AN OVERVIEW ON POWER MANAGING TECHNIQUES IN WIRELESS SENSOR NETWORKS POWERED BY CLEAN ENERGY

TỔNG QUAN CÁC KỸ THUẬT QUẢN LÝ NĂNG LƯỢNG TRONG MẠNG CẢM BIẾN KHÔNG DÂY SỬ DỤNG NĂNG LƯỢNG SẠCH

Dao Xuan Quy, Le Trong Nhan, Nguyen Duy Ngan, Tran Tien Dat

Trường Đại học Quảng Bình; xuanquy.dao@gmail.com

Abstract - Wireless sensor networks (WSN) have attracted much attention in recent years due to their potential monitoring applications in remote places, where wire connections are impractical to deploy. Moreover, energy harvesting capability is also considered as a promising measure to extend the lifetime of the network.As ambient energy can be scavenged as long as desired, the lifetime can be theoretically infinite. To achieve that, a Power manager is required to balance the consumed energy and the harvested energy in a wireless node. In this paper, a survey of recent power managing techniques is presented. It provides an insight into how they can be used and orchestrated so that satisfactory performance can be achieved within a given energy budget. Moreover, the advantages and also drawbacks are analyzed to provide users with a good comprehension of power managers for a better choice.

Key words - wireless sensor network; energy management; energy harvesting; energy neutral operation; MAC protocol.

Tóm tắt - Mạng cảm biến không dây thu hút nhiều sự quan tâm trong những nghiên cứu gần đây nhờ các ứng dụng giám sát đầy tiềm năng, đặc biệt là ở những nơi mà kết nối dây rất khó khả thi trong việc triển khai. Bên cạnh đó, khả năng thu năng lượng sạch đang được xem là giải pháp hứa hẹn để cải thiện thời gian tồn tại của mạng WSN. Vì năng lượng xung quanh có thể khai thác lâu dài, nên thời gian tồn tại của mạng về lý thuyết, xem như vô hạn. Đạt được như vậy, mỗi node mạng cần 1 hệ thống quản lý nhằm cân bằng năng lượng tiêu thụ và năng lượng thu hoạch. Trong bài báo này, chúng tôi trình bày các kĩ thuật hiện có. Bài báo cung cấp cái nhìn tổng quan các phương pháp nhằm sử dụng hiệu quả lượng năng lượng trong giới hạn cho phép và duy trì hoạt động lâu dài của mạng. Những ưu khuyết điểm của từng phương pháp cũng được chúng tôi phân tích chi tiết. Người dùng có thể chọn lựa giải pháp phù hợp nhất cho ứng dụng của mình.

Từ khóa - mạng cảm biến không dây; quản lý năng lượng; thu hoạch năng lượng; hoạt động cân bằng; giao thức MAC.

1. Introduction

Developments of wireless objects in our living spaces such as mobile phones, RFID tags, home appliances or monitoring cameras have opened a future internet, which is referred as Internet of Things (IoT) [1]. Identified by a unique address, any wireless object can join the network and communicate with others as traditional computers through internet, based on standardcommunication protocols. IoT is opening a novel opportunity for proliferation of Wireless Sensor Networks (WSNs), which can provide a wide range of monitoring applications such as monitoring spaces (environment, agriculture) or monitoring objects (human healthcare, smart buildings) [2].

