1
Introduction

"The Internet of Things (IoT) is not a concept; it is a network, the true technology-enabled Network of all networks." – Edewede Oriwoh

Technology is everywhere, from when we wake up to when we go to sleep. The development of our technological world and the highly digital life (Internet and cell phones are some examples) that we lead has become the new normal. The Internet has become a new essential, which has led to its upward growth. According to the [Vision, 2015], by the end of 2015, there were 3 billion internet users, which has increased to around 4 billion by the end of 2019- and more are joining every second (as shown in Figure 1.1), leading to data rate requirement to grow exponentially. The availability of the Internet allows these users to transfer data wirelessly to be networked. Human-centric communication is shifting to machine-centric communication, where data communication between heterogeneous devices takes place without human engagement. This technology is known as "*Internet of Things*."

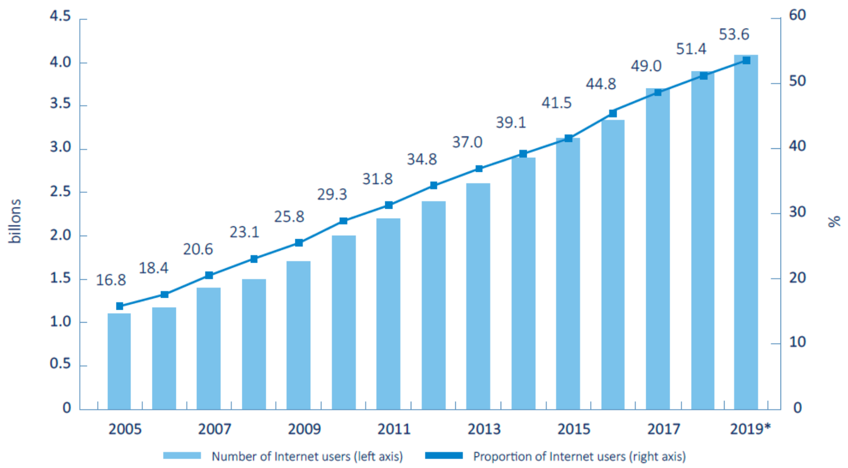

Figure 1.1. : Number of internet users 2005-2019 [Union, 2019]

The Internet of Things (IoT) is a nascent technology that tends to revolutionize the entire world by connecting low-power devices through the Internet. The notion of IoT has seen wide use by many researchers with the end goal of ensuring that wearables, sensors, tablets, smart phones, intelligent applications, etc., and other entities are interconnected via a common medium. IoT's conducive environment is expected to influence various aspects of daily life and contribute to the world's financial growth. According to a report by [Oyj, 2016], the machine-to-machine (M2M) communication is estimated to have 30 billion connected devices by the end of 2025. A significant number of connections (around seven billion by 2025) are expected to be connected by cellular technologies such as 2G, 3G, and 4G, and LPWA network, while most of the connections will still be connected by fixed and short-range communication, as shown in Figure 1.2. With the ever-increasing connected devices leading to ubiquitous computing, there are currently many diverse IoT applications. Each of these applications has varied features and requirements. Thus,

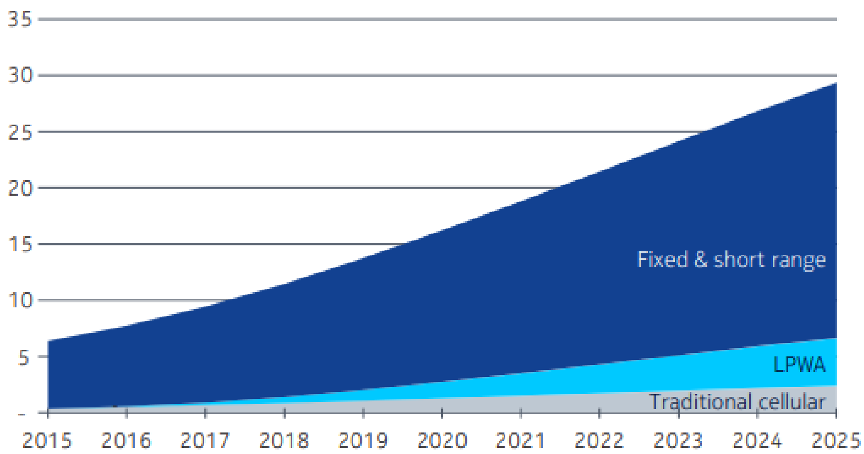

Figure 1.2. : Number of IoT connected devices worldwide from 2012 to 2025 [Oyj, 2016].

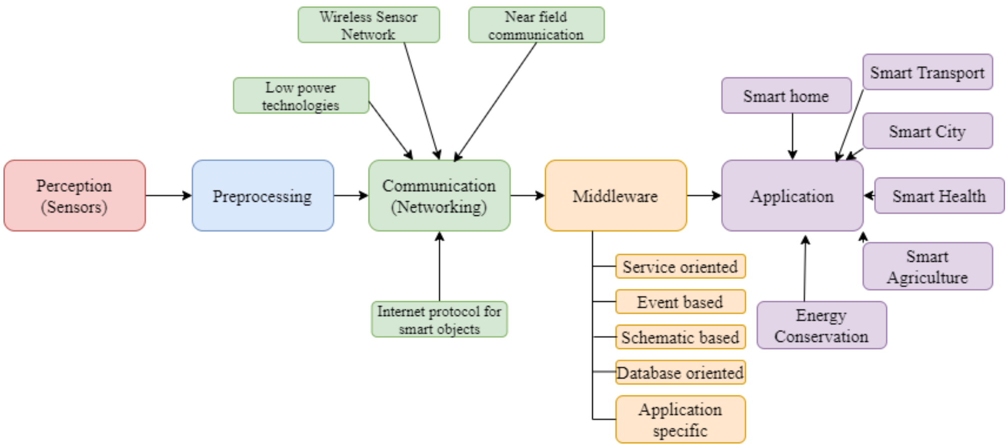

Figure 1.3. : Taxonomy of IoT technologies. Adapted from [Sethi and Sarangi, 2017].

