Ad Hoc Networks 000 (2016) 1–13

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Energy harvested roadside IEEE 802.15.4 wireless sensor networks for IoT applications

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ARTICLE INFO

Article history:
Received 3 February 2016
Revised 29 November 2016
Accepted 6 December 2016
Available online xxx

Keywords:
Adaptive duty cycle
Energy backoff
Energy harvesting
IEEE 802.15.4
IoT
Piezoelectric and vehicular traffic

ABSTRACT

With the increasing deployment of the Internet of Things (IoT) applications, the demand for energy efficiency (EE) and quality-of-service (QoS) guarantee is on the rise. This paper considers the typically contradicting requirements for EE and QoS provisioning in an integrated manner for an IEEE 802.15.4-based wireless sensor network (WSN). Specifically, we consider variable traffic conditions of IoT applications in the presence of an energy harvesting technique based on the movement of vehicles. To this end, we introduce an adaptive energy-efficient algorithm, referred to as ABSD, that adapts the medium access control (MAC) parameters of IEEE 802.15.4 sensor nodes in response to the queue occupancy level of sensor nodes and the offered traffic load levels. By adapting the transmission parameters, the ABSD algorithm minimizes the network contention level which could in turn improve the EE as well as the network throughput. The ABSD algorithm is further enhanced by integrating with an energy harvesting technique and a new MAC parameter known as the *'energy backoff'*. The enhanced algorithm referred to as EH-ABSD offers priority to different classes of traffic by improving the battery lifetime and QoS values under variable traffic load conditions. Numerical results confirm that our proposed algorithms achieve high EE and QoS values while extending the lifetime of sensor nodes for outdoor applications.

1. Introduction

The Internet of Things (IoT) is a concept of an intelligent network infrastructure wherein a large number of uniquely identifiable *things* or *objects* (e.g., sensors, actuators, wireless devices, etc.) are interconnected to perform complex tasks in cooperative manners [1–5]. The IoT has been finding applications in many domains, such as smart grids/buildings, health-care systems, transportation/environmental monitoring and traffic management [3–6].

Communication technology is one of the key components of an IoT infrastructure. Along with a radio frequency identification (RFID) technology, the IoT also inherits the technology developed for wireless sensor networks (WSNs) to support a wide range of applications [7]. WSNs are self-organizing ad-hoc networks consisting of small, low-cost and low-power devices that communicate/cooperate in a multi-hop fashion to provide monitoring and control functionalities in IoT applications. Currently, low-power WSN technology can extend outdoor communication range up to 100 m for single-hop connections [1]. WSN could be deployed in plenty of IoT applications ranging from medicine to military, and from home to industry.

Energy efficiency (EE) is one of the critical issues for the mass deployment of WSNs and IoT applications [2,7,8]. Frequent replacement of batteries of sensor nodes deployed in the outdoor environment introduces significant operational expenditure (OPEX). In some cases, this reason prevents deploying such networks over a wide area. It is therefore pivotal to conserve battery power by improving the EE of the sensor nodes which ultimately prolongs the lifetime of a WSN.

Many studies in the literature have proposed techniques in the Physical (PHY), Data Link and Network layers of the Internet protocol stack to improve EE and prolong the lifetime of nodes. The Medium Access Control (MAC) sub-layer plays a key role in improving the EE since it controls the channel access and transmission/reception of packets. Using MAC sub-layer procedures, a sensor node operates in one of the four basic modes: receiving, transmitting, idle listening and sleeping. Energy consumption of a sensor node depends on the operating modes [9,10]. In practice, the longer idle listening period causes a significant waste of energy in WSNs, while the longer sleeping time helps sensor nodes save their energy [10–13]. Shortening the idle listening period and extending the sleeping time using adaptive duty-cycle mechanisms [13–17] have been considered as effective methods to improve en-

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http://dx.doi.org/10.1016/j.adhoc.2016.12.003
1570-8705/

ergy efficiency and extend the lifetime of nodes. However, such approaches could reduce the network's quality-of-service (QoS) in terms of delay, packet losses and throughput.

Recently, energy harvesting is emerging as a proposal for field-deployable WSNs and IoT applications. The term energy harvesting (EH) refers to the capability of extracting energy from the surrounding environment, such as kinetic energy (e.g., mechanical vibrations and wind), solar energy (e.g., photovoltaics – PV or concentrated solar power – CSP) and wireless energy transfer. The energy from these sources are converted into electrical energy which can be either used to directly power the sensor nodes or stored for later use. By employing the EH techniques, the sensor nodes can recharge their batteries during their operation to reduce the operational cost and to avoid network downtime. EH networks can allow fixed battery-less operation, making it very important for a sustainable '*near-perpetual*' WSN operability [2,18]. Therefore, energy-harvested WSNs (EHWSNs) architecture has been attracting significant attention.

