Wirelessly Networked Telemetry System Architectures for Net-Zero Power Operation

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1. Introduction

The Industrial Internet of Things (IIoT) can be specifically defined as "a system comprising networked smart objects, cyber-physical assets, associated generic information technologies and optional cloud or edge computing platforms, which enable real-time, intelligent and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimize overall production value" [1]. Put succinctly, IIoT devices must have three primary functional components: sensory inputs and/or actuating outputs, computational elements, and a communication interface. Industrial facilities are often turning to IIoT as a method of improving efficiencies, predicting machinery failures, and monitoring supply and inventory levels. The increase in desired IIoT device usage implies that these devices will need to be installed in confined or inaccessible locations. As a result, it is highly desirable to develop an extensible sensor architecture which operates with a net-zero power supply system – requiring neither a connection to mains electrical distribution nor user intervention to replace batteries. Achieving this goal requires a two-pronged approach: reducing power consumption of the device itself and implementing a highly efficient energy harvesting and storage scheme. This paper will present ideas for reducing power consumption using a different approach than traditional mobile ad hoc network (MANET) routing protocols to reduce RF activity. Additionally, an array of energy harvesting and storage methods will be presented.

2. Reducing Power Consumption

2.1. Routing Protocols

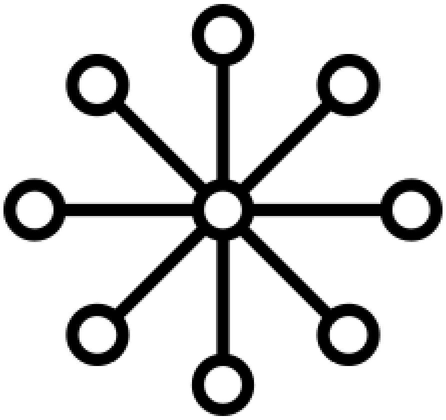

Figure 1: Star topology appropriate for IIoT networks.

The innate nature of traditional MANETs makes their respective routing protocols unsuitable for use in an IIoT network. Specifically, the mobile and ad-hoc nature of such networks requires frequent RF transmissions to maintain accurate routing tables. As nodes move around, a node may lose a previously held link with another node. Similarly, a new link with another node may be established. The frequency of node transmissions is generally proportional to the node speed. Usually, the transmission frequency is set such that the routing tables are updated to accommodate the maximum node speed. However, as mentioned in Section 3.1 these frequent RF transmissions result in substantially reduced battery life, making such a design unsuitable for an IIoT network.

The requirements associated with traditional MANETs do not apply to IIoT networks. First, IIoT devices are stationary, meaning they do not require frequent transmissions simply to maintain updated routing tables. Second, since the intent of IIoT devices is to deliver sensor data to a central node to take further action, IIoT networks usually employ a star topology shown in Figure 1, instead of a mesh topology of traditional MANETs, shown in Figure 2.

It is important to keep in mind that the topology in Figure 1 depicts communication at the "packet" level. Nodes may still communicate with each other at lower levels of the communication stack (although it will not necessarily be a mesh topology). Finally, since IIoT devices may be deployed in areas where accessibility may be impossible or costly, preserving battery life is the primary goal. All the above requirements of an IIoT network require a different approach in developing a routing protocol.

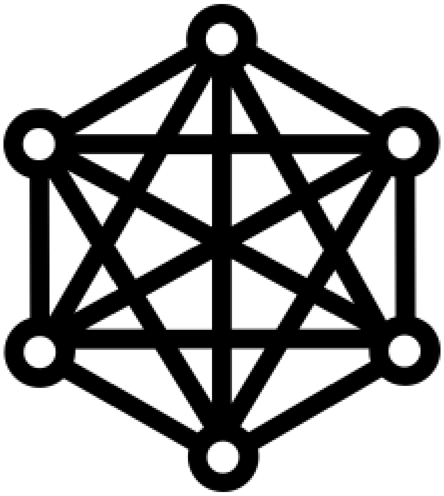

Figure 2: Mesh topology employed in traditional MANETs.

2.2. Hardware Methods

All conventional hardware design techniques used to reduce power consumption should be followed in the effort to maximize efficiency. Wherever possible, high-efficiency switch-mode power supplies (SMPS) must be used to avoid the I-V losses in a conventional linear regulator. When linear regulators must be used, they should be of the low-dropout type (LDO) and use minimal input voltage headroom. This may be accomplished by stepping down a high system input voltage to an intermediate voltage using an SMPS followed by an LDO. Any pull-up or pull-down resistors should be eliminated when possible. This implies that push-pull logic is preferred to open-drain protocols such as I^{2}C. If a pull-up or pull-down resistor must be added, it should have the highest practical resistance possible. On-chip pull-up or pull-down resistors should be investigated for suitability as well.

