A Receiver-Initiated MAC Protocol for Energy Harvesting Sensor Networks

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Abstract. Energy harvesting technology potentially solves the problem of energy efficiency, which is the biggest challenge in wireless sensor networks. The capability of harvesting energy from surrounding environment enables an achievement of infinitive lifetime at a sensor node. The technology promisingly changes the fundamental principle of communication protocols in wireless sensor networks. Instead of saving energy as much as possible, the protocols should keep the efficient operation and maximum performance of networks while guaranteeing the harvested energy is equal or bigger than the consumed energy. In this paper, we propose ERI-MAC a new receiver-initiated MAC protocol for energy harvesting sensor networks. ERI-MAC leverages the benefit of receiver-initiated and packet concatenation to achieve good performance both in latency and energy efficiency. Moreover, ERI-MAC employs a queuing mechanism to adjust the operation of a sensor node following the energy harvesting rate from the surrounding environment. The extensive simulation results in ns-2 show that ERI-MAC achieves good network performance, as well as, enables infinitive lifetime of sensor networks.

Keywords: MAC protocol, energy harvesting, WSNs.

1 Introduction

The developments of sensing, computing technologies and wireless communication drive the appearance of wireless sensor networks (WSNs) with various types of applications such as structure health [1], environmental monitoring [2,3] or healthcare [4]. A WSN usually contains numerous inexpensive sensor nodes, which are spatially distributed over a monitored commonplace. The sensor nodes sense the physical changes of its surrounding environment and wirelessly forward the sensing data to a base station, i.e., a sink. An individual sensor node normally has a small size; and it is powered with a limited capacity battery. Therefore, the operation and performance of WSNs largely depends on the finite capacity of power sources. Traditionally, most of

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research in WSNs pays attention on designing energy efficient communication protocols, especially Medium Access Control (MAC) protocols. That is because the MAC protocols control the operation of radio module, which is the biggest consumer of energy on a sensor nodes. In general, the MAC protocols save consumed energy by adopting the duty cycling mechanism, which periodically turns on and off the radio modules. There are a huge number of power-saving MAC protocols have been published, from low to ultra low duty cycle [5 - 7], or achieves good performance with different types of traffic [8]. However, if the WSN applications requires a long lifetime (months, or years), the capacity of battery is still not sufficient. On the other hand, re-cent advances in energy harvesting technology give a promising solution for the energy problem on WSNs.

Energy harvesting refers to the capability of extracting energy from ambient environment of a sensor node (e.g., from the solar energy, wind power, etc. [9, 10]). Moreover, the extracted or harvested energy can be used to recharge the node's battery. By doing so, the sensor node potentially maintains an infinite life-time of battery. The technology therefore will change the fundamental principle of designing MAC protocols for WSNs. Instead of focusing on the power-saving aspect, the objectives of new MAC protocol on energy-harvesting WSNs include increasing both the network performance and lifetime under a given condition of harvested energy. Different to the traditional MAC protocols, the one in energy harvested WSN achieves infinite lifetime by keeping the sensor node operate at a so-called energy neutral operation (ENO) state [9]. When a node is in the ENO state, its energy consumption is always less than or equal to the energy harvested from the environment. Besides that, WSNs with energy harvesting capability assume the correlation between the performance and energy harvesting. The more energy a sensor node is harvested the better performance it achieves. A sensor node is said to reach the state of ENO-Max when it operates at the maximum performance as well as remains the state of ENO [11]. Generally, the MAC protocols in energy harvested sensor networks are designed with new algorithms of dynamically adapting the duty cycle at a node in order to maximize both the lifetime and performance.

The remainder of the paper is organized as follows. Section 2 describes the design of ERI-MAC protocol. In Section 3 presents the evaluation results. Finally, we conclude the paper in Section 4.

2 ERI-MAC for Energy Harvesting Sensor Networks

In this section, we describe the operation of ERI-MAC protocol. We initially present the basic communication scheme in ERI-MAC, and then we discuss the use of a dynamic queuing mechanism in order to achieve the ENO state.

