Battery Recovery Based Lifetime Enhancement with Temperature Dependance (BRLE-T) for Wireless Sensor Network

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Abstract –The Sensor nodes are battery-powered which limits their energy capacity due to their inability to be recharged. As a result, the significant bottleneck in designing a protocol is energy consumption. For accuracy of results, the design must balance the life-time of the network and other parameters. Sensor networks should be adaptable and sensitive to the changing environment in which they operate. The influence of temperature on battery recovery is analysed in proposed Battery Recovery based Lifetime Enhancement with Temperature dependence (BRLE-T) algorithm. The BRLE-T algorithm proposed is compared with LEACH-C and SEP-M routing protocols to showcase its performance. The survivability of the nodes is higher for BRLE-T when compared with SEP-M and LEACH-C algorithms. The LEACH-C algorithm survives for about 1450 rounds approximately and SEP-M algorithm survives for around 1500 rounds approximately. The proposed BRLE-T algorithm survives for around 1650 rounds which is 1.1 times higher than compared algorithms. The proposed BRLE-T algorithm provides better energy management in varying temperature environments.

Keywords – Recovery Effect, Energy management, Wireless Sensor Networks.

1 Introduction

The Wireless Sensor Network (WSN) is a collection of sensor nodes deployed in a specific Region of Interest (RoI) for the purpose of observing events. The requirement for remote monitoring and surveillance in remote locations necessitates WSN. A sensor node is composed of sensing, processing, transceiving, and powering units, as well as an optional energy harvesting unit. The architecture of the sensor network is classified as Layered and Clustered based on the necessity and RoI[1]–[3]. The clustered architecture in WSN has the capability to cover wide area and work for longer duration when compared with other architectures of sensor network[4]. The sensor node can function as a Gateway, Full Function Device (FFD) which is a Cluster Head (CH) and Reduced Function Device (RFD) which is a Cluster Member (CM). The FFD is capable of transceiving as well as routing the data from other nodes, whereas the RFD is capable of either receiving or transmitting the data. These nodes are deployed in a remote environment where battery replacement is tedious in some cases. Thus, the node’s lifetime is determined by the capacity of the battery[5].

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The sensor nodes are equipped with the battery that has limited storage capacity. The battery discharges evenly for normal load conditions[6], [7]. In case of uneven load conditions or high discharge current, the voltage from the battery reduces drastically resulting in improper energy utilization from the battery. The energy that is retained in the battery is the less than the difference between energy consumed and actual energy [8]. The battery can deliver complete energy if it is allowed to rest for certain duration. This process is called recovery effect. The battery will be given some idle time between every load. The batteries are sensitive to temperature changes and batteries are good to be stored in cold environment[9]. However the batteries are to be warmed before using it for draining purposes[10]. The effect of temperature in the battery is discussed and efficient algorithm is discussed in this research work.

Internal heat diffuses through the battery components until it reaches the surface. It is generated by changes in electrode entropies caused by electrochemical reactions and resistive Joule heating caused by electronic and ionic charge transport through the electrodes, taps, and electrolyte. The performance of Li-ion batteries at various charge and discharge temperatures, as well as the self-generated temperature, has been studied on new laboratory-made, or commercial Li-ion cells, but very rarely on commercial cells in various states of health (SOH). Li-ion batteries are frequently charged at a specific temperature, and the devices they power are used at different temperatures

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2 Related works

The temperature at which Li-ion batteries are charged and discharged has a significant impact on their electrical performance, lifetime, and even safety was investigated in [11].For low and high state of health (SOH) batteries, the discharge capacity of LiCoO2 (LCO) batteries charged at one temperature and discharged at another in the 0 to 50 °C range was investigated [12]. It was discovered that the discharge capacity is affected by the relative charge-discharge temperatures. The battery surface self-temperature was almost constant with the charging Crates when measured at different charging and discharging currents ranging from 0.2C to 2C. However, upon battery SOH dependence, a significant surface temperature rise was obtained in the battery discharges, commensurate to the C rates. The ambient heat where the battery is running, as well as the heat generated internally by the battery's electrochemical reactions, contributes to battery temperature. Internal heat diffuses through the battery components until it reaches the surface, where it is generated by changes in electrode entropies caused by electrochemical reactions and resistive Joule heating caused by electronic and ionic charge transport through the electrodes, taps, and electrolyte. Both heat sources have an impact on battery performance, such as charge capacity, power, Operating Voltage, Current and ageing[12]. The performance of Li-ion batteries at various charge and discharge temperatures, as well as the self-generated temperature, has been studied on new laboratory-made, or commercial Li-ion cells, but very rarely on commercial cells in various states of health (SOH). Li-ion batteries are frequently charged at a specific temperature, and the devices they power are used at different temperatures. However, it is uncommon to find studies in which the battery performance is analyzed when charged at one temperature and discharged at another. It appears reasonable to anticipate that battery performance will be influenced by a synergistic effect of the battery SOH, charge and discharge temperatures, C rate, and battery self-temperature. The temperature profile of the battery surface was measured under various charge and discharge Crates. The relationships between the thermal and electrochemical behaviors of commercial Li-ion batteries of various SOHs were investigated in detail. Storage results in two types of losses: self-discharge, which can be recovered prior to use, and irreversible losses, which permanently reduce capacity. When fully charged, the Li-ion suffers greater losses than when charged to 40% SoC.

