Packet-based nonlinear battery energy consumption optimizing for WSNs nodes

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Abstract: Battery energy nonlinear consumption is a key issue for wireless sensor networks (WSNs) nodes which operate on nonrenewable batteries. The topic has been widely studied by researchers in current years. However, to the best of our knowledge, there is no literature that provides the exact reason for the energy consumption nonlinear character of a battery, and calculates the exact \(n\)th value of a battery energy under nonlinear consumption condition. In this paper, we develop a realistic battery energy consumption model, combining with transmitting signal energy and circuit power consumption in WSNs. Based on the developed model, we study the battery energy consumption based on packets instead of the pulses under two packet assembly approaches that are length-based and time-based assembly approaches. An extensive simulation is given to validate the proposed model and evaluate the performance of the nonlinear battery energy consumption.

Keywords: battery energy consumption, nonlinear, wireless sensor networks

Classification: Electron devices, circuits, and systems

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci: IEEE Commun. Mag. 40 (2002) 102. DOI:10.1109/MCOM.2002.1024422
[2] R. Hou, Y. Chen and G. Xing: IEICE Electron. Express 10 (2013) 20130689. DOI:10.1587/elex.10.20130689
[3] Q. Tang, L. Yang, G. B. Giannakis and T. Qin: IEEE Trans. Wireless Commun. 6 (2007) 1308. DOI:10.1109/TWC.2007.348327
[4] J. N. Laneman, D. N. C. Tse and G. W. Wornell: IEEE Trans. Inf. Theory 50 (2004) 3062. DOI:10.1109/TIT.2004.838089
[5] J. Proakis: Digital Communications (McGraw-Hill, New York, 2001) 4th ed.
[6] D. Duan, F. Qu, L. Yang, A. Swami and J. C. Principe: IEEE Trans. Commun. 58 (2010) 1907. DOI:10.1109/TCOMM.2010.07.080443
[7] Y. Prakash and S. K. S. Gupta: Proc. Wireless Commun. Netw. Conf, New Orleans, LA (2003) 212. DOI:10.1109/WCNC.2003.1200347
[8] F. Qu, D. Duan, L. Yang and A. Swami: IEEE Trans. Signal Process. 56 (2008) 4486. DOI:10.1109/TSP.2008.924142
[9] T. Venkatesh, A. Jayaraj and C. S. R. Murthy: J. Lightwave Technol. 27 (2009) 5563. DOI:10.1109/JLT.2009.2031824
1 Introduction

Battery energy consumption issue is always a hot and critical research topic for wireless sensor networks (WSNs) that are equipped with nonrenewable batteries sensing nodes [1]. In recent years, as the Green Computing concept penetrates into wireless communication systems, researchers concentrate more on the characters of battery energy consumption for WSNs nodes. However, in order to gain power efficiency in WSNs systems, most previous works in the literature treat battery energy consumption as ideal and linear without considering circuit power consumption and battery nonlinearity [2, 3, 4, 5]. Such treatment is too simple to understand the exact reason of battery energy consumption. Literature [6] considers nonlinearity in battery energy consumption and gives a battery model; however, it only deals with single pulse-based systems thus cannot adapt to packet-based WSNs systems. Therefore, it is significant to deeply study the battery energy nonlinear consumption model to improve the lifetime performance of WSNs [7, 8]. To overcome the limitations mentioned above, in this paper, we examine the exact reason of battery energy consumption nonlinearity and develop an analytical model for computation of battery energy nonlinear consumption. Furthermore, based on the quadratic functions of pulse-based model [6], we develop a packet-based battery energy consumption model. Since the approaches of encapsulating pulses into a packet either based on assemble time or packet length, in our proposed model, we consider two packet assembly approaches which are time-based assembly [9] and length-based assembly [10], and evaluate the battery energy nonlinear consumption performance under the two assembly approaches. The remainder of this paper is organized as follows. In Section 2, we develop a packet-based battery energy nonlinear consumption model under two different packet assembly approaches. An extensive simulation has been carried out to validate the accuracy and evaluate the performance of the proposed model in Section 3. In Section 4, we conclude our work and give some prospects for future research.