2.1 Basic Communication Scheme

Receiver-Initiated Mechanism. Receiver-initiated mechanism is always adopted by asynchronous duty cycling protocols, which do not require any clock synchronization between sensor nodes. The MAC protocols equipped the mechanism has been proven to outperform the state-of-the-art of traditional sender-initiated protocol and the synchronous protocols [12]. Moreover, the mechanism is therefore taking part in main stream of designing MAC protocols on real sensor motes, and real deployments [13]. Figure 1 shows a basic operation of receiver-initiated communication. In the Figure 1, SIFS is abbreviated for short inter-frame space, the duration needed to process a packet and switching radio mode. The mechanism is always combined with duty cycling radio (i.e., sleep/wakeup) following operational cycles. In an operational cycle, after waking up each non-sender node immediately broadcasts a beacon packet. The beacon contains the node's address; it is used to announce that the node is ready for receiving a data packet. The node then samples the wireless channel for a short period (called dwell time) to determine there is any potential incoming packet. On the other hand, a sender that is holding a data packet keeps in the listening mode and waits for a beacon from its intended receiver. When the sender receives the expected beacon, it immediately sends the pending packet. A successful transmission is completed when a beacon with acknowledge (ACK) function arrives at the sender. This beacon however can serve not only as an ACK packet but also as a new receiver-initiated beacon. After the completed transmission if the sender has no queued packet, it becomes a non-sender. The node then broadcasts a beacon right after its next wakeup time. ERI-MAC also adopts the same collision detection and retransmission schemes from RI-MAC and AQ-MAC [8]. When a collision occurs at a receiver, it retransmits a new beacon, which includes a value of back-off window. Each contending sender utilizes a random backoff period before a retransmission to avoid collisions.

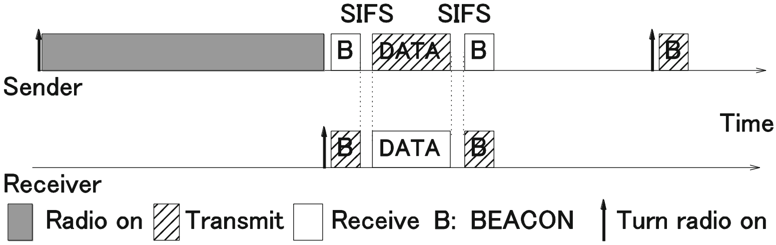

Fig. 1. ERI-MAC 's basic communication scheme

Packet Concatenation. Packet concatenation refers to the implementation of concatenating several small packets, which share a same characteristic in to a bigger one. In WSNs, this scheme is common and necessary since the nodes periodically sleep to save energy while the sensing activities are continuous. As a result, the sensing information has to be stored in queued packets, that are normally destined to one sink. Therefore, the scheme improves the network performance both in latency and energy efficiency by reducing control overhead and queuing time. Implementing packet concatenation at MAC layer is originally proposed in our previous work [14]. The original scheme is equipped to a synchronous multi-hop duty cycling MAC protocol. However, the scheme can be adopted by other duty cycling protocols whenever the protocols have to handle with queuing packets such as in [8]. In our packet concatenation, we define the big packet as super packet. The size of super packet is limited by a threshold value depending on the radio's capability.

2.2 Queuing Mechanism to Achieve ENO

The queuing mechanism is first proposed to handle with Quality of Service (QoS) provision for low priority traffic in AQ-MAC. The packets are queued until a timeout value before sending out at a node. The original mechanism uses a fix and predetermined values of timeout and very efficient in terms of energy and latency efficiency. We found that that the mechanism can fit well in the context of energy harvesting sensor networks. Therefore, we extend the mechanism in order to achieve the ENO state at a ERI-MAC's node. The timeout value is now dynamic and controlled by a node. The node compares it energy consumption with harvest energy from it environment. If the amount of energy consumption is bigger than the amount of harvested one, the sensor nodes reduce its transmissions and waiting for the harvested energy. Therefore, a node can reach to the desired state.

In ERI-MAC, we assume that the node knows the energy harvesting rate, its capacity of battery and a safe duration, which is the maximum period of awake state of radio. If the radio keeps on over that duration, the battery can be exhausted. After each safe duration, the nodes compare its consumed energy to the harvested energy by investigating the proportion between them. If the value is less than one, the node immediately goes to sleep until it can guarantee the battery is sufficiently safe. In our evaluation, we use the operational cycle with the length of one ms, and the safe duration is determined following the appropriate energy harvesting rate and the consume energy rate in the real sensor nodes' specifications.

3 Evaluation

Table 1. Networking Parameters

Bandwidth	250 Kbps	Slot time	320 us
CCA Check Delay	128 us	Tx Range	250 m
Carrier Sensing Range	550 m	SIFS	191 us
Backoff Window	0-255	Beacon size	6-9 bytes
Retry Limit	5	Dwell Time	10 ms
Tx Power	31.2 mW	L_{TH}	112 bytes
Rx Power	22.2 mW	Sleep Power	3 uW

3.1 Experiment Settings

We evaluate the performance of ERI-MAC using the network simulator ns-2 [15]. We demonstrate correlations of energy consumption to the performance of wireless sensor networks by modifying the energy module of ns-2. Table 1 lists the network parameters of a sensor node. Those parameters are collected from in Micaz mote and

