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Power management in SMAC-based energy-harvesting wireless sensor networks using queuing analysis

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ABSTRACT

One of the most important constraints in traditional wireless sensor networks is the limited amount of energy available at each sensor node. The energy consumption is mainly determined by the choice of media access mechanism. SMAC is a typical access mechanism that has drawn much attention in recent years. In WSNs, sensors are usually equipped with capacity-limited battery sources that can sustain longer or shorter period, depending on the energy usage pattern and the activeness level of sensor nodes. To extend the lifetime of the sensor networks, ambient energy resources have been recently exploited in WSNs. Even though solar radiation is known as the superior candidate, its density varies over time depending on many factors such as solar intensity and cloud states, which makes it difficult to predict and utilize the energy efficiently. As a result, how to design an efficient MAC in a solar energy harvesting based WSN becomes a challenging problem. In this paper, we first incorporate a solar energy-harvesting model into SMAC and conduct its performance analysis from a theoretical aspect. Our research works provide a fundamental guideline to design efficient MAC for energy harvesting based WSNs. Our major contribution includes three folders: firstly, we model solar energy harvesting in a photovoltaic cell and then derive the throughput of SMAC in the energy-harvesting based WSNs. Second, we develop a new model based on queuing theory to calculate the average number of energy packets in battery in terms of both duty cycle and throughput. Finally, we form an optimization problem to find a suitable range for the duty cycle to satisfy both quality of service (QoS) and network lifetime requirements.

1. Introduction

Sensor networks consist of hundreds of spatially distributed sensors, called nodes, to cooperatively monitor a specific quantity which can be the level of pollutants, temperature, sound, vibration, pressure, and so on. These networks have been utilized in a wide variety of civil, industrial and military applications. They have also been widely used for healthcare monitoring, object tracking and assembly line sensing. WSNs (wireless sensor networks) is composed of different layers, first of which is the MAC (Medium Access Control) layer, which grants access of the wireless channel to different nodes. Depending on the type of MAC protocol being utilized, wireless sensor networks are divided into two general categories: scheduled networks and contention-based networks (Luo et al., 2007).

In scheduled networks, the wireless channel is divided into sub-channels in terms of either time (Time Division Multiple Access, TDMA), frequency (Frequency Division Multiple Access, FDMA), orthogonal codes (Code Division Multiple Access, CDMA), or a combination of them and each of these sub-channels are assigned to each node. However, each of these protocols has its own challenges such as time synchronization in the case of TDMA, frequency generation/filtering and bandwidth requirements in the case of FDMA, and power control in the case of CDMA. These requirements cannot be simply satisfied using tiny, incapable sensors that are usually located in a place with no replacement/maintenance possibility. As a result, contention-based access methods are more suitable due to their simple, autonomous and scalable nature. Here, nodes compete with each other to win the access to the shared medium. They are also flexible toward network topology changes, which is typical in wireless networks.

Another important constraint in WSNs is the amount of energy available to each node. The power consumption should be uniform over the network to extend the network lifetime. Otherwise, there will be some portions of the network consisting of dead sensors that will degrade the overall QoS (quality of service) performance. As a result, in WSNs, power metric is more important than other QoS metrics or fairness of access. To circumvent this problem, the power consumption should be considered as

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a distributed parameter in the network instead of a point parameter in only one node, which demands careful considerations in MAC layer.

Numerous works have been carried out to design energy-efficient MAC protocols. In fact, it has been shown in Stemm et al. (1997) that, the energy consumption using IEEE 802.11 MAC is very high when nodes are in the idle mode. Some of such recently proposed MAC protocols include PAMAS (Singh and Raghavendra, 1998), SMAC (Ye et al., 2002), TMAC (Dam and Langendoen, 2003), and PMAC (Pan et al., 2009), among which, SMAC is of particular interest in this paper and is explained in detail in the next section. PAMAS is an improvement over MACA (Multiple Access Collision Avoidance) protocol by adding a separate signaling channel for exchanging the RTS/CTS packets, which enables the nodes to switch themselves off when they are not receiving or transmitting any packets. Therefore, this protocol is more efficient than the original MACA protocol. As the authors claim in Singh and Raghavendra (1998), it could increase the power efficiency of most Ad Hoc networks by 10–70%. In Cohen and Leshem (2010), a distributed Time-varying Opportunistic MAC Protocol (TOP) is proposed to maximize the network lifetime through transmission scheduling, based on Channel State Information (CSI) and Residual Energy Information (REI). In fact, a higher priority is assigned to the sensor node with better channel condition and higher residual energy. The authors show that this approach increases the network lifetime compared to other distributed MAC protocols like DPLM (Chen and Zhao, 2007), and Pure Opportunistic (Chen et al., 2007). In Yadav et al. (2010), the authors propose an optimized MAC protocol to deal with the energy inefficiency and nodes' latency. They prove, analytically and via extensive simulations that this scheme achieves high energy efficiency under a wide range of traffic loads and is able to adjust itself to improve the delay performance when the network traffic load is high. In Zhou et al. (2010, 2011a,b), authors aim at achieving minimal video distortion and certain fairness by jointly considering media-aware distribution and network resource allocation.

