate	1 Mbps	11 Mbps	250 Kbps

7. Describe the hardware requirements for implementing Zigbee-based WSN

Implementing a Zigbee-based Wireless Sensor Network (WSN) requires hardware that supports low-power, short-range, and mesh-networking capabilities, typically operating on the IEEE 802.15.4 standard at 2.4 GHz. The hardware architecture is generally categorized into three main components: Zigbee End Devices (sensors), Zigbee Routers, and a Zigbee Coordinator.

1. Core Node Components (Sensor Nodes)

Each node in a Zigbee WSN typically consists of four functional units:

Microcontroller Unit (MCU): The "brain" of the node that processes sensor data and manages communication. Common examples include PIC16F88, PIC18F45K22, Arduino-compatible ATmega328P, or low-power ARM Cortex-M3 (e.g., STM32).

Zigbee Transceiver Module: Handles wireless communication (PHY and MAC layers).

Popular Choice: XBee series 2 or S2C modules.

System-on-Chip (SoC): CC2530 (Texas Instruments) or ESP32-H2/ESP32-C6, which integrate the radio and MCU on a single chip.

Sensors: Components to measure physical parameters. Examples include:

Environmental: Temperature/Humidity (e.g., LM35), Light, or Pressure sensors.

Security/Industrial: PIR motion sensors, proximity sensors, vibration, or ultrasonic sensors.

Power Unit: Battery power (e.g., LiPo rechargeable batteries 7.4V/1000mAh) or mains power.

For energy efficiency, nodes often incorporate regulators to reduce power to 3.3V or 5V

Network Infrastructure Components

Zigbee Coordinator (ZC): The central hub of the network responsible for network initiation, security, and managing data packets.

Requires a more robust power source (typically mains-powered).

Often connects to a computer via a serial interface (USB or UART) to serve as a gateway.

Zigbee Routers (ZR): Intermediate nodes that extend the range of the mesh network

8(a) Illustrate the importance of energy harvesting in extending network lifetime

Energy harvesting extends network lifetime by converting ambient environmental energy (solar, thermal, vibration, RF) into electricity, enabling perpetual, maintenance-free operation of low-power IoT and sensor devices. By reducing reliance on disposable batteries, this technology eliminates frequent manual battery replacements, thus overcoming the primary bottleneck in network sustainability and lifetime.

Contributions to Network Lifetime Extension:

Perpetual Operation: Energy harvesters enable nodes to operate for years without battery changes, allowing for Zero-energy Sensors.

Reduced Maintenance Costs: In remote or dense deployments (e.g., smart agriculture, industrial monitoring), harvesting reduces the need for human intervention to replace batteries.

Self-Sustaining IoT Nodes: By combining harvesters (e.g., piezoelectric, thermoelectric) with rechargeable storage (supercapacitors/batteries), devices can function on harvested energy alone, creating long-lived, Zero Maintenance Systems.

Overcoming Battery Limitations: Traditional batteries degrade over time; harvesting provides continuous power, supporting persistent monitoring and communication in Wireless Sensor Networks (WSNs).

Common Energy Harvesting Methods & Sources:

Solar PV Cells: Generate

from sunlight or artificial light.

Vibration Harvesting: Uses piezoelectrics to turn motion into power.

Thermal Harvesting: Utilizes Thermoelectric Generators (TEGs) to capture temperature differences.

RF Energy Harvesting: Extracts power from ambient radio waves

Wireless Sensor Networks (WSNs) have emerged as a transformative technology with diverse applications ranging from environmental monitoring to industrial automation . The sustained operation of WSNs, however, hinges on the efficacy of their power sources. In response to the growing need for prolonged autonomy and environmentally conscious practices, energy harvesting technologies have risen to prominence.

8(b) Explain different power sources used in WSN with advantages and limitations.

