2012 2nd International Conference on Information Communication and Management (ICICM 2012)
IPCSIT vol. 55 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V55.18

Lifetime Estimation of Sensor Device with AA NiMH Batteries

Wilawan Rukpakavong [1 +], Iain Phillips [1] and Lin Guan [1]

[1] Department of Computer Science, Loughborough University, Loughborough, UK

Abstract. Lifetime is the primary issue in wireless sensor networks. Temperature is one of important factors affecting node lifetime since it may increase or decrease lifetime of node. This paper proposes a novel equation for node lifetime estimation which covers the effect on both battery capacity and current draw of node. The effectiveness of the proposed scheme is evaluated by using an experimental testbed with various brands, capacity and aging of commercial batteries. Two lifetime estimation techniques are evaluated and compared to the actual node lifetime. By using the proposed technique, lifetime can be estimated for different starting voltages, brands, capacities, ages of batteries and static load programmes without detailed knowledge of electrical and electrochemical.

Keywords: Wireless Sensor Networks, Energy Consumption, Lifetime, NiMH Battery, Voltage, Temperature

1. Introduction

Node lifetime is one of major concerns for Wireless Sensor Networks (WSNs). With accurate lifetime estimation of the sensor nodes, applications or routing protocols are able to make intelligent decisions that can help conserve energy. A WSN node is typically battery powered by AA-size batteries. For example, a pair of AA cells is used for Sensinode N740 NanoSensors using CC2430/2431 SoC [1]. These sensors support battery and temperature monitoring. A common AA rechargeable battery is a nickel-metal hydride cell (NiMH) at 1.2 volts which has capacity ranging from 1100 mAh (milliampere-hour) to 3100 mAh and the self discharge rates are 5-10% or more in first 24 hours and then 0.5-1% per day at room temperature [2]. The starting voltage of fully charged cell in good condition is about 1.4-1.45 volts.

Calculations based on datasheet are usually used to estimate node lifetime for many studies both in simulation and on real hardware. Fixed voltage and fixed temperature are normally assumed (e.g., 3 volts and 25 °C). This means running the static load programmes for multiple times always consume the same energy. However, in reality, they might require different powers which results in the different lifetimes. Moreover, the non-linear behaviour of the batteries should be taken into account. This paper proposes the lifetime estimation by using starting voltage of battery and temperatures. The effect of temperature on battery efficiency and current consumption is covered. The testbed experiment is used to verify the proposed idea with different brands, capacities, ages of NiMH AA-size of batteries and different programmes.

2. Related Work

There are variables used to describe about voltage. Terminal voltage (Vt) is the voltage between the battery terminals with load applied, while open-circuit voltage (VoC) is voltage with no load applied, and V_{dd} is the positive supply voltage. SoC is the present percentage of maximum capacity (C_{max}). Lifetime (L_t) of a node depends on current battery capacity (C_b) and consumption needed by that node (I). Lifetime of a node is expressed as [3].

+ Corresponding author. Tel.: + 44 1509225903; fax: N/A.
E-mail address: W.Rukpakavong@ lboro.ac.uk.

$$L_t = C_b / I^k \quad (1)$$

where C_b is SoC*C_{max} and k is the peukert constant which can be assumed k=1 for low current consumption (less than 0.2 of C_b) [4, 5, 6]. To estimate the lifetime of node, it is necessary to estimate both battery capacity and current consumption. Since chemical energy in battery cells is converted into electrical energy through an electrochemical reaction, Nagarajan and Zee [7] proposed the electrochemical models based on the chemical processes that take place in the battery. This model described the battery processes in great details but it is very complex and required highly detailed knowledge of electrochemical which make a difficult setting. Guoliang et al. [8] proposed NiMH battery capacity estimation based on Electromotive Force Method (EMF). From their study, SoC can be modelled as a linear function, for example, during capacity 80-100% as $(0.8+(0.2*[(VoC-VoC_{80})/VoC_f-VoC_{80})]))$, where VoC_{80} and VoC_f are the voltages at capacity 80% and 100% and VoC ≥ VoC80. However, the maximum possible battery capacity may decrease due to capacity loss, which is caused by many factors, such as battery ages, number of charge cycles, and charge and discharge behavior on a regular basis. To cover capacity loss, the equation can be expressed as:

$$SoC = (1-\%loss) * (0.8 + (0.2 *[(VoC-VoC_{80})/(VoC_f-VoC_{80})])) \quad (2)$$