it is not wrong to say that IoT is not a single technology; instead, a combination of several various technologies like sensing (perception), preprocessing, communication, and middleware, as shown in Figure 1.3. All these technologies work together in tandem to make IoT applications successful. IoT's vision to transform and enrich how information is perceived and interaction is made with the real world often uses micro-distributed devices for which wireless sensor network continues to play an important role. Thus, a wireless sensor network has been one of the key enabling technologies for IoT since its paradigm inception [Lazarescu, 2017].

1.1 WIRELESS SENSOR NETWORK : TECHNOLOGY ENABLER OF IOT

A Wireless Sensor Network (WSN) is a network of sensors that cooperatively monitors and records the physical environment, such as temperature, sound, humidity, pressure, etc., processes the captured data, and wirelessly communicates the data towards the sink (destination). Microcontroller and communication technology advancement has helped embed the sensing, processing, and communication units into a small device known as *sensor node*, which forms the core of the sensor network. When randomly deployed in or near the monitoring area (sensor field),

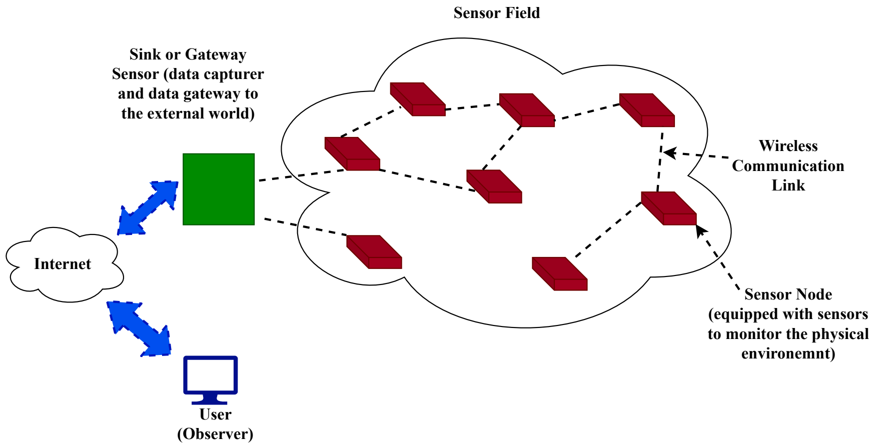

Figure 1.4. : A typical wireless sensor network

these sensor nodes form a network through self-organization and deliver the data to the destination or gateway node, as shown in Figure 1.4. The gateway node is a special node that can communicate with the sensor node and the communication network. From the gateway node, the data is communicated to the external world through the Internet to the user. The modern-day networks are bi-directional, i.e., they can collect the data from distributed sensors and simultaneously enable control of sensing technology. The development of wireless sensor networks was influenced by military applications such as battlefield surveillance, but with the emergence of smart devices, such networks have gained recognition in many industrial and consumer applications. To understand how the wireless sensor network works, we will first understand the sensor node architecture, as discussed below.

1.1.1 Sensor Node : Architecture

The sensor node, also known as a mote, is an electronic device that links the physical medium and the data communication network [Vieira *et al.*, 2003]. It can gather sensing information, do some processing, and then communicate the data with other sensor nodes in the network. Figure 1.5 shows the architecture of a typical wireless sensor node. The sensor node mainly consists of four units:

1. *Sensing unit*: The sensing unit forms the sensor node's perception layer (physical layer), consisting of two main subunits: sensors and an analog-to-digital converter (ADC). Sensors are hardware devices used for sensing and gathering information from the surrounding. It produces a measurable response to any physical change. Different sensors measure different values, like temperature sensors for temperature, IR sensors for remote control detection, etc. Thus, sensors are basic components of smart objects, which are of small size, low cost, and with less power consumption. Sensors receive an analog signal from the physical world, converted to digital signals by using the analog-to-digital converter, and sent further to the processing unit. Passive and omnidirectional sensors are widely used in theoretical studies on wireless sensor networks.

2. *Processing unit*: The processing unit is a part of the network layer. The data received by the sensors is enormous, which requires computation and storage resources to analyze, store, and process the data. The processing unit extracts the relevant information from digitized data and implements the network protocol. Subsequently, it also calculates the energy consumption and the comparison capability of the sensor node [Vieira *et al.*, 2003].

