Ethernet Energy Harvesting

Master’s Thesis

by

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ABSTRACT

Improvements in embedded electronics which have effectively reduced power consumption requirements as well as advancements in IC technology allowing utilization of low power inputs have made Energy Harvesting a popular power solution for low power applications such as WSNs. In many implementation areas, we can see solar, thermal, and vibration energy harvesting techniques have taken the role of batteries as power source. Now that Energy Harvesting is a popular and considerably mature technology, with proper design and installation, any object exposing energy has the ability to be promoted as a power source.

We are currently living in Internet age where we connect to the world through network packets. Ethernet, by far, is the most popular LAN technology which allows us to plug and play. Therefore, on an Ethernet link, billions of packets where our data are encapsulated in are traversing every hour. We assume each of these packets exposes some level of energy on an Ethernet link. The challenge here is harvesting the energy available from Ethernet packets and transforming it into useful energy so that it can be used to power devices such as WSNs. In this thesis work, we have revealed how much energy is available from Ethernet packets, and how much of it can be made usable. We have also designed a system where a WSN is generating all of its operating power solely from Ethernet packets and consuming this energy in communication with a base station.
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1. INTRODUCTION

Advancements in integrated circuit (IC) technology have triggered a rapid evolution of electronics devices in size and power efficiency. This evolution has provided us with battery powered wireless devices that we are commonly using such as smart phones and MP3 players. With continuous improvements, developing even smaller volumes and reduced power consumption of the devices is targeted. Through all these improvements and emerging integration technologies, it is aimed to remove battery dependency and create energy autonomous systems [1]. The reason for targeting eliminating the batteries is that even though the batteries are cost-effective and well-known technology, they require user intervention since they have a finite lifetime, and require replacement which may not be an option in some implementation areas.

To overcome this problem, energy harvesting from the environment has appeared as solution. After years of research in energy harvesting field, efficiently capturing low amounts of energy from the environment and converting them into electrical energy has been made possible. In parallel, efficient power management techniques increasing the available energy by power optimization and smart shut down – wake up procedures have been developed. Along with the improvements in IC technology which have remarkably reduced power requirements, developing applications relying solely on energy harvesting for powering the system has been achieved.

Energy harvesting is quite attractive especially when long-term deployment is required under the circumstances where natural energy sources such as heat or vibrations are permanently available. Such energy supplies available anytime are advantageous over batteries because of providing the systems which have limited accessibility with extended lifetime and energy autonomy.

Energy harvesting technology is mostly focusing on energy sources naturally available from environment. However, besides natural sources, there may be other objects around us with the ability to provide free energy which, through correct power management techniques, can be captured and transformed into useful energy. An
Ethernet link can be a good example for such objects. Ethernet, standardized in IEEE 802.3 [2], is the most popular local area network (LAN) technology allowing stations to transfer their data in form of packets called frames over twisted pair or fiber optic cables. Ethernet over twisted pair is the most popular Ethernet standard deployed at end-user side [3]. Ethernet enables users to get connected with simply plugging-in to a wall socket or switch. Since Ethernet is so popular, large amount of data encapsulated in frames are intensively transferred over an Ethernet link. These frames compose of ‘0’ and ‘1’ bits which generate a signal on the link. Depending on the number of the bits traversing on the link and the amplitude of the signal produced by these bits, some level of energy must be exposed on an Ethernet link.

Ability to build devices which can be powered solely by the energy harvested from Ethernet packets traversing on an Ethernet link would be an attractive solution at points where access is limited but Ethernet cables and/or ports are present. Such a device would not require maintenance since it would be battery independent. We can see Ethernet cables installed in buildings passing through underfloor or ceilings as well as Ethernet sockets placed on walls which are potential power sources for an Ethernet powered device. A good example for a device which can take advantage of Ethernet packets as a power source could be a wireless sensor node (WSN). Think of a datacenter, environmental conditions of which must be carefully observed, as a sample implementation area. In datacenters, preserving appropriate environmental conditions such as temperature and humidity as well as preventing water leakage are crucial. The majority part of the Ethernet cables connecting routers, switches and server computers are located under the floor. Therefore, measuring the environmental conditions of the underfloor of a datacenter is vital. Considering the limited accessibility of underfloors, installing WSNs which generate their operating power from Ethernet packets traversing on these cables and measuring environmental conditions would be a perfect solution for such situations. Moreover, a smart Ethernet powered device with the ability to send message when not being charged could be used in monitoring an Ethernet link, and detecting when the network is down because of the failure of the link. When the network is down, the packet flow on the link will stop, so the charging of the device will cut which will trigger it for sending message to the concerned units.
This thesis report is dedicated to determining the feasibility of energy harvesting from Ethernet packets, revealing how much energy can be made available from an Ethernet link as well as designing a real world environment where Ethernet can be implemented as power source. The rest of this report is organized as follows. Section 2 gives an overview of Energy Harvesting technology along with brief descriptions of the most popular energy harvesting techniques. Section 3 introduces and compares some commercially available power management ICs. Section 4 describes the main units used in the development of Ethernet Energy Harvesting system. The steps followed in the examination of Ethernet as a power source are described in section 5. Section 6 and 7 explain the development of the implementation environment for Ethernet Energy Harvesting system and analysis of the system respectively. Finally, section 8 draws the conclusion and suggests possible further extensions for the project.
2. ENERGY HARVESTING

The desire for eliminating batteries in many applications which would provide the devices with energy autonomy has brought the ambient energy harvesting concept as a power solution. Energy harvesting has increasingly become popular recently, especially with expressive progress in the functionality of low power embedded electronics. Energy harvesting simply is the action of capturing, converting and storing the energy available from the environment in order to use in electronics applications.

While a variety of methods exists in powering applications such as wireless applications, batteries are the most mature and common technology among them [4]. Although batteries are a low-cost, immanent, and well known powering technology, they come along some critical drawbacks such as limited lifetime and replacement cost. As there are many applications batteries are an ideal power solution for, there are also many other applications where they fail to meet the application requirements due to their drawbacks. For example, in applications where battery replacement is considerably costly over the device lifetime or the device is located in an environment with limited accessibility, using batteries as power solution is not the wise choice. On the other hand, the applications with these requirements present an ideal stage for energy harvesting as powering technology.

For energy harvesting a variety of sources exists such as solar power, piezoelectricity, and thermoelectricity. In the section below, the most popular energy harvesting techniques used in powering applications such as WSNs are explained briefly and compared in terms of energy availability.

2.1. Popular Energy Harvesting Techniques

Number of energy harvesting techniques exists for use in powering electronics applications. The harvestable energy and the load to be supplied should be considered while choosing which technique to employ. In this section, the most popular ambient energy harvesting techniques used in sensor applications are briefly explained.
2.1.1. Vibration Energy Harvesting

In this technique, the vibrational energy obtained from mechanical systems such as engines and bridges is converted into electrical energy. Vibrations produce mechanical acceleration which causes a spring-mass system to take action and expose kinetic energy [5]. This kinetic energy can be converted into electrical energy via different techniques including electric field, magnetic field, or strain on a piezoelectric material. Below, these three methods are separately explained in brief since the conversion types of these methods differ even though the energy source is same.

2.1.1.1. Piezoelectric

In this technique, mechanical energy is converted into electrical energy by placing a piezoelectric material under a mechanical strain which causes the material to become electrically polarized [6]. The degree of polarization is proportional to the applied strain level. However, the level of the voltage drop caused by polarization depends on the characteristics of the piezoelectric material as well. Typical power density level that can be provided using piezoelectric energy harvesting technique is around 300µW/cm³ [7].

2.1.1.2. Electromagnetic

This technique converts mechanical energy into electrical using magnetic field. The magnetic field created by a stationary magnet is traversed through by a coil which is attached to the oscillating mass [8]. During this action, the coil travels through a changeable amount of magnetic flux, and the change in flux generates a low voltage which can be promoted as an acceptable energy source via a number of methods such as using a transformer, increasing the number of turns of the coil, and/or increasing the permanent magnetic field. The power can be extracted from generator simply by adding a load across the terminals of the coil which causes current flow in the coil. Power density of up to a few hundreds µW/cm³ can be provided using this technique [6, 8].
2.1.1.3. **Electrostatic (Capacitive)**

This technique is based on an initially charged variable capacitor (varactor). A varactor is made of two opposing metal plates; one is fixed, and the other one moves when external force is applied. In presence of vibrations, the plates of the initially charged varactor are separated which causes capacitance change. As result, a voltage proportional to the capacitance change is produced. That varactor must be initially charged requires the usage of a separate voltage source. Using this technique, power density that can be achieved is usually less than 50µW/cm³ [5]. However, availability of micro-electromechanical system (MEMS) varactors brings IC compatibility feature to electrostatic method which is quite attractive for energy harvesting systems [8].

The table below indicates the advantages and disadvantages of the three vibrational energy harvesting techniques.

<table>
<thead>
<tr>
<th>Harvesting Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piezoelectric</strong></td>
<td>• Does not require external voltage source</td>
<td>• Output impedance is high</td>
</tr>
<tr>
<td></td>
<td>• Can be integrated in microsystems</td>
<td>• Produces low output current</td>
</tr>
<tr>
<td></td>
<td>• Produces high output voltage</td>
<td></td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td>• Does not require external voltage source</td>
<td>• Difficult to integrate in microsystems</td>
</tr>
<tr>
<td></td>
<td>• Produces high output current</td>
<td>• Poor performance in micro-scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Produces low output voltage</td>
</tr>
<tr>
<td><strong>Electrostatic</strong></td>
<td>• Easy to integrate in microsystems</td>
<td>• Requires external voltage source</td>
</tr>
<tr>
<td></td>
<td>• Produces high output voltage</td>
<td>• Output impedance is high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Produces low output current</td>
</tr>
</tbody>
</table>

Table 1 - Comparison of vibrational energy harvesting techniques [5, 10]
2.1.2. Thermal (Thermoelectric) Energy Harvesting

Thermal gradients, one of the oldest techniques for generating electricity, are directly converted to electrical energy through the Seebeck (thermoelectric) effect [11]. Junction of two dissimilar wires with a temperature difference between the junction and the wire ends simply forms a thermocouple. This temperature difference causes heat flow and, by natural, charge flow through the metal wires. An N-type and P-type semiconductor connected by a metal plate composes the core of a thermoelectric generator (TEG). Connecting many PN junctions in series electrically and in parallel thermally produces a large voltage output which is proportional to the heat flow [12]. As the produced voltage and power level depend on the temperature differential and the Seebeck coefficient, which is the ratio of the resulting voltage and the temperature difference, of the thermoelectric materials, in order to generate viable voltage and power levels, large thermal gradients are required. With this method, power density of 15µW/cm³ can be achieved at 10°C gradient. However, since temperature differences higher than 10°C are not frequently available, this method usually generates low voltage and power levels [8].

2.1.3. Light Energy (Solar Energy) Harvesting

Some certain materials which have photovoltaic effect release electrons when exposed to light. These electrons can be captured and converted into electrical energy [13]. The power output obtained by this method is proportional to the intensity of the light hitting the surface of the photovoltaic cell. From outdoor solar energy, power density of 15mW/cm³ can be achieved [7]. In these conditions, adequate power level to run a microsystem can be provided by coupling a solar panel with harvesting circuitry to ensure operation near the maximum power point [12]. However, for indoor environments, the power density that can be provided from solar energy can be as low as 10–20 µW/cm³ [7]. Solar energy harvesting is a well-known IC compatible technique generating generally higher level power output comparing to the other energy harvesting techniques.

2.1.4. RF Energy Harvesting

Sources generating high electromagnetic fields such as TV signals, wireless radio networks and cell phone towers emit radio frequency energy which can be captured
and converted into usable DC voltage using a power processor circuit linked to a receiving antenna through a diode rectifier [14]. However, RF energy harvesting is not as gainful as is interesting since power density achievable using this technique is usually less than 1µW/cm³ [15].

