Wireless energy harvesting for Internet of Things

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Wireless Energy Harvesting for Internet of Things

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Abstract

Internet of Things (IoT) is an emerging computing concept that describes a structure in which everyday physical objects, each provided with unique identifiers, are connected to the Internet without requiring human interaction. Long-term and self-sustainable operation are key components for realization of such a complex network, and entail energy-aware devices that are potentially capable of harvesting their required energy from ambient sources. Among different energy harvesting methods such as vibration, light and thermal energy extraction, wireless energy harvesting (WEH) has proven to be one of the most promising solutions by virtue of its simplicity, ease of implementation and availability. In this article, we present an overview of enabling technologies for efficient WEH, analyze the life-time of WEH-enabled IoT devices, and briefly study the future trends in the design of efficient WEH systems and research challenges that lie ahead.

I. Introduction

Internet of Things (IoT) is an intelligent infrastructure of uniquely identifiable devices capable of wirelessly communicating with each other, services and people on a large scale, through the Internet [1].

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IoT aims at making the Internet ubiquitous and pervasive and has the potential to affect the quality of life for the users in many aspects. The networked heterogeneous devices connected in an IoT structure are typically equipped with sensors, controlling processors, wireless transceivers, and an energy source (e.g., a battery) to monitor their environment and send/receive data. Applications envisioned for IoT span a wide range of fields like home automation, healthcare, surveillance, transportation, smart environments and many more. One of the dominant barriers in implementing such a grandiose scheme is supplying adequate energy to operate the network in a self-sufficient manner without compromising quality of service. Therefore, it is imperative to improve the energy efficiency and longevity of devices in IoT.

Although there are numerous methods to achieve energy efficiency, such as using lightweight communication protocols [2] or adopting low-power radio transceivers [3], the recent technology trend in energy harvesting provides a fundamental method to prolong battery longevity. Thus, energy harvesting is a promising approach for the emerging IoT [4]. Practically, energy can be harvested from environmental sources, namely, thermal, solar, vibration, and wireless radio-frequency (RF) energy sources [5]. While harvesting from the aforementioned environmental sources is dependent on the presence of the corresponding energy source, RF energy harvesting provides key benefits in terms of being wireless, readily available in the form of transmitted energy (TV/radio broadcasters, mobile base stations and hand-held radios), low cost, and small form factor implementation. This article presents an overview of wireless energy harvesting units in the context of wireless energy harvesting-Internet of Things (WEH-IoT) systems. In this scenario, multiple sensor nodes typically transmit data to a common sink node. The sink node, also known as gateway, is connected to the network and is accessible to the outside world over the Internet.

A WEH-enabled sensor device usually constitutes of an antenna, a transceiver, WEH unit, power management unit (PMU), sensor/processor unit and possibly an onboard battery. Among those components, there are two essential units for energy harvesting; namely, WEH unit and PMU:

- WEH unit is in charge of harvesting the RF energy and producing a stable energy source for the rest of the device. It also interfaces with the PMU.
- The PMU controls the transceiver, sensing unit functionality and manages the energy consumption of each unit and/or accommodates battery charging using the harvested energy.

In this article, we also focus on the enabling technologies including high-efficiency wireless/RF energy harvesting rectifiers and low-power wake-up radio for WEH units. We propose a PMU architecture that accommodates a battery charging scheme using the harvested energy through WEH unit. Furthermore, we analyze the lifetime of the proposed WEH-IoT system in the context of two common scenarios in IoT networked systems. The energy cost model is described using uniform and random distribution topology of sensor devices. It is shown that the lifetime is increased substantially using the wireless harvesting techniques. Finally, we conclude with a discussion on future research challenges.

II. Wireless Energy Harvesting Unit

The WEH receives the transmitted radio waves with an antenna and converts the received RF energy into a stable direct current (DC) energy source to supply the sensor device. Generally, in the context of IoT, wireless sensor networks (WSNs) and radio-frequency identification (RFID) tags, wireless energy sources can be classified into two categories [6]:

1) *Dedicated source* : Dedicated RF sources are deployed to provide a predictable energy supply to the device. Dedicated sources can be optimized in terms of frequency and maximum power to meet the requirements of the sensor devices. Sink node is an example of a dedicated source.