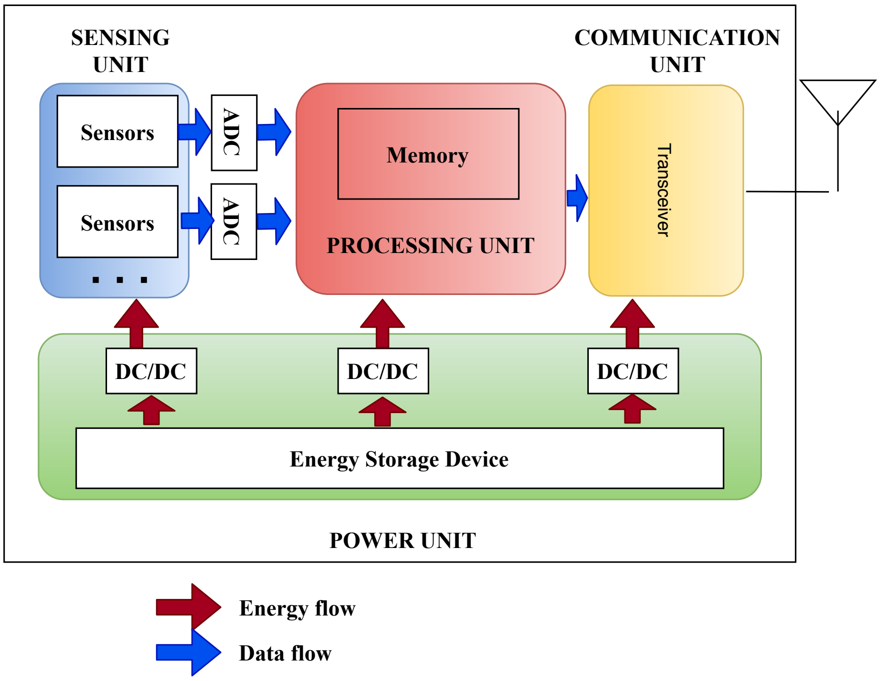

Figure 1.5. : Wireless sensor node Architecture. Adapted from [Sendra Compte *et al.*, 2011]

Many different types of CPUs can be integrated into sensor nodes like microcontrollers, microprocessors, digital signal processors, FPGAs, and ASICs.

3. *Communication unit*: The next architectural component, which is also a part of the network layer, is the communication unit. It consists of a transceiver that acts as both the transmitter and receiver. The radio system provides communication between the two sensor nodes and to the outside world. The communication unit uses radio frequency (RF) based wireless communication using license-free communication frequencies- 173, 433, 868, and 915 MHz; and 2.4 GHz. They also use a diverse set of protocols and standards for different scenarios like RFID (Radio Frequency Identification), NFC (Near Field Communication), Bluetooth, Zigbee, and WiFi. The transceiver operates in four modes: transmit, receive, idle, and sleep [Rao and Saxena, 2018].

4. *Power unit*: To operate and perform the desired operations, all three sensor node units require power, which is supplied through the power unit. The power unit consists of an energy storage device (ESD) and a DC-DC converter. Mostly, the sensor nodes use Li-ion batteries as an energy storage device.

1.1.2 Wireless Sensor Network Design Parameters

The communication between the sensor nodes in the sensor network is provided by considering some factors dependent on the type of application. Table 1.1 and Figure 1.6 describe the wireless sensor network design parameters along with their description and values, respectively, for an IoT application.

1.1.3 Limitations of Wireless Sensor Network

Sensor networks have been a promising technology for the growing IoT based solutions, but there are still some barriers to overcome.

Table 1.1. : Wireless Sensor Network Design Parameters [Sendra Compte *et al.*, 2011]

Parameters	Description
Node deployment	The node deployment deals with the placement of the sensor nodes based on the application, which can be deterministic (nodes are placed manually) or random distribution (not uniformly distributed). However, the nodes placed may have to find an optimal clustering that allows the best connectivity and is energy-efficient.
Connectivity	It usually refers to the probability that any node in a network can be reached by any other node in the same or different network through routing. The network is said to be connected if there is at least one path between each pair of nodes in the network.
Coverage	How well are the sensor nodes deployed in the target area so that they are connected to other sensor nodes to collect the target area's information. The coverage range is set based on the wireless technology, the accuracy of transmission, and the data rate
Scalability	In IoT applications, the number of connected devices is increasing rapidly, and thus the network should be able to handle multiple sensor nodes.
Network Dynamics	The sensor nodes in a network architecture may be stable or moving, depending on the application. The routing of messages between the mobile devices is complicated as it is dependent on the path stability, bandwidth, energy, etc.
Localization	As the network dynamics change for mobile sensor nodes, it is essential to determine the sensor nodes' location dynamically or statistically to route the messages between the sensor nodes.
QoS	QoS can be characterized by reliability, timeliness, robustness, availability, and security.
Reliability	Sensor information should be sent to the sink with a given probability of success, because missing of these data could lead to incorrect or delayed execution of controlled actions or decisions concerning the phenomena sensed. However, maximizing the reliability may substantially increase the energy consumption [Willig, 2008]. Thus, there is a need to maintain a trade-off between between reliability and energy consumption.

1. *Hardware and Software*: With technology development, the sensor node's size reduces, leading to limited resources like memory, processing speed, and energy as an issue for WSN. The storage capacity of the memory is a few hundred kilobytes, and the processing power is around 8MHz.

2. *Limited Energy Issue*: The sensor nodes are powered by a finite-capacity battery to power the sensing, processing, and communication units. Apart from this, the sensor nodes must also be active for listing sink nodes or base station queries. Thus, the limited energy is to be used so that all the needs can be fulfilled. Energy management is a critical issue in wireless sensor network.