We have briefly introduced popular energy harvesting techniques by explaining how power is acquired and what the typical power density level that can be expected from each technique is. The table below compares the typical power output of each technique, and will allow us to make a comparison against the energy available from Ethernet when we reveal it.

<table>
<thead>
<tr>
<th>Energy Harvesting Technique</th>
<th>Typical Power Density (µW/cm³)</th>
</tr>
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<tbody>
<tr>
<td>Piezoelectric</td>
<td>300</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>1 – 100</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Thermal</td>
<td>15 at 10°C</td>
</tr>
<tr>
<td>Solar</td>
<td>15,000 - Outdoor Light</td>
</tr>
<tr>
<td></td>
<td>15 - Indoor Light</td>
</tr>
<tr>
<td>RF</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Table 2 - Comparison of popular energy harvesting techniques

That energy harvesting devices often have low output power and the harvestable energy from environment is intermittent are the challenges energy harvesting is facing which makes them impractical power sources by themselves. As illustrated in Figure 1, a power management unit performing energy conversion, managing the energy storage and powering the application as well as a storage unit are required to build a complete energy harvesting system.
2.2. Power Management

Due to variations in level, type and availability of its power and voltage, an energy harvester’s output fails to directly fit as power supply for applications. Therefore, a power management unit adapting the electrical energy obtained from energy harvester to the requirements of the application circuit or the energy storage unit is required.

In the development of a power management circuit, the following challenges have to be considered:

- There is a variety of harvesters available with different electrical characteristics which require specific interfacing. For example, the output of the harvester can be AC or DC.
- The AC or DC amplitudes can vary depending on the energy source and environmental conditions.
- The energy source availability is inconsistent over time.

We can categorize harvesters in two groups as DC output producers and AC output producers. In case of DC output producers, a DC-DC converter and a controller are required to carry the appropriate signal to the storage unit. On the other hand, AC output voltage producers necessitate an extra AC-DC converter as interface [16].

The maximum power point (MPP) of an energy harvester where the obtained electrical energy is maximized depends on its peculiar features. A power management
A power management system is also expected to shut down in order not to discharge the output in the case of the harvester producing less energy than the energy used by the power management unit itself. When adequate level of power becomes available again, it is expected to start up again. A power management unit may also need to include a battery management circuit to provide the battery with safe operating conditions.

Furthermore, the battery and load have different voltage and current characteristics. For example, the voltage across a thin-film Li Ion battery is around 4.2V when charged and 2.7V when discharged [20]. However, the load may not outlive supply voltage variations over 1.5V. Hence, a DC-DC voltage regulator which prevents voltage and current variations in the battery from affecting the load is needed to transfer and condition the voltage to the load from the battery.

There are power management ICs (PMICs) available which make it practical capturing small amounts of energy and converting it into a useful power source. Section 3 compares some commercially available PMICs, and investigates how they meet the requirements of a power management unit mentioned above.
2.3. Energy Storage

Energy storage has an important role in energy harvesting systems. Since harvestable energy from environment is inconsistent and/or not adequate, an energy harvesting system should include not only a mechanism to harvest and convert the ambient energy, but also a mechanism to store the harvested energy. Energy storage makes it possible for systems to keep on operating when sufficient ambient energy is not available. Moreover, systems including an energy storage unit do not require initially harvesting energy to start operation that gives the system instant-on capability.

There is a variety of storage technologies suitable for energy harvesting applications such as capacitors, supercapacitors, and rechargeable batteries. In this section, we will compare these technologies in terms of their characteristics as well as advantages and disadvantages over each other.

The terms, ‘specific power’ and ‘specific energy’, used in the comparison of the energy storage technologies are, respectively, the maximum power output level that a storage unit can provide and the maximum energy level that a storage unit can store per unit mass.

Capacitors, using physical charge separation between two electrodes to store charge, have very low specific energy. However, they have very high specific power which allows them to operate under high currents, but only for very short periods because of their low capacitance [25]. Supercapacitors, electric double layer capacitors (EDLC) [26], on the other hand, have much higher specific energy comparing to conventional capacitors [27]. Though supercapacitors resemble conventional capacitors in many ways, their ability to offer higher capacitance in smaller package makes them more suitable for energy harvesting systems. Since conventional capacitors are outperformed by supercapacitors for use in energy harvesting systems, in this section supercapacitors and batteries are compared.

Note that there is a variety of rechargeable batteries such as the lead acid, lithium ion (Li-ion), nickel cadmium (NiCD), and nickel metal hydride (NiMH) [26], and all of these battery types have different characteristics. Therefore, because of their
popularity in use of powering electronics devices, the characteristics of Li-ion batteries are considered when compared against supercapacitors.

Supercapacitors rely on static charge for energy storage whereas energy storage of batteries is by means of electro-chemical process [25]. Therefore, batteries have a harmful impact on the environment unlike supercapacitors which do not release dangerous substances to the environment since they do not involve any chemical actions [26].

The specific energy of the supercapacitors, even though high compared to conventional capacitors, is typically 5 Wh/kg and low considering the specific energy of typically 100 Wh/kg of a Li-ion battery [27]. Another disadvantage of supercapacitors is the discharge curve. The voltage of a supercapacitor decreases linearly from its highest voltage point to zero voltage which reduces the usable power band by leaving much of the stored energy unused. On the other hand, delivering a steady voltage in the usable power band, a battery can deliver the most of its stored energy before reaching the discharge cutoff voltage [27]. For example, we assume that our storage unit can be charged up to 4 V and allowed to discharge down to 3 V because the load cannot be powered with a voltage lower than 3V. If the storage unit is a supercapacitor, it would reach the discharge cutoff voltage within the first quarter of the cycle and the remaining energy which is 75 percent of the total stored energy would be unusable. With a DC-DC converter, some of the remaining energy could be made usable, however, that would increase the cost and energy loss up to 15%. A Li-ion battery, on the other hand, could deliver 90 to 95 percent of its stored energy before reaching the discharge cutoff voltage [27].

A supercapacitor can be charged in seconds, and that is quite fast compared to batteries which would take hours to charge [25]. The crucial advantage of the supercapacitors in terms of charging is that they do not necessitate overcharge protection system since they cannot be overcharged. The reason of not being overcharged is that the current flow simply stops when the capacitor is full [27]. On the other hand, batteries require protection to prevent overcharging which otherwise would damage them.
Supercapacitors can be charged and discharged, in theory, unlimited number of times, unlike a battery which has a limited cycle life. Moreover, a supercapacitor would lose only 20% of its capacity in ten years, however, applying higher voltage than specified would shorten its life. Besides, the operating temperature range of supercapacitors is wider than that of batteries \([25, 27]\).

The self-discharge of supercapacitors is higher than batteries. In a month, a supercapacitor would discharge 50% of its energy reserve, whereas a Li-ion battery would discharge only 5% per month \([25, 27]\).

As we can see, supercapacitors and batteries have advantages over each other. Which one to choose as storage unit depends on the requirements of the system. To summarize, batteries have high specific energy and low self-discharge, but last only a few years because of low cycle-life. Supercapacitors have a very high cycle life, but low specific energy and high self-discharge currents. For example, because supercapacitors can store very less energy, every time a WSN which is powered through a supercapacitor transmits data, a high percentage of the supercapacitor’s reserved energy would be consumed. If the energy source doesn’t have high output and is not consistent, it would be problematic to run the system using a supercapacitor as storage unit. There is also an emerging energy storage technology, micro energy cell (MEC), which can fill the gap between supercapacitors and batteries thanks to their characteristics such as having higher specific energy than supercapacitors and higher cycle-life than batteries.

THINERGY MECs from Infinite Power Solutions \([28]\) have cycle life of over 10,000 full discharge cycles, and over 100,000 shallow (not full) discharge cycles. Furthermore, typical self-discharge rate of THINERGY MECs is lower than 10nA, and they can operate over a broad temperature range. Moreover, thanks to their flexibility and ultra-small package they do not define the form of the system like supercapacitors and batteries do, on the contrary, they may be formed to fit any shape according to the application requirements.

Table 3 compares the characteristics of supercapacitors, Li-ion batteries, and MECs.
<table>
<thead>
<tr>
<th>Property</th>
<th>Supercapacitors</th>
<th>Li-ion Batteries</th>
<th>THINERGY MECs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Time</td>
<td>1 to 10 seconds</td>
<td>10 to 60 mins</td>
<td>10 mins</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40 to +85 °C</td>
<td>-20 to +65 °C</td>
<td>-40 to +85 °C</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>N/A</td>
<td>3.6V - 3.7V</td>
<td>3.9V</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>1,000,000 or 30,000 hours</td>
<td>&gt;500</td>
<td>&gt;10,000 deep discharge &gt;100,000 shallow discharge</td>
</tr>
<tr>
<td>Specific Power</td>
<td>10,000 W/kg</td>
<td>1,000 - 3,000 W/kg</td>
<td>400 W/kg</td>
</tr>
<tr>
<td>Specific Energy</td>
<td>5 Wh/kg</td>
<td>100 - 200 Wh/kg</td>
<td>&gt;10 Wh/kg</td>
</tr>
</tbody>
</table>

Table 3 - Comparison of various energy storage technologies [25, 27, 29]
3. COMMERCIALLY AVAILABLE PMICs

There are some companies producing PMICs specific to energy harvesting. In this section, we examine and compare some PMICs from different companies in terms of how they meet the requirements from a power management unit as mentioned in section 2.2.

One of the requirements from a power management unit mentioned in section 2.2 is AC-DC converter. However, AC-DC converter is needed only for energy sources generating AC signal, and usually not included in the design of the PMICs. An AC-DC converter is to be designed separately by external components and applied to the input of the PMIC if needed. Therefore, the features looked for in a PMIC are, DC-DC converter, MPPT, output voltage regulator and battery protection. In PMICs, the voltage is regulated and transferred to the load application usually through a circuit called low-dropout (LDO) linear regulator. A LDO regulator allows a PMIC to regulate the output voltage as much as the dropout voltage which is the difference between the input and output voltages of the regulator. That is to say, the output voltage to the load application can be regulated until the input and output voltages of the LDO get close to each other. Lower dropout voltage causes less power dissipation at the output [21].

Battery protection includes two conditions; overcharge protection and under voltage protection. When the battery reaches the limit of its maximum charge level, it should cut off charging. Otherwise it is called overcharging and may cause extreme heating of the battery and so damage the battery. Preventing the battery from being overcharged is called overcharge protection. Furthermore, batteries have a discharge cutoff voltage value, and falling under this value can reduce the battery performance or damage the battery. Preventing the battery from falling under its discharge cutoff voltage is called under voltage protection.

3.1. MAX17710

MAX17710 [19] from Maxim Integrated Products is a power management IC designed to charge and protect MECs. MAX17710 has the ability to harvest energy
from various poorly regulated low-energy sources with 1µW to 200mW output levels. The cell can be charged externally from either a 4.21V or higher power source connected directly to the charge pin or a lower voltage source applied to the boost converter pin. The boost regulator controller enables energy harvesting from low-voltage energy harvester devices. Via the boost converter, energy down to 5µW can be harvested. The boost converter can be started with an input voltage as low as 750 mV, and once started, it can continue to harvest energy down to 250 mV input voltage. The IC also includes an internal regulator protecting the cell from overcharging by limiting the charging voltage to 4.125V. The device regulates and transfers voltage from the cell to a load circuit through an ultra-low-quiescent current low-dropout LDO linear regulator which can be configured to give 3.3V, 2.3V, or 1.8V output. It also includes an internal voltage protection preventing the cell from overdischarging by not allowing the cell voltage falling under 2.15V [19].