2) *Ambient source* : This type of source is further divided into two subcategories:

a) ***Static or anticipated ambient sources***, which are transmitters that radiate stable power over time, are not optimized (e.g., in terms of frequency and transmitted power) to supply the sensor device. Mobile base station, broadcast radio and TV are examples of anticipated ambient sources.

b) ***Dynamic or unknown ambient sources*** which are transmitters that transmit periodically in a fashion not controlled by the IoT system. Harvesting energy from such sources require an intelligent WEH to monitor the channel for harvesting opportunities. WiFi access points, microwave radio links and police radios are examples of unknown ambient sources.

Different ambient sources transmit at different frequency bands. Harvesting wireless energy at multiple frequency bands complicates the antenna geometry requirements and demands a sophisticated power converter. Therefore, WEH is typically optimized to harvest from the dedicated energy source (e.g., sink node) and may be devised so as to allow ambient energy harvesting as an auxiliary source.

A. RF-to-DC Rectifier

In practice, the conversion from the received RF power to the usable DC supply comes with a certain amount of power loss in the matching circuit and in the internal circuitry of the power converter. The power conversion efficiency (PCE) of the converter is the ratio of the generated usable DC output power to the input RF power. State-of-the-art RF-to-DC converters (also known as rectifiers) can achieve high PCE values, up to 70% or more [7]. PCE is an indication of the amount of harvested energy that is available for the sensor device. The available harvested power P_H, is given by Friis equation [7] and is directly proportional to the transmitted power P_T, path loss P_L, transmitter antenna gain G_T, receiver antenna gain G_R, power conversion efficiency of the converter PCE_H, square of the wavelength λ and is inversely proportional to the square of the communication distance r between the source and the device (see Fig.1).

The schematic diagram of the wireless energy harvesting unit is shown in Fig.1-(a). The transmission power, communication medium, antenna gains and frequency of operation are typically dictated by the application requirements. Therefore, a viable design parameter to enhance the harvested power P_H, or to maximize the communication distance r, is PCE. The PCE curve as a function of distance/input power level for a typical rectifier is shown in Fig.1-(b). As shown, the PCE is optimized to peak at a certain input level, which corresponds to a specific distance (i.e., PCE_{MAX} at r_{opt}).

In addition to a high PCE, other important characteristics of the WEH unit include high sensitivity, wide high-efficiency range, multi-band operation and ease of implementation. Extensive studies have been performed on techniques to improve the efficiency of the converter unit [7]. One of our recent efforts to enhance PCE for rectifiers operating at small input levels and a technique to enable harvesting RF energy at multiple frequencies with a single antenna (to facilitate energy harvesting from ambient sources) are described in [8].

B. Wake-Up Radio Scheme

Radio transceiver is typically the most power hungry block of the wireless sensor device. Although the transceiver is rarely called into action during each operation cycle, it has to keep monitoring the channel. This idle listening process is a significant contributor to the overall power consumption of the sensor device.

An efficient approach to address the idle-mode energy consumption is *duty-cycling*, in which the receiver on-demand switches between listening and sleeping states. Among the different categories of *duty-cycling*, namely synchronous, pseudo-asynchronous and pure asynchronous. The latter provides the most efficient solution in terms of energy consumption [3].

In the asynchronous approach, the sensor device is in deep sleep mode and only wakes up when signalled by the sink node or its neighbouring devices through an interrupt command generated by a low-power wake-up radio (WUR). The timing diagram of the asynchronous communication approach is shown in Fig.1-(c). Since the WUR is constantly active to monitor the channel, this scheme outperforms other alternatives only if the energy consumption of the WUR is negligible compared to that of the main receiver. The block diagram of a WUR enabled sensor device is shown in Fig.1-(d).

The WUR is a simple receiver that receives the wake-up command (e.g., the device unique address) and generates an interrupt for the main receiver. In WEH device, the implemented rectifier followed by a data slicer (comparator) can perform as a WUR with minimal complexity overhead. We advocate the use of such a WUR (for detection of a simple OOK wake-up message) as schematically shown in Fig.1-(e) [9]. If all the required energy of the WUR circuitry is supplied by the harvested energy from the wake-up message itself, the battery is not used during the idle listening mode (virtually zero energy consumption). Aside from energy consumption, high sensitivity and range, robustness to interferers, selectivity and latency are also of paramount importance in designing a WUR for IoT.

III. Power Management Unit

An integral part of any energy harvesting system is its Power management unit (PMU). PMU is in charge of controlling the storage of the harvested energy. It also manages the distribution of the available energy among different consumers in an effort to maximize the lifetime of the device while maintaining a high quality of service (QoS). We extend the architecture of the PMU proposed in [10] to enable effective cooperation with the WEH unit. The architecture proposed is an event triggered/asynchronous scheme based on the signal generated by WUR. The PMU architecture also detects/pre-empts the failure of a node in the event of energy deficiency.