3. *Communication and Routing Issue*: Mostly, the sensor network nodes only support short-range communication, which consumes a lot of power. Also, the routing and deployment strategy affects the transmission and the performance of the sensor network. Thus, communication

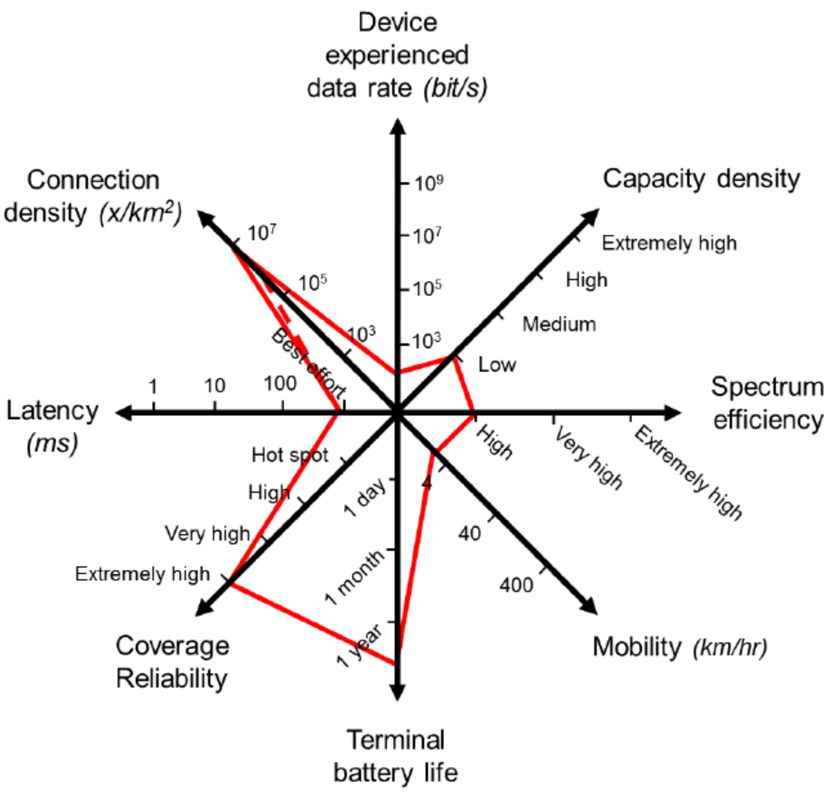

Figure 1.6. : Different capabilities envisaged for wireless sensor network applications [Union, 2015]

is also an issue for wireless sensor network.

4. *Security Issue*: Security is one of the vital issues in a wireless sensor network. As information travels wirelessly through the air, it becomes accessible to everyone. Also, the band used by the wireless sensor network is the license-free ISM band. Thus, security is essential to prevent malicious attacks.

5. *Coverage*: Coverage is necessary for many use cases and deep indoor connectivity is essential for many applications in the utility area.

6. *Scalability and Diversity*: The network capacity should be able to handle gallons of devices. The devices may have diverse applications which require strong connectivity.

From the design parameters, requirements, and challenges, it can be analyzed that all the design parameters can be met only if the sensor node is operational. Also, for any sensor network with an increasing number of smart sensor nodes, connectivity (i.e., how well the sensor nodes are connected) and coverage (i.e., how well the sensor nodes are deployed in an area) are the most important parameters, and to achieve it; the sensor nodes require a long lifetime. In other words, of all the wireless sensor network design objectives, the most pursued is to enhance the network lifetime and prevent information deterioration. Further, in the thesis, we will be focusing on the sensor network lifetime as the design objective and propose novel techniques to achieve the objective.

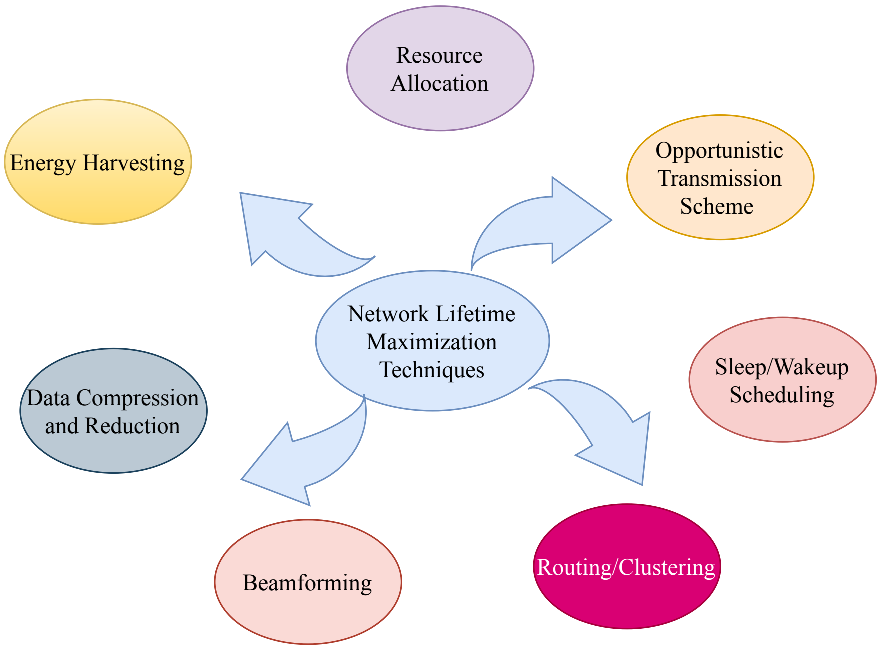

Figure 1.7. : Network lifetime maximization techniques. Adapted from [Yetgin *et al.*, 2017]