3.2. BQ25504

BQ25504 [22] from Texas Instruments is a power management IC specifically designed to efficiently acquire and manage the microwatts to miliwatts of power generated from a variety of energy sources. The IC includes a boost converter which can extract power from low voltage output harvesters. The boost converter can be started with an input voltage as low as 330mV, and once started, it can continue to harvest energy down to 100mV input voltage. The IC also includes a programmable MPPT system to optimize the power transfer from source to the device. The IC can support a variety of energy storage elements such as a re-chargeable battery, super capacitor, or conventional capacitor. Maximum and minimum operating voltages of the storage unit are monitored against the user programmed under-voltage and over-voltage levels in order to protect the storage unit from overcharging and discharging [22].

3.3. LTC3108 & LTC3105

LTC3108 [23] from Linear Technology is an integrated DC-DC converter designed for energy harvesting from low input voltage sources. It allows harvesting from input voltages as low as 20mV. The IC provides two outputs; main output which can be configured as 2.35V, 3.3V, 4.1V and 5V, and 2.2V LDO. The IC is designed
with a storage capacitor which can provide power when the input voltage source is unavailable [23].

Differently from LTC3108, LTC3105 [24] allows harvesting from input voltages as low as 225mV, and also includes a MPPT system in order to maximize the energy that can be extracted from the power source. Main output range can be adjusted between 1.4V and 5V [24].

<table>
<thead>
<tr>
<th>PMIC</th>
<th>Boost Converter</th>
<th>MPPT</th>
<th>LDO</th>
<th>Overcharge Protection</th>
<th>Under Voltage Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX17710</td>
<td>0.75V for startup</td>
<td>No</td>
<td></td>
<td>1.8V, 2.3V, 3.3V</td>
<td>4.125V</td>
</tr>
<tr>
<td></td>
<td>0.25V&lt;VIN&lt;2V</td>
<td></td>
<td></td>
<td></td>
<td>2.15V</td>
</tr>
<tr>
<td>BQ25504</td>
<td>0.33V for startup</td>
<td>Yes</td>
<td>No</td>
<td>3.1V</td>
<td>2.2V</td>
</tr>
<tr>
<td></td>
<td>0.1V&lt;VIN&lt;3V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTC3108</td>
<td>0.02V&lt;VIN&lt;0.5V</td>
<td>No</td>
<td></td>
<td>2.2V</td>
<td>No</td>
</tr>
<tr>
<td>LTC3105</td>
<td>0.225V&lt;VIN&lt;5V</td>
<td>Yes</td>
<td>2.2V</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4 - Comparison of some commercially available PMICs
4. ETHERNET ENERGY HARVESTING

Ethernet Energy Harvesting system that we are committed to develop is simply the process of harvesting and storing the energy that Ethernet packets producing while traversing on an Ethernet link. The challenge here is how to obtain this energy and convert it to useful energy that could be used to run devices such as WSNs. Like other energy harvesting technologies, an energy source, which is Ethernet in this case, a power management unit, and an energy storage component are required. The main difference than other energy harvesting technologies is that energy level does not change according to environmental conditions, however, is expected to vary depending on some factors such as transmission speed.

In this section, the main units used in the research and development of Ethernet Energy Harvesting system are introduced.

4.1. Energy Source: ETHERNET

Ethernet, standardized under IEEE 802.3 specifications [2], is the most widely used LAN technology which defines data link and physical layer operations as compared to the Open Systems Interconnect (OSI) model [30] where network functions are divided into seven layers as seen in Figure 2. The reason Ethernet is compared to OSI model is that OSI model is strictly layered and last two layers of it resemble Ethernet. The other reference model, TCP/IP model, includes only four levels and does not address the physical layer, hence does not perfectly resemble Ethernet [31]. While medium access, frame format and addressing are specified by the link layer, network medium and signaling are described by the physical layer. In this section, Ethernet frame format, medium access, and Ethernet signaling are described.
4.1.1. Ethernet Frame Structure

In an Ethernet network, the data travels in structures called frames. An Ethernet frame defines fields for synchronization, addressing information, error-checking sequence, and additional identifying information to help the data arrive its destination and receiving station determine whether the data arrives untouched.

The format of an Ethernet frame as defined in the original IEEE 802.3 standard is illustrated, and its fields are explained below [30, 32].
Figure 3 – Ethernet Frame Structure

**Preamble**, consisting of 56 bits, is an alternating pattern of ones and zeros, used for synchronization in 10Mbps systems, allowing receiving Ethernet interface to know when to read the bits in the transmitted data. Since different synchronization methods used, preamble field is not needed in newer versions of Ethernet systems, however, maintained to provide compatibility with the original Ethernet frame.

**Start Frame Delimiter**, a sequence of 8 bits with alternating ones and zeros ending with two consecutive ones ‘10101011’, functions together with Preamble, and indicates the start of the frame.

**Destination & Source MAC Addresses**, each consisting of 48 bits, identify the station(s) to receive the frame and the station that has originated the frame respectively.

**Length/Type** field, consisting of 16 bits, depending on whether its value is less or equal than 1500 decimal or equal or above than 1536 decimal, can either indicate the number of bytes of valid data in the data field or protocol type used by the data respectively.

**Data** is the information that source station transmits. The data field must be between 46 and 1500 bytes. If there are less than 46 bytes of data, pad bytes must be included in the field to bring the frame size up to the minimum length. If the source station has more than 1500 bytes to send, it transmits the data in multiple frames.

**Frame Check Sequence (FCS)** helps the receiving Ethernet interface detect errors in a received frame. The corrupted data can be detected by using the 32 bit cyclic redundancy check (CRC) value in the FCS field.
4.1.2. Ethernet Media Access Control

In Ethernet networks, the method of deciding whose turn to transmit is referred as media access control (MAC). In this section, the two MAC protocols defined for Ethernet are described briefly.

4.1.2.1. Half-Duplex Ethernet

Half-Duplex Ethernet is the original form of Ethernet that uses the Carrier Sense Multiple Access/Collision Detect (CSMA/CD) protocol to help prevent collisions and to allow retransmission if a collision occurs. In half-duplex Ethernet, since the cabling structure is common to both the transmitter and the receiver stations, a station cannot send and receive data simultaneously. A station continuously listens for traffic on the medium, and begins transmitting when it detects that no other station is transmitting. If two or more stations begin transmitting at the same time, each station detects the collision, stops transmitting of data, and remains silent for a quasirandom period of time before attempting to retransmit the frame [30, 33].

4.1.2.2. Full-Duplex Ethernet

Full-duplex mode enables that two stations can simultaneously send and receive data, however, is restricted to point-to-point links. Full-duplex mode omits CSMA/CD protocol because that there is no competition for shared medium removes the collision possibility. One of the advantages of full-duplex mode is double throughput provided by simultaneous data exchange. Running full-duplex mode, a maximum bandwidth of 20 Mbps, 200 Mbps and 2 Gbps can be obtained from 10Mbps, 100 Mbps and 1 Gbps system [30, 33].

Furthermore, Ethernet has an optional feature called Auto-Negotiation that allows two stations to determine the best possible connection between them by exchanging information about the link speeds and modes of operation they support. The table below shows the priority of the modes to be chosen by auto-negotiation procedure [30]. Even though Gigabit Ethernet supports half-duplex mode, most of the Ethernet Interface cards are not configured with 1000 Mbps half-duplex support.
<table>
<thead>
<tr>
<th>Priority</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1000 Mbps Full Duplex</td>
</tr>
<tr>
<td>2.</td>
<td>100 Mbps Full Duplex</td>
</tr>
<tr>
<td>3.</td>
<td>100 Mbps Half Duplex</td>
</tr>
<tr>
<td>4.</td>
<td>10 Mbps Full Duplex</td>
</tr>
<tr>
<td>5.</td>
<td>10 Mbps Half Duplex</td>
</tr>
</tbody>
</table>

Table 5 - Auto-Negotiation Priority List

### 4.1.3. Ethernet Physical Layer

Ethernet physical layer where medium type and signaling are defined is the part we are mostly interested in regarding energy harvesting. Most of the existing network interface cards (NICs) are with 10/100 Mbps support, however, NICs supporting 1000 Mbps also have been increasingly being produced. Considering that along with the widespread use of twisted pair wiring, we have based our system design on the three most popular Ethernet standards 10Base-T, 100Base-TX and 1000Base-T as energy sources.

10Base-T supports 10 Mbps transmission speed over Category 3 (Cat3) or newer twisted pair cabling standards while 100Base-TX supports 100 Mbps transmission speed over 100 Ω Category 5 (Cat5) unshielded twisted pair (UTP) or newer [34]. The maximum frequency supported by Cat5 cabling is 100 MHz whereas it is only 16 MHz for Cat3 cabling. Even though 1000Base-T is designed to operate over Cat5, Cat5 cabling is not considered for Gigabit Ethernet installations. A newer specification of it, Cat5 Enhanced (Cat5e) and Category 6 (Cat6) which meet some additional performance requirements are rated for Gigabit Ethernet. In section 4.1.4, more detailed information on the characteristics of cabling standards are given.

Cat5/5e/6 cables contain four pairs of copper wire, however, 10Base-T and 100Base-TX utilize only two pairs: one pair for data transmission and one pair for data receiving. Using separate pairs for transmitting and receiving allows operating at full-duplex mode. On the other hand, 1000Base-T uses all four pairs for transmitting and receiving simultaneously which is achieved through a special circuit known as a hybrid. The hybrid simply separates the outgoing transmit signal from the incoming receive signal [35]. Both ends of the cable are terminated with a RJ-45 connector. Table 6 indicates how 10Base-T, 100Base-TX, and 1000Base-T utilize the wires of a
Cat5/5e/6 cable. Standard Color is important to provide the coherence in cable installation and facilitates troubleshooting. Moreover, since every cabling standard utilizes the same color standard, it provides backwards-compatibility in wiring. Note that ‘BI_Data’ stands for ‘Bidirectional Data’ which means both transmitted and received signals are carried on single wire.

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Standard Color</th>
<th>Ethernet Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10Base-T &amp; 100Base-TX</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>TX+</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>TX-</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>RX+</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>RX-</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

Table 6 - Cat5/5e/6 Pins

The most important difference between 10Base-T, 100Base-TX and 1000Base-T standards, other than available bandwidth, is the signaling methods used in order to transmit the frames on the link. The signaling methods are also the most important part regarding energy harvesting. The rest of this section is dedicated to explain the signaling methods used by 10Base-T, 100Base-TX and 1000Base-T standards.

4.1.3.1. **10Base-T Signaling**

10Base-T devices continuously check the activity of data receiving path by sending link test signals called Link Integrity Test Pulse (LTP) in order to assure that the link is working accurately. These test signals are pulses with duration of 100 ns nominally sent every 16 ms with a tolerance of 8 ms only when the link is idle. LTPs do not cause any performance impact since they are sent only when there is no other data on the link [30].
In 10Base-T system, the data to be transmitted over the link are first encoded using the Manchester encoding system. As seen from Figure 4, in Manchester encoding, a ‘0’ bit is defined as a signal descending from positive to negative while a ‘1’ bit is defined as a signal ascending from negative to positive [36].

![Figure 4 – Bit Transition in Manchester Encoding](image)

The advantage of Manchester codes is being self-clocking. The receiver station does not lose synchronization since even 0 bits define a transition. The price paid for this is that the worst-case signaling rate doubles the bandwidth requirement. That is to say, a 10 Mbps stream of all 1 bits or all zero bits results in a Manchester encoded signaling rate of 20 MHz on the cable [30].

Moreover, the 10BASE-T line signals are transmitted as balanced differential currents. In each wire pair, one wire carries the positive amplitude (0 to +V), and the
other wire carries the negative amplitude (0 to -V) of the differential signal. Each of the wires in a pair carries typically 2.5 volts peak signal which results in a 5 volts peak-to-peak (P-P) signal across a pair [30]. However, this voltage level may vary depending on the interface used. Note that no voltage level has been defined for LTPs, but they are expected to be positive pulses with approximate amplitude of 2.5V.