The detailed block diagram of the PMU for the WEH sensor device is shown in Fig. 2. The PMU starts its operation by a trigger signal generated by the WUR of WEH unit $(INTERRUPT)$. The PMU first activates the main transceiver through $(ON/\overline{OFF})$ and then sends a wake up signal $(WAKE\ UP)$ to the sensing unit to start its operation. The sensing unit toggles the $STOP/\overline{RUN}$ to high, signifying the PMU that it is in running mode. The REQ signal indicates the amount of energy required by the sensing unit. The signals BAT and SE indicate the amount of energy left in the battery device and the WEH unit storage element respectively. Accordingly, the PMU activates switches SW_1 through signal $SENSE$ to fulfill the power requirements of the sensing unit. The sensor unit is in charge of sensing, data processing via a microprocessor (μp) and finally transmitting them to a low-power transceiver based on Bluetooth, WiFi, IEEE 802.15.4, Zigbee, etc. The sensor device requires a minimum power of P_{Dmin} to operate in sensing mode. When the energy in the battery device goes below a certain threshold $P_{TH} < 1.5P_{Dmin}$, the PMU sends a $RECHARGE$ command to the storage element by activating switch SW_2 of WEH unit to charge the battery. When the energy level of the device remains $1.1P_{Dmin}$, the device sends out of service (OUS) command to the sink node, signaling that it goes out of the service till it recharges itself again to more than $1.5\ P_{Dmin}$. The sink node in turn sends a stop all service (SAS) signal to the device. The sink node/gateway puts the device out of the sensing service loop but keeps transmitting RF energy for harvesting. As the device is ready for service again, it sends a $READY$ signal to the sink node which in turn gives resume all services (RAS) signal to the device.

IV. Life-Time Prediction Through Energy Cost Model

Let us consider a network of *k* static and identical sensor devices. As in [11], WSNs are either uniformly distributed in a ring topology, communicating with the sink node in a peer-to-peer fashion, or randomly distributed in a multi-hop ad-hoc topology. As WSNs are a subset of an IoT system, we base our analysis on these topologies. Table I delineates the parameters used for the analysis of our scenarios.

The power transmitted by the sink node has a certain maximum and minimum value of P_{Tmax} and P_{Tmin}, respectively and the sensor devices require a minimum power of P_{Dmin} to function properly. The sink node communicates with sensor devices asynchronously. We define two operational modes for the sensor devices, namely, $active$ and $idle$ modes.

The lifetime of an IoT system (battery operated only/battery with WEH unit) depends on the average energy consumption of the sensor devices E_D per active duty cycle. This involves the combined operations of sensing, processing and communication (receive/transmit).

Let N be the total number of active duty cycles representing the life-time of the sensor device. The communication energy consists of E_{LS} (listening energy), E_{RX} (receiver energy) and E_{TX} (transmitter energy). The computation energy includes E_{PR} (processing energy) and E_{SN} (sensing energy). To capture the energy distribution amongst the aforementioned energy consumers, weighting coefficients $\alpha_{LS} > \alpha_{TX} > \alpha_{RX} > \alpha_{PR} > \alpha_{SN}$ are assigned to them. The total average energy consumption $E_D = \alpha_{LS}\ E_{LS}$ + $\alpha_{TX}\ E_{TX}$ + $\alpha_{RX}\ E_{RX}$ + $\alpha_{PR}\ E_{PR}$ + $\alpha_{SN}\ E_{SN}$. E_B is the total energy stored in the battery and E_H is the available harvested energy per active duty cycle. We assume constant energy consumptions for receiver, processor and sensor. However, the energy consumption of the transmitter (E_{TX}) is directly proportional to r_{ij}^2, where r_{ij} is the distance between the originating device j and the sink node i (in ring topology) or the sink node/sensor device (in multi-hop topology).The harvested energy E_H is inversely proportional to r_{ji}^2 (here j is the sink node and r_{ij}=r_{ji}). Based on these assumptions, the life-time estimation N_H for the sensor device operated with battery assisted by a WEH unit can be formulated as:

$$N_H = \frac{E_B}{C_D + C_{TX} \cdot r_{ij}^2 - \frac{C_H}{r_{ji}^2}} \tag{1}$$

where, $C_D = \alpha_{LS}\ E_{LS}$ + $\alpha_{RX}\ E_{RX}$ + $\alpha_{PR}\ E_{PR}$ + $\alpha_{SN}\ E_{SN}$. C_{TX} and C_H are the proportionality constants for E_{TX} and E_H as mentioned above. We analyze the life-time of the sensor devices for two different scenarios. Note that the life-time of the battery-only device (without WEH) is denoted as N_B.

