Energy-efficient hybrid system for Wireless Body Area Network Applications

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Abstract

Wireless Body Area Networks (WBANs) consist of a number of miniaturized wearable or implanted sensor nodes that are employed to monitor vital parameters of a patient over long duration of time. These sensors capture physiological data and wirelessly transfer the collected data to a local base station in order to be further processed. Almost all of these body sensors are expected to have low data-rate and to run on a battery. Since recharging or replacing the battery is not a simple task specifically in the case of implanted devices such as pacemakers, extending the lifetime of sensor nodes in WBANs is one of the greatest challenges. To achieve this goal, WBAN systems employ low-power communication transceivers and low duty cycle Medium Access Control (MAC) protocols. Although, currently used MAC protocols are able to reduce the energy consumption of devices for transmission and reception, yet they are still unable to offer an ultimate energy self-sustaining solution for low-power MAC protocols. This paper proposes to utilize energy harvesting technologies in low-power MAC protocols. This novel approach can further reduce energy consumption of devices in WBAN systems.

Keywords — Wireless Body Area Network (WBAN), Low-Power Medium Access Control (MAC), Energy Harvesting, Energy Efficiency

1. Introduction

Due to the increasing growth of the aging population around the world and constrained financial resources, existing healthcare systems are encountering new challenges. The “United States Census Bureau” estimates, the number of elderly people worldwide (aged 65 and over 65 years) to be 1.3 billion by 2040 [1]. In the United Kingdom alone, the “Office for National Statistics” predicts that the number of elderly people (aged 80 and over 80 years) is expected to be more than doubled by 2037 [2]. These estimates and statistics indicate that, continuously providing healthcare services to growing number of elderly people with different health issues is increasing the cost of healthcare systems very quickly and becoming unsustainable in its current form. As a result of increased healthcare costs, healthcare budgets are overstretched through increased taxation. However, it is widely accepted that, early disease detection is critically important; on the one hand, it provides the opportunity to effectively slow the progress of illness, on the other hand, it offers economic solution to healthcare costs. Therefore, it is possible to take advantage of latest advances in WBAN systems in order to be able to early detect potential health problems that may occur later in life. This can be done by integrating ultra-low-power none-invasive and/or invasive sensor nodes into WBAN systems for continuous monitoring of health conditions. Each node within a WBAN system is capable of capturing physiological data such as heart rate, respiratory rate, body temperature and movement and transmits the collected data either as raw samples or low-level post-processed information to a base station wirelessly in order to be further processed. A WBAN system is able to provide long-term health monitoring of people without limiting their daily activities. This system can be utilized to develop an intelligent and inexpensive healthcare monitor which can be used as part of diagnostic process. In general, a number of miniaturized sensor nodes are deployed on/in a human body in order to keep track of health status of a person. Body-worn or implanted sensor nodes are primarily battery-powered, thus, the amount of energy consumption is important in these devices. In order to increase the energy conservation, WBAN systems employ low-power communication transceivers and low duty cycle MAC protocols. Low-power communication transceivers usually consist of four operating modes: transmit, receive, sleep and listen. Sleep mode is considered as the most energy efficient operating mode since it uses extensively less energy than all other operating modes. Energy efficiency is increased by spending as much time as possible in sleep mode. However, nodes are not able to transmit or receive in the energy efficient sleep mode. Therefore, a method must be used to guarantee that the sender's transmit and receiver's listen operations coincide. This task of synchronization is achieved by a low-power MAC protocol. FrameComm [3] is one example of such a low-power MAC protocol which will be used as a base for the work presented in this paper.

Although the FrameComm protocol is able to minimize the energy consumption amount of sensor nodes in WBAN systems, it is still unable to provide a comprehensive energy self-sustaining solution for low-power MAC protocols. This paper proposes the integration of energy harvesting technologies with low-power MAC protocols.

The rest of this article is classified into four sections. Section II presents related work. Section III briefly explains the background and motivation for this article. Section IV clearly explains the description of the proposed scheme and section V is the final section which concludes our work.

