

Accurate Online Estimation of Battery Lifetime for Wireless Sensors Network

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Abstract: Battery is a major hardware component of every device in a wireless sensor network. Most of them have no power supply and are generally deployed for a long time. Investigations have been done on battery physical models and their adaptation to sensors. We present an adaptation and instantiation of such a model on a real sensor operating system and how architectural constraints have been considered. Experiments have been made in order to test the impact of several parameters on the battery lifetime.

1 INTRODUCTION

Wireless Sensors Networks (WSN) have a growing presence in industrial and home automation. These constrained networks are made possible by the reduction of processor size and the high performance batteries. Nevertheless these networks have to take care of their energy consumption because they are usually deployed for a long time. The growing interest on battery lifetime estimation for WSN appears in the standardization work of these network (Ed., 2012). They define a routing protocol with one metric being the remaining battery level (Vasseur Ed. et al., 2012).

Battery models that describe relation between the battery lifetime and its use have been proposed since embedded systems (laptop, cellular phone) became popular. These models take into account two phenomena occurring in a battery cell: the *Rate Capacity Effect* and the *Recovery Effect* (Panigrahi et al., 2001). The former gives the energy consumed under a constant current load, when transmitting for example, and the latter gives the energy recovered during inactivity or low current load. Inside a battery, oxidation at the anode electrode induces reduction at the cathode. The reduction decreases the concentration of positive ions near the cathode and so the available energy. But during idle time or low current load positive ions near the anode have time to move toward the cathode, thus increasing the available energy and so the battery lifetime.

The analytical model of this battery behaviour is well known but is too complex to be instantiated on

a sensor board. However, an approximation of this model is available and our contribution in this paper is to fill the last gap between the approximated model and its instantiation within an existing operating system for sensors. The remainder of this paper is organized as follow. We first describe the reference model and its approximation. The next section emphasizes on the elementary operations of WSN node and their current draw. Details of the implementation are given in the section 4 and first results are shown in the last part. We draw some conclusions and forecast future work at the end of the document.

2 REFERENCE MODEL

The most accurate battery modeling is given by the analytical equation (1) (Rakhmatov and Vrudhula, 2001; Rakhmatov et al., 2002; Rao et al., 2003). In this formula, α (coulombs) denotes the total battery capacity that is equals to the current load $i(\tau)$ – in the left additive operand – consumed since the use of the battery until the time L (the battery Lifetime) and – the second operand – the current that was unavailable because positive ion concentration was not sufficient at the cathode. The β parameter is the diffusion coefficient of electroactive species inside the battery. β^2 is expressed in s^{-1} .

$$\alpha = \int_0^L i(\tau) d\tau + 2 \sum_{m=1}^{\infty} \int_0^L i(\tau) e^{-\beta^2 m^2 (L-\tau)} d\tau \quad (1)$$

The use of this model can be found in (Rakhmatov and Vrudhula, 2003; Seungki et al., 2005; Timmermann, 2003; Zhang et al., 2010; Sausen et al., 2010) for various domains, as task scheduling or simulation. The model can not be implemented as is on WSN nodes albeit some results with the first part of equation (1) are reported in (Dunkels et al., 2007; Kerasiotis et al., 2010). In so doing, no work does to our knowledge take into account the *recovery effect* that occurs during idle time despite it is generally more than 90% of the WSN node lifetime. The contribution of (Rahmé et al., 2010) is an approximation of equation (1) that can be implemented on WSN node. The global equation (2) recursively computes $\sigma(L_n)$ that is the consumed charge in Milli ampere minute ($mAmn$) at time L_n . This computation depends on the consumed charge at time L_{n-1} , the time interval, in minute, $\Delta = L_n - L_{n-1}$ being constant.

$$\sigma(L_n) = \sum_{k=1}^n I_k \delta_k + \lambda \left(\sigma(L_{n-1}) - \sum_{k=1}^{n-1} I_k \delta_k \right) + 2I_n A(L_n, L_{n-1} + \delta_k, L_{n-1}) \quad (2)$$

With this approach, we know the remaining charge in the battery at time L_n by the difference between $\sigma(L_n)$ and the initial battery parameter α of equation (1). The *recovery effect* of the battery is computed through the function A given in the equation (3) that is approximated by the use of an f function we detail below.