A. *Scenario I: Uniform distribution in a ring topology*

In the ring topology, sensor devices (*j*'s) are uniformly distributed around the sink node (*i*) at a distance r_{ij} as shown in Fig. 3-(a). Since they are positioned at equidistance from sink node, all the devices receive similar amount of wireless energy for harvesting. Assuming the channel is static between sink node and the sensor devices, the transmitted energy from the device to the sink is the same for all nodes. Fig. 3-(b) schematically shows the distribution of energy among different consumers. The horizontal axis depicts the active duty cycle (T). Energy consumption for E_{TX}, E_{RX}, E_{PR} and E_{SN} occur only for a fraction of the total active duty cycle whereas energy consumption for E_{LS} and harvested energy E_H happen constantly throughout T. Based on these assumptions, the lifetime of the devices is estimated using (1) for N_B (battery only, E_H is zero) and N_H. Fig. 3-(c) shows the estimated lifetime versus the power consumption of the devices (E_D). By incorporating WUR scheme, we reduce the α_{LS} E_{LS} to have almost negligible effect on C_D.

Typical values for the distribution of different energy consumers are from [9] and [12]. Energy harvesting increases the lifetime of the battery assisted device (N_H) by $\sim$30% for low-power sensor devices (such as temperature, pressure, and light sensors). WUR scheme enhances the lifetime by a further $\sim$110% as depicted by $N_H(WUR, r)$. Setting $r_{ij} = \frac{r}{2}$, the lifetime for energy harvesting device increases with the reduction in distance between sink node and sensor node as shown in $N_H(WUR, r/2)$.

B. Scenario II: Randomly distributed multi-hop topology

In the multi-hop topology, sensor devices (j_N's) are randomly distributed following a Poisson's distribution. The maximum distance of the k^{th}-farthest sensor device from the sink node is r_{ijk}. In a multi-hop transmission, the j_k sensor node's data hops $k-1$ times before it reaches the sink node/gateway. The farthest node j_k only acts as a sensor and transmits its own data. However, the remaining j_1, j_2, ... , j_k nodes act both as sensor for their own data and as relay for data coming from farther nodes. So, to compute their lifetime, it is required to add the energy consumption of the relay cycle to that of sensor cycle. The relay cycle energy consumption is E_D-$\alpha_{PR}E_{PR}$-$\alpha_{SN}E_{SN}$, which is the total energy consumption for a device operation minus the processing and sensing energy. Fig. 4-(a) depicts a two-hop scenario. Fig. 4-(b) shows the distribution of energy among different consumers. The transmit mode energy is smaller in this case as compared to Fig. 3-(b) in the ring topology as the transmission distance is reduced to r_{j2j1}. Fig. 4-(c) shows the energy distribution for the sensor node j_1 operating as a sensor and as a relay for j_2. The estimated lifetime of the sensor devices in the two-hop topology is shown in Fig. 4-(d) for node j_2 and node j_1 (life time for battery only, N_B and for WEH assisted battery, N_H). As shown in the figure, energy harvesting extends the lifetime of the nodes. Node j_1 is exercised twice as often as j_2, therefore it consumes more energy and has a shorter lifetime compared to node j_2. The lifetime enhancement through WEH for a node at distance similar to that of the ring topology is approximately 5 times larger ($\sim$510% as compared to $\sim$110% in ring topology) for low power sensor devices. Therefore, for the N-hop topology, the lifetime of the devices is further enhanced.

V. FUTURE TRENDS AND RESEARCH CHALLENGES

The approaches presented in this work are not exhaustive. For the proposed system to become more practically viable there are research challenges ahead which need to be addressed:

A. *Highly efficient, low cost and small form-factor wireless energy harvesting system*

The key challenge in successful large scale deployment of sensor devices in an IoT infrastructure is to minimize their impact on users and environment. Non-intrusive devices need to be small, have to be fabricated and deployed at very low cost and are expected to operate in a self-sufficient manner for a long time. WEH unit as an integral part of such devices must comply with such cost and size requirements. Efficiency is another crucial factor for a WEH system. High efficiency becomes increasingly relevant considering that the transmitted power by the dedicated source is usually limited due to health issues and interference constraints.