This model is much easier than the electrochemical models and computationally less expensive. However, it did not cover the current consumption of devices. Furthermore, this method is less accurate as claimed in [9]. To estimate current consumption of node, Liao et al. [10] tried to find the average leakage current consumption, however, detailed knowledge of electrical circuits are required. Jiang et al. [11] develop a hardware-based mechanism for measuring the energy consumption. However, it is a significantly higher cost for energy estimation. Dunkels et al. [12] proposed a formula to calculate the energy consumption (*E*).

$$E/V = I_a t_a + I_l t_l + I_t t_t + I_r t_r + \Sigma I_c t_c \quad (3)$$

where V is the supply voltage, I_a and t_a are the current consumption of the MCU (Microprocessor Control Unit) and time when the MCU has been running in active mode, I_l and t_l are the current consumption and time of the MCU in low power or sleep mode, I_t and t_t are the current consumption and the time of the communication device in transmit mode, I_r and t_r are the current consumption and time of the communication device in receive mode, and I_c and t_c are the current consumption and time of other components such as sensors and LEDs. In this model, supply voltage and all current consumption were assumed as fixed values which may not accurate in real-world deployments since they are usually dynamic based on temperatures. Moreover, they did not consider the battery capacity. The impact of battery capacity on lifetime was studied experimentally by Nguyen et al. [13] for different alkaline battery brands but temperature effect was not included in this study. The model proposed by Park et al. [14] covered the remaining capacity and the effect of temperature on battery capacity. However, they did not consider the effect of temperature on the current consumption of devices. Furthermore, their assumption that the batteries begin with full capacity voltage might not be applied in real deployments with NiMH batteries because these batteries had a relatively high self-discharge rate on the first day after full charging.

This paper presents formula for lifetime estimation which covers temperature effect on both battery capacity and current consumption. Moreover, many factors of the different capacity of battery, such as starting voltage due to self-discharging, battery models, brands, aging and different programme loads are also investigated. This model does not require detailed electrical and electrochemical knowledge.

3. Lifetime Estimation Model

Normally, higher starting VoC gives the higher battery power which result in the longer lifetime period. Both battery capacity and current consumption are affected by temperatures. As temperature increases, current draw is increased and, consequently, shorten the lifetime of the device. However for NiMH cells, high temperatures can provide increased capacity of battery over the operating temperature range 0 °C to 30 °C. Therefore, it depends on the ratio between increased battery capacity and current draw, which may result in increased or decreased lifetime. The ratio of capacity at two different average temperatures in Kelvin (T_1, T_2) can be expressed as [3]:

$$C_b(T_2)/ C_b(T_1) = \exp^{(A*[(T_2-T_1)/(T_2*T_1)])} \quad (4)$$

where A is a constant ratio between the activation energy and gas of battery. The leakage current draw at two different average temperatures in Kelvin (T_1, T_2) is [10]:

$$I(T_2,V_{dd})/ I(T_1,V_{dd}) = (T_2^2/ T_1^2) * \exp^{(K*[(T_2-T_1)/(T_2*T_1)])} \quad (5)$$

where K is a constant depended on average V_{dd} and is assumed that it is the same for running with the same starting voltage and device. From equation (1), (4) and (5), new equation of full capacity voltage VoC_f at two different temperatures in Kelvin is derived as:

