Analysis of battery energy consumption in relay wireless sensor networks

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Abstract: In this study, the authors develop a realistic packet-based battery energy consumption model that combines the transmitting signal and circuit power consumption in relay wireless sensor networks (WSNs). In their model, two types of packet assembly approaches have been considered: namely, the time-based and length-based packet assembly approaches. A performance analysis is used to determine whether relay transmission is preferable to direct transmission. The results show that the path selection and the amount of battery energy consumption in a relay WSNs depend on the location of the relay node, the number of pulses, and the distance between the source node and the destination node.

1 Introduction

It is very important to research battery energy consumption for wireless sensor networks (WSNs) nodes because they are equipped with non-rechargeable batteries [1]. In recent years, several researchers have studied battery energy consumption of WSNs nodes to improve battery energy efficiency. However, most research works only consider direct data path of transmission while ignoring the relay path [2, 3]. In relay WSNs, the total battery energy consumption can be reduced because the length of each divided relay path is shorter than that of the direct path and the path loss is significantly reduced [2, 4, 5]. On the other hand, the analyses in [6] show that the battery energy consumption is not always perceivable from the relay nodes. The authors put forward a realistic battery model to optimise the energy consumption in relay WSNs in [2, 5, 7]; however, they consider only single pulse-based systems rather than packet-based WSNs systems. Packet-based non-linear battery energy consumption has been studied in [8, 9]; however, they are not used in relay WSNs. Therefore, research on the packet-based battery energy consumption in relay WSNs is significant. In this paper, in order to overcome the limitations mentioned above, we calculate the battery energy consumption based on packets in relay WSNs considering two types of packet assembly approaches, i.e. time-based and length-based approaches. Then, we evaluate the performance of the energy difference between the direct and relay links to determine whether relay transmission is preferable to direct transmission.

2 Battery energy consumption model

We define the following parameters:

(i) ε_p: transmitting pulse energy.
(ii) ε_r: pulse energy at the receiver for a node.
(iii) P_{ct}, P_{cr}: powers of the signal at the transmitter and receiver, respectively.
(iv) M_l: channel link margin.
(v) d: distance between the source–destination node pairs.
(vi) k: path-loss exponent.
(vii) G_1: channel gain factor at $d = 1$ m, which is defined by the antenna gain factor, the carrier frequency, and other parameters.
(viii) ε_n: battery energy consumption for the nth pulse.
(ix) η: transfer efficiency of DC/DC converters.
(x) α: extra power loss factor of a power amplifier.
(xi) T_p: duration of a pulse.
(xii) u_n: voltage for the nth pulse.

2.1 Channel model

Here, we assume that the data transmission channel in the WSN is a path-loss Rayleigh fading channel with additive white Gaussian noise (AWGN). The channel gain factor is expressed as [10]

$$G(d) = \varepsilon_p/\varepsilon_r = P_t/P_r = M_l G_1 d^k. \quad (1)$$

We use bit error rate (BER) as the network performance metric. According to the above-mentioned channel model, the BER is expressed as [11]

$$P_e = \frac{N_0}{4\varepsilon_r}, \quad (2)$$

where N_0 is the power spectrum density of AWGN.

2.2 Two-hop relay path model

For simplicity without loss of generality, a two-hop relay path network topology is considered in this paper, as shown in Fig. 1. The network consists of a source node S_1, destination node S_2, and relay node R, as shown in [5]. In Fig. 1, we can see that the distances $S_1 - S_2$, $S_1 - R$, and $R - S_2$ are d, $d_1 = \theta_1 d$, and $d_2 = \theta_2 d$, respectively, where θ_1 and θ_2 should satisfy $0 < \theta_1 < 1$, $0 < \theta_2 < 1$, and $\theta_1 + \theta_2 \geq 1$, and P_1 and P_2 denote the BER of path $S_1 - R$ and path $R - S_2$, respectively. In addition, the studies of [5] have shown that