$$A(L_n, L_{n-1} + \delta_k, L_{n-1}) = \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 (L_n - L_{n-1} - \delta_k)} - e^{-\beta^2 m^2 (L_n - L_{n-1})}}{\beta^2 m^2} \quad (3) \approx \frac{f(v)}{\beta^2} - \frac{f(\Delta)}{\beta^2}$$

This approximation depends on the idle time of the mote during the Δ interval, given by the difference $v = \Delta - \delta_k$ (v is the idle time of the L_{n-1} period and δ_k its activity time). The recursivity of the model depends on the λ parameter defined as the ratio $\frac{A(L_{n+1}, \delta_1, 0)}{A(L_n, \delta_1, 0)}$ for each n but that can be bounded by the value $e^{-\beta^2 \Delta}$ computed offline.

3 CURRENT DRAW

3.1 Linear Draw

The first term in equation (2) is the sum of products between current load I_k and time interval δ_k since the

beginning of the battery lifetime (when $k = 1$) until the time L_n . The δ_k time interval is a sub interval of Δ during which the battery was used by the node. To compute this value we must know which components of the motes use the current along the time and at which current rate. Mote's current information can be obtained from data-sheet documents. For example, the table 1 shows the current load for two mote types (Sky or WSN430 motherboard, respectively with CC2420 and CC1100 communication chips). The columns are the usual states of the duty cycle for any mote : CPU, LPM, TX and RX respectively for processor, low power mode, transmitting and receiving. Currents are given in mA . The given values for TX and RX are linked to signal power and throughput configuration of the mote. We have launched experiments on the senslab plat-

Table 1: Motes current draw.

Mote	CPU	LPM	TX	RX
Sky	1.8	0.0545	17.4	18.8
Wsn430	2	0.02	16.1	15.2

form (des Roziers et al., 2011) with one tested node (WSN430 based). The senslab testbed provides an external polling service of the current consumed by motes during an experiment. We program the node to print the time of each state change. The figure 1 shows

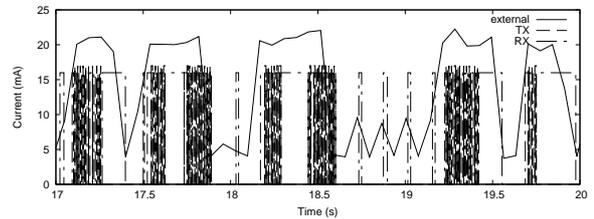


Figure 1: Mote modes and currents.

plots of measured current at the mote endpoints and the duties cycles (we just keep TX and RX mode that have the main current values). Note that start and stop times of duties match with measured current. Consequently, the current draw of a $\Delta = \delta_{CPU} + \delta_{LPM}$ interval is the result of the equation (4) where each C_{state} is the current load (cf. table 1) and each δ_{state} is the sum of all state sub-intervals inside Δ .

$$I_k \delta_k = C_{CPU} \cdot \delta_{CPU} + C_{LPM} \cdot \delta_{LPM} + C_{TX} \cdot \delta_{TX} + C_{RX} \cdot \delta_{RX} \quad (4)$$

4 IMPLEMENTATION CONSTRAINTS

Even with the help of (Rahmé et al., 2010), we must be aware of mote limitations on code size and arithmetical capabilities. The strong constraint is that the MSP430 compiler can not handle floating point values but only signed or unsigned integer.

4.1 Online Computation

We compute the consumed current every Δ time interval. The values $\delta_{CPU,LPM,TX,RX}$ are provided in Milli second and we use the current load of the table 1 with a factor of thousand. The result's unit is in $\mu A.ms$ then it is converted in $mA.mn$ (cf eq. (2)). We compute v with the low power mode period and the radio use :

$$v = \begin{cases} \delta_{LPM} - (\delta_{TX} + \delta_{RX}) & \text{if } \delta_{LPM} > (\delta_{TX} + \delta_{RX}) \\ 0 & \text{else} \end{cases} \quad (5)$$

If the radio is more used than the LPM state then there is no idle time for the battery. The varying part of the recovery function A (equation 3) is rewritten in order to lose as little precision as possible :

$$\frac{f(v)}{\beta^2} = \frac{10^4 \beta^2 v + \pi^2 \cdot 10^3 - 12 \beta \sqrt{\pi} \sqrt{v}}{\beta^2 12 \cdot 10^5} \quad (6)$$

At this step we use a 64 bits intermediary value to get the result (MSP430 compiler allows such data type but they are actually emulated with several 32 bits values).