$$\ln[(L_t(T_2,VoC_f)* T_2^2)/ (L_t(T_1,VoC_f)* T_1^2)] = \sigma_f *((T_2 - T_1)/ (T_2T_1)) \quad (6)$$

where σ_f is the difference between A and K values for full capacity voltage. This value can be obtained after applying $L_t(T_1,VOC_f)$, $L_t(T_2,VoC_f)$, T_1 and T_2 by the experiment measurement values. Time until dead from starting voltage VoC_f can be estimated for any average temperature (T) which is between T_1 and T_2 as:

$$L_t(T,VoC_f) = (L_t(T_r,VoC_f)* T_r^2* \exp^{(\sigma_f*[(T-T_r)/(T*T_r)])})/T^2 \quad (7)$$

where T_r and $L_t(T_r,VoC_f)$ can be either $(T_1,L_t(T_1,VoC_f))$ or $(T_2,L_t(T_2,VoC_f))$. The steps are repeated on another starting voltage VoC_r in order to find $L_t(T, VoC_r)$. If $VoC \geq VoC_r$, total lifetime of starting voltage VoC on average temperature T can be modelled by:

$$L_t(T,VoC) = -\tau * \ln(VoC/VoC_f)+ L_t(T,VoC_r) \quad (8)$$

where τ is the time constant [3] representing capacity affected by self-discharging, and it can be obtained by $-\Delta t/\ln(VoC_r/VoC_f)$, where Δt is the different time period between starting at VoC_f and VoC_r which is $L_t(T, VoC_f) - L_t(T, VoC_r)$.

4. Lifetime Estimation Verification

To verify the lifetime estimation, a testbed consists of four sensors (N740 sensinode), three of NiMH rechargeable battery brands (Energizer 1300, GP 2100 and maxE 2500), and three of different programmes (P1, P2, P3). One node is a reference node reporting temperature values every minute by using temperature monitoring feature of N740 sensinode. Starting VoC is measured by a multi-meter. Mapping between nodes, battery brands and programmes is shown in Table 1 and time periods in each mode of each programme are listed in Table 2. Based on Eq. (1), both battery capacity and current consumption estimation are needed. Owing to battery aging, it is assumed that battery capacity loss 30% for GP2100, 10% for maxE2500 and 0% for E1300. Full capacity is based on battery types, for example, 2100 mAh, 2500 mAh and1300 mAh are for GP2100, maxE2500 and E1300, respectively. From vendor datasheet [4, 5, 6], voltages of 100% and 80% capacity are 2.8 and 2.6V. These values are used for capacity estimation based on equation (2). From CC2430 datasheet [1], current consumption at 25 °C and 3V of V_{dd} for TX, RX, CPU-ACTIVE, CPU-LOW and SENSING are 26.9, 26.7, 0.19, 10.5 and 1.2 mA, respectively. As equation (3), energy consumption rate can be calculated for P1, P2 and P3 as 75.66, 75.13 and 74.70 mA per minute. From experiments, it is observed that full capacity voltages for GP2100, maxE2500 and E1300 are 2.85, 2.83 and 2.90 V, respectively. After one day, their voltages dropped to around 2.70, 2.75 and 2.80 by self-discharging. These full capacity voltages and values of one day voltage drop are used as VoC_f and VoC_r to estimate lifetime based on our proposed technique in Eq (8). To find all constant values, each node needs to run several times for these two starting voltages on different temperatures. After finding all constant values, each node runs 10 times with random starting voltages and different temperatures. Our testbed runs on the room temperature range 17.5 and 22 °C. The comparison between estimated lifetimes and measured lifetimes ordering from low to high starting voltage is illustrated in Fig. 1. The results show that all estimated lifetimes based on Eq. (1) have increased based on starting voltages, while the real measured lifetimes sometimes vary based on temperatures. The temperature effects are more on maxE2500 batteries. Moreover, theirs estimated values are much different from measured ones for GP2100 and maxE2500. This might be caused by error in estimating full capacity and capacity loss. Furthermore, current consumption may not accurate since the calculation is based on datasheet which is for 3V of V_{dd} and 25 °C. In the other way, our estimated values are close to the measured values. Their accuracy is normally in the range of ± 1-10 minutes (0-1%) for E1300, while it is ± 1- 30 minutes (0-2.5%) for GP2100 and maxE2500. The different range of accuracy might be due to battery aging since an older battery can produce inconsistent power. Moreover, an error on estimation might be caused by number of charge cycles, and the accuracy of battery voltage and temperature measurements.

