Energy Harvesting Technology for Maintenance-free Sensors

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Energy harvesting is a technology that gathers energy such as sunlight, artificial light, and vibration and heat from machinery to obtain electric power. Applying this technology to wireless sensor modules in a machine-to-machine (M2M) wireless sensor network will eliminate the need for grid-based power and primary batteries and create new value in the form of maintenance-free, battery-free, and cable-free operation. Energy harvesting can also promote environment-friendly, clean technology that saves energy and reduces CO_2 emissions, which makes it a useful technology for achieving the next-generation smart city and sustainable society. This paper introduces oxide-based thermoelectric material, all-solid-state secondary battery technology, and energy-harvesting tester technology now being researched and developed at Fujitsu Laboratories as elemental technologies for applying energy harvesting technology to M2M wireless sensor modules and achieving maintenance-free operation.

1. Introduction

Energy harvesting technology captures energy from the ambient environment such as heat (temperature differential), vibration, and light that to date has not been greatly used and converts that energy into usable electric power. It is sometimes called environmental power-generation technology. The power obtained from such energy conversion is minimal (in the μW to mW range), but generating it in the right way in the right places can provide new value for locations outside the power grid including a maintenance-free supply of power, battery-free operation, and no power cables. Energy harvesting technology is particularly suitable for machine-to-machine (M2M) wireless sensor networks. Applying it to M2M wireless sensor modules makes it possible to configure maintenance-free wireless sensor networks using diverse types of sensors.

The concept of applying energy harvesting technology to a smart city is shown in **Figure 1**. Energy harvesting technology enables the arrangement of numerous wireless sensors and their installation in places that people cannot easily access such as restricted underground areas or special facilities. It allows for more detailed monitoring and visualization of monitored locations and the visualization of locations for which monitoring has heretofore been insufficient. Energy harvesting technology should make major contributions to saving energy and resources in a smart city and providing safe and secure living conditions.

A storage device is essential to making effective and efficient use of the small amount of power generated by an energy-harvesting device. The approach taken to achieving a power-supply platform that combines an energy-harvesting device and storage device is key to the development of an M2M wireless sensor module. This is because a whole series of operations including sensing and radio transmission must continue even if the energy-harvesting device stops generating power because of environmental factors. A power-supply platform that combines an energy-harvesting device and storage device makes it possible to control generated power and provide a stable supply of power regardless of the type of sensor (**Figure 2**).

This paper introduces oxide-based thermoelectric material, all-solid-state secondary battery technology for harvesting use, and an energy-harvesting tester. All of these are being researched and developed at Fujitsu Laboratories as elemental technologies for a power-supply platform. Our aim with these technologies is to