Commercial RF harvesting systems currently existing in the market enable single-band RF harvesting at sub-mW power levels with efficiencies as high as 50%. However, extensive studies are still being carried out to improve the performance of WEH systems at circuit and system levels. Energy beamforming [5], high gain antennas and multi-band harvesting are among the other hot topics in the context of WEH systems for IoT.

B. *Channel statistics for wireless energy harvesting IoT systems*

The scenarios and their respective analysis in our paper assume the channel as static and time invariant. Practically, channel characteristics vary depending on the environment in which the number of interferers and the number of paths available from source device to the sink. Harvested energy depends on the distance between the sink and sensor node. In the presence of fading or multipath, the received energy for the purpose of harvesting and the transmitted data are adversely affected. In [13], a compressive sensing based approach is proposed to recover sparse signals from multiple spatially correlated data transmitted to a fusion center. Recently in [14], researchers have proposed techniques to reduce the amount of packets to be retransmitted in case of faulty transmission eventually saving energy.

C. Cross-layer design of wireless energy harvesting

Although the recent development of energy harvesting technologies mitigates energy scarcity issue, the sensor device still has to operate in duty-cycled mode due to limited energy collection from the environment, and dynamically adjust duty cycles to adapt to the availability of the environmental energy. Such dynamic duty cycles pose challenges for MAC layer protocol design in terms of synchronization, reliability, efficiency of utilizing channel resource and energy, etc. Therefore, solutions of duty-cycling-aware middleware between Media access control (MAC) and physical layer power management are highly desired. Moreover, dynamic duty cycling also has non-trivial impact on the end-to-end performance of the network layer, including end-to-end delay, throughput, etc. However, the current routing protocol design for IoT has taken very little attention to duty cycling. The problem of seamlessly integrating duty-cycle awareness into the multi-path routing scenario has been dealt in [15] using a sleep scheduling mechanism, however it still remains an open question.

D. Smartphone relays: wireless energy harvesting in 5G systems

Fueled by increases in traffic and data demand, mobile technology is moving towards 5G where everything will be connected via Internet and accessed through the cloud. Relay techniques utilized by 5G can benefit wireless/RF energy harvesting [6]. Also, the smartphones owing to their mobility can act as a gateway/sink node relaying data for sensors in personal area network and as a source of RF energy for harvesting purpose.

VI. Concluding Remarks

In this article, we have overviewed technologies and schemes to enable WEH for IoT systems. With an emphasis on improving the efficiency of the WEH unit and reducing the energy consumption of the devices, the lifetime of WEH-assisted battery-operated systems in an IoT architecture are analyzed for two different scenarios. A study of the specific energy requirements of IoT devices reveals that achieving self-sustainability requires improved design techniques both at circuit and system levels.