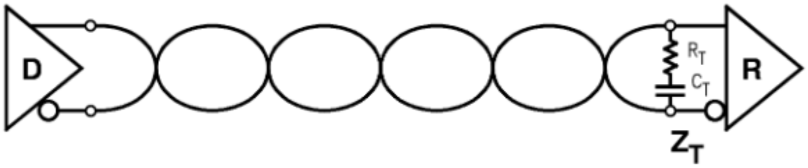

Figure 3: An example differential R-C termination [20].

Some digital signaling protocols often require shunt terminations such as RS-422/RS-485. In these situations, termination resistors should be carefully chosen such that they do not dissipate excessive power. In the event that they do, such as the 120Ω RS-422 termination, an exploration of R-C terminations should be undertaken. An R-C termination replaces the shunt resistor with a resistor-capacitor series network. This allows the high-frequency components to pass through the termination resistor when the signal toggles but blocks the low-frequency current. The net effect is a reduction in power dissipation over the resistor. The designer must take care to use an appropriate capacitor which blocks an effective portion of the low-frequency components yet does not negatively impact the rise-time of the signals.

3. Energy Harvesting and Storage

The idea of harvesting excess energy out of the ambient environment is not a new one, but recent advances in harvesting technologies combined with modern, low-powered computational and communications devices have made it a more viable source of power.

For the IIoT device to operate at net-zero power, there must be both a source of energy and a storage method. If the storage method is omitted, the device may operate for short periods when the energy is actively harvested but would be unable to operate otherwise. Alternatively, using an energy storage device allows perpetual energy collection regardless of the duty cycle of the IIoT device operation – limited only by the availability of the energy source and the capacity of the storage system. Net-zero power operation is defined within this paper as a system capable of collecting waste energy from its ambient environment, storing that energy for its own use, and never requiring supplemental energy in the form of an external power supply or discharged battery replacement. Achieving net-zero power operation will require that the amount of energy collected and stored is always greater than the amount of energy required for operation.

3.1. Calculating Energy Requirements

The most accurate power consumption data can be acquired via measurement. Prior to building hardware, however, the designer must make estimates. Using a combination of system requirements, software-defined behavior and datasheet specifications, the designer should first determine the various states of the system and power consumption during each state. Next, the duty cycle of each state should be approximated to gauge the equivalent steady state power draw. In an IIoT device with a wireless transceiver, the period of highest power consumption will come during data transmission. For example, if a system will be transmitting for T_1 hours per day at P_1 watts and idle for T_2 hours per day at P_2 watts, then average power can be calculated as shown in (1).

$$P_{avg} = \left[\frac{T_1}{24} \cdot P_1\right] + \left[\frac{T_2}{24} \cdot P_2\right] \{watts\} \tag{1}$$

This value may then be used for sizing the energy harvesting and storage system, assuming the operational duty cycle on-time is much smaller than the energy storage capacity. Alternatively, a very small energy storage system may be used if the load is triggered to activate upon reaching a predefined supply voltage threshold. This paper will only consider architectures where the energy storage system has enough energy capacity such that it is able to power the device for durations much longer than the duty cycle of operation.

3.2. Energy Harvesting Sources

As described in [2, pp. 28-29], there are six methods of creating electromotive force, or emf, in our physical world: friction, pressure, heat, light, chemical action, and magnetism. This paper will focus on heat, light, magnetism, and pressure. Friction-generated emf is most associated with static electricity generation and will not be explored here. Batteries create emf through chemical action, and while batteries will be discussed in Section 3.3, this paper will also not investigate this source for energy harvesting. Piezoelectricity is the primary source of pressure-generated voltage and while it is actively used in energy harvesting applications [3], it requires active force from moving bodies not necessarily available at remote IIoT device placement locations.

3.2.1. Heat Sources

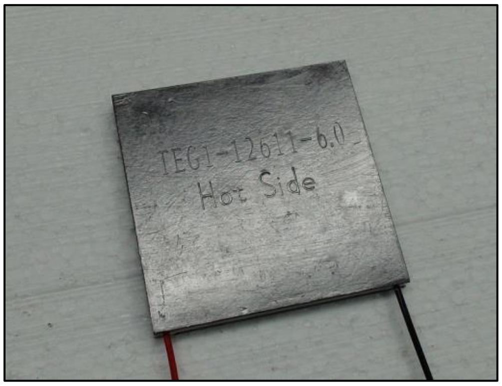

Figure 4: Thermoelectric generator [14].