4.1.3.2. 100Base-TX Signaling

100Base-TX transmits data using the "4B/5B" signal encoding scheme which is a technique that codes each group of four bits into a five-bit code. For example, the binary pattern 0110 is coded into the five-bit pattern 01110. The code table seen below has been designed in such a way that no combination of data can ever be encoded with more than 3 zeros on a row. 4B/5B allows the carriage of 100 Mbps data by transmitting at 125 MHz, as opposed to the 200 Mbps required by Manchester encoding [30]. Furthermore, as we see from Table 7, IDLE symbol is defined as 11111 in 5B which provides a permanent signal on the link even when there is no data transmission.

<table>
<thead>
<tr>
<th>4B</th>
<th>5B</th>
<th>4B</th>
<th>5B</th>
<th>4B</th>
<th>5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>11110</td>
<td>0110</td>
<td>01110</td>
<td>1100</td>
<td>11010</td>
</tr>
<tr>
<td>0001</td>
<td>01001</td>
<td>0111</td>
<td>01111</td>
<td>1101</td>
<td>11011</td>
</tr>
<tr>
<td>0010</td>
<td>10100</td>
<td>1000</td>
<td>10010</td>
<td>1110</td>
<td>11100</td>
</tr>
<tr>
<td>0011</td>
<td>10101</td>
<td>1001</td>
<td>10011</td>
<td>1111</td>
<td>11101</td>
</tr>
<tr>
<td>0100</td>
<td>01010</td>
<td>1010</td>
<td>10110</td>
<td>Quiet</td>
<td>00000</td>
</tr>
<tr>
<td>0101</td>
<td>01011</td>
<td>1011</td>
<td>10111</td>
<td>Idle</td>
<td>11111</td>
</tr>
</tbody>
</table>

Table 7 – 4B/5B Conversion [36]

Multilevel Threshold-3 (MLT-3) is the encoding system used in transmitting 5B symbols over twisted-pair cables. MLT-3 defines three levels (-V, 0, +V) which a signal can have one of them in each clock transition [20]. A ‘1’ bit causes the signal to change level whereas a ‘0’ bit keeps the signal constant. By this method, the total signaling frequency on the wire is reduced since the signal is not changing level when the transmitted bit is ‘0’. Due to 4B/5B encoding, the highest frequency can be
produced on the link when the link is IDLE, and after MLT-3 encoding, IDLE signal decreases from a 125MHz tone to a 31.25MHz tone (125/4) which is within the support range of a Cat5/5e cable.

Furthermore, prior to MLT-3 signaling, the 4B/5B block encoded data is scrambled in order to spread out the electromagnetic emission patterns in the data. Like 10Base-T standard, 100Base-TX uses differential signaling, but with an approximately 1 volt peak signal in each wire generating a total of 2 volts P-P signal across a pair [30]. This voltage level is a typical value and may vary depending on the interface used. Figure 6 illustrates a sample bit stream encoded by MLT-3.

Figure 6 – Sample Bit Stream Encoded by MLT-3

4.1.3.3. 1000Base-T Signaling

Signal encoding used in 1000Base-T standard is quite complex since it requires squeezing 1000 Mbps data into 125 MHz signals. The bullet points below try to simplify the explanation of how 1000 Mbps is achieved over a category cable [35].

- The signaling rate is 125 MHz, as 100Base-TX standard, allowing 125 Mbps symbol rate.
- Transmitting on all four pairs of cable results in 500 Mbps.
- By using a five-level symbol and encoding 2 bits per symbol achieved is 1000 Mbps.
- Ability to transmit and receive simultaneously on each pair enables full-duplex.
The reason for using five-level signaling is that to encode 8 bits, 256 ($2^8$) symbols are required. If a three-level signaling like MLT-3, which is used in 100Base-TX standard, were used across all four pairs, only 81 ($3^4$) symbols would be available. By using a five-level signaling, 625 ($5^4$) symbols are available. Using a four-level signaling would yield 256 ($4^4$) symbols which is sufficient to encode data, however, in this case there would be no symbols remaining for redundancy and control signals (e.g. idle, start of frame and end of frame).

The encoding scheme used to achieve above is 4D-PAM5 which is a four-dimensional, five-level pulse amplitude modulation. PAM5 works in a similar way to MLT-3, but defines five levels (-V, -0.5V, 0, +0.5V, +V). Only four levels are used for data encoding, and 0 level used for forward error correction (FEC) [30]. The differential P-P voltage is typically 2 volts. In 1000Base-T also, the signal is scrambled to spread out the electromagnetic emission patterns in the data. Furthermore, in the absence of data on the link, the IDLE symbol is sent continuously at 125 MBaud. Note that using multi-level signaling also reduces the frequency of the transmitted signal as it does in 100Base-TX allowing Gigabit Ethernet to be supported by Cat5 cables.

It is important to mention that the given peak voltage values for the standards are typical output differential peak voltages defined by majority of 10/100/1000 Mbps Ethernet physical interfaces. Even though the encoding methods are constant for all interfaces, P-P voltage obtained from the link may vary depending on the transceiver and cable used.

4.1.4. Characteristics of Category 5/5e/6 Cables

Cat5, Cat5e and Cat6 cables all have a characteristic impedance of 100 Ω. However, Cat5 and Cat5e support frequencies up to 100 MHz whereas Cat6 supports up to 250 MHz. We believe that the characteristics of category cables would have an important effect on the power level that can be provided from an Ethernet link. The characteristics defined for category cables, other than frequency and impedance, are propagation delay, delay skew, attenuation (also referred as insertion loss), near end crosstalk (NEXT), power sum NEXT (PS-NEXT), equal level far end crosstalk (ELFEXT), and power sum ELFEXT (PS-ELFEXT). Note that near end is the end of
The cable where the signal is generated whereas far end is the opposite end where the signal is received. Below, these characteristics are briefly explained [34].

- The time that it takes for the signal to be transmitted from one end of the cable to the other is called *Propagation Delay*.
- The signal transmission speed difference between the fastest and slowest pairs in the cable is measured by *Delay Skew*.
- As the signal is transmitted from one end to the other end of the cable, the signal strength reduces. This loss in strength is called *Attenuation*. Loss is measured in decibels (dB), and lower dB value means better performance.
- Radiation emission at the near end of the cable causes some amount of signal to be coupled from one pair to another pair within the cable. The amount of the signal coupled is measured by *NEXT*. It is measured in dB, and higher value of it means that the signal is lost due to coupling is less.
- The difference of *PS-NEXT* from *NEXT* is that it measures the effects of the coupling to one pair from other three pairs instead of measuring the effect of one pair to another pair.
- The coupling of the signals which is because of the radiation emission at the far end of the cable is measured by *ELFEXT*.
- Differently from *ELFEXT*, *PS-ELFEXT* considers the effects of the other three pairs on each individual pair. It also considers the attenuation factor.
- The amount of the signal reflected back to the source where the signal was generated is measured by *Return Loss*. Higher value of it means less energy is reflected.

Table 8 compares the characteristics of Cat5, Cat5e and Cat6 cables. Note that the dB values given in the table are per 100 meters and the minimum values defined at 100 MHz frequency.
<table>
<thead>
<tr>
<th></th>
<th>Category 5</th>
<th>Category 5e</th>
<th>Category 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>100 MHz</td>
<td>100 MHz</td>
<td>250 MHz</td>
</tr>
<tr>
<td>Characteristic Impedance</td>
<td>100 Ω ± 15%</td>
<td>100 Ω ± 15%</td>
<td>100 Ω ± 15%</td>
</tr>
<tr>
<td>Attenuation</td>
<td>22 dB</td>
<td>22 dB</td>
<td>19.8 dB</td>
</tr>
<tr>
<td>NEXT</td>
<td>32.3 dB</td>
<td>35.3 dB</td>
<td>44.3 dB</td>
</tr>
<tr>
<td>PS-NEXT</td>
<td>no specification</td>
<td>32.3 dB</td>
<td>42.3 dB</td>
</tr>
<tr>
<td>ELFEXT</td>
<td>no specification</td>
<td>23.8 dB</td>
<td>27.8 dB</td>
</tr>
<tr>
<td>PS-ELFEXT</td>
<td>no specification</td>
<td>20.8 dB</td>
<td>24.8 dB</td>
</tr>
<tr>
<td>Return Loss</td>
<td>16.0 dB</td>
<td>20.1 dB</td>
<td>20.1 dB</td>
</tr>
<tr>
<td>Propagation Delay (per 100m)</td>
<td>548ns</td>
<td>548ns</td>
<td>548ns</td>
</tr>
<tr>
<td>Delay Skew (Max. per 100 m)</td>
<td>no specification</td>
<td>45 ns</td>
<td>45 ns</td>
</tr>
</tbody>
</table>

Table 8 - Comparison of the characteristics of Cat5/5e/6 [34]

Cat5, Cat5e, and Cat6 cables all are used in the development of Ethernet Energy Harvesting system in order to reveal whether the cabling standard is a variable affecting the energy availability on an Ethernet link.

### 4.1.5. Energy Potential of Ethernet Standards

Now that we know what the typical differential output voltage of each standard and the characteristic impedance of category cables are, we can calculate the energy potential of each standard.

For 10Base-T, 100Base-TX and 1000Base-T links, the P-P voltages on a pair are typically 5V, 2V, and 2V respectively. Considering the 100 Ω characteristic impedance \((R)\) of category cables, from the formula below, we can calculate the power potentially available from 10Base-T, 100Base-TX and 1000Base-T links as 250 mW, 40 mW, and 40 mW respectively.

\[
P(\text{Power}) = \frac{V^2}{R}
\]

However, the above is a coarse calculation of the available potential energy. In order to get more robust results, we have to calculate the energy available per bit. As we know from 10Base-T signaling section, every bit, 0 or 1, transmitted on a 10Base-T link generates a 5V P-P signal on the transmitting wire pair for a period of 100 ns. A transmitted bit, depending on whether it is ‘0’ or ‘1’, produces a +2.5 V during the
first 50 ns and -2.5 V during the second 50 ns, or vice versa. Therefore, in theory, every bit produces a power of 62.5 mW during 100 ns which means the energy available per bit on a 10Base-T link, implementing the formula below, is 6.25 nJ.

\[ W(\text{Energy}) = P \times t \]

On the other hand, on a 100Base-TX link, every 1 bit states a level change whereas 0 bits keep the signal on the same level. Since three level encoding is used, the signal on a wire can change between -1, 0, and 1 V which produces a power of 0 or 10 mW for a period of 8 ns. That means the energy available per bit on a 100Base-TX link can be 0 or 80 pJ.

Differently from 100Base-TX standard, 1000Base-T uses five level encoding. As we have learned, two bits are transmitted per clock as a combination of ‘00’, ‘01’, ‘10’, or ‘11’. The four voltage levels representing these combinations are -1, -0.5, 0.5, or 1 V on a pair. The fifth level, 0 V, is used for FEC as we mentioned earlier. That means every two bits combination would produce a power of 2.5 mW or 10 mW respectively for a period of 8 ns. As a result, the energy available per two bits combination on a 1000Base-T link can be 20 or 80 pJ.

Note that these values are the results of the calculations made according to typical voltage values and do not give the exact energy available per bit. How much of this energy can be extracted depends on the impedance of the load or circuit attached between the pins of a wire pair. Moreover, how much of this energy can be transferred to the load application depends on the characteristics of the harvester circuit.