Table 1: Mapping of nodes, batteries and programmes

Node	Battery(Aging)	Programme
Node1	GP2100(>24 months)	P1(send 50 bytes/3 seconds)
Node2	MaxE2500(12-24 months)	P2(send 100 bytes/6 seconds)
Node3	E1300(6-12 months)	P3(send 50 bytes/6 seconds)

Table 2: Time (millisecond) spent in each state of each programme

	P1	P2	P3
TX	38.75	35.00	19.38
RX	2011.25	2038.13	2011.25
CPU-ACTIVE	1042.50	924.38	950.63
CPU-LOW	57950.00	57926.88	57969.38
SENSING	0.39	0.39	0.39

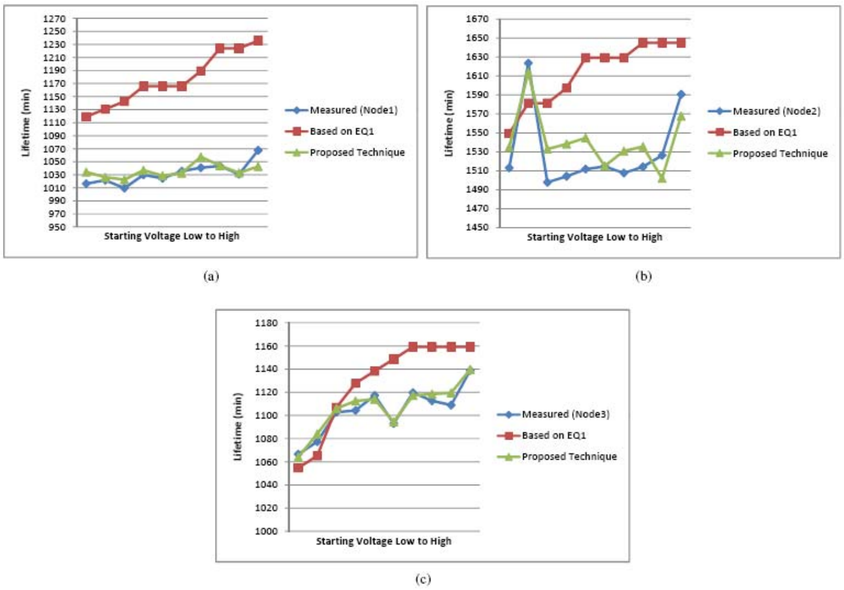

Fig. 1: Comparison between Measured [blue], Calculated Lifetime by Equation (1)[red] and Proposed Equation [green] with Different Starting Voltages and Temperatures of Node1-GP2100 (a), Node2-maxE2500 (b) and Node3-E1300(c)

5. Conclusion and Future Work

Lifetime of node depends on battery capacity and current consumption of node. Temperature is one of key factors affecting the lifetime of sensor node since it increases both battery capacity and current consumption. This paper proposes equations to estimate node lifetime with different starting voltages and temperatures. All constant factors can be obtained by using real experiments. The results show that node lifetime can be predicted for different brands, capacities, ages of NiMH batteries and programmes. However, it does not include other factors which may affect battery capacity, such as charging techniques and number of charge cycles. Finally, this technique is proposed for predicting static load behaviour of one sender node on a single-hop network; therefore, it should be extended for real multi-hop environment with many nodes.

