ON-LINE MONITORING OF BATTERY STATE IN WIRELESS SENSOR NETWORKS
Using Two Battery Models in WSN Constraints

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Abstract: This paper addresses the class of wireless sensor networks where the nodes are using batteries as power sources. It describes the adaptation of an existing analytical battery model to fit the constraints of the wireless sensors in terms of available resources, the algorithm complexity being reduced to O(n) in case of constant loads. The analytical battery model obtained is used together with another existing battery model to provide real time information about the remaining capacity of the battery, based on the electric current draw and elapsed time. The current consumption is estimated using application specific power profiles, thus the monitoring solution proposed does not imply additional hardware on a mote and can be used on each node of a WSN during network employment as a real time decision support.

1 INTRODUCTION

The purpose of wireless sensor networks (WSN) is acquiring and processing the information about natural or technological systems and transmission of the obtained data toward a collecting center. These networks are characterized by a high density of intelligent and autonomous sensor nodes and an efficient use of available resources is required. A significant factor influencing the design of wireless sensor networks is the energy consumption at the network node level, which determines the remaining battery capacity and implicit the time in which that node can be operated. Thus, the energy efficiency is a goal in both, hardware design and software that implements the communication protocols and the strategies used to prolong the network lifetime. Although research in this area is heavily focused on energy efficiency, paradoxically, the interest in monitoring the state of the battery is very low, even if a network management that takes into account the energy consumption and the energy available at a node level can lead to significant network improvements. As an example, if the battery properties are taken into account in selecting the level of transmission power, the amount of data transmitted by a node can be improved with more than 50% (Park et al., 2005).

In this context, the paper presents a work around the equations of an analytical battery model in order to obtain a form which is proper to be implemented in a real-time monitoring software that runs on wireless sensors. The battery model obtained is interfaced with an energy consumption monitoring software that estimates the charge drawn from battery and provide this information using two parameters, the current draw previously determined for the operations performed and the related time interval.

The section 2 gives an overview of the solutions used in wireless sensor networks for current draw monitoring at a node level, while some of the batteries properties are highlighted in section 3. An existing battery analytical model for constant loads is processed until it is reduced to a shorter form which is than approximated with several expressions that are proper for real-time computations. The expressions obtained are than compared with the one proposed in the referenced paper, better results being obtained for longer time intervals. Finally, a second battery model is briefly described, this being used to model the behavior of variable loads as it is taking into account the rate capacity and recovery effects. The section 4 concludes the paper and introduces the further work in finding solutions that avoid the drawbacks of the used battery models in terms of computational effort.

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2 WSN ENERGY CONSUMPTION MONITORING

Even if the optimization of the energy consumption is a key element in designing the wireless networks, using a current draw monitoring system during network employment is not an usual thing in WSN. The energy consumption is optimized through development of energy efficient strategies and protocols which are not aware of the amount of charge available in battery at a certain time.

A 2007 survey (Sohraby et al., 2007) gather the main research topics in WSN into a list which is sorted based on the number of scientific articles related to a subject. The network monitoring, in general, is only on position 21 with 2.12% from all papers. The lack of interest in monitoring the energy consumption and available charge in nodes batteries, if the benefits described by (Park et al., 2005) are taken into account, can be explained by the absence o a solution offering a reasonable trade-off between these benefits and resources implied, as an accurate monitoring solution implies hardware components which means additional energy consumption.

There are two types of monitoring solutions in WSN, off-line monitoring performed in the lab using testbeds or simulators, and on-line monitoring performed during network employment.

Related to the topic of on-line monitoring, only a few solutions can be found in literature. As hardware solutions, the JAWS platform (Beutel, 2006) and SPOT (Jiang et al., 2007) system can be found but they require additional costs and energy consumption. There are three software solutions identified for on-line monitoring of sensor nodes: Levels (Lachenmann et al., 2007), another solution based on a theoretical model calibrated with accurate measurements (Kellner et al., 2008) and a solution based on power profiles defined according to the states of the microcontroller and transceiver (Dunkels et al., 2007).

The monitoring system for power consumption used in this paper is a software one and provides the consumption information using two parameters: the estimated current draw and the related time. Thus the battery model to be used should be able to provide information about charge available based on the two input parameters.