The operating temperature has a major influence in the battery available charge[6]. The increase in temperature increases the self-discharge of the battery and reduces the available charge. It is highly advisable to utilize the energy of the battery operating in higher temperatures.

3 Battery recovery based Lifetime enhancement algorithm with temperature dependence (BRLE-T)

The batteries operating under room temperature conditions will have better performance when compared to outdoor environments. When the battery is exposed to higher temperatures, the internal resistance of the battery is reduced. The mobility of the electrolyte materials are increased, thereby increasing the capacity of the battery. However, continuous exposure to higher temperature may reduce the number of charge cycles of the battery. The influence of temperature on the recovery effect of the battery is analyzed for different temperature values 25 deg Celcius, 32 deg Celcius, 37 deg Celcius and 42 deg Celcius. The figure 1 represents the battery recovery process with influence of temperature. The node with higher temperature shows faster recovery than the nodes with lower temperature.

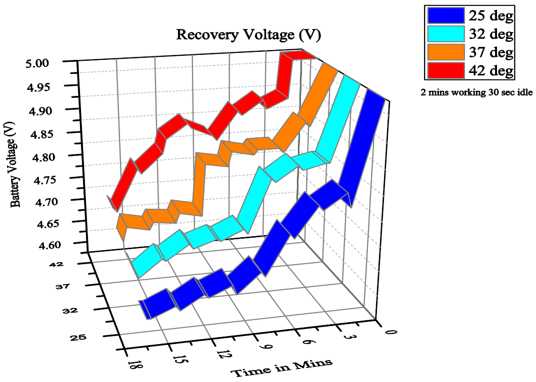

Figure1 Effect of Temperature on battery recovery

In different temperatures, the battery has varied characteristics. The battery's recovery effect and discharge nature are highly influenced by the effect of temperature. A piecewise linear equation is used to model the battery status. The voltage limits V_1 and V_2 are set based on the battery voltage curve in equation 1, where V_1 refers to the high voltage set limit and V_2 refers to the low voltage set limit of the battery. The normal voltage curve is depicted in figure 2, which includes the battery's recovery process. The time taken by the battery to regain the charge it loses during heavy discharge or constant discharge currents is represented by the difference between t_2 and t_1.

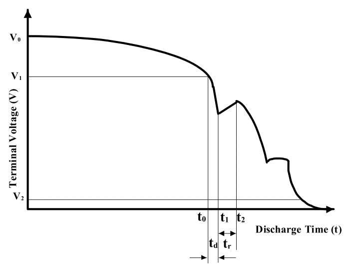

Figure 2Sensor node battery voltage curve

The usual voltage equation of the battery during discharge and recovery is shown in equation 1. After each recovery phase, the battery's voltage is increased, allowing charges in the battery's centre to move to the battery's terminal ends.

$$F(V) = \begin{cases} mt & for \quad t < t_1 \\ \frac{e^{-\beta^2(t_k - t_f)} - e^{-\beta^2(t_k - t_i)}}{\beta^2} & for \quad t_1 < t < t_2 \\ 0 & otherwise \end{cases} \quad (1)$$

where F (V) is the Battery's voltage function, m indicates the slope of the curve; t is Time of discharge; V indicates the Voltage value, β is the Battery's diffusion parameter, t_k is the time for task k; t_i is the time when the load is switched on; t_f indicates the time when the load is turned off; t_1 is the Voltage of the battery when recovery starts; $t_2$is the Voltage of the battery when recovery completes

When the voltage falls below a threshold value of 3.2 V, the current pulled from the battery increases to compensate for the node's energy demand. This process lowers the voltage level even further, causing the node to run out of energy quickly.