A temperature differential may be used to harvest energy for an IIoT device with a thermoelectric generator (TEG) or thermopile. They operate by creating a bimetallic junction with dissimilar metals such as copper and iron. When heated, electrons tend to move away from the hot end in copper and towards the hot end in iron. When a circuit is completed, the electrons may then flow through a small load connected at the cold end. More power is generated when there is a greater temperature differential between the hot end and the cold end [2].

These devices could easily be coupled with an energy harvesting IC such as the LTC3108 from Analog Devices (Wilmington, MA, USA) to create a full harvesting and storage solution. The use of thermal energy for harvesting would be ideal for situations where the TEG could be placed against some equipment which consistently has a much higher temperature than the ambient environment such as the case of a high-powered, oil-cooled transformer. Thermal energy harvesting has a typical energy density of 20 – 60 μW/cm^2 when the heat source is a human body [4].

3.2.2. Light Sources

Using light as an energy harvesting source has the incredible advantage of higher power density and scalability from extremely small, low-powered systems up to large systems capable of significant power output. It has the disadvantage of only being able to source energy when light is available – typically only a fraction of the day for outdoor systems in most of the world.

Figure 5: Ubiquitous energy harvesting system present in waterways across the globe. Here, a buoy fitted with a 155mm lantern and 10W solar panel is being repaired in St. Thomas, USVI after a vessel collided with it [17].

Solar energy systems have been used for decades to power critical infrastructure. For example, the United States Coast Guard began exploring a modernization effort to upgrade illuminated aids to navigation (lighthouses and other lighted beacons) in the 1970’s and by 1986, the U.S.C.G. had converted approximately 3,000 navigational aids to solar power [5]. As of today, all navigational aids without access to commercial power utilize a solar charging system except for one: Boston Light, which maintains an on-site lighthouse keeper for historic reasons. A typical solar installation can generate up to 100 mW/cm^2 [4] – easily the best performing energy harvesting system. If the installation space is suitable, solar energy has the benefit of being easy to set up with commercial components widely available. Utilizing a solar energy harvesting system must account for factors such as the orientation of the panel and the amount of daylight available as a function of latitude and local terrain. Additionally, the energy storage system should be sized such that it accounts for extended periods of cloudy weather.

Interestingly, illumination technology has progressed significantly since the beginning of the modernization effort and even high-powered incandescent lamps are being replaced by programmable LED lanterns built by companies such as Sabik Marine (formerly Vega and Carmanah [6]). These lanterns are available with or without built-in solar panels and batteries and may be retrofitted into existing lighthouse control systems.

Figure 6: An example of critical infrastructure powered fully by solar energy harvesting. Southwest Ledge Lighthouse in New Haven, CT was fully automated in 1973. The solar panel array is located to the left of the main structure and the energy storage batteries are located on the main level inside the structure. Note the many various loads powered by this system: a primary VRB-25 rotating beacon, an emergency 300mm lantern, both primary and emergency FA-232 fog signals and a VM-100 fog detector – all visible within this image [7].

3.2.3. Magnetism Sources

Using electromagnetic fields for power transfer is not a novel idea, but modern components and simulation tools allow for optimal efficiencies. Any time a moving magnetic field is in the presence of a wire (or a moving wire in a magnetic field), emf is induced [2]. Both near-field and far-field radiation can be used for magnetic power transfer. Near-field energy harvesting is typically referred to as wireless power transfer and typically have high efficiency [4].

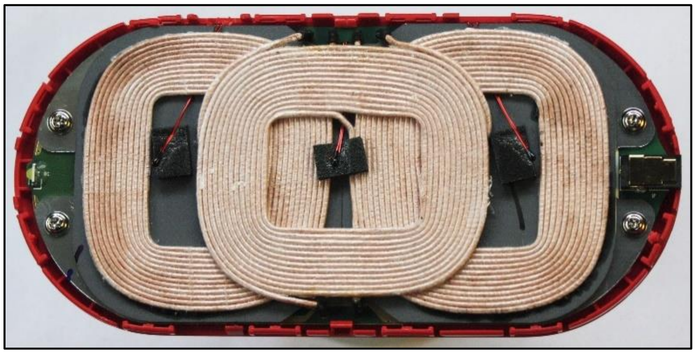

Figure 7: Internal image of a wireless charging receiver for near-field RF power transfer [15].