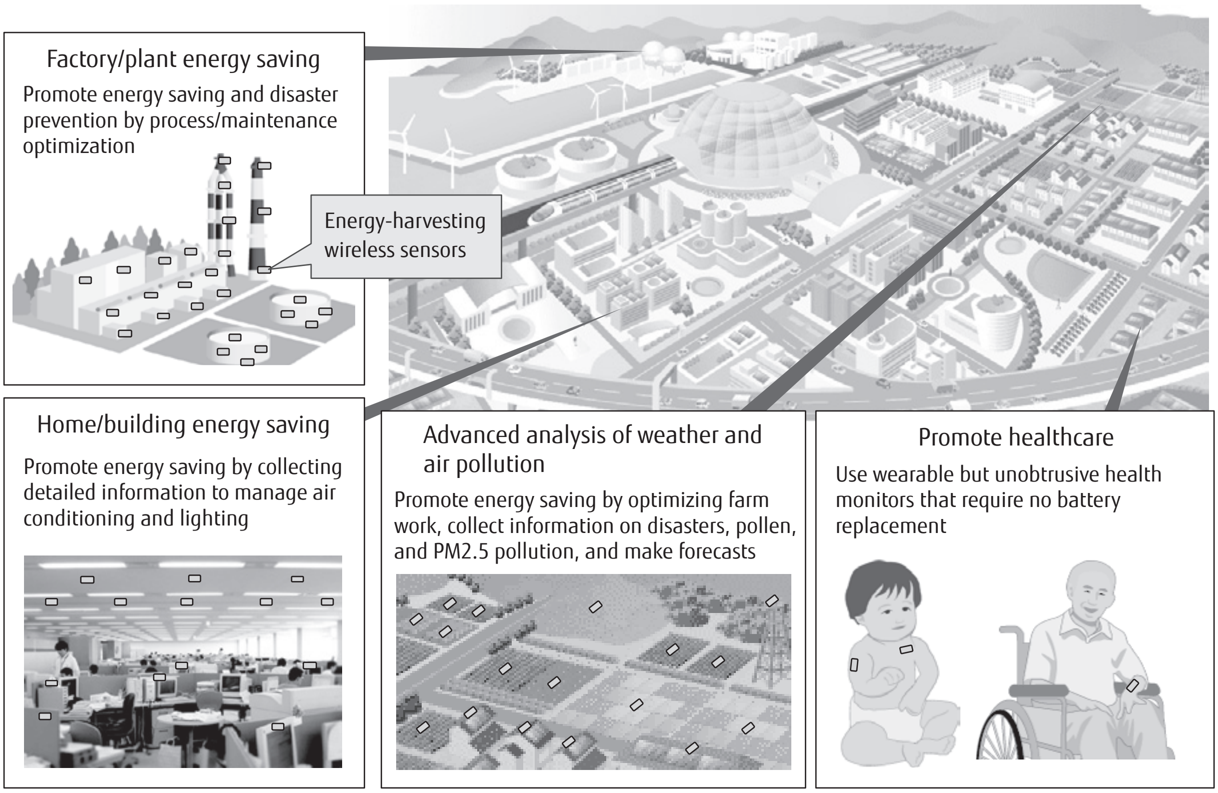


Figure 1
Application of energy harvesting technology to a smart city (using unlimited amounts of pinpoint data to effectively promote energy saving, resource saving, and a safe and secure environment).

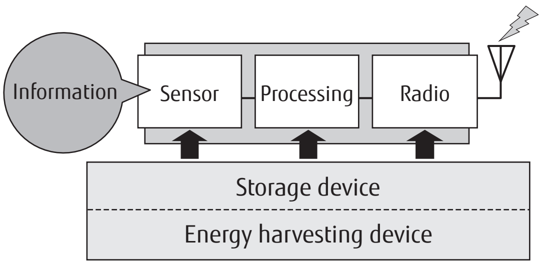


Figure 2
Self-powering wireless sensor module.

apply energy harvesting to M2M wireless sensor modules for maintenance-free operation.

2. Thermoelectric materials

Thermoelectric conversion, in which the temperature difference between the two ends of a material creates an electromotive force (Seebeck effect), is an effective elemental technology for energy harvesting. Placing a device composed of material with this property (thermoelectric material) between, for example, human skin and ambient air can generate usable electric power due to the difference between body temperature and air temperature. Consequently, a battery-free healthcare module could be developed by using the power generated from this temperature difference that would sense and wirelessly transmit health-related information such as that person's temperature and pulse.

The characteristics of a thermoelectric material can generally be evaluated by using a non-dimensional performance index called ZT:

$$ZT = S^2\delta T/\kappa$$

ZT: thermoelectric figure of merit
S: Seebeck coefficient (thermal electromotive force)
δ: electrical conductivity
κ: thermal conductivity
T: temperature

It is said that a material must have a ZT value greater than 1 to be practical for thermoelectric conversion, but the only materials that presently satisfy this requirement at room temperature are heavy metals such as BiTe and PbTe, which are not only scarce but hazardous as well. There is therefore a need for developing new non-heavy-metal materials having a small environmental load for use in healthcare applications.

Against the above background, the material that we are presently developing is a non-toxic, environment-friendly oxide thin film based on $SrTiO_3$ (STO). This material has both a large Seebeck coefficient and high thermal conductivity, so the ZT value for bulk single crystal at room temperature is only about 0.1. We tested two methods for improving the thermoelectric property of STO:

1) Lower thermal conductivity through film thinning
2) Increase Seebeck coefficient through energy filtering

