Thermoelectric Generators for Powering Sensors in Smart Cities

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***Abstract*. Multitude of sensors have been and are being deployed to support the distributed computing that is required in smart cities. These network of sensors nodes mainly perform environmental sensing, processing of the acquired information, actuation and/or transfer of information. By design, the nodes are usually limited in their computational resources as well as in the energy they can store. Guaranteeing the longevity of these nodes thus entails finding a sustainable and long lasting source of energy, so making the node fully autonomous. Currently batteries are the most common means of powering nodes but, as batteries are inherently limited in their energy storage capability, other reliable energy sources had been explored. Energy harvesting is a viable way for the realization of such electrical energy sources. In this paper, the feasibility of powering wireless sensors network nodes distributed across a city using small size, low cost and efficient thermoelectric generators is explored.**

Keywords. Smart Cities; TEG; WSN.

I. INTRODUCTION

Building a smart city involves the deployment of infrastructures that support the improvement of the quality of life and efficiency of services to citizens. From a technological viewpoint, this includes a massive deployment of distributed network of wireless nodes for ubiquitous sensing, computing and actuation, so implementing the so called internet of things (IoT). The integration of IoT and the existing information and communication technology (ICT) infrastructure makes information about almost everything in the city readily available, thus providing the platform for building real-time services such as traffic management, pollution monitoring, and parking space availability.

As the deployment of wireless sensor networks (WSN) continues to grow and to improve capabilities, we must find ways that enables us to use them in the least intrusive way. One facet of this issue is finding a portable, long-lasting energy source which enables nodes to become energetically autonomous. Until recently batteries have been the primary sources of energy for distributed WSN nodes, but batteries have intrinsic limitations on the amount of stored energy hence the need for frequent replacements poses a major drawback as the number ofg nodes grow, especially if they are deployed remotely. In such cases, energy harvesting from ambient sources is the most viable way to ensure sustainable power sources. For instance, energy can be collected from the sun (using photovoltaic cells), from mechanical vibration (using piezoelectric harvesters), or from heat flow (using thermoelectric generators (TEGs)). Environment energy harvesting tends to be unregulated, intermittent and small. Hence, long and intensive research activities have been performed to find ways to make harvesters reliable sources of energy.

This paper is organized in the following way. Section 2 provides an overview of the different ambient energy sources for WSN along with their limitations. The third section illustrates different aspects related to TEGs and their effectiveness for powering WSN. The last section provides a case study of a prototype that was developed in the electronic lab of the Department of Industrial Engineering at the University of Trento, developed as a proof of concept.

II. POWER SOURCES FORWSN NODES IN SMART CITIES

A typical WSN architecture is shown in Fig.1. The first block of a WSN is a sensor that transform variations of a physical quantity into variations of an electrical quantity. The data acquisition block performs the needed transformations on the electrical signal, such as amplification, analog to digital conversion, and filtering The microprocessor adds intelligence to the system. The radio link allows wireless data exchange.

WSN nodes are powered from sources with limited energy storage capacity. Hence longevity of the node is a key issue during design.

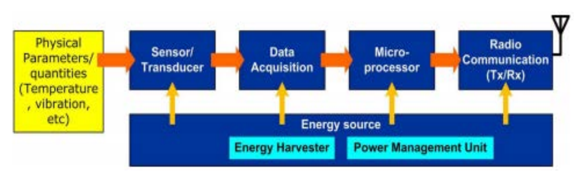

Fig.1. A typical WSN architecture.

The following are the most common ways of powering WSN

a) Batteries

Batteries are the most popular sources of energy for sensor nodes. The performance of batteries is determined by parameters such as the energy density (referred to the weight in Wh/kg or to the volume in Wh/m^3), the power density (W/kg) and cost. The energy and power densities determine the storage and charge/discharge capacity of the battery respectively. Batteries are characterized by high energy density and low power density. The improvement in capacity of batteries is slow compared to the evolution of computing electronics.

b) Super Capacitors (supercap)

The high-power density, low equivalent series resistance (ESR), low charging time and low leakage current makes supercaps ideal for powering WSNs. Having high power density means being able to deliver large amount of energy in short time and this property makes supercaps ideal for applications that require burst of energy. The only downside of supercaps is their low energy density (storage capacity) which makes them unsuitable for an extended use with a single charge.

c) Energy Harvesting

The life time of WSN based applications for smart cities is expected to be years. That requirement is rarely achievable by exploiting only finite power sources such as batteries and supercaps. Consequently, sensor nodes must find ways to sustain themselves by converting available ambient energy into electrical energy. Energy harvesting is the process of capturing energy from different ambient energy sources and transforming it into electrical energy for immediate use or storage.

Sources of ambient energy can be broadly classified into the three classes “radiant”, “thermal” and “mechanical”, as depicted in Fig.2. Thermal sources include TEGs while radiant energy sources include solar cells and RF harvesters. Mechanical sources of electricity are related to mechanical forces such as vibration, air flow, or movement of massive objects.