The energy dissipation (E) is represented in terms of current and voltage in equation 2.

$$E = V \times I_b \times t_d \qquad (2)$$

Where V is the Battery end Voltage, I_b is the Current drawn from battery and t_d is time required to transmit N_{frames}.

The voltage curve is used to calculate the drop in voltage as a function of residual energy. The radio energy model is used to calculate the total number of frames that can be delivered.

4 Recovery Effect Modeling Of the Battery

The charge that is discharged during the n^th slot is given in equation 3

$$F(T, n\delta, (n+1)\delta, \beta) = \delta + \frac{\pi^2}{3\beta^2}\left[e^{-\beta^2(T-(n+1)\delta)} - e^{-\beta^2(T-n\delta)}\right] \qquad (3)$$

where

$(n\delta, (n+1)\delta)$is the energy dissipated at n^th time slot, $\delta$is the readily available energy for consumption,

$\frac{\pi^2}{3\beta^2}\left[e^{-\beta^2(T-(n+1)\delta)} - e^{-\beta^2(T-n\delta)}\right]$ indicates the Recoverable energy and $\beta$is the battery diffusion rate

Here, $\beta = \frac{2\pi\sqrt{D}}{W}$ the diffusion rate which depends upon the distance between the electrode and width of the battery

D is the Distance between the electrodes, W is the Width of the battery and T indicates Task deadline

Substituting battery diffusion constant in equation 3 the charge discharged at n^th time slot is obtained in equation 4.

$$F(T, n\delta, (n+1)\delta, \beta) = \delta + \frac{W^2}{12D}\left[e^{-\left[\frac{4\pi^2 D}{W^2}\right](T-(n+1)\delta)} - e^{-\left[\frac{4\pi^2 D}{W^2}\right](T-n\delta)}\right] \qquad (4)$$

The battery recovery charge with respect to discharge rate, distance between electrodes, width and depth of discharge is given in equation 5. The available energy δ at K^th slot is given by δ_K.

$$\delta_K = V \times I_b * \frac{W^2}{12D}\left[e^{-\frac{4\pi^2 DK\delta}{W^2}} - e^{-\frac{4\pi^2 D(K+1)\delta}{W^2}}\right] \qquad (5)$$

From equation 5 the approximate recovery time t_r at n^th time slot for total battery capacity (C) is given in equation 6.

$$t_r = \frac{W^2}{4\pi^2 D\delta} \log \frac{I_b W^2 (1 - e^{-\frac{4\pi^2 D\delta}{W^2}})}{12DC} \qquad (6)$$

The algorithm is designed considering the recovery time given in the equation 6 and with the temperature parameter.

5 Radio Energy Modeling

The radio model is used to simulate the nodes' energy dissipation. Equation 7 and 8 calculates the energy expended by the sensor node when transmitting and receiving a bit of data, E_{tx} and E_{rx} respectively.

$$E_{tx}(k, d) = E_{elec}k + E_{fs}kd^2; \quad d<d_0$$
$$= E_{elec}k + E_{mp}kd^4; \quad d>d_0 \qquad (7)$$
$$E_{rx}(k) = E_{elec}k \qquad (8)$$

where

k is the Number of bits, d is the Distance in meters,

E_{elec} is Energy dissipated per bit to run the transmitter or the receiver circuit
E_{fs} is the Energy dissipated on free space model (pJ/bit/m^2) and E_{mp} is the Energy dissipated on multipath model (pJ/bit/m^2).

The voltage decay with respect to data transmission is derived from equation 7, equation 8 on equating with equation 1 and equation 2. During the recovery phase, the node is set to idle. This helps the battery to recover for a time t_r. Following the recovery duration, the nodes are eligible to vote in the CH election.

When a node is designated as a CH, equation 9 reflects the total amount of frames transferred to the sink before exceeding the limit. The N_{frame} is the time required for the battery to reach the voltage limit V_1. When the battery's voltage limit falls below the voltage limit V_1, the N_{frame} is calculated for the discharge time t_d.

$$t_d = N_{frames} * \text{Number of bits in a packet} * 1/f \quad (9)$$

f : Frequency of the node normally 868, 968 or 2.4 Ghz

The nodes with the shortest intra cluster distance and those closest to the sink can send the most frames. Because the energy dissipation of the battery is mostly determined by the distance of data transmission, this method reduces the battery's energy dissipation. By selecting CH based on this strategy, the network's throughput and lifetime is increased.