Thinning film by as much as several tens of nm can lower thermal conductivity through changes in phonon mode. For STO, however, thinning the film to that extent has the unfortunate effect of decreasing electrical conductivity significantly with the result that the ZT value becomes lower than that for bulk single crystal. As a thermoelectric material, STO can be doped with niobium (Nb), for example, to raise electrical conductivity, but thinning the film magnifies the lattice-distortion effect caused by doping, which in turn lowers electrical conductivity. This phenomenon has been clarified by detailed analysis of the lattice constant by x-ray diffraction. To resolve this problem, we decided to simultaneously dope the material with lanthanum (La) and Nb as substitutes for Sr and Ti, respectively, and to adjust the amount of doping so that distortion caused by La and that by Nb cancel each other out. With this approach, we successfully thinned out the material without degrading the Seebeck coefficient and electrical conductivity. A cross-sectional transmission electron microscopy (TEM) image of 30-nm-thick $(Sr, La)(Ti, Nb)O_3$ thin film formed on the surface of an STO single-crystal substrate is shown in **Figure 3**. This image reveals the formation of a high-quality thin film with no defects or distortion that is difficult to distinguish from the substrate. We determined that the thermal conductivity of this material is approximately one-half that of bulk single crystal and that its ZT index could be raised to 0.23.[1)]

Energy filtering is a phenomenon by which stacking two thin films with slightly different band gaps results in the filtering of low-energy electrons at the layer interface, which has the effect of greatly increasing the Seebeck coefficient. This phenomenon, which was theoretically predicted some time ago, has been confirmed using a compound semiconductor for which band-gap control is relatively easy. However, there have been no reports to date of this phenomenon in oxides. Using precise measurements of the electron structure and band-gap characteristics of oxide thin films by x-ray photoelectron spectroscopy (XPS)[2)] and material simulation of the same by first-principle computations,[3)] we predicted a layered configuration that can produce a high energy-filtering effect. Furthermore, by using the above-mentioned high-precision thin-film formation technology, we have demonstrated for the first time an energy-filtering effect in an oxide thin film. The prototype thin film is a layered structure consisting of individual $(Sr, La)(Ti, Zr)O_3$ and $(Sr, La)TiO_3$ thin films. With this new thin film, the Seebeck coefficient has been raised to about twice that of STO bulk single crystal.

The simulation revealed that the Seebeck

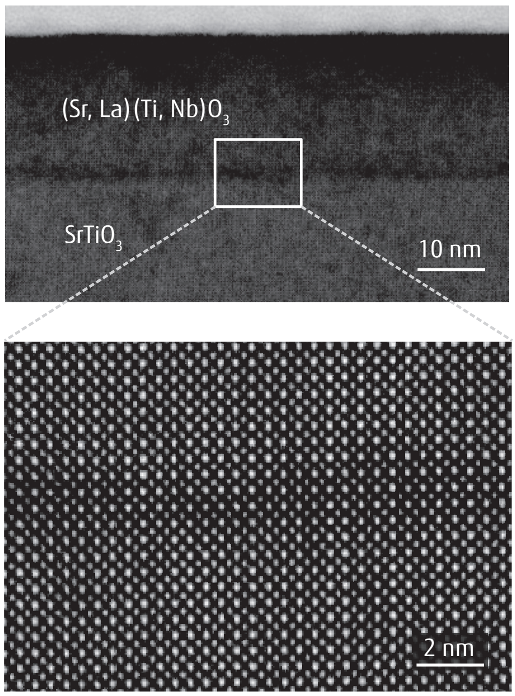


Figure 3
Cross-sectional TEM image of $(Sr, La)(Ti, Nb)O_3$ thin film formed on $SrTiO_3$ substrate.

coefficient can be increased by about nine times, and, with this in mind, we will aim for even further enhancements of thin-film characteristics in the future. We will also study device structures that can effectively use this energy-filtering effect and test their power-generating capability.

3. All-solid-state secondary battery technology

We are researching and developing all-solid-state secondary batteries as a storage device for a power-supply platform. The electrolyte in Li-ion secondary batteries used in laptop computers, smartphones, and other electronic products includes an organic electrolyte solution and polymers, which raises concerns about ignition at high temperatures. It is therefore problematic to apply batteries of this type to the human body in healthcare applications or to use them in places where fires are of particular concern. In contrast, an all-solid-state secondary battery features, as the name implies, a solid electrolyte, which makes worrying about combustion unnecessary while also minimizing deterioration even after repeated use. This type of battery can therefore be used as a storage device on a power-supply platform. On the other hand, improving ion conductivity—the index of Li-ion ease-of-movement within the electrolyte—is an issue that needs to be addressed in all-solid-state secondary batteries. In other words, Li ions within a solid electrolyte must be able to move back and forth with ease at high speed. This section reports on the research that we have conducted on improving ion conductivity in the solid electrolyte of all-solid-state secondary batteries and presents, in particular, the characteristics of an LiPBS sulfide solid electrolyte material we have developed.