Conversely, far-field radiation is used primarily at RF with lower power systems and require a carefully designed and tuned antenna. Utilizing far-field radiation has the distinct advantage of being able to be used within inaccessible confined spaces such as a liquid holding tank or large cargo space. Far-field power transfer will typically have very limited power densities, on the order of 0.2 nW/cm^2 to 1 μW/cm^2 while near-field systems may be far higher, with over 80% efficiency in some cases [4].

Wireless energy harvesting of ambient electromagnetic waves is a challenge, but it is possible to obtain high open-circuit voltages if the field strength has a high magnitude and the receiver and rectifier design is sufficient. Even in the presence of 2.4 GHz Wi-Fi signals, there are examples of receiver designs showing over 1.3 V open-circuit voltage [8].

3.2.4. Pressure Sources

Electricity may be generated via pressure when applied to a crystalline structure such as quartz. In that case, the action of compressing and decompressing the crystal creates an electric potential difference between the faces of the crystal [2]. This is commonly known as piezoelectricity, and its converse effect is most often found in crystal oscillators where an applied voltage causes resonance at a specific frequency. The most common occurrence of piezoelectric energy harvesting is in the ubiquitous barbeque grill ignition switch, which uses the compression of a crystal to generate the high voltage required to spark across an electrode gap [9]. It is also possible to use vibration as an energy source to deform a piezoelectric generator such as is shown in Figure 8.

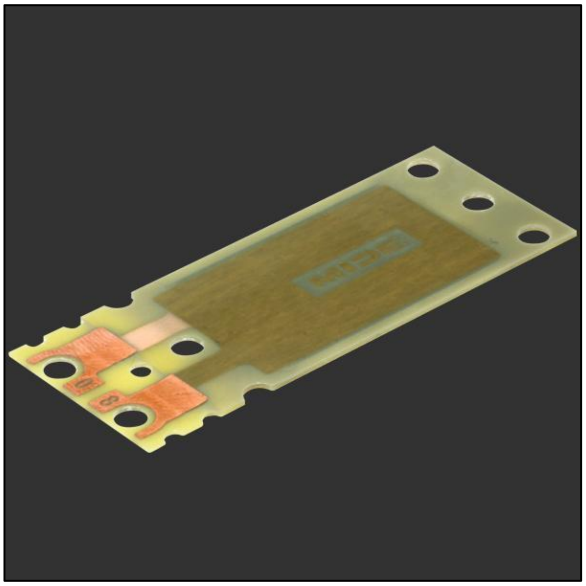

Figure 8: An example of a piezoelectric generator available from a commercial supplier [16].

3.3. Energy Storage

Energy storage in an IIoT device will typically take the form of either a battery or a supercapacitor. There are pros and cons to each, and a selection must be made carefully depending on the requirements of the design.

3.3.1. Batteries

Many different battery chemistry options are available such as lithium-ion (Li-ion), lead-acid, nickel-cadmium (NiCd), and nickel metal hydride (NiMH) as well as countless others. These listed chemistries are all known as "secondary cells", indicating that they are rechargeable. Primary cells are non-rechargeable and include the common alkaline battery and lithium coin-cell batteries. The various chemistries do include different energy densities although its common to be able to trade increased volume for increased energy storage capacity. One important comparison between the various batteries is the difference in required charging voltage. Typical charging voltages for the listed secondary cells range from 1.25 V per cell for NiCd and NiMH batteries up to 3.6 V per cell for Li-ion. This is important to consider when it comes to the possible voltage from the energy harvesting source, as well as the required voltage to power the IIoT device.

	NiCd	NiMH	Lead Acid	Li-ion
Typical Energy Density [Wh/kg]	45-80	60 ~ 120	30 ~ 50	110 ~ 160
Charge/Discharge Cycle Life [cycles]	1500	300 ~ 500	200 ~ 300	500 ~ 1000
Charge Time [hr]	1	2 ~ 4	8 ~ 16	2 ~ 4
Cell Voltage [V]	1.25	1.25	2	3.6

Table 1: Comparison of battery chemistries (Adapted from [10]).

Many factors must be weighed when selecting a battery chemistry, in addition to simply performance. For example, both up-front and maintenance costs as well as lifecycle length must be considered. Additionally, although Li-ion typically excels in nearly all areas it is not suitable for low temperature areas or locations where safety is critical due to the volatility of the cells [11].

Sealed lead-acid batteries present an excellent option for many situations – not the least of which is the fact that they are commonly available and low cost. Their electrolyte is either gelled or contained within an absorbent glass matting, meaning they can be mounted in any orientation without fear of leaking and they do not require maintenance in the form of checking and filling the electrolyte. Additionally, they are available in many different sizes from extremely small (1.6" x 2" x 2") 4V cells to large 8D marine batteries (20.5" x 10.5" x 9.6") and even massive 2V cells for large infrastructure installations.

