Residual Battery Energy Models in WSN: A Survey

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Abstract: *The sensor Nodes in a Wireless Sensor Networks (WSN) possess limited energy resources due to a fixed battery life that is usually non chargeable. This aspect of sensor nodes necessitates the development of an approach which models the residual battery life in a sensor node battery. A number of residual battery models are studied in this survey. These battery models focus to conserve the energy or capacity of the sensor batteries thus maximizing the network lifetime. The battery modeling may be linear or non- linear. The various battery models are then summarized and compared with the help of a table depicting their advantages and disadvantages.*

I. Introduction:

Wireless Sensor Networks (WSN) is a promising branch of mobile ad-hoc networks having numerous real time applications. Having said that a number of challenges are faced in implementing the WSN effectively. The WSN are highly resource constraint and work independently in a real time environment. The battery powered sensor nodes are deployed in a given area on interest and have to re-deployed once their inbuilt power source gets diminished. The redeployment of sensor nodes in not an easy process and if the sensor nodes keep getting discharged then it becomes quite infeasible to replace them. Therefore the WSN must be highly energy efficient and this is the most important issue in WSN.A host of energy efficient protocols have been discussed in [1] such as zigbee, wireless HART, ISO 100.11a, 6loWPAN, IEEE 802.15.6, RPL,MQTT etc. All these protocols employ certain energy efficient mechanisms like radio power control data cutback, sleep /wake up schemes, energy efficient routing and battery charging.

Different applications are shown to adopt different methods of energy efficiency. For example the main energy sources harvesting in healthcare application are body motion and body heat of the subject whereas in industrial applications mechanical vibrations and acoustic noise contribute to the energy harvesting. Further it is vital to have an energy efficient routing protocol for routing data in WSN. This is necessary because a lot of energy is consumed during the data flow in the network. So a number of energy efficient routing protocols are discussed in [2] which are categorized into four main schemes namely Network Structure, Communication Model, Topology Based and Reliable Routing. The routing protocols belonging to the first category can be further named as flat or hierarchical, belonging to the second category can be divided into Query-based or Coherent and non-coherent based or Negotiation-based, and the third class can be divided as Location-based or Mobile Agent-based. The routing protocols belonging to the fourth category can be further classified as QoS-based or Multipath based. While flat routing protocols are ideal for small networks, the hierarchical routing protocols are best suited for large networks due to their more scalability and formation of cluster heads. In Query-based routing protocols, the end nodes send a query for data and the node having this data sends this data back to the end nodes. Query-based routing is utilized in networks with active network topologies such as WSNs.

An attribute of route-query protocols is the ability to handle multiple route replies. In non-coherent data processing based routing, the sensor nodes process the actual data locally and then send to the other nodes for further processing. Alternatively, the location based protocols may be helpful for high dynamic networks as they do not require a state in routers nor in packet header and does not cause flood in the search. In order to calculate the distance among nodes, they use location information thus minimizing the energy consumption and lengthen the lifetime of the network. Hence the selection of a suitable routing protocol is quite essential and leads to the energy conservation within the network ensuring greater lifetimes for a network. An energy efficient adaptive scheme for transmission (EAST) is presented in [3] which uses an open loop feedback process for temperature conscious link quality estimation and compensation and simultaneously closed loop feedback process divides the whole network into three regions on the basis of RSSI (Received Signal Strength Indicator) and designated power level to every node in order to minimize control packet overhead. The restriction on transmitter power loss and current number of nodes in every region helps in adjusting the transmit power level in accordance with the link quality changes due to temperature variations.

Again considering energy as the paramount aspect of WSN, Hierarchical Energy Efficient Clustering Algorithm (HEEC) has been introduced in [4]. This protocol minimizes the load on each sensor node by evenly distributing it between the different nodes in a given network. Also after the formation of node clusters a cluster head (CH) is chosen to coordinate the cluster and for inter cluster communication. This cluster head is re-elected for the sake of saving the energy and preventing a single CH from being getting depleted in terms of energy. So, overall the HEEC protocol maintains a healthy network lifetime by efficiently balancing the energy load across the network. Various energy efficient target tracking schemes are reviewed in [5]. Apart from this it is shown that power conservation in WSN target tracking systems can be achieved in 2 ways i.e. sensing related and communication related methods which are related to each other by a prediction algorithm. By self-organizing the WSN in clusters, and selecting for activation the most suitable nodes that handle the tracking task, the tracking algorithm can reduce the power consumption at the communication and the sensing layers. Thereby, network parameters (sampling rate, wakeup period, cluster size, etc.) are tailored to the dynamics of the target (position, velocity, direction, etc.). Reliable delivery of data is of extreme importance in WSN but at the same time reliable data delivery has to be energy efficient with sensor nodes having adjustable transmission power and duty cycling. Hence the trouble of minimizing the total transmission power for reliable data distribution is discussed in [6] for duty-cycled WSN. This problem is solved by designing efficient estimation algorithms with certain performance boundaries.