The configuration of the all-solid-state secondary battery used in our experiment is shown in **Figure 4**. We used $LiCoO_2$ as a positive-electrode active material for the plus (+) electrode, placed a solid electrolyte layer (LiPBS) on top of that material, and used LiAl as a negative-electrode active material for the minus (−) electrode on the uppermost layer. We tested two methods for improving ion conductivity in our development of a new solid electrolyte material:

1) Substitute positive ions of different radii to vary the conductive paths of ions in the crystal
2) Substitute positive ions of different valences to vary the amount of Li (the conductive elements)

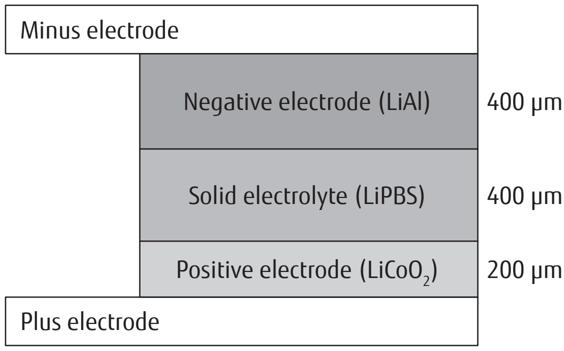


Figure 4
Configuration of all-solid-state secondary battery.

Furthermore, we set as a target an ion conductivity equal to or greater than 10^{-4} S·cm^{-1}, which is a practical level for bulk powder. First, given solid electrolyte material Li_3PS_4, we replaced phosphorus (P) having a valence of 5 with boron (B) having a valence of 3 and a small ion radius and experimented with methods 1) and 2) simultaneously. Specifically, we synthesized a range of materials by varying the amount of B (x) in the solid-solution system $Li_{3+3/4x}P_{1-3/4x}B_xS_4$ from 0.10 to 1.00 and conducted a comparison experiment.

The results of measuring the ion conductivity of the synthesized materials are shown in **Figure 5**. As shown, ion conductivity was maximum at x = 0.35 and decreased when the amount of B (x) was increased. Ion conductivity at x = 0.35 was 2.2×10^{-4} S·cm^{-1}, which is higher than the target value. To analyze the cause of this change in ion conductivity in more detail, we performed Rietveld analysis using synchrotron-radiation x-ray diffraction data obtained from SPring-8, the world's largest synchrotron radiation facility, in Harima Science Park City, Hyogo Prefecture, Japan. This analysis revealed that there were three main types of structures and that structure B, the one corresponding to maximum ion conductivity, had a crystalline structure and a Pnma space group. In this structure, ions are thought to conduct via Li at the center of an edge-sharing LiS_6 octahedral. The analysis also revealed that the level of ion conductivity depended on the size of the triangular window of the LiS_6 octahedral through which the Li ions pass.[4)]

The results of repeatedly charging and discharging a prototype all-solid-state secondary battery using

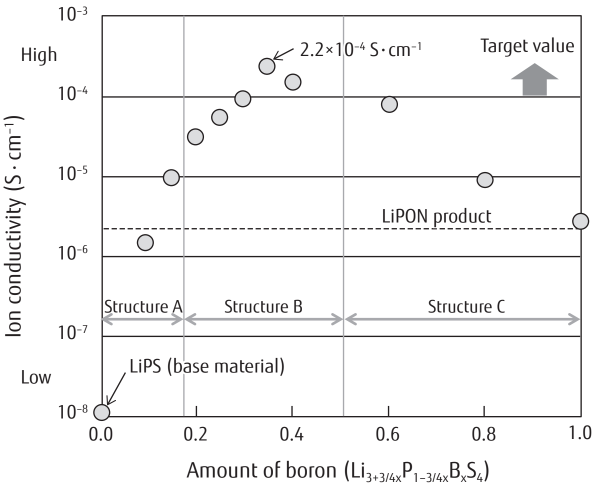


Figure 5
Dependence of ion conductivity of synthesized materials LiPBS on amount of boron (B).