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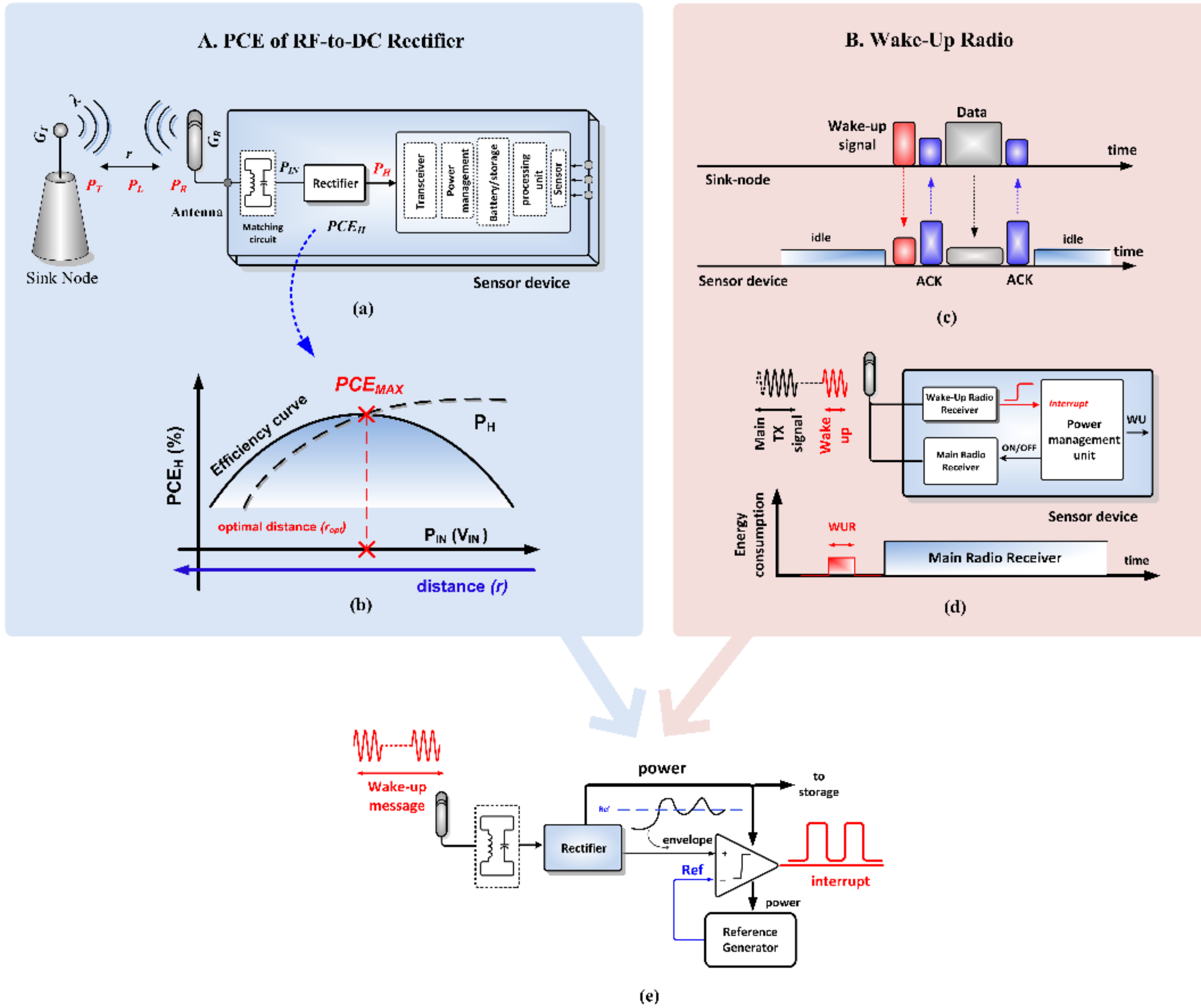


Fig. 1. WUR enabled energy harvesting unit: (a) Block diagram of the WEH sensor device, (b) Efficiency curve (solid line) and harvested energy of the rectifier (dashed line), (c) Timing diagram of asynchronous wake-up scheme, (d) Block diagram and energy consumption of the WUR, and (e) Zero-power interrupt generation unit.

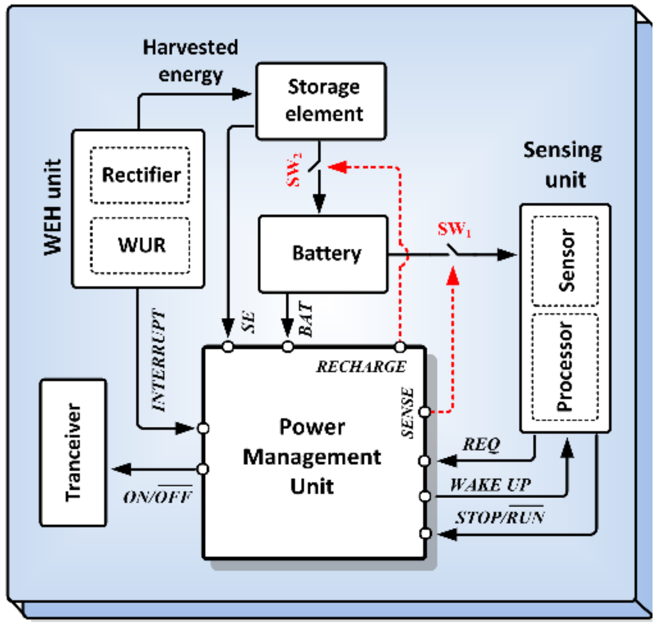
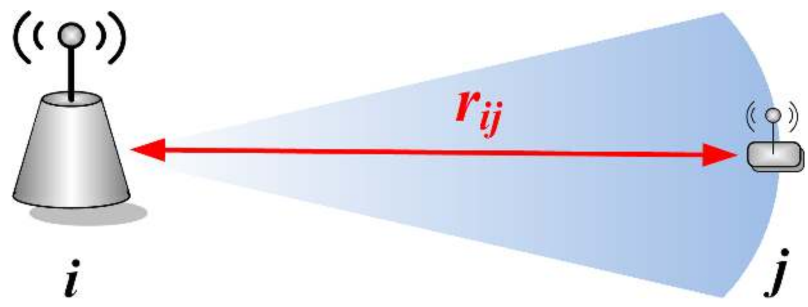


Fig. 2. Proposed Power Management Unit.