2. Related Work

The design and development of power efficient MAC protocols for WBAN systems has been a popular research subject over the past few years. A significant amount of research is being conducted to explore new energy efficient MAC protocols in order to meet strict requirements of WBAN systems. Ullah et al. proposed in [4] a very low-power MAC protocol based on existing wake up radios called VLPM. This protocol is designed to reduce the energy consumption in addition to improving the response time of a sensor node in low traffic conditions of a WBAN system. In [5], the authors presented a new energy efficient MAC protocol for BAN that uses out of band wake up radio via a centralized external wake up mechanism. In this paper, each node includes an additional wake up radio circuit in order to activate other nodes to wake up from sleep mode. Yuan et al. proposed Enhanced MAC (EMAC) protocol in [6]. This protocol reduces the energy consumption of sensor nodes in WBAN systems by utilizing relay mechanism and dynamic power control algorithm. Other energy efficient MAC protocols such as B-MAC [7], X-MAC [8], WiseMAC [9], WASP [10], H-MAC [11] and CICADA [12] are presented and used in WBAN applications.

3. Background and Motivation

In this section, we explain how low-power MAC protocols are able to increase the energy efficiency of sensor nodes in WBAN systems. We then describe the current limitations, in terms of energy efficiency of existing low-power MAC protocols.

A. Low-Power Medium Access Control Protocols

Wireless sensor nodes in WBAN systems consume a great portion of their energy for data transmission and reception. In order to deal with this issue, researchers have suggested a number of communication protocols which are energy efficient. A lot of platforms take advantage of the abilities of current low-power radio transceivers (such as the Microchip MRF24XA [13]) to acquire significant power savings. These radios generally support four modes of operation; listen, receive, transmit and sleep. As an example, MRF24XA radio consumes 25 mA at transmit mode, 15.5-16.5 mA at receive mode, 13.5 mA at listen mode and less than 40 nA at sleep mode [13]. Therefore, energy efficiency is usually increased by spending as much time as possible in ultra-low power sleep mode, which consumes merely some nA or µA compared with a few mA when using the other modes. However, since communication between the two nodes cannot happen if either node's radio is in sleep mode, a mechanism is required to ensure that the sender's transmit and the receiver's listen operations coincide. This coordination of send and listen activities is known as transmitter–receiver rendezvous. If the listen/sleep cycle of the receiver is fixed and known, then a transmission can be simply extended such that an overlap between the transmission and the listen phase is guaranteed to occur. Traditionally, this was achieved using a long preamble immediately followed by the packet payload. A receiver hearing the preamble would keep its radio in a listen state until the packet was received. This duty-cycle concept was, for example, implemented in B-MAC [7] and is shown in Figure 1.