$$P_e \simeq P_1 + P_2, \quad (3)$$

and

$$P_1 = \frac{1}{(\theta_1/\theta_2)^{k/2} + 1} P_e. \quad (4)$$

According to Hou and Zheng [8], the energy consumed in dealing with the nth pulse through paths $S_1 - S_2$, $S_1 - R$, and $R - S_2$ can be written as

$$\varepsilon_n = A_n \cdot \frac{d^{2k}}{P_e^2} + B \cdot \frac{d^k}{P_e} + C, \quad (5)$$

$$a_n = A_n \cdot \frac{(\theta_1 d)^{2k}}{P_1^2} + B \cdot \frac{(\theta_1 d)^k}{p_1} + C, \quad (6)$$

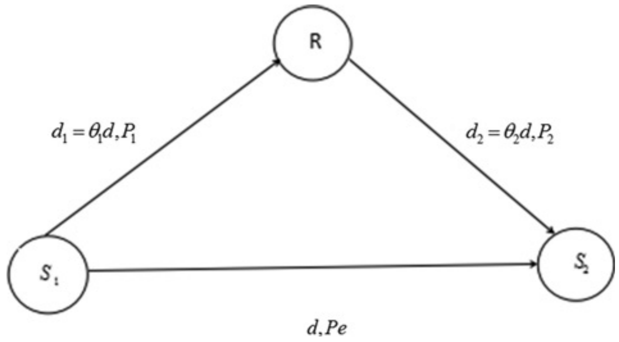

Fig. 1 *Two-hop relay path*

and

$$b_n = A_n \cdot \frac{(\theta_2 d)^{2k}}{P_2^2} + B \cdot \frac{(\theta_2 d)^k}{p_2} + C, \tag{7}$$

where $A_n = M_1 G_1 \omega N_0^2/16u_n\eta^2 T_p(1-\alpha)^2$, $B = M_1 G_1 N_0/4\eta(1-\alpha)$, and $C = ((P_{ct}+P_{cr})/\eta)T_p$.

From (3), (4), (6), and (7), we can obtain

$$a_n + b_n = A_n(\theta_1^{k/2} + \theta_2^{k/2})^2(\theta_1^k + \theta_2^k)\frac{d^{2k}}{P_e^2} + B(\theta_1^{k/2} + \theta_2^{k/2})^2\frac{d^k}{P_e} + 2C. \tag{8}$$

3 Battery energy consumption

In WSNs, there are two types of packet assemblies: time-based and length-based [8, 9]. We denote the battery energy consumption of direct transmission $S_1 - S_2$ and relay transmission $S_1 - R - S_2$ as ε and ε_R, respectively.

3.1 Time-based packet assembly

In the time-based assembly approach, a packet is transmitted in a relay WSN every T time unit. According to Hou and Zheng [8] and Hou *et al.* [9], the battery energy consumption of a packet for the direct transmissions can be written as

$$\varepsilon = \sum_{i=1}^{u}\left[P\{X=i\}\sum_{j=1}^{i}\varepsilon_j\right], \tag{9}$$

where u denotes the number of pulses in a packet and the function of i pulses arriving in T time unit can be written as

$$P[X=i] = \frac{(\lambda T)^i \cdot e^{-\lambda T}}{i!}. \tag{10}$$

Therefore, the battery energy consumption of a packet for the relay transmission path can be expressed as

$$\varepsilon_R = \sum_{i=1}^{u}\left[P\{X=i\}\sum_{j=1}^{i}a_j\right] + \sum_{i=1}^{u}\left[P\{X=i\}\sum_{j=1}^{i}b_j\right]. \tag{11}$$

Table 1 Simulation parameters

$\omega = 0.05$	$M_1 = 40$ dB	$\alpha = 0.33$	$U_1 = 1.5$ V
$k = 3$	$G_1 = 27$ dB	$N_0 = -342$ dBm/Hz	$P_{ct} = 105.8$ mW
$\eta = 0.8$	$T_p = 1.33 \times 10^{-4}$ s	$P_e = 10^{-4}$	$P_{cr} = 52.5$ mW