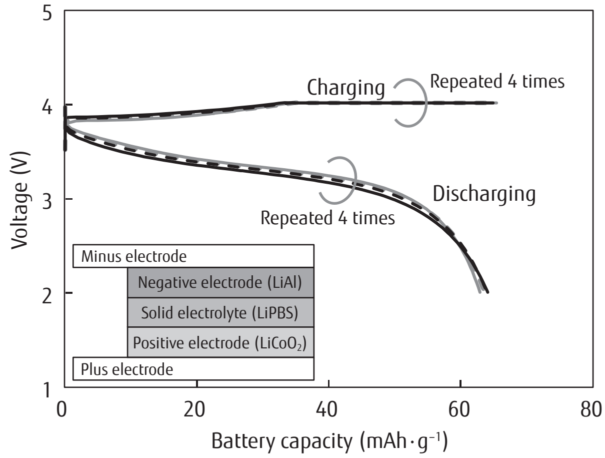


Figure 6
Repeated-charging/discharging characteristics of all-solid-state secondary battery.

our newly developed LiPBS solid electrolyte material (crystalline structure B) are shown in **Figure 6**. The battery was fabricated by applying pressure of approximately 1 t to a layered structure consisting of positive-electrode material, solid electrolyte material (400 μm), and negative-electrode material. On repeating charging/discharging four times, charge/discharge curves with no deterioration were obtained, demonstrating that the prototype product was functioning as an all-solid-state secondary battery. Further repetition of charging/discharging produced no deterioration.

As described above, we researched and developed an all-solid-state secondary battery as a storage device for use on a power-supply platform and successfully developed solid electrolyte material exhibiting high ion conductivity. In future research, we will evaluate the characteristics over the long term, work to lower the cost of manufacturing, and research techniques for raising performance with the aim of developing a practical power-supply platform using an all-solid-state secondary battery.

4. Energy-harvesting tester

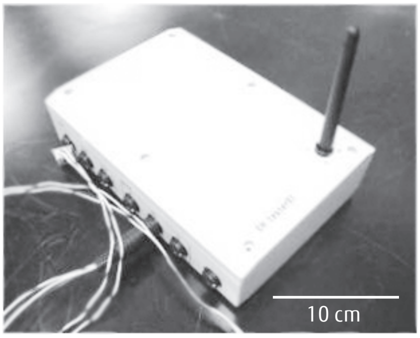
When setting out to apply energy harvesting technology, the first step is to determine the amount of power that can be generated in the environment where the sensors are to be installed and to perform a total product design. If conditions for the constant generation of light, vibration, or temperature difference are found to exist, the method for generating power in accordance with each condition may then be selected and the amount of generated power can be estimated. However, when applying energy harvesting technology to industrial machinery, for example, the lighting environment will be greatly dependent on whether the machinery is installed indoors or outdoors. Similarly, vibration or heat-generation conditions will vary greatly depending on whether the machinery operates all night or intermittently. It is difficult to estimate the amount of power that can be generated in such cases. Furthermore, while it is common to incorporate some sort of storage mechanism such as a capacitor to configure a stable power supply from an unstable source provided by energy harvesting, the capacity of such a storage mechanism might not be sufficient for the application in question. It then becomes necessary to incorporate a secondary battery such as an all-solid-state one.

The next thing that must be considered in applying energy harvesting technology is how to operate the sensing device from the amount of power generated. It is often the case in energy harvesting that the amount of generated power is not necessarily sufficient, which means that some limitations arise on the power-consuming side. A common approach is to select low-power sensors, or depending on the application, to set long intervals for sensing, data processing, or data transmission. Various combinations of such measures may be selected.

Needless to say, setting up a sensing application using energy harvesting requires that the amount of generated/stored power be sufficiently greater than the amount of power consumed. As described above, however, the values of generated power and consumed power depend greatly on a variety of conditions, and considering that the amount of power consumed by the sensing device may vary according to the amount of generated power, an even more complex set of combinations can arise.