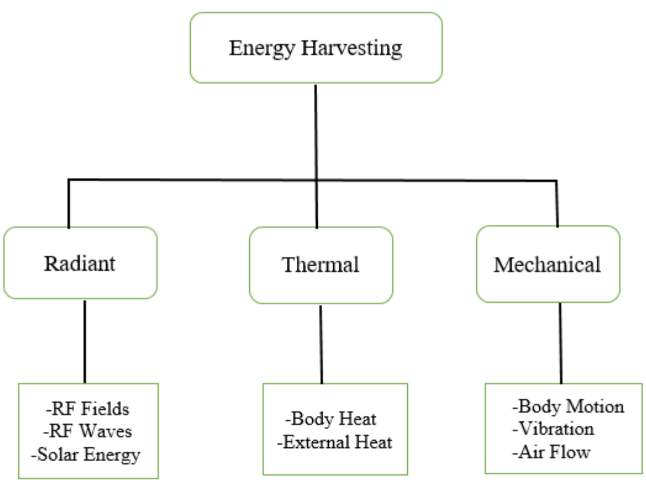

Fig.2. Classification of energy harvesting sources.

III. WHY TEGS?

Harvesting sources are compared according to their electrical properties (such as power density) physical properties (such as size, shape and weight), environmental properties (such as water resistance and operating temperature range), as well as operational and maintenance properties.

Essential information about the amount of power that can be generated from different harvesting sources is reported in Tab. I.

TABLE I. ELECTRICAL POWER DENSITIES PROVIDED BY DIFFERENT AMBIENT SOURCES.

Harvesting Source	Power Density ($\mu W/cm^2$)
Solar	10000
Piezoelectric	330
RF	0.1
Temperature	40

Due to its high power density, solar is the most common energy source used for powering autonomous sensing nodes [1]. However, in situations where there is a lack of consistent sun light other forms of ambient energy sources need to be considered to power the nodes. RF harvesting exploits the unused radiation energy from sources such as WiFi transceivers, cellular base stations, and TV/Radio stations. RF power is transformed into usable DC form using rectifier antennas (rectennas). The disadvantage of harvesting energy from RF sources is the low efficiency of the rectennas and the exponential decrease of collected power when moving away from the source. Mechanical vibrations are usually highly intermittent and hence energy obtained from these sources cannot ensure a continuous supply of the system. Thermoelectric generators, on the other hand, offers a continuous source of energy where there is a constant heat flow. Both the low conversion efficiency and high cost had been the major drawbacks that limited the adoption of TEGs. However, the situation is now changing thanks to the advent of low power electronics and the lowering cost of TEGs.

IV. THERMOELECTRIC TECHNOLOGY AND APPLICATION

Thermo-electricity is a well-known physical phenomenon: the temperature difference between the junctions of two different metals creates an electric potential between them; conversely, an electric potential (a flow of current) between the junctions creates a thermal difference between the junctions themselves. Thermoelectric generators exploit the Seebeck effect [2]. Fig.3 depicts the architecture of a thermoelectric module, which can be used as a power source or a heat pump.

In general, TEGs provide electrical power at a voltage that is usually too low to supply most electronic devices. A voltage boosting circuitry is thus required, thus adding complexity to the power supply circuitry. This issue is slightly being alleviated as the latest microcontrollers come with an embedded boosting circuitry [3]. In addition, progress in materials technology allows now the production of TEGs that can provide nominal voltages up to 0.7V at matched load. Such ranges of voltage are enough to properly supply a wide range of low power electronics without the need for a boosting circuit [4].

TEGs have been employed for number of applications also because of their high reliability, which is due to the use of solid-state components and the absence of moving parts. A typical TEG life time is greater than 200,000 hours [5]. Such a high value is important especially in applications where sensors are deployed in places difficult to be reached by humans. Issues such as degradation of TEG interfaces and thermal expansion mismatch are mainly related to the harvesting of large quantities of thermal energy and they are not of concern in low energy harvesting. This contributes to the durability of the TEGs used in WSN.

The low efficiency of TEGs – which can be an issue in other applications – is not a major drawback when harvesting small energy amounts (of the order of mW). The TEGs used for this kind of application consist of a series of connected small thermopiles as shown in Fig.3. This makes the TEGs highly scalable. Depending on the surface area of the heat source and the power requirement of the application of interest additional TEGs can be easily plugged into the WSN modules.