Powering Wireless Sensor Networks (WSNs) is a critical challenge, as nodes are often deployed in inaccessible, hazardous, or remote locations. Power sources in WSNs are primarily categorized into energy storage (batteries) and energy harvesting

Primary Batteries (Disposable)

Primary batteries are the most common, cost-effective, and straightforward power source for WSN nodes, especially where low-cost deployment is necessary.

The wind is the natural movement of air in the Earth's atmosphere. It is caused by the uneven heating of the Earth's surface by the sun. As warm air rises above, cooler air rushes in to fill the void, resulting in air movement, which we perceive as wind.

Wind can occur at different speeds and directions, and it can have a significant amount of impact on the environment and weather patterns. To harness wind as a renewable energy source, wind turbines can also be used.

Wind Turbines

Wind Turbines

How do Wind Turbines Work?

Wind turbines generate electricity by converting the kinetic energy of the wind into mechanical energy. A wind turbine's basic components are the tower, rotor blades, and a nacelle that houses the gearbox and generator.

Solar energy harvesting

Green leaf solar energy harvesting involves using organic leaves or biomimetic leaf structures to generate electricity, often by converting sunlight, moisture, and wind into power. Technologies include treating fallen leaves with carbon and iron hydrogel to create sustainable energy harvesters

Solar energy harvesting converts solar radiation into usable electrical energy, primarily through the photovoltaic (PV) effect, where photons knock electrons loose from semiconductor materials, creating a DC current. It involves absorbing sunlight via materials to generate electricity directly or by heating, with systems often requiring converters to stabilize and store the power.

(WSN) Photovoltaic (PV) Effect: This is the direct conversion of light into electricity. Photons strike a semiconductor material (e.g., silicon), releasing electrons and creating a flow of electricity. This DC power is often converted to AC for use.

Solar Thermal (Heating): Solar energy is absorbed by collectors (such as glazed glass or reflective surfaces) to produce heat, which can then be used directly or converted to electricity.

RF energy harvesting

Simple Rectenna Circuit

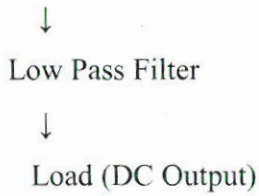
Electromagnetic Waves

↓

Antenna

↓

Diode



Construction And Geometry of Microstrip Patch Antenna

A microstrip patch antenna consists of a thin metallic patch of any shape on a dielectric slab whose other side is grounded. The thickness of the dielectric slab is from 0.03λ - 0.05λ .

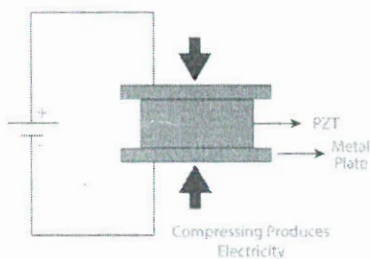
The dimensions of the patch are in the range $\lambda/3$ to $\lambda/2$ with the dielectric of the slab varying from 2.2 to 12. The choice of substrate is limited by the RF or Microwave circuit coupled with the antenna that has to be built on the same board.

Microwave circuit and antenna are usually etched together using photo-etching technology.

vibration energy harvesting piezoelectric

Working of Piezoelectric Transducer

Piezoelectric Transducer works with the guideline of piezoelectricity. The essences of piezoelectric material, normal quartz, is covered with a thin layer of conducting material like silver. At the point when stress has applied the particles in the material move towards one of the leading surface while getting away from the other. This outcomes in the age of charge. This charge is utilized for adjustment of stress. The extremity of the delivered charge relies on the heading of the applied pressure. Stress can be applied in two structures as Compressive pressure and Ductile pressure as shown in figure.



Thermal energy harvesting

Another ambient energy source is thermal energy, which can be found in any environment. Significant sources of thermal energy are wasted heat from industries and vehicles, geothermal energy from the earth's crust, ocean thermal energy (difference between deep and shallow sea water), houses, the human body, etc.