2 Battery energy consumption analytical model

We begin by defining the following notations:

1. \( e_p \): the energy of a single transmitting pulse.
2. \( P_{ct}, P_{cr} \): circuit power of the transmitter and the receiver, respectively.
3. \( M_l \): the channel link margin.
4. \( G_1 \): the channel gain factor at \( d = 1 \text{ m} \), which is defined by the antenna gain factor, the carrier frequency, and other parameters.
5. $k$: the path-loss exponent.
6. $\eta$: transfer efficiency of DC/DC converters.
7. $\alpha$: extra power loss factor of a power amplifier (PA).
8. $\varepsilon_t$: the battery energy consumption of sending a single pulse for a node.
9. $\varepsilon_r$: the battery power consumption of receiving a single pulse for a node.
10. $\varepsilon_i$: the total battery energy consumption of transmitting the $i$th pulse, which can be expressed as $\varepsilon_i = \varepsilon_r + \varepsilon_t$.
11. $T_p, T_d$: the duration and the demodulation duration of a pulse, respectively.
12. $V_p$: battery physical volume which we set as 1.5 cm$^3$ in this paper.
13. $U_l$: the original voltage of a battery.

**A. Channel model**

In this paper, we assume that the data transmission channel is a path-loss Rayleigh fading channel with additive white Gaussian noise (AWGN) [6]. The channel gain factor is expressed as [11],

$$G(d) = \frac{\varepsilon_p}{\varepsilon_r} = \frac{P_t}{P_r} = M_1 \cdot G_1 \cdot G_k$$

(1)

**B. Pulse-based battery energy consumption model**

As mentioned in [3], the nonlinear behavior of the battery discharge process consists of transmitting signal energy and circuit power consumption. According to [6], we can get the total battery energy consumption for transmitting one pulse under the base-band binary phase-shift keying (BPSK) condition shown as follows:

$$\varepsilon_1 = \frac{M_1^2 G_1^2 \omega N_0^2}{16U_l \eta T_p (1 - \alpha)^2} \cdot \frac{d_{\text{c}}} {\frac{P_c}{T_c}} + \frac{P_c}{\eta} T_p$$

(2)

where $\omega$ is a positive parameter, $N_0$ is the power spectrum density (PSD) of AWGN, and $P_c$ is the bit error rate (BER) which can be expressed as $\frac{N_0}{\eta}$ [12].

**C. Nonlinearity of battery energy consumption**

The nonlinearity of battery energy consumption has been studied in [6]. However, the authors in [6] consider nonlinearity only through a quadratic function for one single pulse and at one time transmission, and thus lose the generality. In this paper, to examine the nonlinearity character of battery energy consumption, we give the battery energy consumption for $n$ pulses in a WSN node and derive from it an iterative function of battery energy consumption for the $n$th pulse in the node. Here, we introduce two concepts which are battery energy volume (BEV) and battery energy density (BED), and nonlinearity can be evaluated by the analysis of the performance of BEV and BED. BEV can be explained by seeing Fig. 1. In this graph, we define that the original value of BEV $V_0$ is equal to $V_p$ under the condition that there is no energy consumption of the battery. After the battery processes a pulse, we assume the remaining BEV is $V_1$. Thus we can derive the consumption of BEV.
for the pulse is $V_0 - V_1$. The BED denotes the energy per unit BEV, and it is a parameter with fixed value.

Thus, we can give the relationship of $V_0$ and $V_1$ which is shown as follows:

$$V_1 = V_0 - \left( \frac{2\varepsilon_1 t^2 S^2}{\rho} \right)^\frac{1}{2}$$

where $S$ denotes the cross-section area of the battery, and $t$ denotes the total time for processing a pulse which can be expressed as $t = T_p + T_d = 2T_p$ under the BPSK applied condition. Thus, we can rewrite Eq. (3) as follows:

$$V_1 = V_0 - \left( \frac{8\varepsilon_1 S^2 T_p^2}{\rho} \right)^\frac{1}{2}$$

Then, we can derive the iterative function of BEV after the battery process $n$ pulse,

$$V_n = V_{n-1} - \left( \frac{8\varepsilon_{n-1} S^2 T_p^2}{\rho} \right)^\frac{1}{2}$$

We assume the resistance of the battery is unchangeable with the impedance value of $R$, the electric current value of $I$, and the amount of electric charge in a unit volume of $Q$. Thus we can get $\frac{Q_1}{V_1} = \frac{Q}{V}$ and $U_n = \frac{Q}{T} \cdot R$. Finally, we can get,

$$U_n = \frac{U_1}{V_1} \cdot V_n$$

Therefore, $\varepsilon$ can be expressed as,

$$\varepsilon_n = \frac{M_i^2 G_i^2 \omega N_0^2}{16U_n \eta^2 T_p (1 - \alpha)^2} \cdot \frac{d^2}{P_c} + \frac{M_i G_1 N_0}{4\eta(1 - \alpha)} \cdot \frac{d^2}{P_c} + \frac{P_{et} + P_{cr}}{\eta} T_p$$

**D. Packet-based battery energy consumption model**

In a real wireless sensor network, nodes send/receive packets which consist of multiple pulses. The length of a WSNs packet is decided by the number and size of pulses it encapsulates. Two packet assembly approaches have been widely accepted and analyzed, which are time-based assembly and length-based assembly, respectively. In this section, we will give the battery energy consumption model for data packets considering the two assembly ap-
proaches. The result has more practical significance than that of pulse-based analysis.