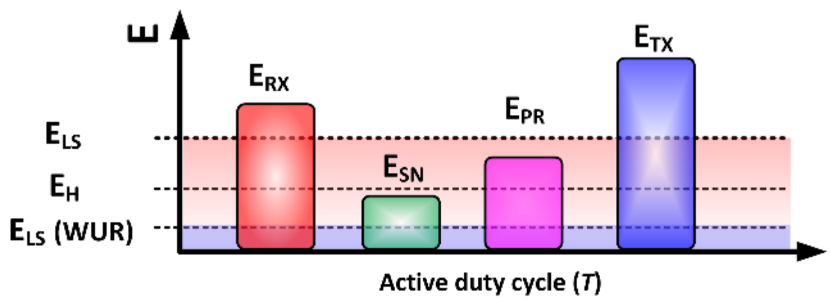
TABLE I

PARAMETERS USED FOR LIFETIME ANALYSIS

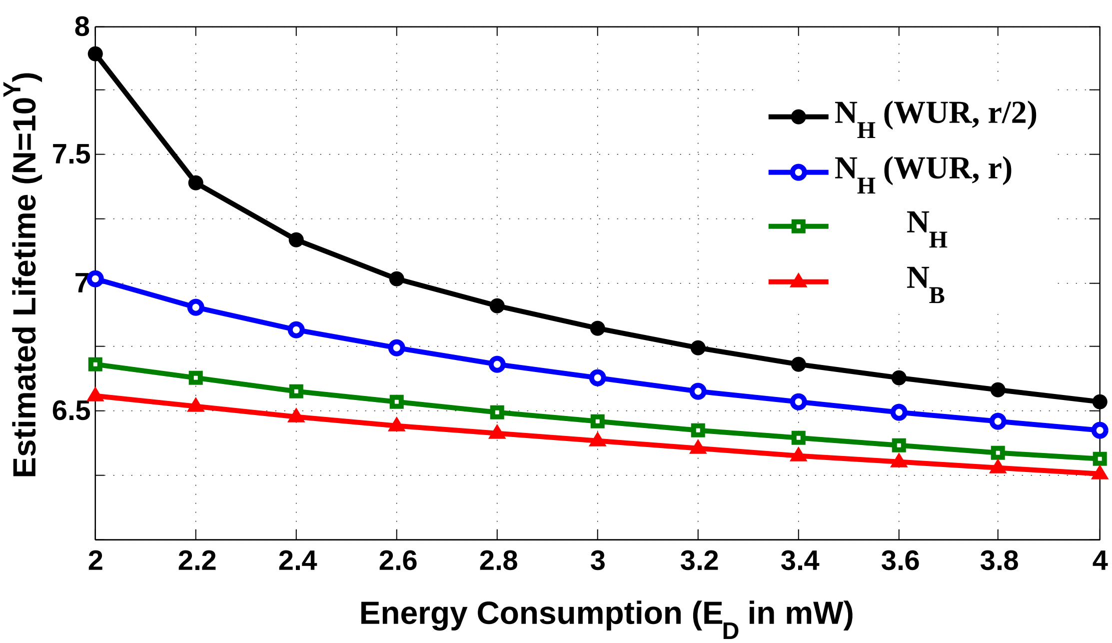
Parameter	**Description**
E_D	Total energy consumption of device
E_B	Energy of the battery
E_H	Harvested energy
E_{LS}	Listen mode energy
E_{RX}	Receive mode energy
E_{TX}	Transmit mode energy
E_{PR}	Processing energy
E_{SN}	Sensing energy
$\alpha_{LS}>\alpha_{TX}>\alpha_{RX}>\alpha_{PR}>\alpha_{SN}$	Weighting coefficients of the respective energy parameters
r_{ij}	Distance of originating device j to sink node i
N	Estimated device lifetime
N_B	Estimated device lifetime (battery only)
N_H	Estimated device lifetime (WEH assisted battery)
$N_H(WUR, r)$	Estimated device lifetime (WUR enabled WEH assisted battery) at distance r = r_{ij}