9(a) Explain battery technologies used in WSN

Battery technologies in Wireless Sensor Networks (WSNs) are critical for node longevity, generally utilizing small, high-density electrochemical cells like Lithium-ion (Li-ion), Lithium-metal, or Alkaline AA batteries.

Commonly Used Battery Technologies in WSNs

Lithium-ion (Li-ion): Common for rechargeable, high-capacity, and long-life needs.

Lithium Iron-disulfide (

): Often used for high-reliability, long-lasting, and wide temperature tolerance.

Alkaline batteries: Commonly used AA/AAA sizes for low-cost, disposable applications.

Ni-MH (Nickel-Metal Hydride): Rechargeable option for specific, often moderate-power, sensor needs.

9(b) Explain RF energy harvesting and its working principle

RF energy harvesting

Simple Rectenna Circuit

Electromagnetic

Waves

↓

Antenna

↓

Diode

↓

Low

Pass

Filter

↓

Load (DC Output)

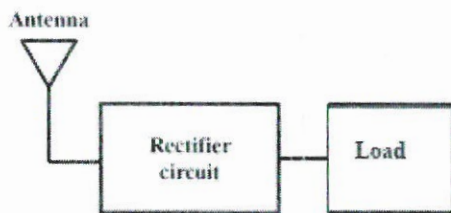


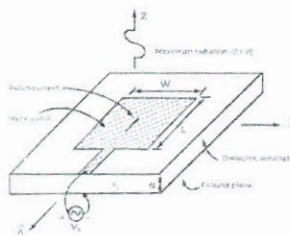
Fig. 1. Structure of a rectenna

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Patch Antenna

Working of Microstrip Patch Antenna

The working of microstrip patch antenna can be explained as:

The microstrip patch contains a conducting patch on a dielectric slab whose other side is grounded. When current through a feed line reaches the strip present on the antenna, it leads to the generation of electromagnetic waves.

The waves from patch generate a radiation pattern as waves begin to radiate from the sides of the patch. The waves produced depends upon the thickness of the substrate, due to the small thickness of substrate, the waves get reflected from the edges.

It is important to note that the continuous structure of strip doesn't let the emission of the radiation. After certain discontinuity, transmission of radiation again begins from the second side of patch.

Patch antenna only radiates certain portion of energy which makes it inefficient. It acts more of a like cavity than a transmitter. The inefficient radiation doesn't allow it to be used widely.

Types of Microstrip Patch Antenna

There are various types of microstrip patch antenna:

- Square
- Rectangular
- Dipole
- Circular
- Ellipse
- Triangular
- Disc Sector
- Circular Ring

Square: The microstrip patch antenna which has a square-shaped radiating patch is called square type microstrip antenna. This type of antenna is widely used in many devices and can find large applications primarily due to its ease of design.

Rectangular: The microstrip patch antenna which has a rectangular-shaped radiating patch is called rectangular type microstrip antenna. This type of antenna is majorly used in communication systems because it offers flexibility in tuning.

Dipole: The microstrip patch antenna which has a radiating patch similar to the structure of dipole therefore it is called dipole type microstrip antenna. It is primarily known to offer broadband performance and is used in applications that demand broader frequency coverage.

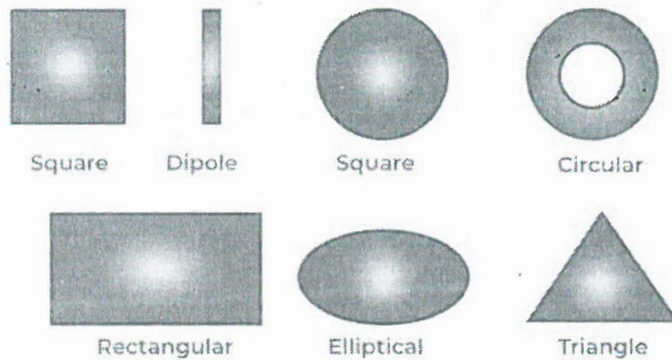
Circular: The microstrip patch antenna which has a circular-shaped radiating patch is called circular type microstrip antenna. This type is suitable to perform circular polarization. It is also used in satellite and mobile communication.