3 BATTERY MODELS

An accurate battery model should be able to cover the following behavior (Rao et al., 2003): charge diminution over time - self discharge; rate capacity effect - at high discharge rates the effective capacity of the battery will be lower than the nominal capacity; relaxation effect - at very small discharge rates, the batteries can partially recover their capacity; temperature influence and the capacity fading in case of rechargeable batteries.

There are several types of battery models developed. The linear models are elementary and none of the previous properties are taken into account. The initial battery capacity is decreased with the charge drawn until it reaches a cut_off value when the battery is considered fully discharged. These models require a minimum computational effort but are the worst from accuracy point of view. The electric circuit models are using equivalent electric schemes that describe the batteries behavior while the stochastic battery models are based on simulations. Electrochemical models are the most accurate, describing the battery properties through reduction-oxidation chemical reactions. They are used as a reference in validation of other models but due to their complexity and required computational effort can not be used in on-line monitoring systems. These models are solved using numeric integration and have solutions very close to the real system behavior.

Analytical models are usually derived from electrochemical models and therefore quite accurate but not so computational intensive. Such a model is proposed in (Rakhmatov and Vrudhula, 2001) where the authors are taking into account the ions diffusion in the electrolyte, or the Kinetic Battery Model from (Rao et al., 2007). These two models are used as reference in this paper as they are representative for the class of analytical models.

3.1 Battery Model for Constant Loads

The battery mathematical model presented in (Rakhmatov and Vrudhula, 2001) is used for the case of constant loads as it is less computational intensive than its approach for variable loads. The model is based on the principle of diffusion and is described by the following equations and boundary conditions:

$$-J(x,t) = D\frac{\partial C(x,t)}{\partial x}$$

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

$$\frac{i(t)}{\nu FA} = D\frac{\partial C(x,t)}{\partial x}\bigg|_{x=0}$$

$$0 = D\frac{\partial C(x,t)}{\partial x}\bigg|_{x=w}$$

where

- $C(x,t)$ is the concentration of species at time $t \in [0,L]$ at distance $x \in [0,w]$
- $C^* = C(x,0), \forall x$ is the initial concentration
- $J(x,t)$ is the flux of species at time t at the distance x
- D is the diffusion coefficient
- $i(t)$ is the current
- $F = 96485,31C\ mol^{-1}$ is the Faraday's constant
- A is the area of the electrode.

Starting from the relation for $C(0,t)$ obtained in (Rakhmatov and Vrudhula, 2001) we have:

$$C(0,t) = C^* - \frac{2iw\sqrt{t}}{\nu FA\sqrt{\pi D}} - \frac{4iw}{\nu FAD\sqrt{\pi}} \cdot \sum_{m=1}^{\infty}\left[-m\sqrt{\pi} + \frac{\sqrt{Dt}}{w}e^{-\frac{w^2m^2}{Dt}} + \sqrt{\pi}m \cdot \mathrm{erf}\left(\frac{mw}{\sqrt{Dt}}\right)\right] \tag{1}$$

where $\mathrm{erf}(y)$ is the error function that, for $y \ll 1$ may be written in the following form:

$$\mathrm{erf}(y) = \frac{1}{\sqrt{\pi}}e^{-y^2}\sum_{n=0}^{\infty}\frac{(2y)^{2n+1}}{(2n+1)!!}$$

We take the first 3 terms from its power series and after calculating the sum expression with 1000 terms, the equation (1) becomes:

$$\begin{aligned} C(0,t) &= C^* - \frac{2iw\sqrt{t}}{\nu FA\sqrt{\pi D}} - \frac{4iw}{\nu FAD\sqrt{\pi}} \\ &\cdot \frac{10\sqrt{Dt}}{3(Dt)^5 w}[300(Dt)^5 - 15150\sqrt{\pi}(Dt)^{\frac{9}{2}}w \\ &+ 100150050(Dt)^4w^2 - 1025166665(Dt)^3w^4 \\ &+ 8874428471430(Dt)^2w^6 \\ &+ 46471109244533332Dtw^8 \\ &+ 767939313947393539400w^{10}] \end{aligned} \tag{2}$$