3.2 Length-based packet assembly

In the length-based assembly approach, we assume that the length of a packet is L unit and the inter-arrival time of a packet is T unit in the relay WSN. The number of pulses in a packet m is an exponentially distributed random variable [11]. Therefore

$$f(m) = (\lambda T)e^{-(\lambda T)\cdot m}. \tag{12}$$

According to [8, 9], we can obtain

$$\varepsilon = \int_0^m f(m)\left(\sum_{i=1}^{m}\varepsilon_i\right)dm, \tag{13}$$

and

$$\varepsilon_R = \int_0^m f(m)\left(\sum_{i=1}^{m}a_i\right)dm + \int_0^m f(m)\left(\sum_{i=1}^{m}b_i\right)dm. \tag{14}$$

In relay WSNs, the battery energy consumption difference between direct transmission and relay transmission can be expressed as

$$\Delta\varepsilon = \varepsilon - \varepsilon_R. \tag{15}$$

4 Performance evaluation

In this section, the battery energy consumption in relay WSNs is analysed, and the difference in energy consumption between direct transmission and relay transmission under both packet assembly approaches are compared. MATLAB is used as the simulation tool and the parameters used are taken from [7], as shown in Table 1. We assume that the battery in our simulation is a standard no. 7 non-rechargeable battery.

Figs. 2 and 3 are the battery energy consumption of packets for the relay transmission under time-based and length-based assembly approaches, respectively. It can be observed from the two graphs that battery energy consumption increases non-linearly with an increase in the number of pulses in a packet, the packets' assembly time, and packet arriving rate.

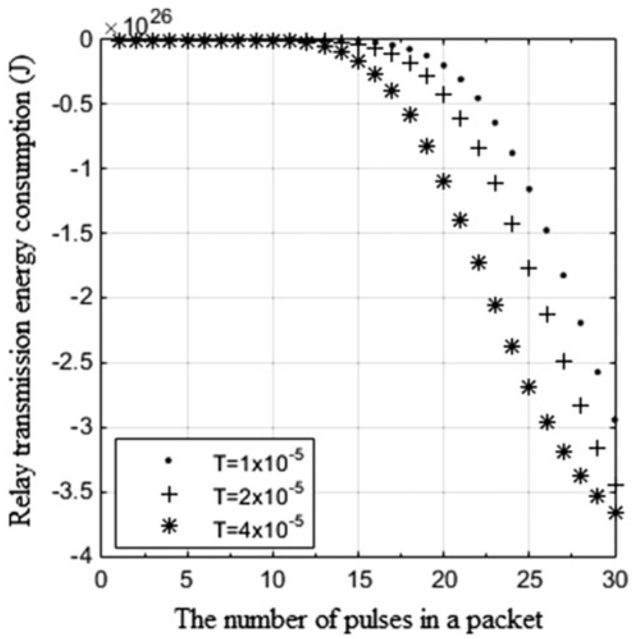

Fig. 2 *Battery energy consumption of the relay transmission for packets under the time-based assembly approach*

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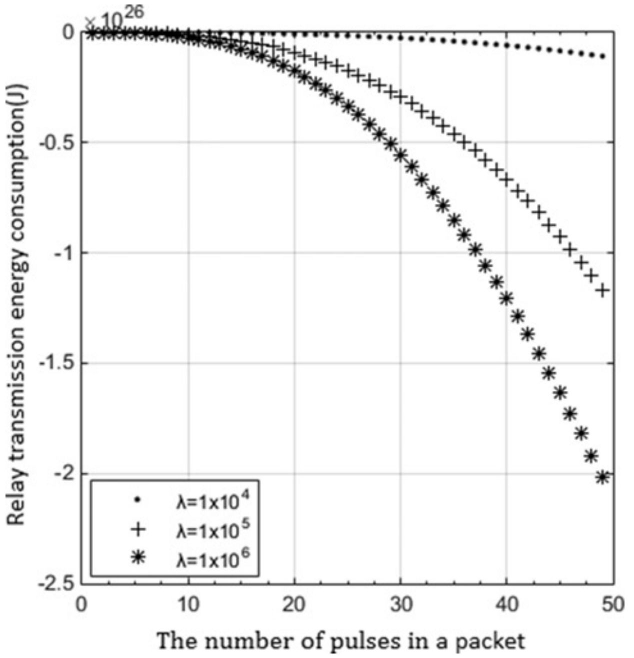