A Battery Recovery based Lifetime Enhancement with Temperature dependence (BRLE-T) algorithm is proposed by considering the influene of temperature in the network. In this algorithm, the node with higher temperature is given a higher chance of being a Cluster Head as the reovery rate will be faster for high temperature nodes. Meanwhile, the nodes with lower temperature will have sufficient time for better recovery. The proposed BRLE-T algorithm described in algorithm1.

Algorithm 1: Battery Recovery based Lifetime Enhancement with Temperature Dependence (BRLE-T)

Step 1 Check if Voltage of CH V_{CH} is less than the threshold voltage (V_t) resign from the CH and move to recovery

Step 2 Calculate the Voltage level V_i greater than voltage limit V_1 and maximum temperature other than the previous CH

Step 3 Check if the voltage level V_i is greater than Voltage limit and the with maximum temperature.

Step 4 Calculate total number of frames (N_{frames}) sent to the destination

Step 5 Select the eligible candidate (N_m) for Cluster Head from all the participants

Step 6 Sleep when voltage is less than V_2, Repeat Step 1

6 Results and discussion

The BRLE-T protocol is also simulated with the parameters as discussed in table 1.

Table 1 Simulation preliminaries

Parameters	Values
Network size	100×100 m^2
Number of nodes	100
Base station Location	(50,125)
E_{elec}	50nJ/bit
E_{fs}	10pJ/bit-m^2
Initial Energy	2J
Probability of becoming a CH	0.1
Data size	2000 bytes
Header size	50 bytes

The BRLE-T algorithm is compared with LEACH-C and SEP-M routing protocols to showcase its performance. .The figure 3 shows that the survivability of the nodes is higher for BRLE-T when compared with SEP-M and LEACH-C algorithms. The LEACH-C algorithm survives for about 1450 rounds approximately and SEP-M algorithm survives for around 1500 rounds approximately. The proposed BRLE-T algorithm survives for around 1650 rounds which are approximately 1.1 times higher than LEACH-C
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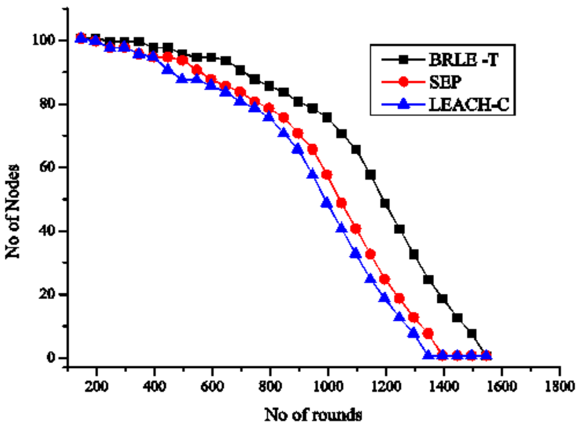

Figure 3 Lifetime comparison of LEACH-C, SEP-M and BRLE-T

The figure 4 shows the analysis of network throughput with LEACH-C, SEP-M and BRLE-T algorithms. The LEACH-C algorithm is capable of transmitting 3000 packets and SEP-M algorithm is capable of transmitting 3250 packets approximately. The proposed BRLE-T algorithm shows better network throughput by transmitting 3650 packets which is approximately 1.12 times higher than the compared algorithms.

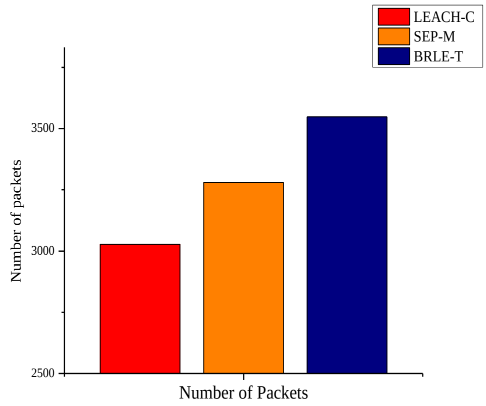

Figure 4 Total numbers of packets sent to sink on LEACH-C, SEP-M and BRLE-T protocol

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The figure 5 represents the stability of the network by analysing the round at which the first node becomes dead and the half of the network loses its energy. The first nodes dies after 335 rounds and 370 rounds approximately for LEACH-C and SEP-M algorithm respectively whereas for BRLE-T algorithm the first node loses its energy after 410 rounds approximately. When the half life of the network is considered, the LEACH-C and SEP-M algorithm loses its energy after 830 and 960 rounds approximately whereas for BRLE-T loses half of its network approximately after 1210 rounds which is 1.26 times better when compared with existing algorithms.