4.2. Power Management & Storage: MAX17710 & THINERGY MEC101

As we have learned from Ethernet section, the typical P-P voltage on an Ethernet link can be 2V or 5V depending on the standard type. Since the output signal is AC, an interface circuit converting this AC signal to DC signal will be needed before inputting it to a PMIC. This conversion will cause reduction in voltage and power input of the PMIC. Therefore, it is critical that the PMIC that will be used in the development of Ethernet Energy Harvesting system can operate with low voltage inputs. Among the storage units we have examined, MEC seems as the most suitable
option for us thanks to its satisfying specific energy and cycle life capacity. However, using MEC in system requires attention since it has limitations such that the charging voltage should not exceed 4.15V and it should not be discharged under 2.1V. Therefore, the PMIC should allow over-voltage and under-voltage protection to provide the storage unit with safe operating conditions. Moreover, the PMIC should not drive much current from the storage unit when the output is disabled which means the quiescent current value should be low. Among the PMICs we have examined, not only because it provides all the conditions we are looking for, but also because it is specifically designed to operate with Thinergy MECs, MAX17710 is a good option for, and so MAX17710 evaluation kit (EVKit), integrating MAX17710 and Thinergy MEC101 together, have been used in the development of Ethernet Energy Harvesting system. Figure 7 illustrates the simplified operating circuit of MAX17710 [19]. Note that the Thinergy MEC model used on the EVKit is MEC101-10SES [39] with 1mA discharge and 14J stored energy capacity which can be recharged by currents down to 1 µA. The information given about MAX17710 in this section is adapted from and more detailed information about how it functions is available in MAX17710 datasheet [19].

Figure 7 – Simplified Operating Circuit of MAX17710
As we can see from Figure 7, MAX17710 can charge the cell from either a 4.21V or higher power source connected directly to the CHG pin or a lower voltage source applied to the boost converter. When a power source is applied to the boost converter, the 47µF harvest-source capacitor is charged until the voltage on FB pin exceeds the 0.75V boost enable threshold voltage. At this point, the IC pulls LX pin low to force the current through the inductor which makes LX start oscillating at a fixed 1.0 MHz with 90% duty cycle. The inductor forces the voltage of LX pin above CHG every time LX is released, and charges the 0.1µF CHG pin capacitor. When the voltage on CHG pin rises above the voltage of VBATT, the charge is delivered to the cell. This process continues until the harvest-source capacitor voltage collapses which causes the voltage on FB pin fall under the 0.25V boost disable threshold voltage. The process repeats after the harvest-source capacitor is recharged [19].

The IC regulates and transfers voltage from the cell to a load circuit on the REG pin through a LDO regulator which can be configured for 3.3V, 2.3V, or 1.8V operation. When charging, if the charging voltage on VBATT pin reaches 4.125V, the current flow is limited to regulate the cell voltage to 4.125V. When discharging, if the cell voltage falls down to 2.15V, the regulator output is disabled to prevent overdischarging. Remember that the maximum charge voltage and discharge cut-off voltage values of MEC101 are 4.15V and 2.1V typically [39].
5. EXAMINATION OF ETHERNET FOR ENERGY HARVESTING

Determining the feasibility of Ethernet Energy Harvesting technique and evaluating the performance of Ethernet as a power solution require performing a number of experiments with detailed measurement and careful observation. As we have learned from the previous section, the signal we get on an Ethernet link may vary depending on a number of variables such as used Ethernet standard and interface. That means available power from Ethernet also depends on these variables. Moreover, since every bit defines a voltage level, as the number of bits traversing on an Ethernet link increases, the available power exposed on this link is also expected to increase which can be achieved by higher transmission speed. This section, through a number of experiments, examines Ethernet as an Energy source and aims to determine the feasibility of Ethernet Energy Harvesting and to reveal the effects of the mentioned variables on the available power level.

5.1. Packet Transmitter Application

In 100Base-TX and 1000Base-T standards, whether there is packet transmission on the link and transmission speed have no effect on the availability of Ethernet signal, because in the absence of packet transmission, IDLE symbols are transmitted continuously. However, it has a remarkable effect on 10Base-T standard. As we have learned from section 4.1.3, if there is no data transmission, only LTPs occur on an Ethernet link. Therefore, in order to be able to examine 10Base-T standard, we need an application allowing us to transmit packets. Further, in order to discover the relation between transmission speed and available power, this application is expected to provide us with the ability to choose to send the packets with the desired transmission speed.

In this regard, we have developed a Java application allowing us to transmit User Datagram Protocol (UDP) packets, also called datagrams. The application creates a frame in size of 1000 bytes (8000 bits), and transmits this frame with optional time intervals. Figure 8 indicates the frame captured by Wireshark [40]. For example, if the
frame is transmitted with 100 ms time intervals, the transmission speed is 10KB/s (80000Kbps), and if it is transmitted with 1 ms intervals, the transmission speed is 1MB/s (8Mbps). In case of no value is chosen for time interval, it means full bandwidth, 1.25MB/s (10Mbps) transmission speed, is used to transmit the frame. On a Windows environment, choosing in which Ethernet standard the NIC will operate can be achieved by configuring Speed & Duplex property of the NIC. On a Linux environment, it can be achieved from the command line using ethtool [41]. The commands below are to show how ethtool can be installed and how Ethernet card can be configured to operate at 100Mbps Full Duplex mode.

```
# apt-get install ethtool net-tools
# ethtool -s eth0 speed 100 duplex full
```

In addition, the application provides a graphical user interface (GUI) allowing user to choose among different transmission speed options as seen in Figure 9.

![Figure 8 – A 1000 Bytes Frame Captured by Wireshark](image)

![Figure 9 – Packet Transmitter GUI](image)

### 5.2. Probing and Testing 10Base-T, 100Base-TX and 1000Base-T Signals

In this first experiment, the purpose is to measure the available signal on an Ethernet link and observe how it varies depending on the standard type and transmission speed. In this regard, as seen from Figure 10, a Sony Vaio laptop with a Marvell Yukon 88E8059 model NIC and Netgear DS104 model hub are point-to-point connected using a Cat5e UTP cable. HP 54645D mode mixed signal oscilloscope is used for the measurement of the signals. The oscilloscope probe is
connected to the transmitting wires of the laptop’s NIC in order to observe the
differential encoded signal transmitted by the NIC. Note that the experimental setup
seen below is for testing 10Base-T and 100Base-TX systems. For testing 1000Base-T
system, since the hub does not support Gigabit Ethernet, it has been replaced by a
desktop personal computer (PC) with D-Link DGE-528T model NIC which supports
1000Mbps. This replacement applies only for testing 1000Base-T system in all related
experimental setups in the report. The hub has been used in testing 10Base-T and
100Base-TX systems. The same wire pair, which is TX+ & TX- for 10Base-T and
100Base-TX systems, but +BI_DA & -BI_DA for 1000Base-T system, has been
probed.

![Experimental Setup for Testing Ethernet Signals](image.jpg)

Figure 10 – Experimental Setup for Testing Ethernet Signals

With the setup above achieved, we have measured 10Base-T, 100Base-TX and
1000Base-T signals both when the link is IDLE (there is no packet transmission) and
when the link is BUSY (there is packet transmission). The figures below (Figure 11 -
15) indicate 10Base-T IDLE, 10Base-T BUSY, 100Base-TX IDLE, 100Base-TX
BUSY, and 1000Base-T IDLE signals respectively.
When the 10Base-T Ethernet link is IDLE, the only available signal is 100 ns width LTP as expected.

When we transmit packets with full bandwidth usage on the 10Base-T link, a P-P 4.375V signal with 10 MHz frequency occurs as seen from the figure above. The amplitude of the signal is within the range of tolerance, and the frequency is as expected. Furthermore, we have observed that as we decrease the transmission speed,
the frequency of the signal also decreases due to less number of bits traversing on the link.

![Figure 13 – 100Base-TX IDLE](image)

Unlike in 10Base-T standard, there is a continuous signal on the 100Base-TX link even when the link is IDLE. From the figure above we can observe every bit causing a state change and a frequency of 32.52 MHz. The P-P voltage of the signal is very close to the typical P-P value of 100Base-TX signal.

![Figure 14 – 100Base-TX BUSY (Transmission Speed = 1MB/s)](image)
Since 4B/5B conversation of the bits of the transmitted frames include ‘0’ bits, and a ‘0’ bit does not define level change, as we see from Figure 14, sometimes signal stays on the same level during a clock time which causes lower frequency on the link comparing to IDLE signal. However, the amplitude of the signal is same as IDLE signal as expected.

![Image]

Figure 15 – 1000Base-T IDLE

Since the IDLE symbol in 1000Base-T standard is not static as it is in 100Base-TX it can be any combination of ‘0’ and ‘1’ bits, and so the data. Therefore we cannot discriminate the IDLE and BUSY signals. The important thing to notice from the figure above is the number of levels.

We can see that our measurements of the 10Base-T, 100Base-TX and 1000Base-T signals overlap with the information given in section 4.1.3.

Furthermore, with the same setup, but with a load accommodated between TX+ and TX- wires, we have measured the voltage across the load to observe how the power transfer from source (Ethernet) to load varies depending on the load resistance. Table 9 shows how P-P voltage varies depending on the used standard and load resistance. Figure 16 is the symbolic illustration of Ethernet as power source. Source voltage ($V_s$) is the differential output voltage of a NIC whereas source impedance ($R_s$) is the characteristic impedance of a category cable. Typical P-P power of
Ethernet is 250 mW for 10Base-T and 40 mW for 100Base-TX and 1000Base-T. How much of this power can be transferred to the load depends on the load impedance.

$$I = \frac{V_S}{R_s + R_L}$$

$$P_{TOT} = I^2 \times (R_s + R_L)$$

$$P_L = I^2 \times R_L$$

Figure 16 – Symbolic Illustration of Ethernet as a Power Source

Note that the values seen in the table below are specific to the interface and cables initially used. Using different NICs and/or cables, measuring different P-P values are most likely. Moreover, on 100Base-TX and 1000Base-T links, whether there is packet transmission and transmission speed do not make a difference in the availability and amplitude of the voltage across the load, because in the absence of data, IDLE symbols are transmitted. Therefore, only the values obtained when the link is IDLE are indicated in the table.

<table>
<thead>
<tr>
<th>RL</th>
<th>VL (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10Base-T</td>
</tr>
<tr>
<td>Open</td>
<td>4.375</td>
</tr>
<tr>
<td>10M</td>
<td>4.348</td>
</tr>
<tr>
<td>1M</td>
<td>4.348</td>
</tr>
<tr>
<td>100K</td>
<td>4.348</td>
</tr>
<tr>
<td>10K</td>
<td>4.321</td>
</tr>
<tr>
<td>1K</td>
<td>4.183</td>
</tr>
<tr>
<td>100Ω</td>
<td>2.302</td>
</tr>
</tbody>
</table>

Table 9 – Voltage drop across the load

From the table above, we can extract how the efficiency of power transfer from source (Ethernet) to the load decreases as the load resistance decreases. Since the impedance of the Cat5e cable is typically 100 Ω, maximum power transfer from source to load is achieved when the load resistance is 100 Ω, however the maximum power efficiency is least and limited to 50%. For example, from the formula given in Figure 16, when 100 Ω resistor is accommodated between the TX+ and TX- pins on
the 10Base-T link from which the values in the table were obtained, ‘I’ would be 21.875 mA. Knowing ‘I’ we can calculate ‘PTOT’ as 95.7 mW and ‘PL’ as half of ‘PTOT’, 47.85 mW. Defining ‘n’ as power efficiency, from |n = PL / PTOT| n would be 50%. On the other hand, when the load is 1M, ‘I’ would be 4.3756 µA. In this case PT and PL would be 19.138µW and 19.136µW respectively, and so ‘n’ would be 99.99%. As we can see, in the latter case the power efficiency is higher, however, the total power and the power transferred to the load is less. Note that depending on the real impedance of the used category cable which can be within the 15% tolerance range of 100 Ω, the actual values of ‘PTOT’, ‘PL’, and ‘n’ can be slightly lower or higher than the values calculated here.

Since the signal obtained from an Ethernet link is AC, before inputting to PMIC, it needs to be converted to DC. In this regard, the next step is designing the most appropriate and low power consuming interface circuit taking into consideration the characteristics of Ethernet signal along with the variables affecting the signal.