6. References

[1] A True System on Chip solution for 2.4 GHz IEEE 802.15.4 /ZigBee®. *CC2430 Data Sheet (Rev. 2.1)*, May 2007.

[2] J. J. Kopera. Considerations for the Utilization of NiMH Battery Technology in Stationary Applications. *In BATTCON*, Florida, 2005.

[3] H. Bergveld, W. Kruijt, and P. Notten, *Battery Management Systems: Design by Modeling (Philips Research Book Series)*, Springer, 2002.

[4] *Energizer nickel metal hydride (nimh) handbook and application manual* (2010). [Online]. Available: http://data.energizer.com/PDFs/nickelmetalhydride appman.pdf

[5] *Gp nickel metal hydride technical hand book*. [Online]. Available: http://www.gpbatteries.com.hk/html/pdf/NiMH technical.pdf

[6] *Ansmann specifications* (2009). [Online]. Available: http://docseurope.electrocomponents.com/webdocs/0d49/0900766b80d49194.pdf

[7] G. S. Nagarajan and J. V. Zee. Characterization of the performance of commercial NiMH batteries. *Journal of Power Sources*, 1998, 70(2):173 – 180.

[8] W. Guoliang, L. Rengui, Z. Chunbo, and C. Chan. State of charge estimation for NiMH battery based on electromotive force method. *In Vehicle Power and Propulsion Conference* VPPC '08. IEEE, 2008:1 –5.

[9] M. R. Jongerden and B. R. Haverkort. Battery modeling. *In Technical Report TR-CTIT-08-01*, Centre for Telematics and Information Technology University of Twente, 2008.

[10] W. Liao, L. He, and K. M. Lepak. Temperature and supply voltage aware performance and power modeling at micro architecture level. *In IEEE transaction on computer-aided design of integrated circuits and systems,* 2005, 24 (7): 1042–1053.

[11] X. Jiang, P. Dutta, D. Culler, , and I. Stoica. Micro power meter for energy monitoring of wireless sensor networks at scale. *In Proceedings of the 6th international conference on Information processing in sensor networks*, IPSN 07, Massachusetts, USA, 2007:186–195.

[12] A. Dunkels, F. Osterlind, N. Tsiftes, and Z. He. Software-based on-line energy estimation for sensor node. *In Proceedings of the 4th Workshop on Embedded Networked Sensors*, 2007: 28–32.

[13] H. A. Nguyen, A. Forster, D. Puccinelli, and S. Giordano. Sensor node lifetime: An experimental study. *In IEEE International Conference on Pervasive Computing and Communications Workshops*, PERCOM Workshops, 2011:202 – 207.

[14] K. L. C. Park and A. Ranghunathan. Battery Discharge Characteristics of Wireless Sensor Nodes: An Experimental Analysis. *In The 2nd Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON05)*, CA, USA, 2005.

Ms. Wilawan Rukpakavong graduated BSc in Computer Science from Thammasat University in 1990, M.Sc. in Computer Science from Asian Institute of Technology in 1991, and MSc in Computer Network from the University of Derby in 2008. She has served as a Lecturer at Thammasat University, Thailand since 1991. Now she is a PhD student at the Department of Computer Science, Loughborough University. Her research interests include efficient energy and lifetime of wireless sensor networks.

Dr Iain Phillips received BSc and PhD degrees in Computer Science from the University of Manchester, UK. He is currently a Senior Lecturer in the Department of Computer Science at Loughborough University. His current research interests include: algorithm performance at large scales in wireless sensor networks; any aspects of Internet Engineering including performance measurement; hard real-time networking in wired and wireless LANs.

Dr Lin Guan received her BSc from Heilongjiang University, China in 2001 and PhD in Computer Science from University of Bradford, UK in 2005. She is currently a Senior Lecturer in the Department of Computer Science at Loughborough University. Her research interests focus on performance modelling/evaluation of heterogeneous computer networks, QoS analysis and enhancements, congestion control mechanisms, mobile computing and wireless sensor networks.