A wireless sensor node, the basic object of WSNs, is usually comprised of a low-power sensing device, an embedded microcontroller, and a wireless transceiver. The embedded microcontroller is generally used for collecting and processing the signal data taken from the sensors. Sensor elements produce a measurable response to a change in the physical world such as temperature, humidity, pressure and moisture. The wireless transceiver provides a medium to transfer information extracted from the sensors to a base station or through intercommunications among many nodes. Recent advancements in micro-electro-mechanical-systems (MEMS) technology, radio transceivers for wireless communications, and digital electronics have facilitated the development of low-cost, low power, multi-functional sensor nodes that are small in size and more and more efficient for processing wireless communications. Due to the short distance of the radio frequency (RF) transceiver (e.g. 30m with CC2420, the transceiver from Texas Instruments), monitoring applications on remote places or large areas require a large number of randomly deployed wireless sensor nodes that constructs a WSN. Many types of sensors such as seismic, magnetic, thermal, visual, infrared, and acoustic provide various WSN applications ranging from home automation, parking guidance to patient healthcare [2]. However, these applications require a long-term lifetime but the available energy in battery is limited. Therefore, to extend the system lifetime to be theoretically infinite, everlasting ambient energy is used to power the WSN node. It is obvious that when the consumed energy is always less than or equal to the harvested energy, the node can last until its hardware is out-of-date. To guarantee this condition, a Power Manager is embedded in each WSN node, to adapt the power consumption according to the amount of harvested energy. In this paper, an overview of existing techniques is presented. We classify them into three different categories: The dynamic power manager (DPM), dynamic voltage and frequency scaling (DVFS) and the duty cycle power manager (DCPM). These power managers are applied in different layers in the WSN applications. While the first one is usually implemented in the application layer, the second one is carried out by the physical layer. Finally, the last technique is suitable for MAC (Medium Access Control) layer, which is in charge of the wireless communications among nodes. The advantages and drawbacks of these techniques are also presented in this paper.

The rest of this paper is organized as follows. In Section II, an introduction of WSN using harvested energy such as solar, wind or thermal is presented. The main contribution of this paper is presented in Section III, where popular power managing techniques are gathered and classified. Finally, the paper ends with a conclusion.

2. Energy harvesting wireless sensor networks

In the last decade, many platforms of wireless sensor nodes from academia to industry are proposed such as Crossbow Mica2 or BTnode [3]. All of these platforms are low cost, small size and have especially, high energy efficiency since energy consumption is the main constraint in WSNs. Although WSNs can be easily used for monitoring applications in some places where cables are difficult and costly to draw, battery maintenance becomes a burden if widely used (e.g. large factories, dangerous places). This issue opens two different approaches in extending the system lifetime of WSNs. In the first one, a variety of methods and techniques to reduce power consumption and therefore increase the system lifetime, have been proposed.

Table 1. *Power density of popular harvesting technologies [5]*

Harvesting device	Power density
PV-direct sun	15mW/cm^2
PV-cloudy day	0.15mW/cm^2
PV-indoor	6µW/cm^2
PV-desk lamp	0.57mW/cm^2
Piezoelectric-shoe	330µW/cm^2
Thermoelectric-100C gradient	40µW/cm^2
Wind generator-15Km/h	7.93mW

RFenergy consumption of the devices significantly reduces thepower consumption so there are a number of novel hardware (e.g. wake-up radio receivers [4]) and software (e.g. MAC androuting algorithm [4]). Although system lifetime is improved, itis still crippled by the limited energy in the batteries, which are used for the energy storage.

In a second approach, alternative energy sources have beenintegrated to supplement, or even replace batteries. Thanksto advancements in harvesting energy techniques, everlasting environmental friendly energy can be extracted and brings a breakthrough to design completely autonomous Energy Harvesting (EH) WSNs. A wide range of harvesting devices, which are cheap, tiny, and high power density have been proposed and can be applied to EH-WSNs such as photovoltaic (PVs) forsolar energy, thermoelectric for thermal energy orwind generator for air-flow energy. Table 1 summarizes their potential power density. It can be observed that solar energy extracted by PVs provides the highest power density.Moreover, PVs are small in size, inexpensive and easy todeploy compared to other harvesters. Therefore, PVs are currently, themost widely used in EH-WSN platforms.