5.3. Interface Circuit Design

The design of the interface circuit is one of the challenging steps in the development of Ethernet Energy Harvesting system. The different signaling of 10Base-T, 100Base-TX, and 1000Base-T standards, the variables affecting the signal such as the electrical characteristics of the interface used, transmission speed, power consumption of the interface circuit itself, and the limitations of the power management unit have to be considered in the design.

The first step in the design of the interface circuit is the rectifier stage to be used to convert the AC signal obtained from TX+ & TX- (+BI_DA & -BI_DA in 1000Base-T) wires of the cable to DC signal. High frequency of Ethernet signal and power consumption of rectifier circuit itself are the most crucial factors to consider. Therefore, in the rectifier part, because of their quick response time and low forward voltage drop, schottky diodes have been used.

The diode power loss is the sum of the forward bias power loss that occurs while charging and the reverse bias power loss that occurs during reverse recovery. Since each of these events happens once per cycle, the diode power loss is proportional to frequency. This means that because of the high frequency of the Ethernet signal, a
noticeable amount of power loss is inevitable, especially while using 100Base-TX and 1000Base-T standards. However, in order to minimize this power loss as much as possible, we are using “BAT54” Schottky diodes which have a very low forward bias voltage (320 mV when $I_F=1mA$, 400 mV when $I_F=10mA$ and 500 mV when $I_F=30mA$, ‘$I_F$’ stands for forward current) and a response time as low as 5 ns. The figure below shows the initial version of the interface circuit used as a peak detector.

![Figure 17 – Peak Detector Circuit](image)

As we know, the maximum P-P voltage on an Ethernet link can be obtained using 10Base-T standard. In order to see what the maximum output voltage of the peak detector using 10Base-T, 100Base-TX and 1000Base-T Ethernet as input would be, we have applied TX+ and TX- wires of Cat5e cable as input to the rectifier, and measured the output.

Using 10Base-T standard with full bandwidth usage, the average DC output voltage is 3.37 V while it is 1.39 V and 1.47 V respectively when the inputs are 100Base-TX IDLE and 1000Base-T IDLE signals. As mentioned in section 4.2, for a power source to be applied to CHG pin, it has to be generating output voltage over 4.21 V which is above the maximum output voltage we can obtain from our peak detector. In this case we have to apply the output of the peak detector to the boost enabler pin of MAX17710. However, the boost enabler input has to be limited to 2 V which is below the maximum output of the peak detector. Therefore, though it causes extra power dissipation, we have limited the output of the peak detector to 2 V by placing a zener diode to its output as in Figure 18, and measured the output.
The zener used at the output of the interface circuit is BZX 55/C2V7, a 2.7V zener diode. We have also tried 2V (BZT 55C2V0) and 2.4V (BZX 55C2V4) zener diodes at the output and observed that as the zener voltage decreases, the zener dissipates more power as expected. The reason for higher power dissipation by lower voltage zener diodes is that in order to regulate the voltage drop, zener diodes draw more or less current. Regulating the voltage at a lower value requires drawing higher current which causes higher power dissipation. Therefore, in order to minimize the power dissipation caused by zener diode, after making sure that the peak detector output voltage never reaches over 2V under any circumstances while using 2.7V zener at the output, we have designed the interface circuit with 2.7V zener diode at the output.

Note: Even though the output of peak detector circuit is lower than 2 V when the input is 100Base-TX or 1000Base-T, we have observed that with some NICs, until the output voltage of the peak detector becomes stable, it gives values over 2 V which can damage MAX17710. Therefore, even for 100Base-TX and 1000Base-T it is required to limit the output voltage to 2V for protection purposes.

![Experimental Setup for Measuring the Output of Interface Circuit](image)

Figure 18 – Experimental Setup for Measuring the Output of Interface Circuit

Figure 19 illustrates the output signal of the interface circuit when the input is 10Base-T link and the transmission speed is 500 KB/s.
Figure 19 – Output of Interface Circuit when the input is 10Base-T (500KB/s)

The table below indicates the average DC voltage values obtained from the output of the interface circuit when 10Base-T signal with alternating packet transmission speeds as well as 100Base-TX and 1000Base-T IDLE signals applied to its input as power source.

<table>
<thead>
<tr>
<th>VOUTPUT – INTERFACE CIRCUIT (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Base-T</td>
</tr>
<tr>
<td>IDLE 10 KB/s 100 KB/s 500 KB/s 1 MB/s Full BW</td>
</tr>
<tr>
<td>0.61 0.71 1.05 1.45 1.71 1.74 1.09 1.17</td>
</tr>
</tbody>
</table>

Table 10 – Output Voltage of Interface Circuit

Note: We have done the same experiment using different NICs and different cabling standards to get more robust results. We have observed that the output voltage values of 10Base-T are in approximately 5% tolerance range of the values above whereas the tolerance range is approximately 15% for 100Base-TX and 1000Base-T standards.

With the design of the appropriate interface circuit, now we are ready to go to next steps where the feasibility of Ethernet as a power source has been determined, the performances of 10Base-T, 100Base-TX and 1000Base-T have been compared, and the variables affecting the level of available energy have been discovered.
5.4. Testing the Charging Performance of 10Base-T, 100Base-TX and 1000Base-T

In this step, we have observed and compared the charging performance of 10Base-T standard with alternating packet transmission speeds, 100Base-TX standard and 1000Base-T standard. To this end, the experimental setup has been achieved as seen in Figure 20. In the measurement of BATT pin voltage and R6 voltage, UNI-T UT33D model digital multimeter has been used in this and the following experiments. While charging, the subtraction of R6 voltage from BATT pin voltage gives the voltage the cell is being charged with, namely the charging voltage. Multiplication of the charging voltage by the charging current which can be calculated from the voltage drop on R6 will give the charging power. The same multimeter has also been used for the measurement of the input voltage and current of the MAX17710 boost pin, multiplication of which will give us the input power to MAX17710.

![Figure 20 – Experimental Setup for Measuring Charging Performance](image)

The reason of measuring the CHG pin and R6 voltage is that the higher values of them means greater energy is available from the source, which provides the cell with faster charging. From the boost regulator operation described in section 4.2, we know that increasing power available at the output of the interface circuit will cause faster charging of the harvest-source capacitor connected to boost enabler, and so the CHG pin voltage to rise above the battery voltage more frequently. Considering that the
charge is delivered to the MEC101 when CHG rises above the voltage of VBATT, by observing how often CHG rises above VBATT we would be able to compare the charging performance of each standard. Moreover, from the voltage dropping on R6 we can extract the charging current which is directly proportional with the charging performance.

Below in the figures (Figure 21 - 24) indicated are the signals observed on CHG pin while charging using 10Base-T standard with 10KB/s and 1 MB/s transmission speeds, 100Base-TX and 1000Base-T standards respectively. Furthermore, Table 11 indicates the charging current of 10Base-T with a number of speed options, 100Base-TX and 1000Base-T. Since transmission speed has no effect on either CHG pin voltage or R6 voltage while charging with 100Base-TX and 1000Base-T standards, we have done all our experiments regarding these standards using only IDLE signal.

Figure 21 – VCHG while charging with 10Base-T (Transmission Speed = 10KB/s)
Figure 22 – VCHG while charging with 10Base-T (Transmission Speed = 1MB/s)

Figure 23 – VCHG while charging with 100Base-TX
From the figures above we can extract that while charging with 10Base-T standard, as the packet transmission speed increases, CHG pin voltage raises over VBAT more frequently which means the charging performance increases. The table below indicates the charging current of different standards obtained by dividing the voltage dropping on R6 by ten.

<table>
<thead>
<tr>
<th></th>
<th>10 Base-T</th>
<th>100Base-TX</th>
<th>1000Base-T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 KB/s</td>
<td>100 KB/s</td>
<td>500 KB/s</td>
</tr>
<tr>
<td>IR6(µA)</td>
<td>5</td>
<td>39</td>
<td>216</td>
</tr>
</tbody>
</table>

Table 11 – Charging Current of Ethernet Link

As we see from the table above, as the transmission speed increases in 10Base-T standard, the charging current also increases as expected. The interesting point is that the charging current increases almost linearly with transmission speed. Double transmission speed causes approximately double charging current. This is actually not very surprising since the transmission speed is directly proportional with the number of bits on the link. Two times of bits traversing on the link expose two times of energy on the link which causes two times of charging current.
Since the typical differential output voltage and clock frequency for 100Base-TX and 1000Base-T standards are same, approximate level of energy availability is expected. The difference comes from that, on a 1000Base-T link, the signal goes to 0V level less comparing to 100Base-TX link, because five levels are used instead of three, and 0V level is used only for FEC as mentioned in section 4.1.3.3.

Note: The values above have been measured when the cell had just started being charged. Over time, VBATT & VCHG increases, and after VBATT reaches 4.125V, IR6 (charging current) decreases since current flow is limited to regulate the cell voltage to 4.125V for protection purposes as described in section 4.2.

5.5. The Effect of Different Cabling Standards on Available Energy Level

Furthermore, we have performed the same experiment above using different cabling standards to see if the different characteristics of various cabling standards will result in a difference in the charging performance. The table below indicates the charging current of the Ethernet link built up with the Marvell Yukon interface and various cabling standards. Note that each cable was approximately four meters, and the signal was pulled from around two meters far from the transmitting end of the cable.

<table>
<thead>
<tr>
<th>Interface: Marvell Yukon 88E8059</th>
<th>10 Base-T</th>
<th>100Base-TX</th>
<th>1000Base-T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 KB/s</td>
<td>100 KB/s</td>
<td>500 KB/s</td>
</tr>
<tr>
<td>Cat5</td>
<td>5</td>
<td>38</td>
<td>205</td>
</tr>
<tr>
<td>Cat5e</td>
<td>5</td>
<td>39</td>
<td>216</td>
</tr>
<tr>
<td>Cat6</td>
<td>5</td>
<td>43</td>
<td>218</td>
</tr>
</tbody>
</table>

Table 12 – The Effect of Cabling Standard on Charging Current

From the table above it can be seen that higher energy is available from an Ethernet link through newer cabling standards. However, we have used other sets of Cat5 cables with different lengths and observed charging currents as low as 11 uA and as high as 65uA on a 100Base-TX link with the same interface. That means the length of the cable also is an important variable affecting the energy available from Ethernet. The bullet points below are to generally summarize the cable effect on energy availability from an Ethernet link:
• With the same length of cables, Cat6 cables always give better performance than Cat5/5e cables. Cat5e cables usually gives better performance than Cat5 cables.
• Various cables from the same cabling standard and length give slightly different performance.
• The length of the cable has the most effect on Cat5 cables whereas has the least effect on Cat6 cables which must be mostly because of better attenuation characteristics of Cat6 cables.

5.6. The Effect of Different Ethernet Interfaces on Available Energy Level

Since it is giving the best performance, we have built another Ethernet link using the same Cat6 cable used in the previous experiment along with various Ethernet interfaces to observe the effect of different NICs on the available energy level. The table below shows the charging currents provided from the Ethernet link using three different NICs.

| NIC 1: Marvell Yukon 88E8059, NIC 2: D-Link DGE-528T, NIC 3: NETGEAR DS104 Port | IR6 (µA) |
|---|---|---|---|---|---|
| Cabling Standard : Cat6 | 10 Base-T | 100Base-TX | 1000Base-T |
| | 10 KB/s | 100 KB/s | 500 KB/s | 1 MB/s | Full BW |
| NIC 1 | 5 | 43 | 218 | 438 | 539 | 45 | 51 |
| NIC 2 | 4 | 41 | 213 | 429 | 523 | 58 | 63 |
| NIC 3 | 5 | 42 | 214 | 431 | 528 | 69 | N/A |

Table 13 – The Effect of various NICs on Available Energy Level

As we can see from the table above, different charging currents from different interfaces can be obtained. The interesting point is that with some interfaces even though the charging current of 10Base-T standard is better, it can be worse in 100Base-TX and 1000Base-T standard. The difference in charging performance of different NICs must be mostly because of the difference in the differential output voltage defined by these NICs specific to each standard.
An interesting point regarding 1000Base-T is that with some of the interfaces when we connect the +BI_Data_A and –BI_Data_A pins to the input of the interface circuit, we see that the link disconnects in less than a second. On the same interface, same thing happens with all wire pairs. In this case, we have connected +BI_Data_A and -BI_Data_B pins to interface circuit which provides slightly different charging current. We assume that the disconnection problem occurs because of the characteristics of the hybrid circuit used in 1000Base-T line transmission.