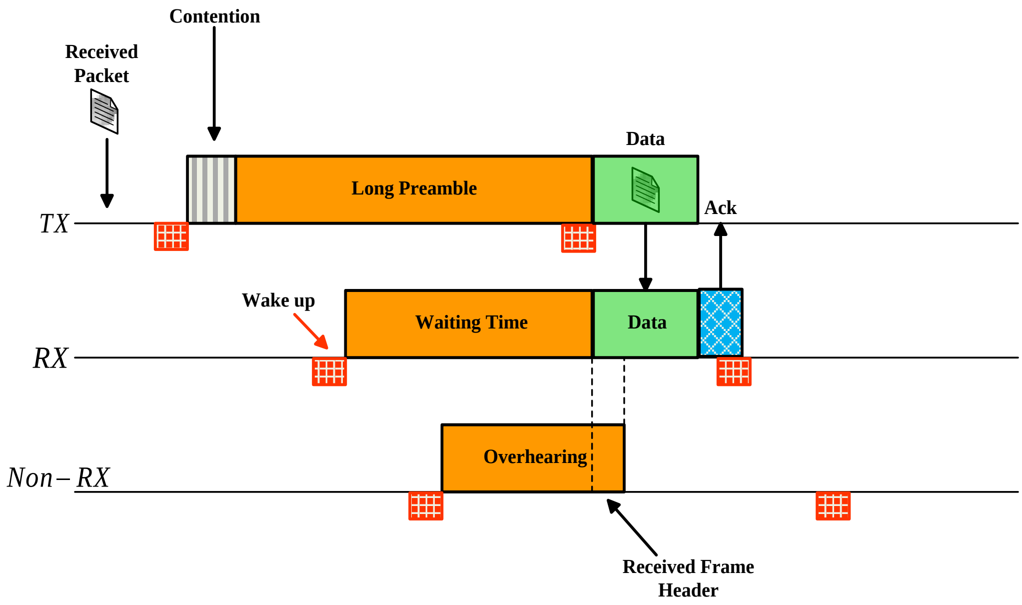

Figure 1. B-MAC protocol with long wake up preamble

A number of modern radios such as the AVR AT86RF212 [14] provide additional features such as automatic packet header processing and CRC computation and are normally used to send complete packets rather than individual bits. Therefore, channel access control can only be performed on a per packet level. With these transceivers it is possible for a sender to transmit a 'message' as a series of identical packets, in such a way that the receiver is guaranteed to catch at least one. Despite the overhead for the sender the scheme is very energy efficient, requires no additional hardware and no active coordination among the nodes. This duty-cycle concept was implemented in FrameComm [3] as shown in Figure 2. We use FrameComm as a base for the work presented in this article.

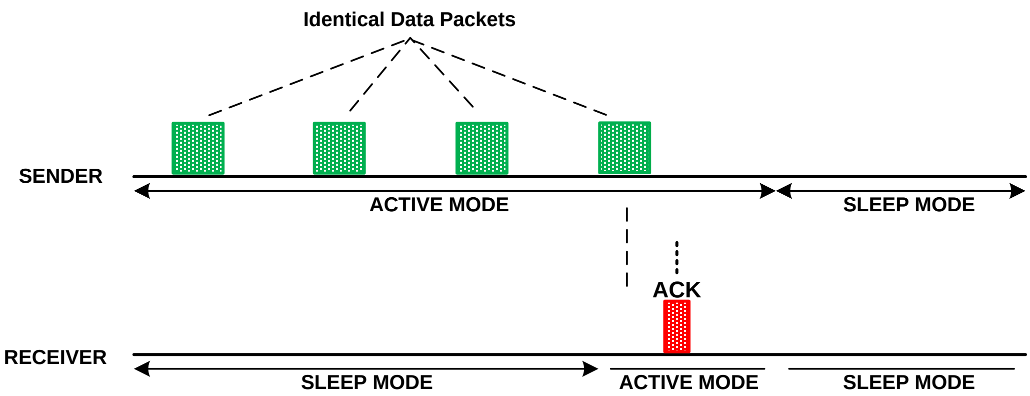

Figure 2. Energy conservation mechanism in FrameComm protocol

In Figure 2, the duty cycle period consists of sum of Δ & Δ_0, where Δ is the time duration that radio stays in its active mode and Δ_0 is the time duration that radio sleeps. Therefore, the duty cycle ratio is represented in equation (1). In Figure 2, battery is considered as the main source of power, thus energy to power up both active and sleep modes are merely driven from battery as shown in equation (2).

$$\text{Duty Cycle} = \frac{\Delta}{\Delta + \Delta_0} \quad (1)$$

$$P_{\text{battery}} = P_{\Delta_0} + P_{\Delta} \quad (2)$$

B. Energy Efficiency Limitations of Low-Power Medium Access Control Protocols

Almost all low-power MAC protocols that we have considered so far take advantage of duty cycling mechanism to decrease the energy consumption of the sensor nodes by keeping their radio in sleep mode for majority of the time without reducing the capability of the sensor nodes to take part in network communication. Although, keeping the radio in sleep mode for most of the time can significantly reduce the energy consumption of the nodes, we are still unable to provide a comprehensive energy self-sustaining solution for duty-cycle based radios. In section IV, we clearly explain how to overcome this limitation.

4. Description of Proposed Scheme

In this section, we clearly explain how our proposed scheme is able to further maximise the energy efficiency of devices in WBAN systems. This section is classified into two subsections. Subsection A concisely explains the sources of small-scale energy harvesting. Subsection B explains how energy harvesting techniques can be combined into low-power MAC protocols.