Although environmental friendly energy can be scavenged for as long as desired, the amount of harvested energy has temporal variations due to the change of environmental conditions.Moreover, different energy sources usually have different behaviors. While solar energy in outdoor and light energy inindoor are periodic and can be predicted in a short future, thermal and wind energy are more arbitrary and unpredictable.The EH-WSN node cannot work at a fix performance as it canbe underflowed (the node is shut down) when harvested energy is reduced and overflowed (harvested energy is wasted) when harvested energy is increased. Therefore, a Power Manager (PM) is often embedded in the EH-WSN node to adapt its computation load according to the harvested energy. Instead of minimizing the consumed energy tomaximize the system lifetime as in battery-powered WSN, thePM makes the harvesting node converge to Energy NeutralOperation (ENO) [6], which means that consumed energy isequal to harvested energy for a long period. This strategy canprovide a theoretically infinite lifetime (until its hardware isoutdated). The next section will present an overview of current PM techniques in EH-WSN.

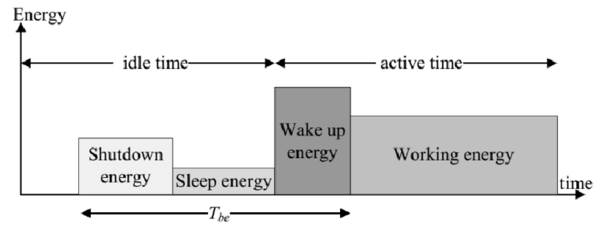

Figure 1. *Break-even time based dynamic power manager. If idle time is less than T_{be}, the system is not required to shutdown as additional energy to wake-up will be greater than running energy during this period*

3. Power manager in energy harvesting WSNs

Power manager techniques which are applied in EH-WSNs are classified into three categories: dynamic power manager, dynamic voltage and frequency scaling, and duty cycle power manager. Among these techniques, duty cycle power manager is the most popular approach. Their basic principles are described in the following subsections.

3.1. Dynamic power manager

Dynamic Power Manager (DPM) techniques are well studied and practiced in embedded systems. A fundamental principle of DPM techniques is that, all components composed a system are not required to work at their full performance. Because most systems are designed to perform multiple functions (e.g. sensing, processing, and communicating in WSNs), many components are not required to be activated at a given time. As a consequence, these components can be turned into low-power states such as idle or sleep by the DPM for energy saving. DPM does not have a fixed shape and can be implemented in either software or hardware. In software, DPM can be implemented on the Operating System (OS) or directly at the application level. In hardware, DPM can be applied to a circuit module or a chip. However, the main drawback of DPM techniques is that once in a low power state, bringing a component back to the active state requires additional energy and especially, the latency to serve incoming tasks.

In addition, simply shutting off components as soon as they are not used might waste energy. It is due to the fact that it takes time to recover system states and sometimesthe saved energy is less than the consumed energy during state transitions. The concept of break-even time (T_{be}), which means the minimum length of idle time to achieve energy saving, is proposed to reduce this problem. The system should only be shutdown when idle time is greater than T_{be} because of the consumed energy to wake-up. This concept is illustrated in Figure.1. Authors in [7] introduce a simple DPM strategy that uses a timeout value $T_{out}$and assumes the system will continue to be idle for at least T_{be} as shown in

Figure.2. The timeout strategy can be classified as adaptive or non-adaptive. In the non-adaptive technique, a fixed timeout strategy is proposed as T_{out} is a predefined value. In adaptive approach, T_{out} can be updated from recent historical values. However, timeouttechniques have two main disadvantages. First, theprediction must be accurate or the system will lose rather than save power. Second, there is still some energy dissipated during the waiting period. This method can be useful for systems such as WSNs in which, the idle time is long on average.