1.2 NETWORK LIFETIME - LIFETIME OF WIRELESS SENSOR NETWORK

Network lifetime can be defined as the time span from the deployment to the instant when the network becomes non-functional, i.e., unable to perform the intended job [Chen and Zhao, 2005]. This could happen when the first sensor node or a fraction of sensor nodes die, or the subnetworks have no communication and the network partitions, or when a loss of coverage occurs [Dietrich and Dressler, 2009; Chen and Zhao, 2005]. Moreover, network lifetime is a crucial metric for maintaining network performance and the QoS in WSNs. Based on the defined conditions defining network lifetime, it can be concluded that sensor network lifetime strongly depends on the sensor nodes' lifetime that constitutes the network. On the other hand, the reasons for sensor node failure could be [Mahapatro and Khilar, 2013] (i) hardware problems like the communication subsystem being faulty, (ii) environmental conditions like the node is damaged due to flood or landslide, or (iii) energy depletion. Since the sensor nodes usually rely on a limited energy storage device capacity, unless they have a direct power source, replenishing the energy storage device or replacing the sensors is generally infeasible for realistic applications. Thus, energy depletion is one of the most significant causes of sensor node failure and is considered a permanent fault.

There are several techniques discussed in the literature for network lifetime maximization, as classified in Figure 1.7. Broadly these techniques can be divided into two methods: (i) the methods that conserve the amount of energy consumed over time by the sensor node, and (ii) the methods that replenish the consumed energy.

1.2.1 Energy Conservation Methods

The objective of the energy conservation methods is to reduce the amount of energy consumed by the different components of the sensor node, as shown in Figure 1.8. Of all the components, the data communication that involves transmission and reception expands the maximum amount of energy. Also, the sensor node operating in the ideal mode results in high energy consumption, almost equal to the energy consumed in the receiver mode [Raghunathan *et al.*, 2002].

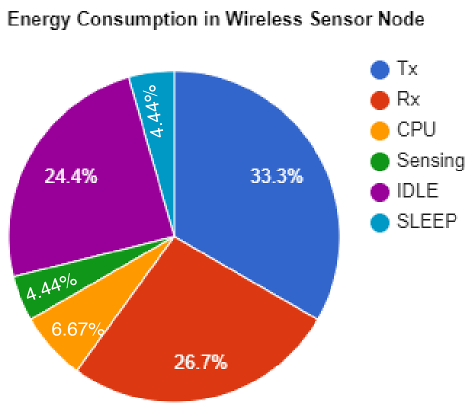

Figure 1.8. : Energy consumed by different components of Sensor Node. Adapted from [Engmann *et al.*, 2018]

For battery-powered sensor nodes constrained in energy resources, energy conservation methods are employed to prolong the sensor node lifetime [Chang *et al.*, 2016]. The initial step is to use low and ultra-low power electronics to help in energy conservation up to a few units but at the cost of lesser computation complexity and lower transmission ranges. Some other methods, such as radio optimization technique, sleep/wake-up scheme, transmission power control, etc., are used to control the energy consumption by the various components.

1.2.2 Energy Replenishing Methods

A holistic approach to improve the sensor node lifetime should not be limited to energy conservation because the energy conservation methods reduce the rate of use of energy, but the energy is to deplete at some time. Thus, there is also a need to increase the amount of energy available. Energy harvesting (EH) is a technique of scavenging energy from the external environment, such as wind, solar, vibrations, thermal, RF, etc. The energy harvesting technique converts the energy from the environment into electrical signals, which are further used by the wireless sensor node. Although energy harvesting does not guarantee immortal nodes, it overcomes the energy depletion problem and increases the sensor node's lifetime.

Working on these technologies can help improve sensor node and network lifetime. Before working on these technologies, we need to know how these technologies are crosslinked together and how they are placed in terms of architectural and function complexity, as discussed in the next section.

1.3 INTRODUCTION TO ENERGY HARVESTING - PROMISING NEW APPROACH

Energy harvesting (or energy scavenging) is a technique that is used to collect ambient energy to help power systems, and possibly store the harvested energy in batteries, capacitor or springs, when it is not required. Energy harvesting is most applicable to the applications that require small amount of continuous power, or have short periods of high power use that can be fulfilled by the previously harvested and stored energy. Energy harvesting can also supplement more

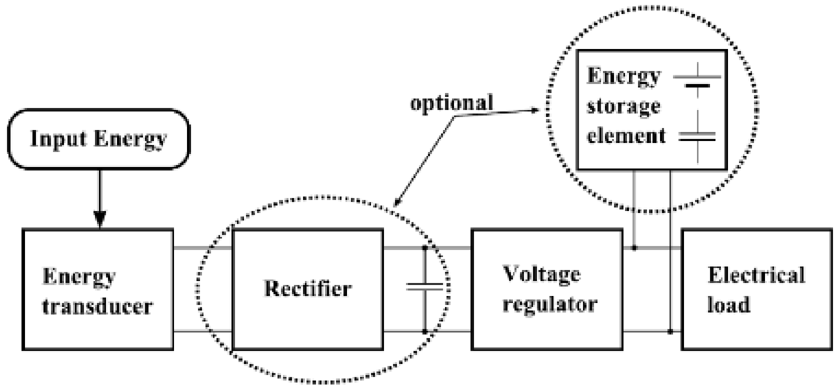

Figure 1.9. : Schema of a Energy Harvesting Unit [Spies *et al.*, 2015]

conventional energy sources - like if a mobile user extensively uses a computer for a short period of time, an energy harvesting system can make sure that the battery is always topped up during the standby period, when the computer is not in use [Want *et al.*, 2005].
A self-powered system based on energy harvesting is composed of several block, as shown in Figure 1.9:

1. Energy transducers (also known as energy generator) are used at the input of the energy harvesting system to convert the input ambient energy into electrical energy.