Figure 9: Typical sealed lead-acid (SLA) battery [19].

3.3.2. Supercapacitors

Another consideration is to use a bank of supercapacitors. While the supercapacitors may not have as much total energy capacity as a battery, it would be significantly smaller and never require replacement. It would also be easier to integrate with COTS energy harvesting management integrated circuits since the SLA would require a higher charging voltage than the supercapacitor.

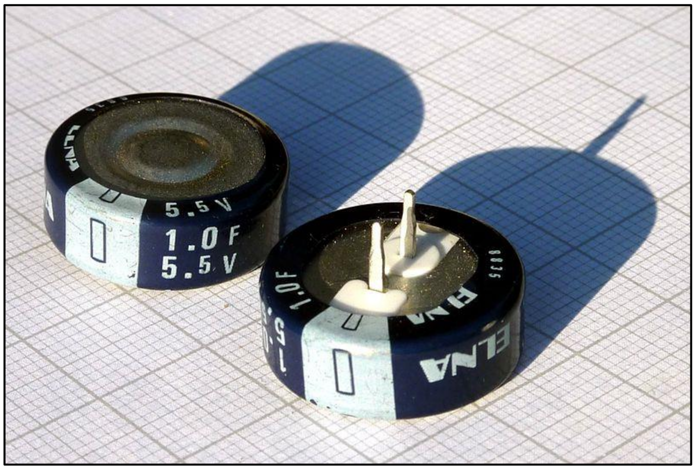

Figure 10: An example of a radial, thru-hole technology (THT), 1 Farad supercapacitor [18].

A supercapacitor offers a viable alternative to batteries as the energy storage mechanism in an IIoT device, depending on the requirements. Essentially, a supercapacitor is simply a capacitor with much higher-than-normal charge storage capacity. Where a typical electrolytic capacitor used for power supply filtering might be as high as 470 μF, a supercapacitor is commonly on the order of many hundreds of milli-Farads. Supercapacitors have the benefit of being small and quick to charge although they typically do not carry the same energy density as a battery. Unfortunately, supercapacitors tend to have more energy leakage than batteries, meaning they are not suitable for long term storage with an extremely intermittent energy source [12]. If the IIoT device will operate at extremely low duty cycles, with its energy source available constantly, a supercapacitor is an excellent option for miniaturization of the device. They do not suffer from the same hazardous restrictions that lithium-ion batteries require.

4. Example IIoT Device Architecture

Combining all the guidelines included in previous sections, we can develop a generalized architecture for any IIoT device. A device following this framework need only specify the precise method for each of the colored blocks. For example, a system may easily swap out a battery storage system for a supercapacitor-based storage system, provided the requisite analysis has been completed. Similarly, one version of the device may utilize a solar harvesting system, while another may implement a vibration-based energy collection scheme. Various methods of sensing and interacting with the environment may be used, or even different transceivers depending upon the required communication interface.

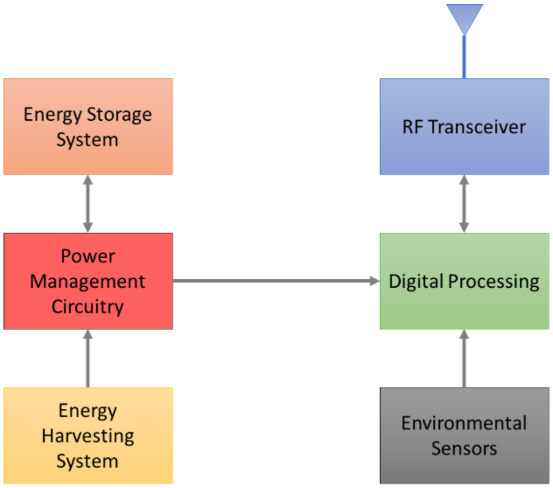

Figure 11: Example architecture for energy harvesting IIoT device.

5. Conclusion

In this paper, MAB Labs and Shield Digital Design have outlined the need for highly efficient, net-zero operation IIoT devices for wireless telemetry systems. We have shown both software-based routing methods as well as hardware circuit design methods for reducing power consumption in these devices. Additionally, a comprehensive review of energy harvesting and energy storage techniques has been presented. Lastly, a generalized architecture is given which the designer may use as a guide to develop their own energy-harvesting wireless telemetry IIoT device.

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