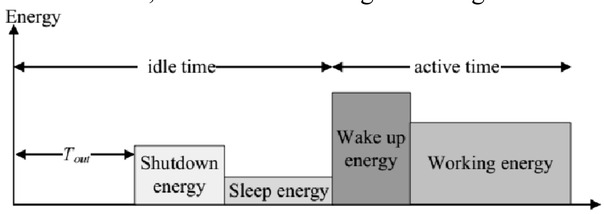

Figure 2. *Timeout strategy in dynamic power manager*

In two different surveys of DPM techniques presented in [8], authors classify DPM into two categories: predictive schemes and stochastic schemes. Instead of waiting for a fixed time period as in timeout schemes, predictive schemes attempt to predict the timing of future input events of the system and schedule shutdown (usually to a single power efficient state) based on these predictions. However, predictive approaches suffer wrong predictions as shown in Figure.3. The system can be turned into low-power state too late or wake-up too early, that causes the waste of energy. Therefore, it is necessary to improve the average error of prediction methods and reduce the delay overhead in predictive schemes. On the other hand, stochastic schemes, rather than eliminating uncertainty of predictions, model the system and the workload as Markov chains [8]. In these approaches, the energy consumption and transition times between many states (e.g. active, idle, sleep) of the system and other complex components (e.g. buffers, queues) are modeled as an optimization problem. Then, a trade-off between energy consumption and performance of the system is determined [8]. Stochastic schemes are well-researched category of DPM techniques due to their several advantages compared to predictive schemes. The greatest advantage is that, they present global optimizations as different states and resources of a system are considered in Markov models. In addition, they provide a solution (in polynomial time) to the performance-constrained energy optimization problem. Finally, the strength and optimality of randomized policies can be exploited in stochastic schemes [8]. However, the limitation of stochastic techniques is an assumption of the prior knowledge of the system and its workload. In reality, workloads are often non-stationary and depend on real-time activities of a system.

3.2. Dynamic voltage and frequency scaling (DVFS)

Dynamic Voltage and Frequency Scaling (DVFS) technique is another technique which is aimed at changing the system energy consumption profile. This technique exploits the variations in the workload for dynamically adjusting the voltage and frequency of processors in order to reduce power and energy consumption. These techniques have a potential for reducing the energy consumption. The challenge, however, is to preserve the feasibility of schedule and provide deadline guarantees.

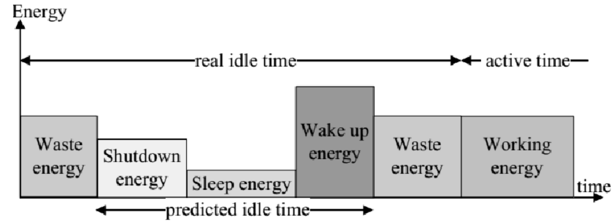

Figure.3. *Predictive scheme in dynamic power manager. Waste energy occurs when the system turns to idle too late or wakes-up too soon*

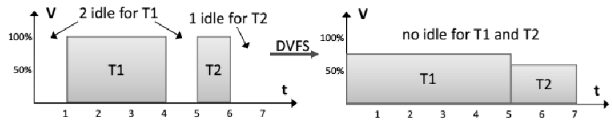

Figure 4. *Two tasks are scaled by using DVFS techniques*

These techniques are of particular effectiveness and interest because energy consumption of the processor is quadratically related to the supply voltage. Another advantage of these techniques is that, when the energy availability is low, they allow the system to keep running at a low speed with reduced energy consumption, without compromising the execution of important tasks.

DVFS techniques save energy consumption by using idle time of sensor nodes. Figure.4 illustrates a simple example of how a DVFS technique saves energy consumption under the control of a scheduler. There are two tasks T1 and T2 where deadlines are 5 and 7, respectively. Taking into account the idle time for each task, DVFS schemes might reduce the system voltage, and therefore, prolong the system lifetime. They have been demonstrated to obtain significant energy savings for time constrained system. However these algorithms do not perform well without considering the WSN workloads. Researches in [9] proposed a task-driven feedback algorithm according to the workloads of a sensor node and fix the errors through the PID control model. The improved algorithm could save 30% energy consumption compared to previous DVFS techniques.