Fig. 3 *Battery energy consumption of the relay transmission for packets under the length-based assembly approach*

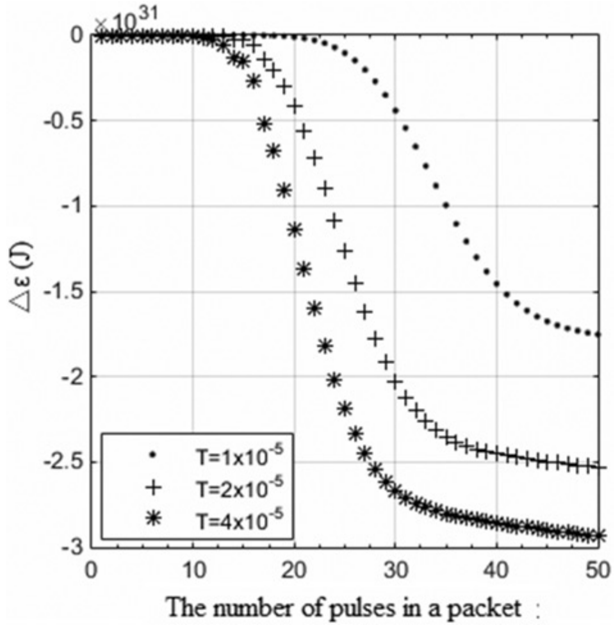

Fig. 5 *Battery energy consumption difference between direct and relay transmissions for packets under the time-based assembly approach*

Figs. 4 and 5 illustrate the difference of battery energy consumption between direct and relay transmissions for packets under the time-based assembly approach. In Fig. 4, θ_1, θ_2 are satisfied with the conditions of $\theta_1 + \theta_2 < 1.4$, and one of them is ≤ 0.8 or $\theta_1 + \theta_2 = 1$; thus $\varepsilon > \varepsilon_R$, which means that relay transmission is preferable to direct transmission. In Fig. 5, θ_1, θ_2 are satisfied with the condition of $\theta_1 + \theta_2 \geq 1.4$, and one of them is >0.8; thus, $\varepsilon < \varepsilon_R$, which means that direct transmission is preferable to relay transmission. The energy saved increases with an increase in the number of pulses in a packet and the assembly time.

Figs. 6 and 7 illustrate the difference in battery energy consumption between the packets under direct and relay transmissions under length-based assembly approach. In Fig. 6, θ_1, θ_2 are satisfied with the conditions of $\theta_1 + \theta_2 < 1.4$, and one of them is <0.8 or $\theta_1 + \theta_2 = 1$; thus $\varepsilon > \varepsilon_R$, which means that relay transmission is preferable to direct transmission. In Fig. 7, θ_1, θ_2 are satisfied with the condition $\theta_1 + \theta_2 \geq 1.4$, and one of them is >0.8; thus $\varepsilon < \varepsilon_R$, which means direct transmission is preferable to relay transmission. From the graphs, it can also be observed that with the increase in the number of pulses in a packet and packet arrival rate, battery energy can be saved significantly.