(a)

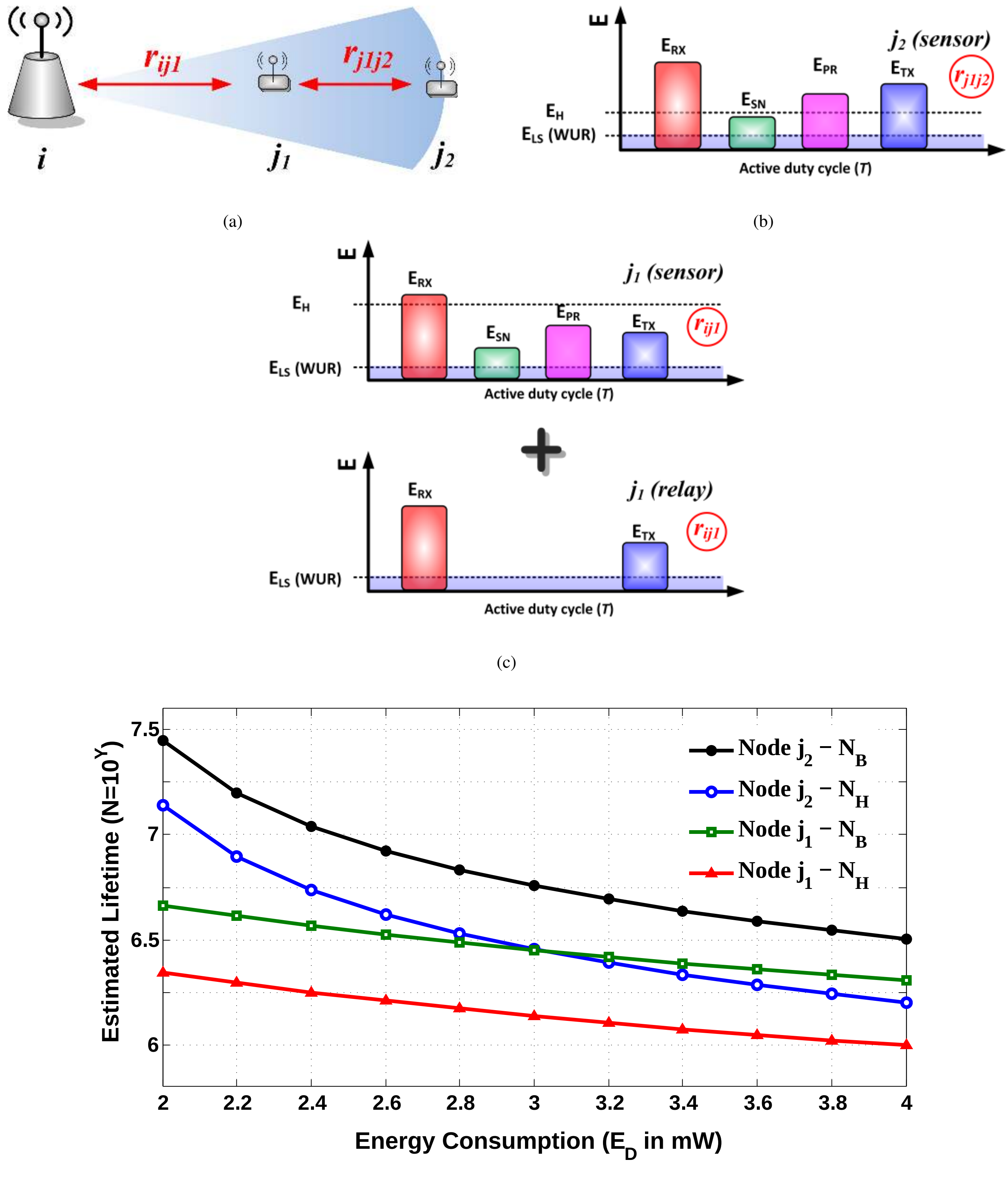


(b)



(c)

Fig. 3. Life-time prediction through energy cost model: (a) Ring topology architecture, (b) Energy distribution, and (c) Estimated lifetime versus energy consumption.



(d)

Fig. 4. Life-time prediction through energy cost model: (a) Random distribution architecture, (b) Energy distribution of sensor j_2, (c) Energy distribution of sensor j_1 as sensor and relay, and (d) Estimated lifetime versus energy consumption.