The advantage of this form is derived from the type of arithmetic operators used, the most complex being the square root. Instead of the big values that requires operations on 64 bits, it is easier to be implemented in the software running on a wireless sensor than the original form used in the referenced paper, where the function $\mathrm{erf}(y)$ is approximated to the following exponential form:

$$\mathrm{erf}(y) \approx 1 - \frac{e^{-y^2}}{\sqrt{\pi}\left(y - \frac{y}{\pi} + \frac{\sqrt{y^2+\pi}}{\pi}\right)}$$

In Fig. 1, we compare our results with the ones obtained using the (Rakhmatov and Vrudhula, 2001) approximation. On the horizontal axes we have the time in seconds while on the vertical axes the difference between real C, given by 1, and the values of C obtained through $\mathrm{erf}(y)$ function approximations. It can be observed that for small time intervals, the approximation we proposed behave worst than the one from referenced paper but it performs much better for longer time intervals, where it is quite the same as the real solution.

The drawback of this model in case of our approach is related to the limitations of the Micaz mote we are using. The mote is based on a 8 bit microcontroller (ATmega128L) which has no instructions defined for floating point operations or 64bit data, therefore all computations are slow as they are handled through library functions.

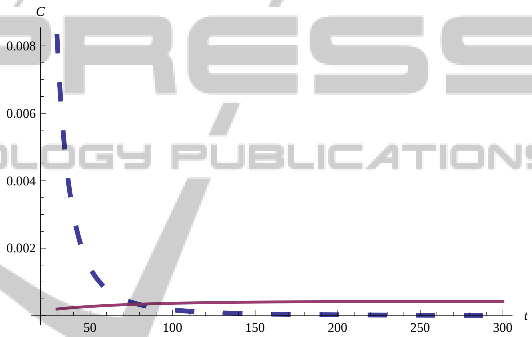

Figure 1: The difference between the proposed approximation (dashed), the referenced solution approximation (continuous) and the real solution.

3.2 Battery Model for Variable Loads

Taking into account that results obtained in the previous subsection can be used only when there are constant loads longer than a certain time interval, we focused also on a battery model capable to take into account the rate capacity and relaxation effects. It is the modified Kinetic Battery Model from (Rao et al., 2007), from which we removed the probability approach. The model used can be summarized as:

```
bool chrg_clc(int32_t cons,uint32_t t){
     uint32_t n; double I_n;
     I_n=1.0*cons;
     n=t/CHRG_TIME_UNIT;
     while(n--){
       if (i<I_n) return FALSE;
       if(I_n<J&&h_1>=h_2){
           i-=I_n*c_ct;j-=I_n*(1.0-c_ct);}
       else{
          j-=J; i=i-I_n+J;
          h_1=i/c_ct; h_2=j/(1.0-c_ct);
          J=k_ct*(h_2-h_1)*h_2;}
      }
   return TRUE;}
```

where the current draw is denoted by I_n and the algorithm is processed as long as the $h\_2 > h\_1$. The parameters c_ct and k_ct are battery specific and are linked with the rate capacity and recovery effects. After each change in the load, the time elapsed from the previous change is computed and the Kinetic Battery Model is triggered with the load given as current draw and the time interval transformed in time units (I_n). Even if the algorithm described is very short, it requires additional 20 bytes of RAM memory and more than 2 Kilobyte of ROM on a Micaz mote. Unlike the previous model, the floating point data can be substituted with integer operations but the computational time is also affected by the existence of a loop.

4 CONCLUSIONS

This paper analyze the usage of two battery models for monitoring the state of charge at a node level in a wireless sensor network. It describes the adaptation of an existing analytical model derived from a realistic battery model, this adaptation being required to fit the constraints of the wireless sensors in terms of available resources. The algorithm complexity was reduced to O(n) in case of constant loads as only classic arithmetic operators are used, and no loops are necessary. The biggest computational effort is required to process the square root function and to obtain the order power of 10 for numbers represented on more than one byte. On the other hand, when there are variable loads, the Kinetic battery model used will not require more complicated operations than multiplications on larger data types but some loops should be performed, depending on the load value and the related time.

The monitoring solution used in conjunction with these battery models can be implemented on each node of a WSN during network employment as a decision support. The drawbacks of the proposed methods are linked with the related computational effort which is significant if we take into account that only simplified and not quite accurate versions of referenced battery models were used.

Further work consist in modeling the battery through interpolation tables based on the electrochemical model solution given as an intersection of two surfaces through Hamilton-Poisson Geometry.

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