We have shown that the Ethernet links built by different cabling standards and interfaces give different charging performance. We have also observed that newer cabling standards give better performance. In order to set the most optimum environment regarding energy harvesting, revealing what characteristics of category cables and interfaces affect the available energy level can be a separate project.

5.7. Power Efficiency of MAX17710

In order to reveal how much of the power the PMIC is able to transfer from its input to the cell, we have indicated the measured input and charging voltage and current values and the calculated power values in Table 14. Furthermore, Figure 25 compares the input power with the charging power to evaluate the efficiency of MAX17710.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Input Voltage (V)</th>
<th>Input Current (µA)</th>
<th>Input Power (mW)</th>
<th>Charging Voltage (V)</th>
<th>Charging Current (µA)</th>
<th>Charging Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Base-T</td>
<td>10KB/s</td>
<td>0.531</td>
<td>51</td>
<td>0.027</td>
<td>3.9</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>50KB/s</td>
<td>0.539</td>
<td>255</td>
<td>0.137</td>
<td>3.9</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>100KB/s</td>
<td>0.540</td>
<td>505</td>
<td>0.273</td>
<td>3.9</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>200KB/s</td>
<td>0.542</td>
<td>1010</td>
<td>0.547</td>
<td>3.9</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>500KB/s</td>
<td>0.558</td>
<td>2530</td>
<td>1.412</td>
<td>3.9</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td>1000KB/s</td>
<td>0.582</td>
<td>5130</td>
<td>2.986</td>
<td>3.9</td>
<td>438</td>
</tr>
<tr>
<td>Full BW</td>
<td>0.582</td>
<td>6300</td>
<td>3.667</td>
<td>3.9</td>
<td>539</td>
<td>2.102</td>
</tr>
<tr>
<td>100Base-TX</td>
<td>0.639</td>
<td>547</td>
<td>0.350</td>
<td>3.9</td>
<td>45</td>
<td>0.176</td>
</tr>
<tr>
<td>1000Base-T</td>
<td>0.648</td>
<td>625</td>
<td>0.405</td>
<td>3.9</td>
<td>51</td>
<td>0.199</td>
</tr>
</tbody>
</table>

Table 14 - Comparison of Input Power vs. Charging Power
Note that the charging voltage increases by time and is limited to 4.125V. When the charging voltage reaches 4.125V, the charging current starts decreasing to prevent overcharging (see Figure 26 and 27). As the charging voltage increases, the charging power also increases. The maximum charging power will be reached when the charging voltage reaches 4.125V just before the charging current starts decreasing. At this point, the charging power is maximum but only 6% above the charging power values given in the table. Moreover, with 100Base-TX and 1000Base-T standards, even after 1 hour charging, the charging power will reach only 1% above the values given in the table. Therefore, in all calculations the charging power values given in the table are used. From Figure 25 we can see that MAX17710 is able to transfer over 50% of its input power to the cell.

![Figure 25 – Input Power vs. Charging Power](image)

Figures 26 and 27 illustrate the variation in the charging voltage and charging current over time respectively. Note that, in case of charging, V\text{BATT} gives the charging voltage whereas otherwise it gives the cell voltage. On the other hand, in case of charging, I\text{R6} gives the charging current; in case of discharging, it gives the discharging current; in case of simultaneously charging and discharging, it gives the subtraction of the discharging current from the charging current. When the cell
reaches the level that it holds the maximum energy of its capacity, it means that the cell is fully charged. When no energy is left from its reserved energy, then it means the cell is fully discharged.

From Figure 27, we can extract that fully charging using 10Base-T standard with Full BW, 1MB/s and 500 KB/s took around 3 hours, 3.5 hours, and 5.5 hours respectively. However, fully charging time using 100Base-TX and 1000Base-T standards is estimated over 50 hours. Comparing the two graphs, we can see that the charging current starts decreasing when the charging voltage reaches 4.125 V. When the charging voltage reaches 4.125V, the cell is approximately 85% charged, and reaching up to that level takes approximately 1.5 hours, 2 hours, and 4 hours charging with 10Base-T Full BW, 1 MB/s, and 500 KB/s respectively. We can say that even though fully charging time is non-linear-inversely proportional with transmission speed, the time until it takes for charging voltage to reach 4.125V is almost linear-inversely proportional with the transmission speed. These results prove us that the available power from a 10Base-T link is almost linear-directly proportional with the transmission speed.

Figure 26 – Charging Voltage over Time
5.8. Testing Discharging Performance

Since very long charging times are expected while charging with 100Base-TX and 1000Base-T standards, we have not gone for fully charging the cell with these options. However, in order to get more robust results, we have also observed and compared the fully discharging time of the cell after charging it using 10Base-T standard with different transmission speeds, 100Base-TX and 1000Base-T standards. In this regard, we have set the experiment as seen in Figure 28. We have set the REG output of MAX17710 as 2.3V, and connected a LED circuit as load which draws maximum 1.24mA current. We have charged the fully discharged cell during 1 hour using 10Base-T standard with 10KB/s, 100KB/s, 500KB/s, 1MB/s, Full BW speeds, 100Base-TX and 1000Base-T standards respectively. The reason for charging 1 hour is to ensure that the charging voltage will not reach 4.125V, and so the cell will always be charged by the maximum power that can be provided by each option.
Figure 28 – Experimental Setup for Observing Discharging Time

Figure 29 and 30 show how the discharge current and cell voltage vary over time, and also indicate the time it takes until the cell is fully discharged.

Note: With this LED circuit it takes 46 minutes to discharge the fully charged cell.

Figure 29 – Discharging Current over Time
Through the experiments and measurements performed during this step, we have revealed how much energy can be obtained from Ethernet, and the factors affecting the available energy. The next step is to design a real-world implementation environment to utilize Ethernet as a power source.
6. DEVELOPMENT OF WIRELESS SENSOR NODE TO BE POWERED BY ETHERNET

WSNs are a popular implementation area for energy harvesting techniques since they present an ideal match between energy available from harvesting and power requirements of the application. Therefore, we have also chosen WSN as implementation environment to test Ethernet Energy Harvesting system in a real world problem. In this regard, we have developed a WSN to be powered by Ethernet. In our design, the WSN establishes connection with a base station and transmits sensor data with specific time intervals. The sensor data is received by another radio unit directly connected to a PC and displayed on the PC used as base station through a console application. Figure 31 illustrates the setup of the simple wireless sensor network where the performance of Ethernet as a power solution has been tested and the optimum operation conditions have been determined.

The idea behind this implementation is to prove that a WSN can generate all of its operating power by harvesting energy from Ethernet packets, and so exclude the use of any battery or other energy storage devices except for the MEC which is a part of the harvesting circuit. The system works by harvesting energy from Ethernet packets while the sensor node is in a low power state, and at intervals the sensor node comes out of low power state and sends sensor data to base station. The goal is to see how often that can be done depending on the Ethernet standard used.
Note that the setup above is for demo purposes. The sensor node actually does not need to be connected to the same Ethernet link with the base station. HUB is used to establish Ethernet connection with PC so that EEH Board can capture the energy from the Ethernet packets transmitted by PC to HUB. Any device with an Ethernet interface can be replaced by HUB, and the system will work the same way. The reason that PC must be connected to HUB or any other Ethernet interface is that if both ends of the Ethernet cable are not connected to an Ethernet interface, Ethernet connection cannot be established and no packet can be transmitted by PC.

As the power consumption requirements of an application decrease, longer run time of the application with lower energy source can be achieved. Therefore, in our design of the sensor node, by choosing low power units and efficient configuration, we have tried to minimize power consumption.

6.1. Sensor Node Units

Our sensor node simply comprises of a sensor, the data of which will be processed and transferred, a microcontroller (MCU) unit which will process the sensor data, and a radio unit which will be used to provide wireless communication with the base station and transfer the sensor data received from MCU.
As MCU, ultra-low power MSP430F2252 [42] from MSP430 family has been used. MSP430F2252 also allows usage of low frequency external clock sources of 32.768 kHz for lower power consumption. Furthermore, it has low-power modes enables optionally disabling CPU and clocks when unused which puts the MCU in passive mode and remarkably reduces the power consumption. The details in how MSP430F2252 functions can be found in MSP430x2xx2 datasheet [42].

NRF24AP1 [43], an ultra-low power single-chip 2.4 GHz radio transceiver by Nordic Semiconductor with embedded ANT protocol [44], has been chosen as radio unit. It allows interfacing to a host microcontroller over either synchronous or asynchronous serial interface. It gives the flexibility of choosing from 4800, 19200, 38400, and 50000 Kbps baud rates when in asynchronous mode, and byte or bit modes when in synchronous mode. A 32.768 kHz clock signal may optionally be provided to nRF24AP1 through an external clock source which is recommended for power sensitive applications. For further details, see the nRF24AP1 datasheet [43]. As radio unit, we are using a pre-built radio module, MiRF-NRF24AP1 [45], combining nRF24AP1 with a trace antenna.

ANT is a wireless sensor network protocol running in the 2.4 GHz ISM band designed for ultra-low power. Since it is an extremely compact protocol stack, it requires minimal microcontroller resources which remarkably reduce the system cost. With a few number of specific ANT messages, it is possible to configure an ANT enabled radio chip to establish channel connection and transfer data on the channel. “ANT Message Protocol and Usage” [46] details the protocol and provides examples of how to use ANT for wireless networking.

Moreover, as sensor we are using a light sensor, resistance of which decreases as the light intensity in the environment increases. Figure 32 simply illustrates how the connection between the units forming the sensor node as well as selection of serial interface mode and baud rate of nRF24AP1 is achieved. Note that the MiRF-NRF24AP1 module had to be modified to bring out the SLEEP and EXT32 pins of the radio chip.
6.2. Configuration Aspects

The proper configuration of both MCU and radio unit is crucial to achieve power sensitivity. As we can see from the figure above, serial communication mode (Async), baud rate (4800kbps), and sleep mode of nRF24AP1 are achieved in hardware by tying regarding pins low or high. The channel configuration of nRF24AP1 is achieved by sending ANT specific messages on async serial interface in form of hex data. Detailed information on ANT specific messages can be found here [46]. Sleep pin of nRF24AP1 is connected to an output pin of the MCU, so when unused it can be put into sleep mode for reduced power consumption just by enabling the regarding output pin. Moreover, nRF24AP1 is sourced from an external 32.768 KHz clock for power sensitivity by connecting its EXT32 pin to ACLK pin of MSP430. With this setup, when in sleep mode without any channel activity, the current consumption of nRF24AP1 is typically 2 µA.

Unlike nRF24AP1, communication mode, baud rate, and low power mode of MSP430F2252 are software selectable. As we see from Figure 32, XIN and XOUT pins of the MCU is connected to an external 32.768 KHz crystal which would reduce the power consumption as mentioned before. Moreover, the light sensor is connected to ADC pin directly and to an output pin through a resistor in order to activate the light sensor only when its data needs to be read, so that it will not continuously
consume power. When in low power mode-3 (internal clocks and CPU is disabled), the current consumption of MSP430 is typically 0.7 µA.