Figs. 8 and 9 present the battery energy consumption difference between direct and relay links with specific θ_1 and θ_2 values under the time-based and length-based assembly approaches, respectively. The curves with pairs ($\theta_1 = 0.8$ and $\theta_2 = 0.5$, $\theta_1 = 0.3$, and $\theta_2 = 0.7$)

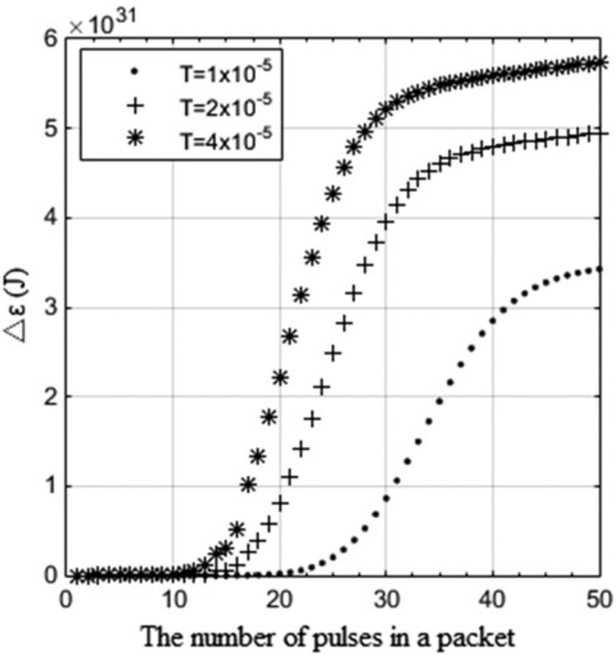

Fig. 4 *Battery energy consumption difference between direct and relay transmissions for packets under the time-based assembly approach*

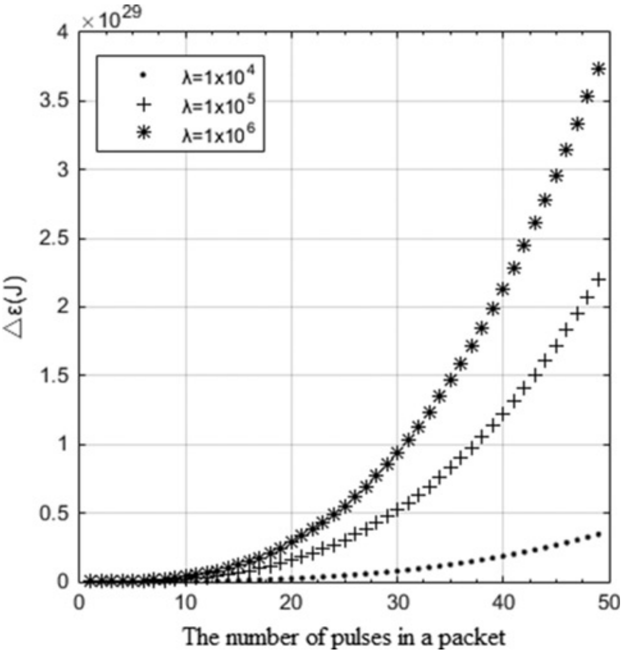

Fig. 6 *Battery energy consumption difference between direct and relay transmissions for packets under the length-based assembly approach*

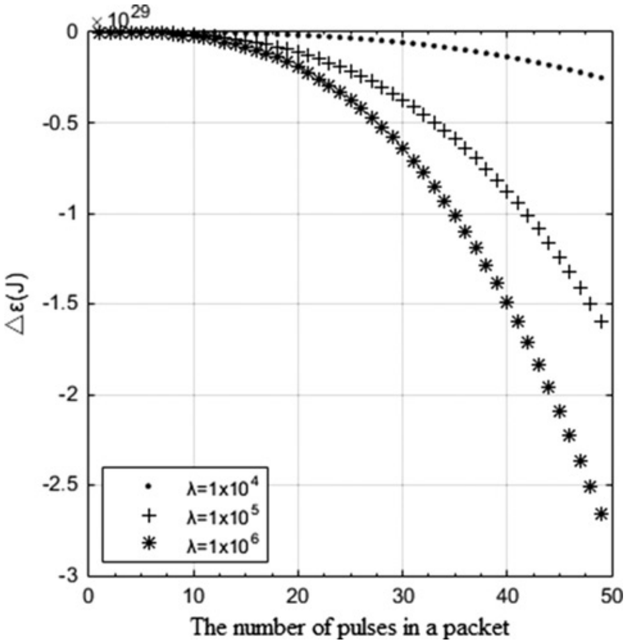

Fig. 7 *Battery energy consumption difference between direct and relay transmissions for packets under the length-based assembly approach*