Ellipse: The microstrip patch antenna which has an elliptical-shaped radiating patch is called elliptical type microstrip antenna. It offers a different radiation pattern than other types thereby can be used specifically when such radiation pattern is required.

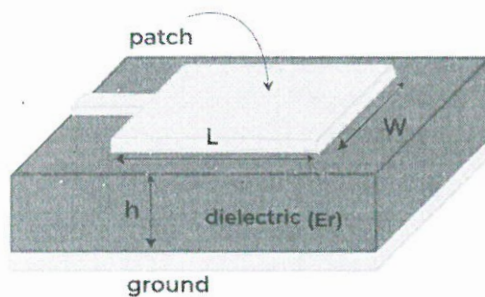
Triangular: The microstrip patch antenna which has a triangular-shaped radiating patch is called triangular type microstrip antenna. It is a very uncommon type and can be advantageous due to its shape.

Disc Sector: The microstrip patch antenna which has a disc-sector-shaped radiating patch is called disc sector type microstrip antenna. Its major advantage is that it provides directional radiation and is used where specific angles are required.

Circular Ring: The microstrip patch antenna which has a circular ring-shaped radiating patch is called circular ring type microstrip antenna. It has the property of variation in radiation characteristics.



Types of Microstrip Antenna



Dimensions of Patch Antenna

10(a) Illustrate precision agriculture using WSN

Precision Agriculture

Another interesting area where wireless sensor networks motivated a large number of researchers is precision agriculture. Traditionally, a large farm is taken as a homogeneous field in terms of resource distribution and its response to climate change, weeds, and pests. Accordingly, farmers administer fertilizers, pesticides, herbicides, and water resources. In reality, a large field exhibits wide spatial diversity in soil types, nutrient content, and other important factors. Therefore, treating it as a uniform field can cause inefficient use of resources and loss of productivity. Precision agriculture is a method of farm management that enables farmers to produce more efficiently through a frugal use of resources. This encompasses different aspects, such as micro-monitoring soil, crop, and climate change in a field, and providing a decision support system (DSS). Precision agriculture uses Geographic Information System management tools; GPS, radar, aerial images, etc., to accurately diagnose a field and apply vital farming resources.

A large number of technologies have been developed over the last several years to facilitate and automate precision agriculture. Some of these are:

- **Yield monitors:** These are devices that use, among other things, mass flow sensors, moisture sensors, and a GPS receiver to monitor instantaneous yield based on time and distance. The sensors enable measurement of the mass or the volume of grain flow (grain flow sensors), separator speed, ground speed, grain moisture, and header height.
- **Yield mapping:** Couples GPS receivers with yield monitors to provide spatial coordinates for the yield monitor data.
- **Variable rate fertilizer:** Manages the application of liquid and gaseous fertilizer materials.
- **Weed mapping:** Enables a farmer to map weeds while combining, seeding, spraying, or field scouting.
- **Variable spraying:** By knowing weed locations from weed mapping, spot control can be implemented. This enables booms to be turned on and off electronically and alter the amount (and blend) of herbicide applied. Applications
- **Topography and boundaries:** Enable the production of very accurate topographic maps that can be used to interpret yield maps and weed maps as well as planning for grassed waterways and field divisions. Field boundaries, roads, yards, tree stands, and wetlands can all be accurately mapped to aid farm planning.

- Salinity mapping: This is used to map fields that are affected by salinity. Salinity mapping is valuable in interpreting yield maps and weed maps as well as tracking the change in salinity over time.
- Guidance systems: These are devices that can accurately position a moving vehicle within a 12 in. radius (or less). They are useful for spraying and seeding as well as field scouting. The main challenge in applying precision agriculture technologies is the need to collect amount of data over several days that is large enough to characterize the entire field. In this regard, wireless sensor networks can be excellent tools as large-scale sensing technologies

10(b) Illustrate WSN applications in traffic control and health care.