2. Rectifier and Storage capacitors are used to rectify the current and store it in the capacitor in case the transducer do not provide DC power.

3. Voltage Regulator is necessary to control or adjust the voltage level according to the requirement of the powered circuit or the energy storage element.

4. Further, depending on the requirement of the application, a battery or a capacitor can be employed as an energy storage element. The use of energy storage device is optional and also depends on the requirement of the application. For example, in some applications the powered device can be completely switched off during certain intervals and a storage element is not required, while in other cases permanent supply is required.

5. Then to the system is connected an electronic load, which typically has different power consumption modes allowing the device to operate in low-power consumption modes.

In the next section, we will look at the different energy storage elements present in the literature.

1.4 INTRODUCTION TO ENERGY STORAGE DEVICES

As discussed in the above sections, storage devices play an important role in the wireless sensor network. The energy storage devices store the harvested energy, which is used to drive the components of sensor node, which further construes the network lifetime. From early days, there have been a lot of energy storage devices that have been used for different applications. In energy harvesting technology, the energy is being harvested from different energy sources and is to be stored in electrical energy form. This can be done in two different ways [Buchmann *et al.*, 2001]: **electrochemical energy storage**, which involves the use of various devices which convert chemical energy into electrical energy and **electrical energy storage**, which involves the use of electric field for energy storage. The examples of electrochemical energy storage involves batteries and fuel cells and examples of electrical energy storage include capacitors. In this section we describe the different energy storage devices that have evolved during the time and why there is a need for new energy storage device.

1.4.1 Capacitor

A capacitor is a passive electronic device that stores electrical energy in the form of electrical charges. A capacitor is made from two parallel metal plates which are separated by an insulator called a dielectric [Conway, 2013]. When a capacitor is connected to a power source, it accumulates energy in the form of electrical charges on the metal plates, and when the power source is disconnected, the accumulated energy can be released. The energy within the electrical charge is stored in an "electromagnetic field" between the two plates. When an electric current flows into the capacitor, it charges up, so the electrostatic field becomes much stronger as it stores more energy between the plates. Likewise, when the current is flowing out of the capacitor (discharging it) the potential difference between the two plates decreases and the electrostatic field decreases as the energy moves out of the plates. This property of capacitor to store charge on its plates in the form of electrostatic field is known as Capacitance of the capacitor.

1.4.2 Batteries

Batteries have been the most common option to store harvested energy. A battery is a chemical device that stores electrical energy by means of chemical reaction. The electrochemical reaction in the battery involves transfer of electrons from one electrode. Batteries are classified mainly into two types: primary batteries (i.e., non-rechargeable batteries) and secondary batteries (i.e., rechargeable batteries). A rechargeable battery is a battery that can be charged again by the reverse mechanism. On the other hand, non-rechargeable batteries can be used only once and then need to be disposed.

Depending on the purpose to be fulfilled, harvested energy is to be stored multiple times and for that, rechargeable batteries are an appropriate choice. A number of technologies for rechargeable batteries have evolved in past few years. Few most commonly used batteries are Sealed lead-acid(SLA), Nickel cadmium (NiCd), Nickel Metal Hydride (NiMH) and Lithium ion (Li-ion) battery [Buchmann *et al.*, 2001]. The different batteries are characterized by different specifications and these specifications make it reliable to be used for some specific applications. Table 1.2 provides a comparison of rechargeable batteries technologies developed till date.

1.4.3 Fuel Cells

A fuel cell is an electrochemical cell that converts the chemical energy of the fuel and an oxidizing agent into electricity through a pair of redox reactions. A fuel cell just works like battery (i.e., it generates electricity by a chemical reaction), but are different as they require continuous source of fuel and oxygen to continue the reaction and use a supply of gaseous or liquid reactants for the reactions rather than solid reactants. Every fuel cell has two electrodes called, respectively, the anode and cathode. Also, the possible reactants or fuel for the reaction are natural types like natural gas, hudrogen, water gas, etc. The reactions that produce electricity take place at the electrodes [Bagotsky, 2012].

In fuel cells, a fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. A catalyst separates hydrogen atoms into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. There are different types of fuel cells available depending on the electrolyte material used in the fuel cell.

Table 1.2. : Comparison of different rechargeable batteries [Buchmann *et al.*, 2001]

Specifications	Nickel Cadmium (NiCd)	Nickel Metal Hydroxide (NiMH)	Lead Acid	Lithium ion
Nominal Cell Voltage	1.25V	1.25V	2V	3.6V
Capacity (mAh)	1100	2500	1300	740
Cycle life (upto 80% of initial capacity)	1500	300 to 500	200 to 300	500 to 1000
Fast charge time	1h	2-4h	8-16h	2-4 h
Self discharge / month	20%	30%	5%	10%
Advantages	Fast and simple charge, large number of charge/discharge cycles, economic, long shell life	Higher capacity than NiCd, simple storage and transportation, less prone to memory, environment friendly	low self discharge, capable of high discharge rates, low maintenance required, simple to manufacture	high energy density, low self discharge, low maintenance
Disadvantgaes	Relatively low energy density, high self discharge, memory effect	Limited service life, limited high current, high self-discharge, high maintenance	low energy density, limited number of full discharge cycles, environmentally unfriendly, thermal runaway can occur with improper charging	requires protection circuit, prone to ageing, modertae discharge current, expensive
Applications	two way radios, emergency medical equipments, professional vedio cameras and power tools	Satellite applications	automobiles, forklifts and large UPS systems	used in portable devices like mobiles, laptops etc.