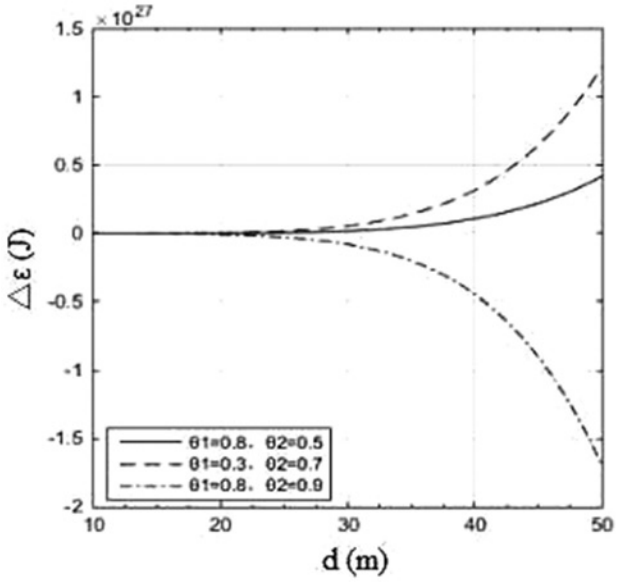

Fig. 9 *Battery energy consumption difference between direct and relay transmissions for packets under the length-based assembly approach for various relay locations*

show relay transmission is preferred; whereas, the curve with the pair ($\theta_1 = 0.8$ and $\theta_2 = 0.9$) shows direct transmission is preferred.

5 Conclusion

We proposed a realistic battery energy consumption model that combines the transmitting signal energy and circuit power consumption. Through this model, we analysed packet-based battery energy consumption of the relay transmission with two types of packet assembly approaches, calculated the energy difference between the direct and relay links, and evaluated the energy saving path. The simulation experiments indicate that the path selection and the amount of energy saved depend on the location of the relay node, the number of pulses in a packet, and the distance between the source node and the destination node. In relay WSNs, further work can focus on multihop path selection considering battery energy consumption.

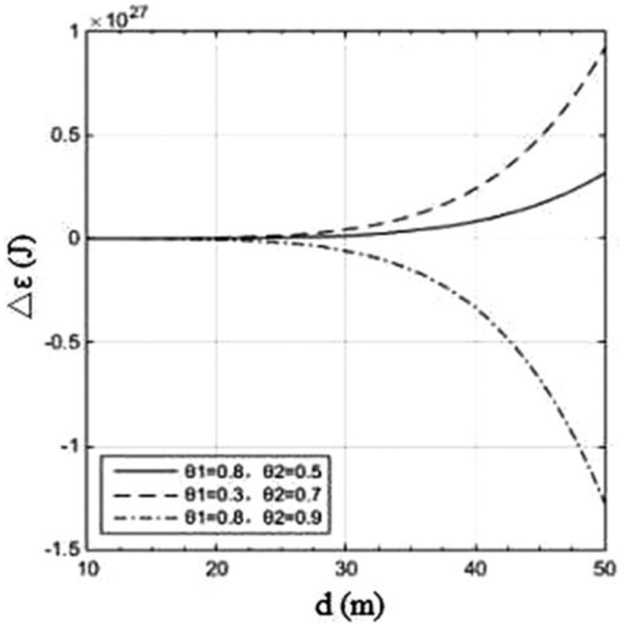

Fig. 8 *Battery energy consumption difference between direct and relay transmissions for packets under the time-based assembly approach for various relay locations*

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