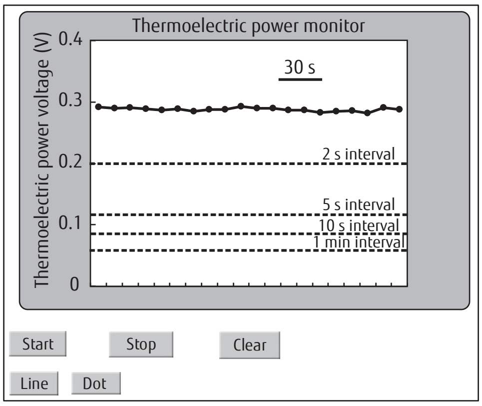
With this in mind, we have designed and constructed a prototype energy-harvesting tester that enables various types of energy harvesting (thermoelectric, solar battery, etc.) to be combined with a storage device such as an all-solid-state secondary battery for use as a power supply and that enables a sensor from among various types to be selected and connected as an input device [**Figure 7 (a)**, **Table 1**]. Connecting this circuit to a radio module enables sensor data to be transmitted wirelessly using the power obtained by energy harvesting and to be stored in a storage device. If the amount of power generated by the energy-harvesting device is low, a button cell may also be used to operate the tester. A radio module conforming to any of various standards may be connected, but we used a module conforming to IEEE 802.15.4 (2.4-GHz band), thereby enabling line-of-sight transmission up to approximately 1 km. The tester circuit was equipped with switches that enabled the monitoring of generated power and storage conditions in addition to various types of sensor data. This general-purpose circuit makes possible not only sensing and data transmission using various types of energy harvesting devices but also the monitoring of generated power and storage conditions for diverse energy harvesting devices using battery power in the event that generated power is insufficient. This is why the equipment has been given the name "energy-harvesting tester" and is mounted so that an energy-harvesting device or sensor can be easily installed externally using connectors and so that the equipment can be immediately brought to a site where the use of energy harvesting technology is envisioned.

Taking up an industrial motor as an example



Radio standard: IEEE 802.15.4 (2.4 GHz)

(a) Appearance of energy harvesting tester



(b) Screenshot of receiving software (thermoelectric power monitor)

Figure 7
Energy-harvesting tester.

Table 1
Basic equipment configuration of energy-harvesting tester.

Power Supply	Storage Mechanism	Sensor Input	Transmitted Data
Energy harvesting Solar battery Thermoelectric Other (5V input) Button cell	All-solid-state secondary battery Capacitor	Room temperature Acceleration Sound A/D (1 ch) I2C (1 ch)	Sensing data Power-generating voltage Storage voltage

of applying energy harvesting, we used our energy-harvesting tester to monitor the amount of power generated by the difference between the high temperature at the surface of the motor (approximately 50°C) and the ambient temperature (approximately 20°C). That amount value was transmitted at 10-s intervals to a notebook computer at a separate location. A screenshot of the receiving software monitoring that data is shown in **Figure 7 (b)**. The power-generating voltage value received and the generated power amount obtained from that value serve as a standard for determining the time intervals for sensing and radio transmission.

As described above, the energy-harvesting tester can be used to visualize generated power and storage conditions for various types of energy harvesting devices from one point to another and to facilitate total design by optimizing power generation, power storage, and sensing for each application. It is a powerful tool for uncovering sensing and radio-transmission applications to which energy harvesting technology can be effectively applied.

5. Conclusion

Fujitsu's vision of a Human-Centric Intelligent Society will require the efficient collection of huge amounts of data from a massive number of sensors. Energy harvesting technology can provide maintenance-free wireless sensors, which should prove to be highly effective in collecting big data in an M2M wireless sensor network.

Energy harvesting technology can also be applied to a smart city, thereby eliminating the trouble of having to replace batteries and making it possible to install and arrange wireless sensors in great quantities. It will also be possible to install sensors in places that are off-limits to people such as restricted underground areas or high-temperature/high-radiation areas. This capability will not only provide more valuable data but also enable the visualization of worlds that have heretofore been unknown. The further development and penetration of energy harvesting technology should make a significant contribution to energy saving, resource saving, and safety and security in society.

At the same time, the power obtained by energy harvesting technology is small (μW to mW order), which makes increasing the amount of generated power a key issue. Also of importance is the skillful use and total design of sensors and microcomputers, energy-saving radio technology, and power-supply technology that uses small amounts of power without waste. Our plan at Fujitsu Laboratories is to accelerate our research and development in collaboration with concerned institutions toward an M2M wireless sensor network using energy harvesting.

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