1.4.4 Supercapacitors

A supercapacitor, like all the capacitors stores potential energy electrostatically, which further helps it to rapidly deliver the energy. But different from the standard capacitors, supercapacitors instead of using a conventional dielectric between the charged plates they operate off of electrostatic double layer capacitance (EDLC) and electrochemical pseudo-capacitance technology. The supercapacitor consists of two electrodes, a membrane separator and an electrolyte that acts as the dielectric. When a voltage is applied, ion absorption occurs on the surface of each electrode and the capacitance is stored in the Helmholtz double layer at the surface the asymmetrical electrodes.

1.4.5 Evolution of Energy Storage Device

As discussed earlier, to improve the lifetime of the sensor node we need to use a energy storage device that has large lifetime. The lifetime of a storage device is determined by the number of charge and discharge cycles of the battery, which further depends on the energy storage mechanism. The energy storage mechanism of a energy storage also defines the different properties like power density, energy density, etc which define the application of use for the energy storage devices.

Since the ancient time there are two dominant kinds of electrochemical energy storage: batteries and capacitors. In a battery, electrical energy is stored as chemical energy where the chemical reaction occurs throughout the bulk of the solid and the reacting species ingress throughout the material. This charge storage mechanism allows the battery to store the energy for a longer time. But, the repetitive chemical reaction significantly degrades the material the chemical reactions are not always readily reversed because structural changes of the materials occur. On the other hand, in capacitors the energy is stored as surface charge and so the structural integrity of a capacitor is not challenged. Also, the charge storage mechanism allows the a rapid discharge of energy in short duration. Pure capacitors can be charge and discharged millions of times without any significant degradation of the material [Whittingham, 2012].

Supercapacitors are new energy storage device which has evolved with time and hybrid between the two, involving both surface charge and some Faradaic reactions in the bulk of the material . This charge storage mechanism allows the device to store energy and quickly release it. It basically captures static electricity for future use. The most significant advantage of this is that a 3V capacitor now will still be a 3V capacitor in 15-20 years. Also, unlike a battery, they have a higher power throughput, which implies it can charge and discharge in a fraction of the time. Still, they have a very low specific energy as compared to batteries. Supercapacitors also have a much longer lifespan than batteries. A regular battery can handle around 2000-3000 charge and discharge cycles, while supercapacitors can usually sustain more than 1,000,000. Thus, all these properties make Supercapacitors best suited for very small bursts of power like, wireless sensor node applications. But supercapacitors have one disadvantage, i.e., they suffer from high self-discharge rate as compared to battery (as shown in Figure 1.10 and 1.11). From the following figures it can be seen that in 6 hrs supercapacitor energy leaks from 2.1 V to 2.3 V while for battery it takes more than days. Thus, the self-discharge rate of battery is negligible as compared to supercapacitor.

In the thesis further we have modelled the self-discharge mechanism of supercapacitor considering the practical reactions that occur during supercapacitor charging and discharging and considered the imperfections in the performance analysis of sensor network for practical application.

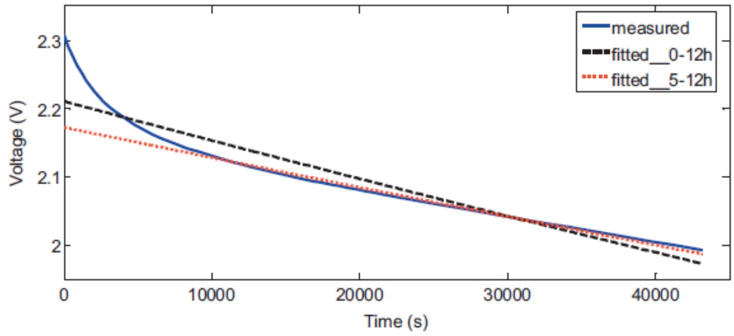

Figure 1.10. : Self-discharge measured for a Panasonic supercapacitor in [Yang and Zhang, 2011]

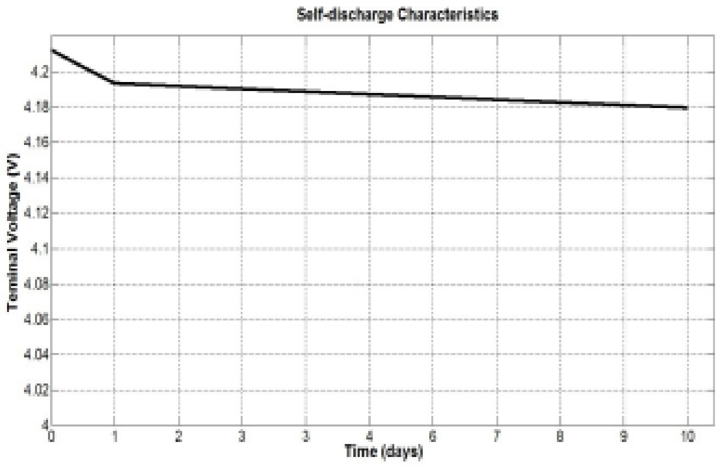

Figure 1.11. : Self-discharge characteristics of a Li-ion Battery [Pathiyil *et al.*, 2016]