Finally, the remaining energy is computed with the values above and the previous remaining energy value (a Δ before). We compute the ratio with 255 as 100%. This value is given by a WSN routing metric recommendation (Vasseur Ed. et al., 2012) and we use it in the present work to implement and test an energy-based routing plane. However we compute the remaining energy with a precision of 5 numbers, that is from $255 \cdot 10^5$, so energy consumption is measured at a very fine granularity.

The code size of the presented implementation is about $12Kb$ out of the $50Kb$ allowed by our sensor board. At the memory level, we store on memory six 32 bits values from one computation to the other (times of CPU, LPM, TX, RX and previous values for $\sigma(L_{n-1})$ and $\sum_{k=1}^{n-1} I_k \delta_k$).

5 SIMULATION RESULTS

For our simulations we use the Cooja WSN simulator (Osterlind et al., 2006) and test a network of nodes

built on the Sky mote platform. All node have an initial battery charge of $880mAh$, that give a value for α of $880 = 52800mAh$ because we consider an ideal battery for these first steps. For the same reason, we choose the value $\beta = 1$.

Nodes use IPv6 and the RPL¹ routing protocol (Ed., 2012) to perform a simple collect application during which one or more nodes, the *Senders*, periodically send sensing information to a receiving node called the *Sink*, configured to be the root of the RPL routing tree. *Senders* send one data packet every second and use the *contikiMAC* radio duty cycle (Dunkels, 2011). We use a linux *Ubuntu 11.0* desktop computer with a *3GHz Intel* processor and *4Gb* of memory to run simulations.

5.1 Booting Node

We start our experiment with the observation of the node booting process. The figure 2 puts together the evolution of the battery lifetime and the time spends by activities of the node. During the first minute, on the part (a), we note a large decrease of the battery² to correlate with the strong activity on the part (b) for the same period. Mainly this activity is related to system and network initialization (remains the strong power for TX and RX of the table 1). The battery recovery is visible at this very detailed level, during the second minute and the two following ones. These recovery periods match with low activity periods.

5.2 Network Building

We continue the simulation shown in the figure 3 (a) where after ten minutes of simulated time, we add five nodes "under" the non-root node to observe the cost of the routing tree building and traffic accumulation. The node 1 is the *Sink* and all other are *Sender*. We leave these nodes sending and forwarding (only for the node 2) data packets during ten minutes and remove the five nodes previously added. This can occurs in real deployment for example with mobile nodes or with lossy communication environment. A final point of interest, at the thirty fifth minute, is when a node has lost its destination node (its default next hop router) because the network has to build itself again. The figure 3(b) plots the remaining battery lifetime of the node 2 along our experiment. The recovery curve is related to the implementation and the linear is a simple additive function of current draw. The strong decrease of the first ten minutes is mainly due to traffic overhead and very few is from