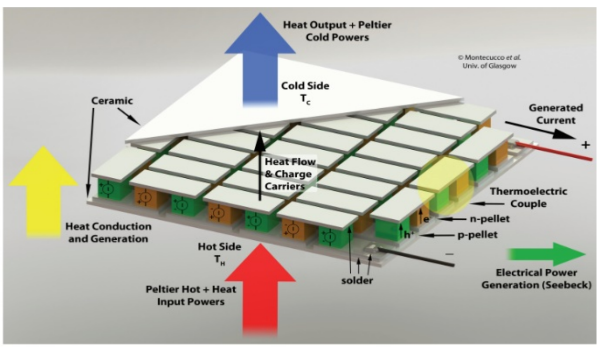

Fig.3. 3-D view of a TEG

The cost of TEGs is usually evaluated as the summation of the thermal energy cost and the module construction cost. However, the first term of the cost is nullified when free ambient heat energy is considered. The manufacturing system cost is decreasing as cheaper thermoelectric materials have started to be used to produce TEGs [6]. Extensive comparison of cost per watt ($/W) of different TEGs clearly shows that the cost of TEGs is lowering over the years [7].

TEGs generate electric energy when there is a temperature gradient between their two faces. For example, one face of the TEG can contact the surface of a building, a lamp post or the ground while the other face can be exposed to the air. The faces can also contact the same material so long as the two contact surfaces are at different temperature [8].

V. CASE STUDY

As a proof of concept, a temperature sensor node powered from a TEG was developed and its performance was tested. To that aim, a Tmote was used since it is an ultra-low power wireless sensor node that is very popular in the field of wireless sensor networks. In particular, the adopted system consisted of a Tmote-sky microcontroller equipped with different environmental sensors of which the temperature sensor was used for this experiment. The node was periodically broadcasting temperature data over the radio link to a receiver. Table 2 shows a summary of the power consumption and the operating conditions of the module [9].

TABLE II SUMMARY OF TMOTE SPECIFICATION

	MIN	NOM	MAX	UNIT
Supply voltage	2.1		3.6	V
Supply voltage during flash memory programming	2.7		3.6	V
Operating free air temperature	-40		85	°C
Current Consumption: MCU on, Radio RX		21.8	23	mA
Current Consumption: MCU on, Radio TX		19.5	21	mA
Current Consumption: MCU on, Radio off		1800	2400	µA
Current Consumption: MCU idle, Radio off		54.5	1200	µA
Current Consumption: MCU standby		5.1	21.0	µA

The application software was developed in C programming language. The application consists of a periodic timer which wakes up the CPU from a sleep state every T seconds; the CPU then reads the temperature sensor, broadcasts the data and finally goes back to sleep again. The transmission takes a time of 6.2 ms during which the node was consuming 62.5 mW and the power consumption in the low power mode was 0.4 mW. The application was powered by a TEG which was producing 1.8 mW of power at 10°C temperature gradient. Based on these values the system was able to run with a duty cycle (i.e. the temperature reporting rate) of 2.3% (6.25 ms every 268 ms). Usually temperature sensors report temperature in periods much longer than 268 ms. Hence, if the duty cycle is decreased the extra energy from the TEG can be stored in a supercap and used later or to charge an on-board rechargeable battery. Installing a rechargeable battery may be necessary to ensure that the system remain operational also when the TEG is not capable to provide enough energy, as might occurs during cold seasons.

The results of this experiment are reported in Fig.4. The capacitor voltage and output current during the charging phase of the output supercapacitor are shown in Fig 4(a). As it can be seen, the module started transmitting soon as the output voltage reached 1.8 V, which took about 45 minutes and continued working for hours without interruption. Fig 4(b) illustrates the output voltage and the output current after the supercap was charged to 3.3 V, while the node went fully operational.

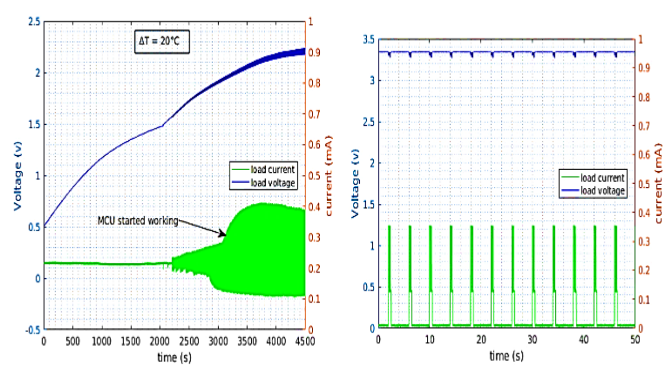

Fig 4. Current and voltage during charging phase (a) and after supercap was fully charged (b).

VI. Conclusion

In smart cities, wireless sensors and actuators are deployed in abundance to gather real time information. It is essential that a WSN node is capable to ensure not only accurate measurement and efficient communication, but also a long lasting operational life. Thus, cost effective and reliable ways for providing power to the networks of sensors distributed across the city need to be identified. This paper investigated the feasibility of utilizing efficient, reliable, low cost and small size thermoelectric generators to powering WSN nodes. A prototype sensor system which was powered from a TEG, under a temperature gradient of 10°C, was developed and its performance was tested. The system, which had a cold start duration of 45 minutes, was able to transmit temperature values with a period of 268 ms. It also became energy neutral and continued to function for hours without fault.

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