The flow diagram (Figure 33) simply illustrates how the MSP430 code and the application at the base station for providing communication with the radio unit are organized. As we can see from the flow diagram, after configuring the MSP430, nRF24AP1 is reset to detect the presence of the external clock source. Actually, the nRF24AP1 automatically detects the presence of the external clock source when powered up, however, in order to avoid timing issues and ensure detection, system reset is applied as recommended.

After reset, sleep pin of nRF24AP1 is driven high by the signal from MSP430 to achieve low power current of 2 µA. Subsequently, interrupt is enabled and MSP430 enters low power mode where internal clocks and CPU are disabled. MSP430 exits low power mode only in case of interrupt which occurs when timer reaches a specific value.

When interrupt is called, if the counter value has reached a predefined value, the sleep pin is driven low, and nRF24AP1 is configured. Now that the ANT channel is configured, the sensor is enabled, through ADC its data is read, and sent over the channel as broadcast data. Then the sleep pin is driven high again while the channel is active to lower the power consumption and a delay is given for waiting for establishing connection with base station and the sensor data to be received by the base station. After the data transfer is succeeded, nRF24AP1 is reset again to terminate all channel connections which is followed by sleep pin being driven high to enter low power mode of 2 µA.

The reason for using a counter variable is to achieve longer IDLE mode periods than 500 ms which is the maximum value the timer can be set. With Timer value set to 500 ms, the desired IDLE mode period can be achieved by setting the counter variable to the value obtained by dividing the IDLE mode period by 500 ms. For example, if we want to achieve 20 seconds of IDLE mode period, we need to set the counter variable as 40. The reason we are sending sensor data as broadcast data is that broadcast data causes the lowest power consumption among all data types.
Furthermore, WSN is set as master node by setting channel type as transmitting channel, and Base Station as slave node by setting channel type receiving channel which are achieved through ANT Assign Channel message. Since power consumption is not an issue at the base station side, all need to be done is configuring and opening the serial com port, configuring nRF24AP1 by sending regarding ANT specific messages to it in forms of hex data, and then check the input buffer continuously. Whenever a broadcast event message is received, nRF24AP1 will pass it on the serial interface, and the message will be processed and displayed on the screen through the console application. One extra configuration in nRF24AP1 at base station side is defining channel search timeout time. By default, search timeout time is 30 seconds which means if the base station cannot find any channel to establish connection within 30 seconds, it will close the channel. In our code we have set the search timeout time as infinite so that the base station will keep the channel always active and searching.
Figure 33 – Flow Diagram
7. ANALYSIS OF THE SYSTEM

In this section, the goal is to measure the power consumption of the sensor node developed in the previous section, and determine the optimum operating conditions of the sensor node according to the charging performance of each Ethernet standard used. In order to find the power consumption of the sensor node, it is connected to the REG output (adjusted as 2.3V) of the already recharged MAX17710 as seen from the figure below. As we know, division of R6 voltage by ten gives us the discharging current, and multiplication of the measured discharging current by the discharging voltage of the cell gives us the power consumption of the sensor node.

![Diagram of experimental setup]

Figure 34 – Experimental setup for measuring the power consumption of the WSN

Initially, in our code, we have defined the low power mode period as 10 seconds for observation purposes where we have measured the current consumption of the sensor node during different states. Furthermore, it has been coded in a way that when the environment is light it sends “Light” message and “Dark” message when it is dark. This has been achieved by comparing the ADC value with the half of VCC value. Note that as the environment gets darker, the ADC value becomes greater. It could also be coded in a way that the ADC value is directly sent as message to the base station. However, for demo purposes, the former case has been preferred.
The table below shows what modes are achievable for sensor node according to the states of MSP430 and nRF24AP1 as well as the measured current consumption and calculated power consumption of the sensor node during each of these modes. Note that even though the sensor node is run by 2.3V through the REG output of the MAX17710, the power consumed by the sensor node from the cell must be calculated using the voltage value of the cell during discharging which is around 3.9V at the beginning and decreases by time. In the table, the voltage value is given as 3.9V to calculate the approximately maximum power consumption of the sensor node in each mode. Using these maximum power consumption values later in the formula which will be used to determine the Idle Mode periods will cause calculating longer Idle Mode periods than required. However, defining longer Idle Mode periods is beneficial since it prevents the cell from being fully discharged and also provides the cell with extra charge which can be needed in failure cases such as when the network is down and no signal (no energy) is available on the Ethernet link.

<table>
<thead>
<tr>
<th>MSP430</th>
<th>NRF24AP1</th>
<th>Sensor Node Mode</th>
<th>Current (mA)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Mode</td>
<td>Channel Active &amp; Sleep Mode Disabled</td>
<td>Active</td>
<td>2.7</td>
<td>3.9</td>
<td>10.53</td>
</tr>
<tr>
<td>Normal Mode</td>
<td>Channel Active &amp; Sleep Mode Enabled</td>
<td>Sleep</td>
<td>0.53</td>
<td>3.9</td>
<td>2.07</td>
</tr>
<tr>
<td>Low Power Mode</td>
<td>No Channel Activity &amp; Sleep Mode Enabled</td>
<td>Idle</td>
<td>0.0055</td>
<td>3.9</td>
<td>0.021</td>
</tr>
</tbody>
</table>

Table 15 – Power Consumption of the WSN

The total current consumption of the sensor node in Idle mode is 5.5 µA. NRF24AP1 consumes 2.5 µA of it whereas MSP430 consumes 3 µA of it. The current consumption of nRF24AP1 is reasonable considering its typical current consumption in sleep mode while all channel activity is disabled is 2 µA. On the other hand, the typical current consumption of MSP430 in low power mode is defined as 0.7 µA in the datasheet [42], however, we see a current consumption of 3 µA. The reason for that is clocking nRF24AP1 through ACLK pin of MSP430. When we do not clock nRF24AP1 by the signal from ACLK pin of MSP430, the current consumption of MSP430 in low power mode is 0.7 µA as expected, however, in this
case, the current consumption of nRF24AP1 goes up to 70 μA since nRF24AP1 operates at 16 MHz frequency, instead of 32 KHz, because of the 16 MHz external crystal between the XC1 and XC2 pins of it [43].

7.1. **Formulation of System Operation**

As seen from Table 15, the power consumption of the sensor node is 0.021 mW in IDLE mode, 2.07 mW in sleep mode and 10.53 mW in active mode. Knowing these values, we can create a formula as below which allows us to determine the IDLE mode period of the sensor node as a function of standard type. IDLE mode period gives the time intervals the sensor node can come out of low power state and transmit sensor data.

- AMP: Active Mode Period (seconds)
- SMP: Sleep Mode Period (seconds)
- IMP: Idle Mode Period (seconds)
- CP: Charging Current of Ethernet Link (mW)

\[
(AMP \times 10.53) + (SMP \times 2.07) + (IMP \times 0.021) = (AMP + SMP + IMP) \times CP
\]

\[
IMP(CP - 0.021) = AMP(10.53 - CP) + SMP(2.07 - CP)
\]

In order to both simplify the formula and to ensure that the cell will never be fully discharged, we have ignored the charging power during AMP and SMP, hence modified the formula as below. Note that ignoring the charging power during AMP and SMP results in charging the cell with energy slightly more than it needs.

\[
IMP(CP - 0.021) = (AMP \times 10.53) + (SMP \times 2.07)
\]

Active mode period of the sensor node is 1s in total because of the delays given after system reset. In the current setup, 2 seconds for sleep mode period is enough for the sensor node to be able to establish communication with the base station and transfer the sensor data. However, we have defined SMP as 5 seconds to ensure that it will have adequate time to send sensor data before entering IDLE mode. With these periods known, all needed is to determine IMP from the formula given below according to the charging current provided from the Ethernet link.

\[
IMP(CP - 0.021) = 20.88 \text{ mJoule}
\]
7.2. Operating Conditions According to Ethernet Standard

Table 16 indicates the charging power of the Ethernet link built with Marvell Yukon 88E8059 NIC and Cat6 cables for each Ethernet standard. With those values, using the formula given earlier, we have calculated the idle mode period for each standard indicated by Table 17.

<table>
<thead>
<tr>
<th>Standard</th>
<th>AMP (sec)</th>
<th>SMP (sec)</th>
<th>IMP (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Base-T</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10KB/s</td>
<td>1</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>100KB/s</td>
<td>1</td>
<td>5</td>
<td>142</td>
</tr>
<tr>
<td>500KB/s</td>
<td>1</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>1000KB/s</td>
<td>1</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Full BW</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>100Base-TX</td>
<td></td>
<td></td>
<td>135</td>
</tr>
<tr>
<td>1000Base-T</td>
<td></td>
<td></td>
<td>117</td>
</tr>
</tbody>
</table>

Table 16 - Charging Power of Ethernet Standards

Table 17 - Operating Conditions According to Ethernet Standard

IMP is the time interval the sensor data can be transferred to the base station. For example with 100Base-TX link, the sensor data can be transferred to the base station after every 135 seconds of Idle Mode. During 135 seconds, since the charging power
is greater than the consuming power, the cell will be charged to be able to power the sensor node during AMP and SMP (6 seconds in total) for it to establish communication and transmit the sensor data.

Testing the formula, we have achieved 1 second of AMP, 5 seconds of SMP, and 135 seconds of IMP in the code. Running the system by 100Base-TX link providing 176 $\mu$W charging power, we have seen the system operating as expected which confirms our formula. Moreover, when we stopped powering the sensor node right after it enters IMP mode for the second time, we have observed that the cell still has some charge in it due to the robustness we have provided in the formula which allowed some extra charging. That means the sensor node actually can transfer its data with shorter time intervals than the IMPs given in Table 17.

The charging power of 100Base-TX (176 $\mu$A) and 1000Base-T (199 $\mu$A) and so the same IMPs can be achieved by 10Base-T system with approximately 75KB/s and 125KB/s transmission speeds respectively. The maximum charging power from 10Base-T line can be provided in case of full bandwidth usage which is 2.102 mW with the current interface and Cat6 cables used. Putting 2.102 mW as CP in the formula, we get an IMP of 10s. When we run the system by 10Base-T with full bandwidth usage, IMP defined as 10s in the code, we have observed the system working flawless.

However, requiring longer or less IMP of the sensor node run by different Ethernet links because of different NICs or cables providing lower or higher energy levels is most likely. In such cases, all need to be done is recalculating the IMP from the formula given above according to the CPs provided by Ethernet links.
8. CONCLUSION AND FUTURE WORK

In this thesis report, we have examined Ethernet as a power solution. We have revealed how much energy is available from Ethernet along with the factors affecting the available power. We have created a real world implementation area where we have used Ethernet Energy Harvesting technique as power source. Specific to standard type, we have determined recommended operation conditions. We have discovered that 10Base-T standard provides more energy, however, comes up with disadvantages such as requiring packet transmission and being obsolete. On the other hand, 100Base-TX provides less energy comparing to 10Base-T, but doesn’t require packet transmission, and currently is the most popular Ethernet standard. 1000Base-T also does not require packet transmission and provides energy levels slightly higher than 100Base-TX. The disadvantage of 1000Base-T is not being supported by most of the existing NICs. Consequently, we have proved that devices like WSNs can be built and installed such that they can generate all of their operating power from Ethernet packets and never need maintenance since they would be independent of batteries or any other extra power supplies.

Ethernet Energy Harvesting project is open to improvements. As we have observed, the characteristics of the Ethernet interfaces and category cables have a remarkable impact on the available energy from an Ethernet link. Revealing what characteristics of them have deterministic effect, which would help setting up the most convenient system for Ethernet Energy Harvesting, could be an improvement to this project. Designing a compact module for Ethernet Energy Harvesting which can be adjusted to use with a variety of applications depending on the application needs would be a good extension of this project. Furthermore, as Ethernet Energy Harvesting is based on accumulating energy from Ethernet packets, an interesting next step would be looking at the feasibility of harvesting energy from wireless network packets such as Wi-Fi packets.
9. REFERENCES