A. Small-scale Energy Harvesting

Energy harvesting is defined as the process of harnessing energy from the surrounding environment or other energy sources and transforming it into electrical energy. One of the most important factors in any energy harvesting architecture is the energy source. It provides vital information regarding the amount of obtainable energy to use. Energy sources are mainly categorized into two groups of ambient energy sources and human power sources. Ambient energy sources utilize energy from surrounding environments such as solar energy and RF energy. Solar energy (more specifically, energy harvested from outdoor light) is usually considered as first choice in many Wireless Sensor Network (WSN) applications. This is because, compared to other energy harvesting power sources, ambient outdoor light is capable of providing more energy to power these types of devices (10-15 mW/cm^2) [15] [16] [17]. However, in indoor medical applications such as health monitoring systems, it is not practical to take advantage of ambient outdoor light. In indoor environments, indoor solar devices are often used to conduct lighting levels. The energy harvested from indoor solar devices under typical indoor lighting conditions is substantially less compared to energy harvested from ambient outdoor devices (typically 10 $\mu W/cm^2$) [17]. Ambient RF energy is another source of energy harvesting. RF energy harvesting technology is considered as an appropriate solution to power small sensor node devices from ambient RF energy sources such as cell phone and television signals. As an example, researchers at Intel managed an experiment to determine the amount of power that can be harvested from ambient RF [17]. In this experiment, a typical terrestrial TV antenna was used to receive the signal of a local TV station (approximately 4 Km away from the receiver). In this testbed, researchers were capable to harvest energy density of 0.1 $\mu W/cm^2$ [17] [18].

Human power sources utilize energy harvested from human body movements. Human power sources are either active or passive. Active human power sources are under human control. In these power sources, a specific force is applied by human (e.g. finger motion or walking) in order to generate the energy for harvesting. Hande, et al. [16], presented that in the process of walking nearly 330 μW/cm^3 of harvested power can be recovered.

In contrast to active power sources, passive power sources are not under human control (uncontrollable). In these power sources, power is recovered passively from blood pressure, body heat, arm motion and breathing. Zungeru et al. [19] presented that; body heat can be sued to passively recover 60 μW/cm^2 harvested power at 5^{o}C.

B. Small-scale Energy Harvesting and Low-Power Medium Access Control Protocols

Energy harvesting technology or scavenging from the ambient environment is considered as an appropriate candidate for energy efficiency. However, the rate and amount of power available for use from energy harvesting sources is not adequate to completely power current wireless sensor devices. These energy harvesting devices are only able to provide extremely limited harvested power which is not sufficient to address the problem of limited device lifetime in WBAN systems. In this paper, we propose to combine previously discussed low-power MAC protocol (FrameComm protocol presented in [3]) with the energy harvesting techniques to further maximize the energy conservation in low data rate monitoring applications. Although, power harvested from energy harvesting circuits (Nanowatts or Microwatts of power) may be very limited and is not sufficient for the current wireless monitoring devices, it is still adequate to provide energy for the sleeping times of radios as shown in equation (3).

$$P_{harvest} \geq P_{\Delta_0} < P_{\Delta} \qquad (3)$$

Therefore, it is possible to provide a self-sustained energy system for sleeping times of radios as shown in Figure 3. As a result, only the consumed energy from the battery needs to be considered when the radios are in the actual transmit/receive mode (NOT sleep mode). Moreover, it is also possible to utilize a combination of different ambient energy sources in order to provide additional harvested energy. The additional harvested energy generated from multiple energy sources is able to provide very small portion (NOT enough) of required energy for the actual transmission and reception. This energy needs to be stored in an energy storage component such as a supercapacitor as shown in Figure 3.