In [10], the authors apply a cooperative technique using DVFS and Dynamic Modulation Scaling (DMS) to sensor nodes for minimizing energy consumption. DMS saves energy by varying the constellation size (the number of bits per symbol) in transmission. Similar to DVFS, DMS reduces energy consumption in exchange of the communication speed. Employing both DVFS and DMS can bring even more reserved energy compared to that used independently. This cooperative architecture is based on the predicted workload of the processor and the transceiver. Prediction algorithm focuses on the periodic operations of sensor nodes such as acquiring temperature and humidity every minute. Therefore, the behavior of threads and communications on the sensor nodes also has periodic characteristics. The system predicts the workload of the processor and transceiver based on the stored log data. After that, it determines the appropriate processor voltage2 (or clock frequency) and constellation size based on prediction results. It can be observed that the cooperative architecture can achieve up to 40% energy reduction when compared to non energy saving systems.

3.3. Duty cycle power manager

This approach directly controls the MAC protocol, which is a source of waste for the radio bearing the channel as transmitting packets [4]. MAC protocols are specifically designed to turn WSN nodes alternately between active and sleeping periods. During the active period, nodes can transmit or receive data, but during the sleeping period, nodes are completely turned off for energy saving. Therefore, the global consumed energy of the node can be adapted by a power manager by changing the sleeping period (or wake-up interval) of MAC protocols as shown in Figure.5. Different MAC protocols for WSNs can be found in [4]. However, we focus on the specific family of duty cycle protocols that can be used by a power manager in EH-WSNs. These duty cycle MAC protocols can be roughly categorized into two categories: synchronous and asynchronous protocols.

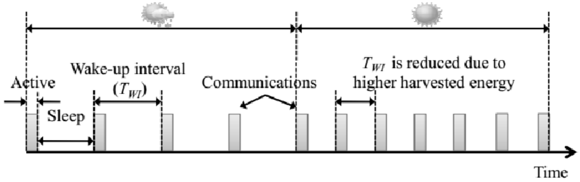

Figure 5. *Duty cycle power manager. The average consumed energy of the node can be adapted by changing its wake-up interval according to the havested energy*

Synchronous approaches such as S-MAC [11] or T- MAC [12] synchronize neighboring nodes in order to align their active or sleeping periods. Neighbor nodes start exchanging packets only within the common active time, enabling a node to sleep for most of the time within an operational cycle without missing any incoming packet. Generally, these approaches aim to reduce the global consumed energy by reducing the idle listening. However, the required synchronization introduces extra overhead and high complexity. Moreover, a node has to wake up multiple times if its neighbors are on different periods. These disadvantages limit the use of synchronous MAC protocols in EH-WSNs.

Existing asynchronous approaches such as TICER and RICER [13], on the other hand, allow nodes to operate independently, with theirown wake-up interval. Such protocols typically employ a low power listening in which, prior to data transmission, a sender transmits a preamble lasting at least as long as the sleep period of the receiver. When the receiver wakes up and detects the preamble, it stays awake to receive the data. These protocolsachieve high energy efficiency and remove the synchronization overhead required in synchronous approaches. Moreover, theyare mainly optimized for low traffic [4] and therefore, suitablefor EH-WSNs which usually have low data rate [14].

Compared to other approaches, duty cycle power managers have two main advantages when applied in EH-WSNs.Firstly, they do not require complex hardware as DVFS, which have to support multiple system voltage and frequency levels. Secondly, duty cycle power manager directly controls the MAC protocol, which is generally the most consumed energy in EH-WSNs instead of optimizing at higher layers as DPM. Therefore, an efficient duty cycle power manager can reduce the global consumed energy to increase the QoS while following the ENO condition. These advantages make duty cycle adaptation the most popular technique for PMs embedded in EH-WSNs [14].