Radio CC2420's specifications except the Transmission range (Tx range) and Carrier Sensing range. L_{TH} is the maximum size of the super packet, which concatenates four original 28-byte packets. Different with other related work in energy-harvesting sensor networks, we investigate the performance of ERI-MAC in a 49-node grid scenario. The distance between two neighbors in the grid is 200 meters, and all the data packets are destined to the sink in the center as shown in Fig. 2. The Random Correlated Event (RCE) model is used in the evaluation. In the model, an event is occurred at a random location within the area. An event is characterized by a so-called sensing range of the event. All nodes, which are within the sensing range of event, are going to generate one packet to the sink. In the evaluation, the inter-event values are randomly within zero to five seconds. We generate a total of 100 events with 500 meter-sensing range. The length of a cycle is one seconds and a safe duration is ve seconds. We adopt the energy harvesting model from previous work [16]. The energy harvesting rates are constant at 0.3 mWatt an 0.6 mWatt.

3.2 Results

This section presents the results of ERI-MAC performance in the evaluation. The values of latency and energy efficiency are shown in Fig. 3 and Fig. 4, respectively. Note that, each value of latency shown in Fig. 3 is calculated between the generated and received time of a packet. In the case of super packet, the generated time of the packet is considered as the one of the first packet in the concatenated form. If the rate of energy harvesting is small, ERI-MAC 's nodes tend to excess the safe duration more frequently. Therefore, the packets in that scenario have to be queued, that leads to the higher values of latency. On the other hand, the value of 0.6 mW harvesting rate is sufficient to guarantee the safe duration of ERI-MAC, hence the network has a good latency performance.

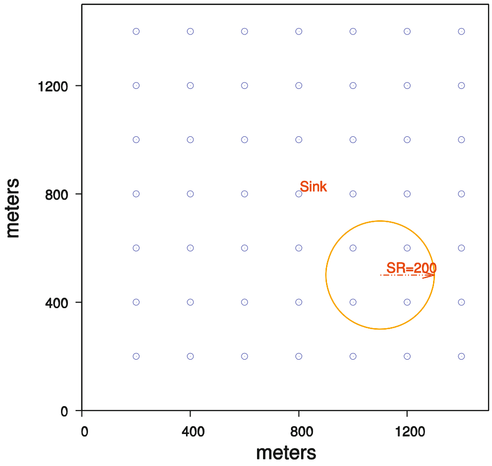

Fig. 2. 49-node Grid Scenario and an event with 200-meter sensing range

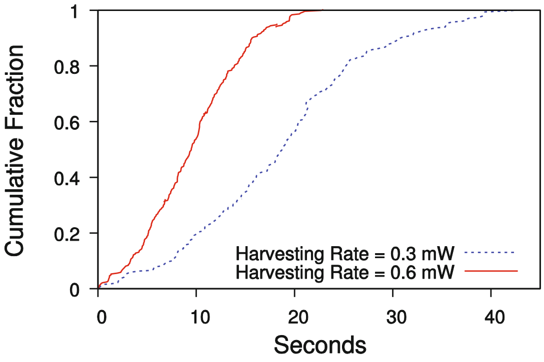

Fig. 3. Cumulative distribution of latency values

In order to investigate the energy efficiency, we use the ratio of consumed energy to harvested energy. If the ratio is smaller than one, the node is confirmed in an ENO state. Since when the harvesting rate is 0.6 mW, ERI-MAC's nodes do not excess the safe duration hence no appearance of adapting duty cycle. Therefore, we focus on the case of 0.3 mW harvesting rate. The results are in the Fig. 4. Since ERI-MAC has the queuing mechanism, each time the nodes consume more energy than the amount of harvested energy, they themselves keep their radio off in order to be in ENO sates. We can observe that all nodes in the grid have the ratio smaller than one. Hence, we can conclude that the network can achieve the infinitive lifetime.