¹Routing Protocol for Low-Power and Lossy Network

²that is only 0.0005% of the total

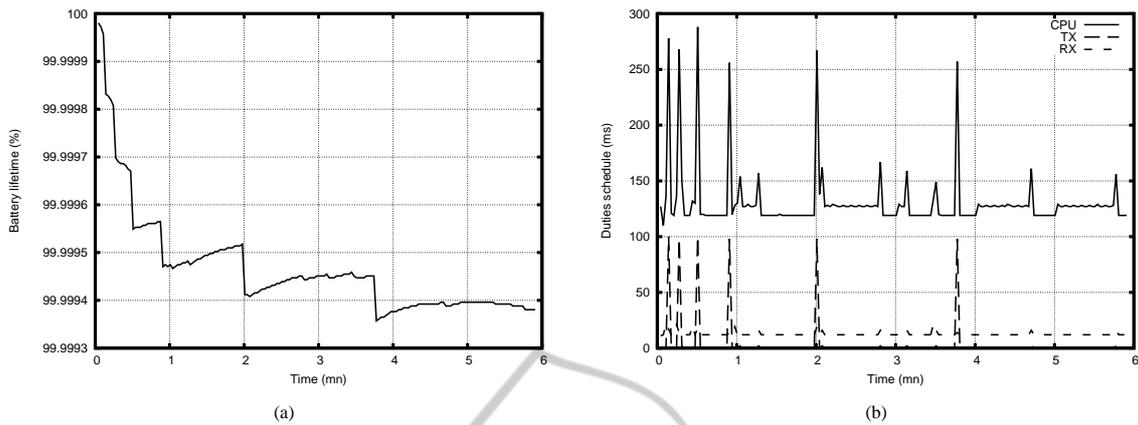


Figure 2: First minutes of battery lifetime.

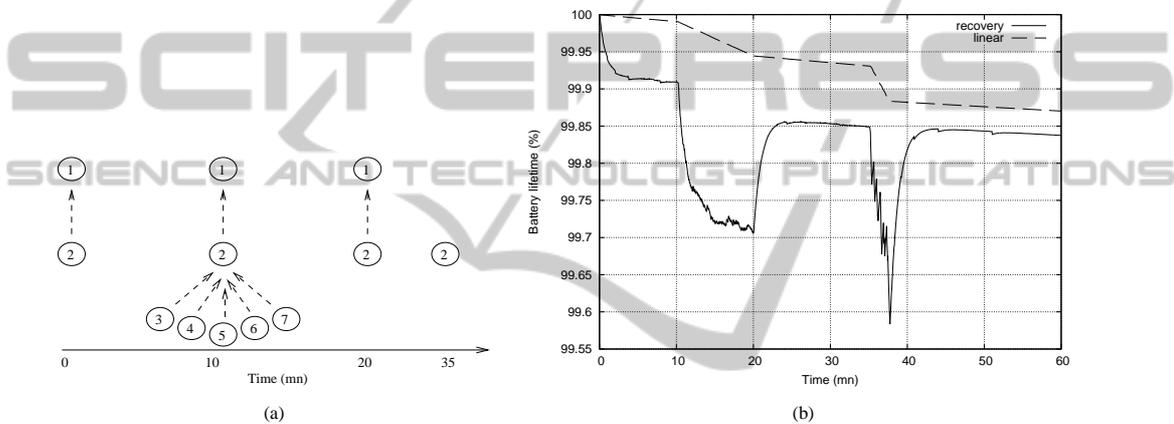


Figure 3: Battery lifetime and RPL.

RPL control messages. Once the routing plane is established, between the tenth and twentieth minute, the battery decreases with a greater slope and with more micro variations. When removing nodes at the twentieth minute, the node 2 shows a quick and strong recovery of its battery lifetime. As given by the model, the fall of current draw lets the battery recovers some of its current charge. During the fifteen following minutes the node sends one packet per second to the *Sink* and the curve is similar to the beginning (without booting process) but at a lower battery level. At the thirty fifth minute we remove the parent of the node 2. The very large decrease of battery is again mainly related to a strong use of communication. The node has no more IPv6 router neighbor then it polls the network with neighbor discovery messages and after three minutes, the node decides to build a new network and just send few RPL control message. One can there observe a very significant recovery at the part (b). The linear model is very less reactive and never grows, as expected. It generally over estimates

the lifetime and it does not take into account the *recovery effect*.

5.3 Radio Duty Cycle

The Contiki operating system supports some RDC implementations we have used in order to compare their energy consumption. The part (a) of figure 4 shows these experiments. All these RDC are asynchronous and packet oriented.

- the contikiMAC allows the greatest battery lifetime. It can sleep up to 99% of the time and was measured as been ten times less energy consumer than X-MAC (Dunkels, 2011).
- X-MAC (Buettner et al., 2006) is a bigger consumer; the sender sends several preamble packets until an acknowledge reception and then sends the data packet.
- CX-MAC (Compatibility X-MAC) is a variation of X-MAC that is provided by Contiki to be usable on more radio chips.