In SMAC (Ye et al., 2002), nodes switch between sleep and active states periodically in order to reduce power consumption. During the sleep mode, the node turns off its radio, and sets a timer to wake up at a later time. The difference between PAMAS and SMAC is that SMAC uses in-channel signaling rather than using a separate channel for signaling, as in PAMAS. Being inspired by SMAC, TMAC (Dam and Langendoen, 2003) also uses the same periodic active/sleep scheme. However, the duty cycle is not fixed in TMAC by dynamically ending the active part of the cycle, which reduces the amount of energy wasted on idle listening. It has been shown in Dam and Langendoen (2003) that, in terms of energy efficiency, TMAC outperforms SMAC by a factor of five. Other recent sensor control protocols have been proposed in Chen et al. (2010a,b,c).

Recently, environmental energy resources like solar or wind power have been exploited in WSNs. An energy-harvesting node is defined as any system, which can absorb part or all of its energy from the environment (Kansal et al., 2007). An important difference between this kind of energy and that stored in the capacity-limited batteries is that ambient (and particularly solar) energy is potentially infinite. However, the energy generation rate at which this type of energy can be generated may be limited; for example, solar power is not available during night and cloudy conditions and the absorption rate continually changes over time. In this paper, our first contribution is to model the solar energy received at a photovoltaic cell. We are inspired by the research works in Niyato et al. (2007) and Alexander and Fairbridge (1999). However, we consider different parameters (like cloud length and sunlight inclination) for modeling the absorbed energy rather than those considered in Niyato et al. (2007). This kind of modeling is necessary for our second contribution, which is the modeling of the number of energy units (we call them *energy packets* from now on) in the battery.

Although power efficiency is the main concern in sensor networks, other QoS requirements also need to be satisfied. There are different methods to evaluate the network's performance. One of them is queuing analysis. In Liu and Lee (2005) an infinite queuing model has been proposed for contention-free sensor networks analysis and a more realistic finite queuing model has been used to analyze the tradeoff between energy consumption and QoS requirements in contention-based sensor networks in Luo et al. (2007). Our second and main contribution is the modeling of the number of *energy packets* in battery of a sensor that uses SMAC as a case study of its MAC protocol. Since the battery has an input (through which energy is absorbed) and an output (through which energy is consumed), queuing theory is applicable to model non-data identities. These identities in our analysis are called *energy packets*, which will be served (consumed) in FIFO order. We assume that there is no energy leakage from the battery, and energy consumption is quantized so that one *energy packet* is consumed to transmit one data packet. The only point that should be noted is that *energy packets* are not distinguishable identities. This should not be a problem, since we are only interested in the number of *energy packets* in the queue (battery) which is irrelevant to serving policy, and each *energy packet*'s position in the queue. The used model in our analysis is G/G/1 queue with batch transmission (due to *message passing* technique used in SMAC). The input process to this queue (battery), $a(n)$, is a point process that represents the number of *energy packets* (n) absorbed by the photovoltaic cell and delivered to the battery. The output process, $b(t)$, represents the discrete time interval between two successful consecutive transmissions from a sensor node. We employ the approaches in Kingman (1962) and Bitran and Tirupati (1989) in our analysis to achieve two goals: first, to prolong the network lifetime by not letting the sensor nodes run out of power or exceed a critical battery level; second, to guarantee the network QoS by not letting the throughput fall below a critical threshold. Since there is tradeoff between the energy consumption and throughput, the two goals can be achieved through solving a constrained optimization problem. Consequently, the third contribution of this paper is modeling the SMAC throughput. To the best of our knowledge, very few works (Yang and Heinzelman, 2009) have been done on finding the throughput of SMAC, and none of them has explicitly extracted a closed form expression for the network throughput for energy harvesting based WSNs. In our analysis, the parameter of interest that shifts the benefits toward each of the above-mentioned targets is the duty cycle, which is the ratio of the active time of a sensor to the whole cycle time.

The rest of the paper is organized as follows. In Section 2, we give a brief introduction to SMAC (Ye et al., 2002). In Section 3, we present our solar energy model that describes the process of feeding the number of solar energy units into the battery. The closed form expressions of SMAC throughput and service time in terms of network parameters are derived in Section 4. Then, in Section 5, we establish our queuing model based on the model described in the previous sections to find the average number of *energy packets* in the queue (battery) and form the optimization problem. Finally, we summarize our results in Section 6.

2. SMAC protocol overview

In the SMAC, nodes go to periodic sleep and active states in order to reduce the energy consumption. As specified in Ye et al. (2002), the active period of each cycle, which is determined by the