Case 1: Time-based assembly approach. In time-based assembly approach, we assume that the inter-arrival time of packets is fixed at $T$ (the time period used in the assembly) while the packet length relies on the distribution of the number of pulses arriving in $T$ and the size of the pulses. We define a random variable $X$ which indicates the number of pulses that arrive in $T$ and define a parameter $\lambda$ as the expected number of pulses per unit time. We suppose that the probability that $n$ pulses arrive in $T$ can be denoted as $P[X = n]$ which follows the Poisson distribution,

$$P[X = k] = \frac{(\lambda T)^k e^{-\lambda T}}{k!}$$  \hspace{1cm} (8)

Therefore, the battery energy consumption for a packet can be written as

$$\varepsilon_{\text{packet}} = \sum_{i=1}^{k} P[X = i] \sum_{j=1}^{k} \varepsilon_j$$  \hspace{1cm} (9)

Case 2: Length-based assembly approach. In length-based assembly approach, we assume the packet length is a fixed value $B$. The packet inter-arrival time $T$ is the sum of the inter-arrival times of the pulses in the packet. We also assume the number of pulses in a packet $m$ as an exponentially distributed random variable. Hence,

$$f(m) = (\lambda T) e^{-(\lambda T) m}$$  \hspace{1cm} (10)

Therefore, the battery energy consumption for a packet in the length-based assembly approach is:

$$\varepsilon_{\text{packet}} = \int_{0}^{m} f(m) \left( \sum_{i=1}^{m} \varepsilon_i \right) dm$$  \hspace{1cm} (11)

3 Performance evaluation

In this section, we evaluate the performance of pulse-related battery energy consumption, and packet-related battery energy consumption with two packet assembly approaches. We also analyze the nonlinearity of battery energy consumption in the above cases. The analytical tool that we use is Matlab Simulator, and the parameters used in our analysis are the same as that used in [6] as shown in Table I. We assume the battery used in a WSNs node is a standard No..7 non-rechargeable battery whose bottom diameter is 1 cm.

Fig. 2 gives the relationship between energy consumed times of a battery and the change of battery voltage. We assume each pulse makes the battery consume its energy one time. From this graph we can see that as the energy

| $M_1 = 40$ dB | $G_1 = 27$ dB | $\omega = 0.05$ | $U_1 = 1.5$ v |
|----------------|----------------|---------------|---------------|
| $N_0 = -342$ dBmHz | $\eta = 0.8$ | $T_p = 1.33 \times 10^{-4}$ s | $P_{cr} = 52.5$ mW |
| $\alpha = 0.33$ | $k = 3$ | $P_e = 10^{-4}$ | $P_{ce} = 105.8$ mW |
consumed times increase, the voltage of the battery reduces. Moreover, we can see that the larger the BED, the smaller the decrement rate of voltage of the battery.

Fig. 3 shows the performance of battery energy consumption after dealing with multiple pulses. From this graph we can see that with the number of pulses the node process increases, the decrement of battery energy is faster. It reveals the nonlinearity of battery energy consumption in WSNs nodes. We also observe that the durability of a battery depends on its BED. This graph shows that the larger the BED the battery has, the more durable the battery is.

Figs. 4 and 5 represent the battery energy consumption for packets under length-based assembly approach and time-based assembly approach, respectively. From the two graphs we can see that nonlinearities of battery energy consumption are obvious under both packet-based conditions with different packet assembly approaches. With the increase of packet arrival rate or packet assembly time, the battery energy consumption increases for the same packet which encapsulates the same number of pulses.
Conclusion

A realistic battery energy consumption model combining with transmitting signal energy and circuit power consumption is proposed in this paper. Through this model, we not only analyse the nonlinearity of battery energy consumption, but also calculate the battery energy consumption for the $n$th pulse, and evaluate packet-based battery energy consumption with two packet assembly approaches. Several analytical results can help to design and analysis WSNs for energy efficiency. Further work can focus on multi-path network scenario considered battery energy consumption in WSNs.

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