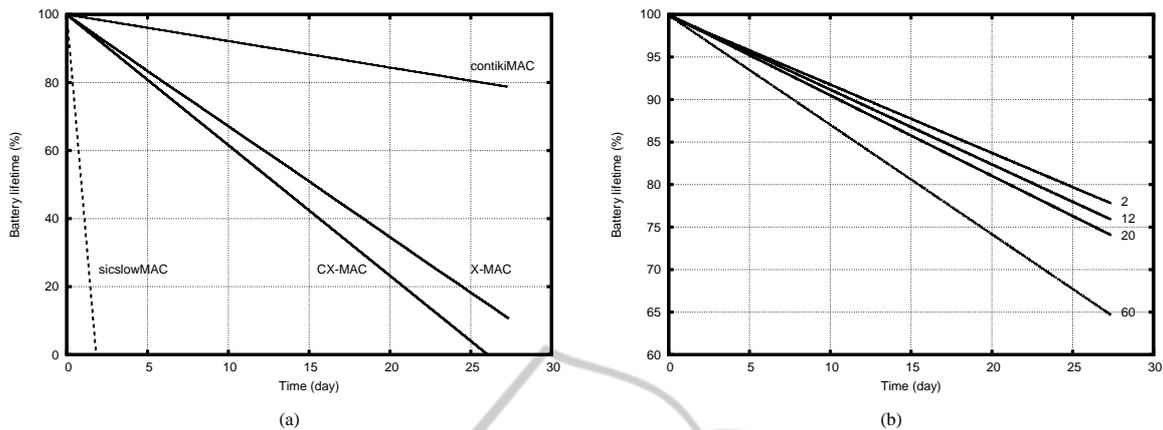


Figure 4: Network life.

- sicslowMAC (also in Contiki) handles 802.15.4 frames and always keeps its radio open.

As one can expect, RDC has a strong effect on the battery lifetime and this effect is mainly due to the use of radio of each RDC.

5.4 Throughput

We have also measured the throughput effect on battery lifetime and plot them in part (b) of the figure 4. The contikiMAC RDC was used because it is the less battery consuming stack and so the impact of the throughput is emphasized. Numbers within the part (b) are the throughput of the application, from 60 packets by minute (pkt/mn) to 1. Each packet has a size around 100 bytes and the application is parameterized by a number of seconds between two packets. These results show that the lifetime is roughly linear with the throughput but other tests with less throughput than $1\text{pkt}/mn$ have no significant improvement on the lifetime. The network traffic is then negligible compared to sensor base activity (indeed the routing protocol is the main radio consumer).

5.4.1 Lifetime Estimation

These figures are very close to a line and we use a linear regression with the least square estimation technique to envision the time when the battery is depleted (i.e. with 0% of remaining energy). Table 2 contains the battery lifetime estimation for each lines in figure 4. The short lifetimes of these networks (no more than four months) is related to the light battery we have used. Battery of node like Sky are usually around $2000mAh$ and should allow WSN be operational for one year. Nevertheless real batteries have a secure cut off level that prevent them to be fully discharged be-

cause they will be damaged and not able to be charged again.

Table 2: Battery life estimation.

RDC	Lifetime (days)	Thput (pkt/mn)	Lifetime (days)
contikiMAC	128	60	77
X-MAC	30	20	105
CX-MAC	26	12	113
sicslowMAC	1.8	2	124
Thgput : $1\text{pkt}/mn$		RDC : contikiMAC	

6 CONCLUSIONS

We presented a first implementation of a battery lifetime estimation inside an existing operating system for WSNs. Based on a recognized theoretical battery model, our work has shown how the sensor internal architecture impacts concrete realizations. Our simulations help us to better understand how sensors use their battery in the bootstrap process or during steady networking phase. This work is useful for many applications like routing optimization that we currently plan. The necessary additional work is to get the implemented model and the real world closer tied. Discharge tests of batteries must be done as precisely as possible (manufacturer data-sheets are not always enough) to parameterize the α and β values of the battery used. Such tests should be done at several ambient temperature level because it is know that it acts on battery lifetime. The sensing chips (temperature, light...) are also current consumer and some sensors have energy scavenging capabilities that should be integrated into the model. We have to launch long time testing (few weeks, months, one year) establishing a

relation between the remaining energy and the cut off level of a battery. Moreover several battery technologies have to be tested to enforce our implementation model.