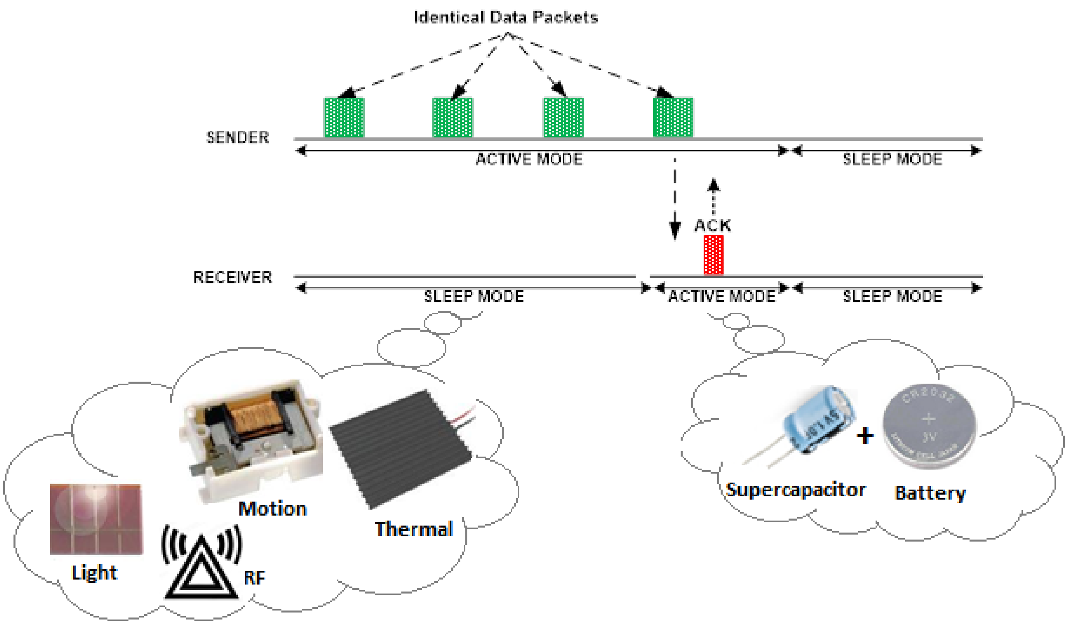

Figure 3. Hybrid System (Low-Power MAC Protocol + Energy Harvesting Techniques)

Table I compares almost all energy harvesting evaluation kits available in the market. Some products are only able to utilize one ambient energy source while others capable of using different combination of energy sources. This table also compares the current consumption of different transceivers. Sleep mode as shown in Table I is considered the lowest current consumption mode among other modes (RX and TX). As explained in previous section, energy harvesting techniques in our proposed scheme are able to provide enough harvested power for sleep mode operations.

Table I: COMPARISON OF AVAILABLE ENERGY HARVESTING EVALUATION KITS

Company Name	Energy Harvesting Evaluation Kit	Modes of Energy Harvesting	Energy Source	Technology	Transceiver Name	Sleep	RX	TX
Atmel - Linear Technology	The Drop	Light, Heat	battery-free	ZigBee	AT86RF230	20 nA	15.5 mA	16.5 mA
Powercast - Microchip	P2110-EVAL-01	RF	battery-free	MiWi, MiWi P2P, ZigBee, Proprietary	MRF24J40	2 µA	19 mA	23 mA
Silicon Labs	Energy-Harvesting RD	Light	battery-free	Si1012	EZRadioPRO	----	18.5 mA	18 mA
Texas Instruments	eZ430-RF2500-SEH	Light	battery-free	ZigBee	CC2500	400 nA	13.3 mA	21.2 mA
Silicon Labs - Cymbet	RF-to-USB2 Wireless RD	Light, Motion, Heat, RF	battery-free	Si1014	EZRadioPRO	----	18.5 mA	18 mA
Cymbet	CBC-EVAL-09	Light, Motion, Heat, RF	battery-free	ZigBee	CC2500	400 nA	13.3 mA	21.2 mA
Cymbet	CBC-EVAL-10	Light	battery-free	Proprietary	CC110L	0.2 µA	14 mA	16.8 mA
Microchip	XLP 16-bit	Light	battery-free	MiWi, MiWi P2P, ZigBee, Proprietary	MRF24J40	2 µA	19 mA	23 mA
Micropelt	TE-CORE /RF	Heat	battery-free	ZigBee	CC2530	1 µA	24 mA	29 mA
EnOcean	EDK 350	Light, Motion, Heat	battery-free	Proprietary	TCM 300	----	33 mA	24 mA
Micropelt	TE-CORE	Heat	battery-free	ZigBee	CC2500	400 nA	13.3 mA	21.2 mA
Digi-Key	Digi-Key TI CC430	Light	battery-free	Proprietary	CC430	2 µA	15 mA	18 mA
Powercast - Silicon Labs	P2110CSR-SL	RF	wireless battery-charging	Si1014	EZRadioPRO	----	18.5 mA	18 mA
Powercast	P2110-EVAL-02	RF	wireless battery-charging	ZigBee	CC2500	400 nA	13.3 mA	21.2 mA
Infinite Power Solutions	IPS-EVAL-EH-02	Light	wireless battery-charging	MiWi, MiWi P2P, ZigBee, Proprietary	MRF24J40	2 µA	19 mA	23 mA

5. Conclusion

This paper has shown how energy harvesting techniques can be integrated into low-power MAC protocols. Although the current MAC protocols are able to reduce the energy consumption of low-power wireless devices, they are still unable to offer an ultimate energy self-sustaining solution for MAC protocols. The proposed scheme in this paper is able to take advantage of power harvested from ambient and apply it into the sleep mode of the duty cycling mechanism to further maximize the energy efficiency in low-power MAC protocols.