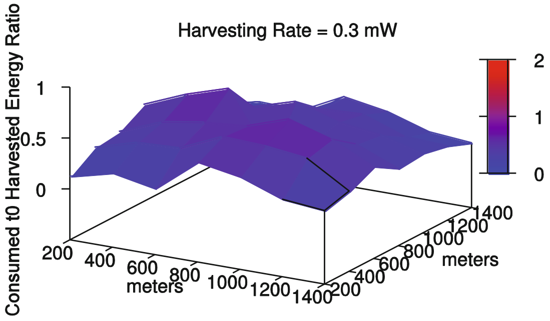

Fig. 4. The ratio of consumed to harvested energy

4 Conclusion

The energy harvesting technology, which lets a battery on a node be recharged by energy in its surrounding environments, is potentially a solution of overcoming the energy problem in WSNs. In this paper, we propose ERI-MAC a new receiver-initiated MAC protocol for WSNs with energy harvesting capabilities. ERI-MAC inherits the advantages of receiver-initiated communication, packet concatenation in order to achieve good network performances. Moreover, ERI-MAC 's nodes use the queuing packet mechanism to adapt the operation of a sensor node to the rate of harvested energy. If the ratio between the consumed to harvested energy is larger than one, ERI-MAC's nodes switch to and stay in sleep modes until the batteries are safe. The simulation results show that the ERI-MAC's network achieves good network performances and keeps all nodes in ENO state, i.e., achieving infinitive lifetime.

In the future, we plan to theoretically analyze the operation and performance of ERI-MAC. The analysis will be added to the queuing mechanism in order to let sensor nodes reach the state of ENO-MAC. Moreover, we also plan to extend ERI-MAC for the other sensor networks with different energy harvesting models.

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References

1. Liu, X., Cao, J., Lai, S., Yang, C., Wu, H., Xu, Y.: Energy efficient clustering for wsn-based structural health monitoring. In: Proc. IEEE INFOCOM, pp. 2768–2776 (2011)
2. Mainwaring, A., Culler, D., Polastre, J., Szewczyk, R., Anderson, J.: Wireless sensor networks for habitat monitoring. In: Proc. 1st ACM International Workshop on Wireless Sensor Networks And Applications, WSNA 2002, pp. 88–97 (2002)
3. Tolle, G., Polastre, J., Szewczyk, R., Culler, D., Turner, N., Tu, K., Burgess, S., Dawson, T., Buonadonna, P., Gay, D., Hong, W.: A macroscope in the redwoods. In: Proc. 3rd ACM SenSys, pp. 51–63 (2005)
4. Shnayder, V., Chen, B.-R., Lorincz, K., Jones, T.R.F.F., Welsh, M.: Sensor networks for medical care. In: Proc. 3rd International Conference on Embedded Networked Sensor Systems, SenSys 2005, p. 314 (2005)
5. Ye, W., Heidemann, J., Estrin, D.: Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks. IEEE/ACM Transactions on Networking 12, 493–506 (2004)
6. Ye, W., Silva, F., Heidemann, J.: Ultra-low duty cycle MAC with scheduled channel polling. In: Proc. 4th ACM SenSys, pp. 321–334 (2006)
7. Sun, Y., Du, S., Gurewitz, O., Johnson, D.B.: DW-MAC: a Low Latency, Energy Efficient Demand-Wakeup MAC Protocol for Wireless Sensor Networks. In: Proc. 9th ACM MobiHoc, pp. 53–62 (2008)
8. Nguyen, K., Ji, Y.: Asynchronous mac protocol with qos awareness in wireless sensor networks. In: Proc. IEEE Global Communications Conference, GLOBECOM 2012, pp. 555–559 (2012)
9. Kansal, A., Hsu, J., Zahedi, S., Srivastava, M.B.: Power management in energy harvesting sensor networks. ACM Trans. Embed. Comput. Syst. 6(4) (September 2007)
10. Voigt, T., Ritter, H., Schiller, J.: Utilizing solar power in wire-less sensor networks. In: Proc. 28th IEEE Conference on Local Computer Networks LCN (2003)
11. Vigorito, C.M., Ganesan, D., Barto, A.G.: Adaptive control of duty cycling in energy-harvesting wireless sensor networks. In: Proc. 4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON 2007, pp. 21–30 (2007)

12. Sun, Y., Gurewitz, O., Johnson, D.B.: RI-MAC: a Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks. In: Proc. 6th ACM SenSys, pp. 1–14 (2008)
13. Dutta, P., Dawson-Haggerty, S., Chen, Y., Liang, C.-J.M., Terzis, A.: Design and Evaluation of a Versatile and Efficient Receiver-Initiated Link Layer for Low-Power Wireless. In: Proc. 8th ACM SenSys, pp. 1–14 (2010)
14. Nguyen, K., Meis, U., Ji, Y.: MAC^2: a Multi-hop Adaptive Mac Protocol with Packet Concatenation. IEICE Transaction on Information and Systems E95-D(2), 480–489 (2012)
15. The network simulator ns2, `http://www.isi.edu/ns/index.html`
16. Fafoutis, X., Dragoni, N.: Odmac: an on-demand mac protocol for energy harvesting - wireless sensor networks. In: Proc. of the 8th ACM Symposium on Performance Evaluation of Wireless Ad hoc, Sensor, and Ubiquitous Networks, PE-WASUN 2011, pp. 49–56 (2011)