Traffic Control

Ground transportation is a vital and complex socioeconomic infrastructure. Operationally, it is linked with and provides support for a variety of systems, such as supply-chain, emergency response, and public health. In urban areas, this results in potential congestion. The 2009 Urban Mobility Report, issued by the Texas Transportation Institute, reveals that in 2007, congestion caused urban Americans to travel 4.2 billion hours more and to purchase an extra 2.8 billion gallons of fuel. The total congestion cost is estimated to be \$87.2 billion – an increase of more than 50% over the previous decade.

Unfortunately, building new roads is not a feasible solution for many cities of the world owing to the lack of free space and the high cost of demolition of old roads (streets). Many consider better regulation of transportation systems as the only sustainable solution to road congestion.

One approach to dealing with congestions is to put in place distributed sensing systems that reduce congestion. These systems gather information about the density, sizes, and speed of vehicles on roads; infer congestions; and suggest to drivers some alternative routes and emergency exits.

The Sensing Task

A large number of devices are used in traffic control systems. These include video, sonar, radar, inductive loops, magnetometers, microloop probes, pneumatic road tubes, piezoelectric cables, PVDF wire, and pneumatic treadle. Video and sonar-based sensing systems need to be installed on poles, while inductive loops, magnetometers, and pneumatic treadles can be embedded into the transportation infrastructure. Camera-based systems involve human operators to process images, identify incidents, and assign speed rankings. Apparently, this technique is costly and can only be employed in selected streets, such as those that are

frequently traveled. Another way is to fully automate congestion recognition. There are several approaches to do this. For example, automated camera-based systems use machine vision to count and classify vehicles. Alternatively, they target the license numbers of passing vehicles and associate driving history as a means of estimating congestion causes. These approaches are well suited as long as the data from the cameras is reliable. In the presence of fog, smog, dust, snow, or rain, however, roadside cameras are unreliable.

One of the most common in-road traffic sensors is the inductive loop (Knaian 2000). This is a coil of wire several meters in diameter and can be buried under the road and connected to a roadside control box that passes an electric current through the coil. By establishing relationship between the current, the magnetic field strength that is induced as a result of the current, and the speed and size of the passing vehicles, it is possible to infer traffic flow. The exact relationship between the current and a vehicle can be defined by using Faraday's induction law.

According to Faraday's law, when an electric current passes through a conductor, it produces a magnetic field around the conductor. The direction of the field is normal to the direction of the current flow. The strength and density of the magnetic field depends on the length and cross-sectional area of the conductor as well as the material from which the conductor is made, that is, the permeability of the conductor, μ .

11(a) Explain pipeline monitoring using WSN

Pipeline Monitoring

Another area of application for wireless sensor networks is the monitoring of gas, water, and oil pipelines. The management of pipelines presents a formidable challenge. Their long length, high value, high risk, and often difficult access conditions require continuous and unobtrusive monitoring. Leakages can occur due to excessive deformations caused by earthquakes, landslides, or collisions with an external force; corrosion, wear, material flaws or even intentional damage to the structure.

To detect leakages, it is vital to understand the characteristics of the substance the pipelines transport. For example, fluid pipelines generate a hot-spot at the location of the leak, whereas gas pipelines generate a cold-spot due to the gas pressure relaxation. Likewise, fluid travels at a higher propagation velocity in metal pipelines than in polyvinyl

chloride (PVC). There are a large number of commercially available sensors (fiber optics, temperature sensors, and acoustic sensors) to detect and localize thermal anomalies.