Compared to solar and wind energy, vibration-based energy harvesting technology is more efficient and reliable because it is independent of weather, season and to some extent day and night cycle [19]. This technique could be an effective approach for powering sensor nodes. Its basic principle is to convert ambient mechanical energy into electrical energy based on the effects of *piezoelectric, electromagnetic* or *electrostatic* phenomena. The mechanical vibration sources can be found from transportation infrastructure (e.g., cars and trains), household applications (e.g., washing machines), civil structures (e.g., buildings and bridges) and human motions [20,21]. These energy sources could provide unlimited energy over an infinite period of time, however only a limited amount of energy can be obtained at any particular time. Also, the levels of power generated depend on the quantity and form of kinetic energy available in the environment as well as the efficiency of either the generator or the power conversion electronic circuits [21].

In the context of the energy harvesting process from road traffic-induced vibrations, a roadway EH technique is emerging as a new source of renewable energy [22–24]. This technique has a particular potential in metropolitan areas, wherein thousands of vehicles are moving across roadways every day. Deploying roadway energy harvesters to capture even a small percentage of available energy could be a suitable solution for the issue of energy limitation at sensor nodes.

Note that the moving vehicles-based EH is a stochastic process because of the variations in the vehicles' weight (e.g., a semi-truck or a compact car) and in the number of vehicles (e.g., at peak or off-peak hours). The arrival rate and magnitude of the harvested energy may fluctuate dramatically with the time of day. This is the most critical challenge in an EHWSN and it has a strong impact on prolonging the lifetime of sensor nodes [25,26]. Thus, EHWSNs require mechanisms that minimize the overall energy consumption while maintaining the QoS requirements with respect to the random and intermittent energy arrivals.

The main goal of the IEEE 802.15.4 standard [27] is to address the development of low-cost and low-power WSNs. Most applications using the IEEE 802.15.4-based WSNs operate under low and stable traffic load conditions [13]. With the recent emergence of multitude of new IoT applications (see Table 1), the data traffic patterns could vary significantly over time and space [4]. Such variations cannot be properly dealt with by the Carrier Sensor Multiple Access/Collision Avoidance (CSMA/CA) mechanism to maintain high EE and QoS for bursty data traffic sources. It is necessary to develop a packet transmission algorithm that enables the CSMA/CA protocol to adapt with the constantly varying traffic conditions.

With the rapid and wide deployment of IoT devices and applications in different domains such as smart city, smart grid, road traffic and environmental monitoring, the need for the development of self-powered sensor networks is becoming very important. Energy harvesting is one of the key enabling techniques which could enable the development of self-powered WSNs.

Table 1
Data traffic specification for smart city IoT applications [4,6].

Application	Data rate/node	Delay	Priority
Structural health	1pkt/10 min	30 min	High
Air monitoring	1pkt/30 min	5 min	High
Noise monitoring	1pkt/10 min	5 min	Low
Traffic congestion	1pkt/10 min	5 min	High
Smart lighting	On demand	1 min	Low

For WSNs, maintaining high QoS level and EE is a major challenge, particularly when the interactions between EE and QoS parameters are not considered. As mentioned earlier, the methods proposed in [[11–17]] cannot simultaneously satisfy the EE and QoS requirements under variable load conditions. In addition, the stochastic characteristics of the moving vehicles-based energy harvesting process have not been taken into account in the works of [22–24].

Motivated by these challenges, this paper addresses the issues of EE and QoS in the IEEE 802.15.4 WSN under variable traffic conditions of the IoT applications combined with the stochastic energy harvesting processes. The main contributions of our work are summarized as follows:

- We jointly consider the EE and QoS issues for WSNs to develop an adaptive packet transmission algorithm at the MAC sub-layer of an IEEE 802.15.4-based network. Referred to as ABSD, this algorithm tracks both the queue status of nodes and the bursty traffic load generated by IoT applications, and adjusts the IEEE 802.15.4 superframe parameters of sensor nodes accordingly.
- We define a new performance metric by combining both of the QoS and the energy consumption, named energy efficiency η. Expressed in the unit of packets per Joule, this term η determines the number of packets received by the coordinator per Joule of energy spent. This new metric allows us to evaluate the overall performance of the proposed algorithm and other related methods in the literature.
- We introduce a new CSMA/CA MAC parameter, referred to as the '*energy backoff*', which can be integrated into the proposed ABSD algorithm. This new parameter deals with the stochastic characteristics of the energy harvesting sources. Based on the combination of the '*energy backoff*' parameter and the moving vehicles-based EH technique, we propose a new EH algorithm referred to as EH-ABSD. Simulation results show that the EH-ABSD algorithm extends the lifetime of the roadside sensor nodes.

The rest of this paper is organized as follows. Section 2 reviews the related works. Section 3 describes a typical roadside energy harvesting architecture for IEEE 802.15.4 WSN based IoT applications, using the moving vehicles-based EH technique and energy harvesters. Section 4 presents an energy consumption model based on the IEEE 802.15.4 EHWSN structure. Section 5 proposes the ABSD algorithm and the '*energy backoff*' technique for the roadway energy harvesters. Section 6 uses simulation results from OPNET and MATLAB to illustrate the performance of the proposed solutions. Finally, Section 7 concludes the paper.