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REFERENCES

[1] United States Census Bureau. [Online] [Cited: March 10, 2014.] https://www.census.gov/newsroom/releases/archives/aging_population/cb09-108.html.

[2] Office for National Statistics. [Online] [Cited: March 10, 2014.] http://www.ons.gov.uk/ons/rel/npp/national-population-projections/2012-based-projections/stb-2012-based-npp-principal-and-key-variants.html.

[3] Opportunistic Aggregation over Duty Cycled Communications in Wireless Sensor Networks. Benson, J, et al. St. Louis : s.n., 2008. IPSN Track on Sensor Platform, Tools and Design Methods for Networked Embedded Systems.

[4] A Very Low Power MAC (VLPM) Protocol for Wireless Body Area Networks. Ullah, Niamat, Khan, Pervez and Sup Kwak, Kyung . 4, s.l. : Multidisciplinary Digital Publishing Institute, March 25, 2011, Sensors — Open Access Journal, Vol. 11, pp. 3717-3737.

[5] A power efficient MAC protocol for wireless body area networks. Al Ameen, Moshaddique, et al. s.l. : Springer, February 6, 2012, EURASIP Journal on Wireless Communications and Networking.

[6] Energy-efficient MAC in Wireless Body Area Networks. Yuan, Jingjing, Li, Changle and Zhu, Wu. Macau : Atlantis Press, 2013. Information Science and Technology Application.

[7] Versatile Low Power Media Access for Wireless Sensor Networks. Polastre, Joseph, Hill, Jason and Culler, David. Baltimore : ACM, 2004. Embedded Networked Sensor Systems. pp. 95-107.

[8] X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks. Buettner, Michael, et al. Boulder : ACM, 2006. Embedded networked sensor systems. pp. 307-320.

[9] WiseMAC: An Ultra Low Power MAC Protocol for the Downlink of Infrastructure Wireless Sensor Networks. El-Hoiydi, A and Decotignie, J.-D. Alexandria : IEEE, 2004. Symposium on Computers and Communication. pp. 244-251.

[10] The Wireless Autonomous Spanning tree Protocol for Multihop Wireless Body Area Networks. Latre, Benoit, et al. San Jose : IEEE, 2006. 3rd Annual International Conference on Mobile and Ubiquitous Systems. pp. 1 - 8.

[11] Medium Access Control for Body Sensor Networks. Li, Huaming and Tan, Jindong. Honolulu : IEEE, 2007. Proceedings of 16th International Conference on Computer Communications and Networks. pp. 210 - 215.

[12] A Low-delay Protocol for Multihop Wireless Body Area Networks. Latre, Benoit, et al. Philadelphia : IEEE, 2007. Fourth Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services. pp. 1 - 8.

[13] Microchip. MRF24XA Low-Power, 2.4 GHz ISM-Band IEEE 802.15.4™ RF Transceiver. USA, 2011-2013.

[14] Atmel. Atmel Corporation. [Online] [Cited: May 15, 2014.] http://www.atmel.com/images/doc8168.pdf.

[15] Energy Harvesting Sensor Nodes: Survey and Implications. Sudevalayam, Sujesha and Kulkarni, Purushottam. 3, s.l. : IEEE, July 26, 2010, Communications Surveys & Tutorials, Vol. 13, pp. 443 - 461.

[16] Indoor solar energy harvesting for sensor network router nodes. Hande, Abhiman, et al. 6, s.l. : Elsevier, September 1, 2007, Microprocessors and Microsystems, Vol. 31, pp. 420–432.

[17] Donovan, John. Digi-Key. [Online] August 02, 2012. [Cited: March 19, 2014.] http://www.digikey.com/en-US/articles/techzone/2012/feb/energy-harvesting-for-low-power-wireless-sensor-nodes.

[18] Henderson, Tessa. Energy Harvesting Journal. [Online] [Cited: March 19, 2014.] http://www.energyharvestingjournal.com/articles/rf-harvesting-from-ambient-sources-00001395.asp.

[19] Zungeru, Adamu Murtala, et al. Radio Frequency Energy Harvesting and Management for Wireless Sensor Networks. [book auth.] Hrishikesh Venkataraman and Gabriel-Miro Muntean. Green Mobile Devices and Networks. s.l. : CRC Press, 2012, 13, pp. 341-368.