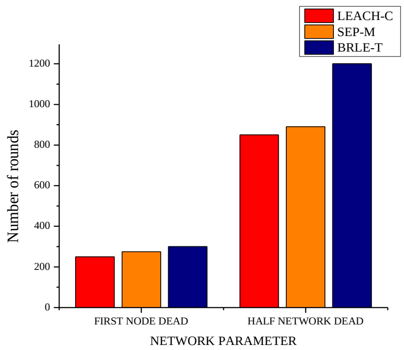

Figure 5 Half Network Dead (HND) and First Node Dead (FND) status of the LEACH, SEP-M and BRLE-T protocols

The figure 6 (a) shows the random distribution of temperature in a network. The figure 6(b) represents network throughput for corresponding temperature in the network.

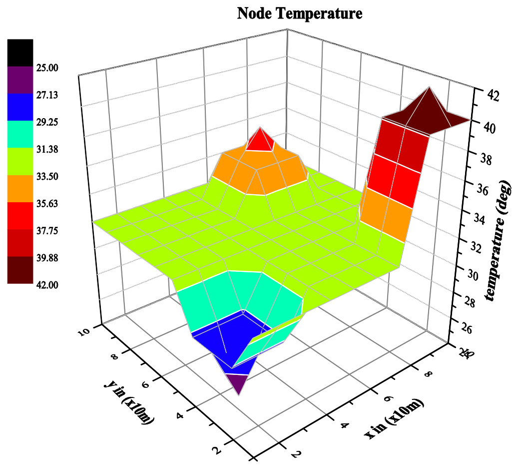

Figure 6 (a) Network temperature status

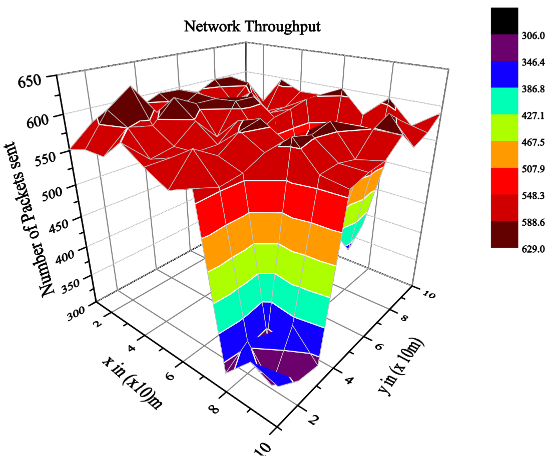

Figure 6(b) Network throughput status of the proposed protocol BRLE-T

It can be observed from figure 6 (b) that there are deficient holes in low temperature zones. The throughput of the network is higher in areas where the temperature is high. The nodes with high temperature show better performance when compared with nodes with low temperature.

Conclusion

The BRLE-T algorithm proposed is compared with LEACH-C and SEP-M routing protocols to showcase its performance. The survivability of the nodes is higher for BRLE-T when compared with SEP-M and LEACH-C algorithms. The LEACH-C algorithm survives for about 1450 rounds approximately and SEP-M algorithm survives for around 1500 rounds approximately. The proposed BRLE-T algorithm survives for around 1650 rounds which is approximately 1.1 times higher than compared algorithms. The LEACH-C algorithm is capable of transmitting 3000 packets and SEP-M algorithm is capable of transmitting 3250 packets approximately. The proposed BRLE-T algorithm shows better network throughput by transmitting3650 packets which is approximately 1.12 times higher than the compared algorithms. The first nodes dies after 335 rounds and 370 rounds approximately for LEACH-C and SEP-M algorithm respectively whereas for BRLE-T algorithm the first node loses its energy after 410 rounds approximately. When the half life of the network is considered, the LEACH-C and SEP-M algorithm loses its energy after 830 and 960 rounds approximately whereas for BRLE-T loses half of its network approximately after 1210 rounds which is 1.26 times better when compared with existing algorithms.

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