4. Conclusion

Power manager is considered a heart of WSNs powered by energy harvesting. The design of an energy efficient power manager is indeed, a challenge due to the low resource of a wireless node. In this paper, an overview of popular power manager techniques is presented. The paper provides important concepts and summarizes popular power manager approaches. Based on the advantages and drawbacks of each approach, the adaptation by tuning the duty cycle in the MAC layer is the most efficient approach as its technique directly controls the MAC layer, which is responsible for wireless communications and is the dominant energy consumption in WSNs. As a result, this technique is amenable to EH-WSNs which requires optimized energy consumption.

REFERENCES

[1] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” Computer Networks, vol. 54, no. 15, pp. 2787 – 2805, 2010.

[2] D. Christin, A. Reinhardt, P. S. Mogre, and R. Steinmetz, “Wireless sensor networks and the internet of things: selected challenges,” Proceedings of GI/ITG KuVSFachgespr¨ ach Drahtlose Sensornetze, pp. 31–33, 2009.

[3] J. Beutel, M. Dyer, M. Hinz, L. Meier, and M. Ringwald, “Nextgeneration prototyping of sensor networks,” in International Conference on Embedded Networked Sensor Systems (SenSys), 2004, pp. 291–292.

[4] I. Demirkol, C. Ersoy, and E. Onur, “Wake-up receivers for wireless sensor networks: benefits and challenges,” IEEE Wireless Communications, vol. 16, no. 4, pp. 88–96, 2009.

[5] M. K. Stojcev, M. R. Kosanovic, and L. R. Golubovic, “Power management and energy harvesting techniques for wireless sensor nodes,” in Telecommunication in Modern Satellite, Cable, and Broadcasting Services (TELSIKS), 2009, pp. 65–72.

[6] A. Kansal, J. Hsu, S. Zahedi, and M. Srivastava, “Power management in energy harvesting sensor networks,” ACM Transactions on Embedded Computing Systems (TECS), vol. 6, no. 4, p. 32, 2007.

[7] D. Ramanathan and R. Gupta, “System level online power management algorithms,” in Design, Automation and Test in Europe Conference and Exhibition 2000. Proceedings, 2000, pp. 606 –611.

[8] L. Benini, A. Bogliolo, and G. De Micheli, “A survey of design techniques for system-level dynamic power management,” IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 8, no. 3, pp. 299 –316, 2000.

[9] W. Tuming, Y. Sijia, and W. Hailong, “A dynamic voltage scaling algorithm for wireless sensor networks,” in International Conference on Advanced Computer Theory and Engineering (ICACTE), 2010, pp. 554–557.

[10] T. Hamachiyo, Y. Yokota, and E. Okubo, “A cooperative power-saving technique using dvs and dms based on load prediction in sensor networks,” in International Conference on Sensor Technologies and Applications (SENSORCOMM), 2010, pp. 7–12.

[11] W. Ye, J. Heidemann, and D. Estrin, “An energy efficient mac protocol for wireless sensor networks,” in IEEE Conference of the Computer and Communications Societies (INFOCOM), 2002, pp. 1567–1576.

[12] T. V. Dam and K. Langendoen, “An adaptive energy-efficient mac pro-tocol for wireless sensor networks,” in ACM Conference on Embedded networked sensor systems (Sensys), 2003, pp. 171–180.

[13] E. Y. A. Lin, J. M. Rabaey, and A. Wolisz, “Power-efficient rendez-vous schemes for dense wireless sensor networks,” in IEEE International Conference on Communications, 2004, pp. 3769 – 3776.

[14] A. Castagnetti, A. Pegatoquet, C. Belleudy, and M. Auguin, “A framework for modeling and simulating energy harvesting wsn nodes with efficient power management policies,” EURASIP Journal on Embedded, Systems, pp. 1–16, 2012.

(The Board of Editors received the paper on 16/07/2015, its review was completed on 30/09/2015)