1.5 COMPLEXITY OF SENSOR NETWORK TECHNOLOGY ENABLERS

Wireless sensor network leverages a wide variety of heterogeneous technologies, spanning from hardware (HW) to software (SW). The architectural and functional complexity of these technologies, along with their interdependence on each other, is shown in Figure 1.12. The graph is a plot between the hardware/software complexity of the system/subsystems and the functional complexity of functions implemented by these system/subsystems. From the figure, it can be analyzed that energy harvesters, sensors and actuators, and the energy storage unit lie on the lower part of the space, i.e., they have low hardware/software and functional complexity. For more sophisticated functions and functionalities of other technologies, the processing increases, so there is an increase in hardware/software complexity. In this regard, modern electronics, radio transceivers, and cameras are important components at high complexity for the sensor network. The graph in Figure 1.12 also shows how the mentioned technologies are linked and interfaced with each other, sketched by the bidirectional arrows. The interface over here interprets how the system/subsystem are connected to each other and also the execution of algorithms or functions (i.e., SW) within a system or subsystem.

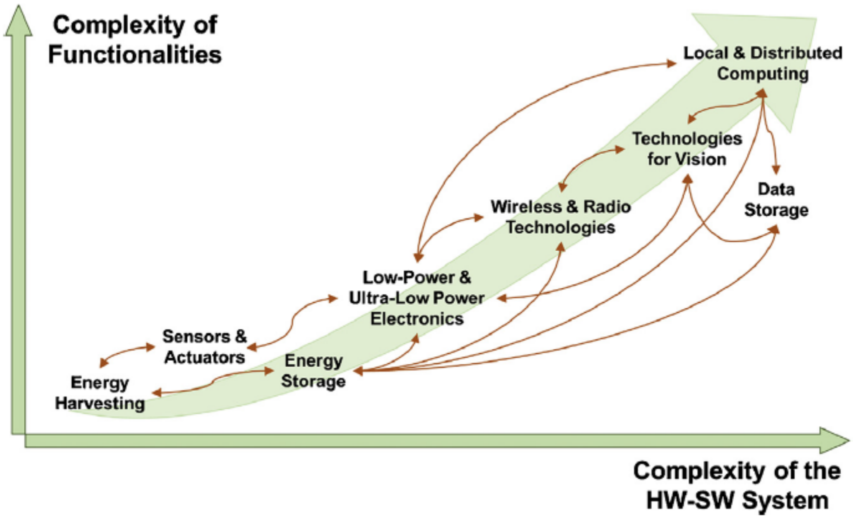

Figure 1.12. : Scattering of the wireless sensor network technologies based on their HW-SW complexity and the complexity of functionality/functionalities they realise/implement [Iannacci, 2018].

1.6 MOTIVATION

Wireless sensor network is a crucial component of omnipresent computing in various applications like home automation, military, security, and many more. Sensor Networks are usually deployed in remote and inaccessible environments where it is unfeasible to replace or recharge the sensor nodes whenever required. The lifetime of the sensor nodes is typically an issue due to limited battery capacity. Thus, there is a need to prolong the sensor nodes' lifetime.
Energy management schemes should be implemented to keep the sensor node alive for longer duration, making the network more operational and efficient. The energy harvesting technology can be a boon for low-power systems, like sensor networks, but the efficiency of the transducers limits them. Thus, designing software that judiciously manages power and extends sensor node lifetime is also necessary. Apart from this, sensor node lifetime is also dependent on the energy storage element lifetime; thus, using a storage element with a long lifetime can also help extend sensor node lifetime.

1.7 OBJECTIVE AND ORGANISATION OF THESIS

The present thesis is aimed at improving the lifetime of the sensor node making it more reliable for practical applications including deployment in inaccessible areas by using energy consrvation method and energy harvesting system. Thesis has been divided into six chapters. The organisation is done as follows:

1. Chapter 1 includes the introduction to the wireless sensor network and its core components. The architecture of the sensor node is discussed. The different design parameters of the WSN, along with its limitations and challenges are also discussed. Network lifetime along with the factors and solutions to improve it have been introduced followed by motivation.

2. Chapter 2 discusses the state-of-the-art of the energy harvesting wireless communication system. The survey of the literature has been divided based on the main development research areas including energy harvesting models, protocols and transmission schemes in point-to-point communication system. It is then followed by research gaps of state-of-the-art.

3. Chapter 3 deals with proposing a new low complexity energy-efficient transmission policy so that the energy consumption can be reduced, which is a factor for sensor node lifetime improvement. Along with low complexity, the proposed policy also provides near-optimal performance which will make it more suitable for low power sensor nodes.

4. Chapter 4 deals with identifying an energy storage device with a longer lifespan that can help further improve the sensor node lifetime. The imperfections of the storage device are identified and modelled to make the analysis much closer to the practical application.

5. Chapter 5 deals with the performance analysis of the sensor node with the storage device identified in chapter 4 and using the transmission policy proposed in chapter 3. The combination of both the methods helps improve the sensor node lifetime making it more closer to the practical application. Also, this analysis helps identify the suitability of the energy storage device for sensor node practical applications.

6. Chapter 6 concludes the thesis.

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