REFERENCES

- Buettner, M., Yee, G. V., Anderson, E., and Han, R. (2006). X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks. In *Proceedings of the 4th international conference on Embedded networked sensor systems*, SenSys '06, pages 307–320, New York, NY, USA. ACM.
- des Roziers, C., Chelius, G., Ducrocq, T., Fleury, E., Fraboulet, A., Gallais, A., Mitton, N., Noel, T., Valentin, E., and Vandaele, J. (2011). Two demos using senslab: Very large scale open wsn testbed. In *International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS)*, pages 1–2.
- Dunkels, A. (2011). The contikimac radio duty cycling protocol. SICS Technical Report T2011:13 ISSN 1100-3154, Swedish Institute of Computer Science.
- Dunkels, A., Osterlind, F., Tsiftes, N., and He, Z. (2007). Software-based on-line energy estimation for sensor nodes. In *Proceedings of the 4th workshop on Embedded networked sensors*, EmNets '07, pages 28–32, New York, NY, USA. ACM.
- Ed., T. W. (2012). Rpl: Ipv6 routing protocol for low-power and lossy networks. RFC 6550, Internet Engineering Task Force.
- Kerasiotis, F., Prayati, A., Antonopoulos, C., Koulamas, C., and Papadopoulos, G. (2010). Battery lifetime prediction model for a wsn platform. In *Fourth International Conference on Sensor Technologies and Applications (SENSORCOMM)*, pages 525 – 530. IEEE.
- Osterlind, F., Dunkels, A., Eriksson, J., Finne, N., and Voigt, T. (2006). Cross-level sensor network simulation with cooja. In *Local Computer Networks, Proceedings 2006 31st IEEE Conference on*, pages 641 – 648.
- Panigrahi, D., Dey, S., Rao, R., Lahiri, K., Chiasserini, C., and Raghunathan, A. (2001). Battery life estimation of mobile embedded systems. In *Proceedings of the The 14th International Conference on VLSI Design (VLSID '01)*, VLSID '01, pages 57 – 63, Washington, DC, USA. IEEE Computer Society.
- Rahmé, J., Fourty, N., Al Agha, K., and Van den Bossche, A. (2010). A recursive battery model for nodes lifetime estimation in wireless sensor networks. In *Wireless Communications and Networking Conference (WCNC)*, pages 1 – 6. IEEE.
- Rakhmatov, D. and Vrudhula, S. (2001). An analytical high-level battery model for use in energy management of portable electronic systems. In *Computer Aided Design, 2001. ICCAD 2001. IEEE/ACM International Conference on*, pages 488 – 493.
- Rakhmatov, D. and Vrudhula, S. (2003). Energy management for battery-powered embedded systems. *ACM Trans. Embed. Comput. Syst.*, 2(3):277–324.
- Rakhmatov, D., Vrudhula, S., and Wallach, D. (2002). Battery lifetime prediction for energy-aware computing. In *Proceedings of the 2002 International Symposium on Low Power Electronics and Design (ISLPED'02)*, pages 154 – 159. ACM.
- Rao, R., Vrudhula, S., and Rakhmatov, D. (2003). Battery modeling for energy aware system design. *Computer*, 36(12):77 – 87.
- Sausen, P. S., Spohn, M. A., and Perkusich, A. (2010). Broadcast routing in wireless sensor networks with dynamic power management and multi-coverage backbones. *Inf. Sci.*, 180(5):653–663.
- Seungki, H., Daeyoung, K., and Jae-eon, K. (2005). Battery aware real time task scheduling in wireless sensor networks. In *11th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, pages 269 – 272. IEEE.
- Timmermann, D. (2003). Simulation of mobile wireless networks with accurate modelling of non-linear battery effects. In *In proceedings of Applied simulation and modeling (ASM)*.
- Vasseur Ed., P., Kim Ed., M., Pister, K., Dejean, N., and Barthel, D. (2012). Routing metrics used for path calculation in low-power and lossy networks. RFC 6551, Internet Engineering Task Force.
- Zhang, J., Ci, S., Sharif, H., and Alahmad, M. (2010). An enhanced circuit-based model for single-cell battery. In *Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE*, pages 672 – 675.