Prototype

The PipeNet prototype was developed as a collaboration project between Imperial College, London, Intel Research, and MIT to monitor water pipelines in urban areas. Its main task is to monitor (1) hydraulic and water quality by measuring pressure and pH, and (2) the water level in combined sewer systems (sewer collectors and combined sewer outflows). Sewerage systems convey domestic sewage, rainwater runoff, and industrial wastewater to sewerage treatment plants. Historically, these systems are designed to discharge their content to nearby streams and rivers in the event of overflow, such as during periods of heavy rainfall. Subsequently, the combined sewer overflows are among the major sources of water quality impairment. Nearly 770 large cities in the US, mainly older communities, have combined sewer systems (Stoianov et al. 2007).

PipeNet is deployed in three different settings. In the first setting, pressure and pH sensors are installed on a 12 in. cast-iron pipe which supplies drinking water. Pressure data is collected every 5 min for a period of 5 s at a rate of 100 Hz. The wireless sensor node can locally compute minimum, maximum, average, and standard deviation values and communicate the results to a remote gateway. Likewise, pH data is collected every 5 min for a period of 10 s at a rate of 100 Hz. The sensor nodes use a Bluetooth transceiver for wireless communication. The pressure sensor is a modified version of the OEM piezoresistive silicon sensor. It has an error compensation mechanism to deal with the effects of nonlinearity and hysteresis. The sensor has a startup time of less than 20 ms and a fast dynamic response. It consumes less than 10 mW. The pH sensor is a glass electrode with an Ag/AgCl reference cell.

11(b) Describe the role of WSN in underground mining safety systems.

Underground Mining

Finally, another application domain for which wireless sensor networks have been proposed is underground mining. Underground mining is one of the most dangerous working environments in the world. Perhaps the incident of 3 August 2007 at the Crandall Canyon mine, Utah, USA, is a good example of the danger associated with underground mining. It also highlights some of the contributions of wireless sensor networks to facilitate safe working conditions and rescue operations. In this fateful incident, six miners were trapped inside the coal mine. Though their precise location was not known, experts estimated that the men were trapped 457 m below ground, 5.5 km away from the mine entrance. There were different opinions about the exact cause of the accident. The owners of the mine claimed that a natural earthquake was the cause. Seismologists at the University of Utah observed that seismic waves of 3.9 magnitude were recorded on the same day in the area of the mine, leading scientists to suspect that mine operations were the cause of the seismic spikes.

Sources of Accidents

Seismic shifts are not the only danger in underground mining. Explosions sparked by methane gas and coal-dust can cause significant damage. The following are some of the sources responsible for methane production:

1. A large portion of methane is created during a coalification process. [This is a process by which plant biomass is converted by biological and geological forces into coal. The methane is then stored in coal seams and the surrounding strata, most likely to be released during coal mining.]
2. Inadequate ventilation.
3. Methane from a fallen coal.
4. Methane from the mining faces.
5. Methane from the walls and ceilings of coal and rock roadways.
6. Methane from the gob of a coal mine.

Besides being the cause of mining explosions, methane emission from underground mining is a serious ecological threat. For example, the EPA2 expects methane emissions from US coal mines to reach 28.0 MMTCE (4.9 Tg) by 2010, excluding possible Climate Change Action Plan (CCAP) reductions. This is because underground coal production – mined at increasingly greater depths – is projected to grow faster than surface production. At present, methane emission from underground (coal) mines accounts for around 10% of the total US

anthropogenic methane emissions. Coal dust is produced at every step of the mining process and accumulates through the movement of air and the transportation of coal: on the floors, walls, and ceilings of the mine, all the way from the mine entrance to the deepest shafts. Methane gas explosions create carbon monoxide when the density of the gas is high, but if there is not much gas, it is dispersed in the air. When a coal-dust explosion occurs, the coal dust does not burn completely, since the dust is a solid substance.

The Sensing Task

Several sensing tasks can be defined for wireless sensor networks. First, they can be deployed to locate individuals under normal or abnormal (such as during an entrapment) situations. Second, they can be used to locate collapse holes. Third, they can be used to measure and forecast seismic shifts due to internal (mining operations) as well as external (earthquake) causes. Fourth, they can measure the concentration of gases, including methane, oxygen, and carbon dioxide.