To aid the algorithm design, the new concept of Time-Reliability-Power (TRP) space for designing data distribution algorithms in WSNs is presented. This approach takes into account different aspects including duty cycling, wireless broadcast advantage, defective links, and power adjustability, and provides assured bounds for energy-efficient reliable data dissemination in data centric WSNs. A two way Multiple-Input Multiple-Output (MIMO) scheme for wireless sensor networks is presented in [7] which aims to present an optimal number of sensor nodes to be deployed to minimize the energy requirements and maximize the energy efficiency. It is shown that the number of energy efficient sensor nodes increases linearly with the number of sinks. Further in cooperative WSN, the energy utilization per bit is minimized by calculating number of cooperative nodes and the optimal BER (bit error rate) [8]. Firstly an energy model of a single hop WSN is established which is later extended to multi hop WSN. Then after analyzing the energy cost of different nodes like the cluster head , cooperative nodes or simply basic nodes, the network lifetime is prolonged by adjusting the transmit BER. Also it is shown that cooperative node communication is more suitable for tough environments. A data collection protocol named EDAL (Energy efficient Delay aware Lifetime balancing data collection) is presented in [9]. Further in order to reduce the computational overhead of the protocol, a centralized heuristic is proposed and a distributed heuristic is proposed for the protocol to attain large scale scalability. EDAL is also combined with compressive sensing, a novel method that ensures substantial reduction in total traffic cost. This protocol is inspired by the recent techniques developed for open vehicle routing problems with time deadlines (OVRP-TD) in operational research. This protocol achieves the goal of generating the routes that connect all source nodes with minimal total path cost. The lifetime of the deployed sensor network is also balanced by assigning weights to links based on the remaining power level of individual nodes.

Time synchronization and coordination between wireless sensor nodes is very important in WSN. While maintaining these 2 parameters, the energy efficiency of the network is often compromised. Hence a Recursive Time Synchronization Protocol (RTSP) is introduced in [10] that accurately synchronize all nodes in the network to a universal clock using multi-hop architecture and at the same time conserving the energy. A superior performance is achieved due to the MAC-layer time-stamping which is based on the Start of Frame Delimiter byte, occasional broadcasts by a reference node elected dynamically, compensation of the transmit delay and adjustment of the timestamps at each hop, estimation of the relative offset using least square linear regression on two data points, adaptive re-synchronization interval, aggregation of the synchronization requests, and energy awareness. RSTP gives an average accuracy of 0.23 μs per hop in a large multi-hop clustered network using seven-times lesser energy than that of the best known alternative protocol in the long run. Nodes with enhanced computational power and lifetime called representatives [11] can be employed to maximize network lifetime of WSN under specified QoS. An adaptive clustering scheme is presented where neighboring nodes form coalitions in order to increase energy conservation at the cost of convenient data-accuracy cutback. The spatial correlation of the sensed phenomenon measurements is exploited to devise a cooperative scheme that reduces drastically the number of node transmissions.

II. Comparison of various battery models

After discussing the various energy efficient schemes for WSN, it is quite clear that energy conservation is the prime aspect for WSN. The sensor node battery is the main source of energy for all the functions performed by the sensor. Hence an efficient battery model has to be in place for increasing the network lifetime. Various residual battery models are suggested by researchers which will be discussed in detail. Voltage and residual energy relations in an alkaline battery through the measurements on TelosB sensor have been studied in [12] and an integrated scheme has been suggested for estimating remaining energy. The given scheme utilizes the temperature and load information along with voltage. This scheme presents a better estimation of residual energy from battery voltage than a linear model. The scheme is actually an integration of offline and online information about the load (mA) and temperature (^{O}C) of a node. Hence the estimate of residual battery from voltage and current consumption only does not give accurate results as the battery residual energy also depends upon temperature and load [13]. Hence an efficient residual energy estimation scheme is proposed which not only considers the voltage but also the load and temperature characteristics of the battery.

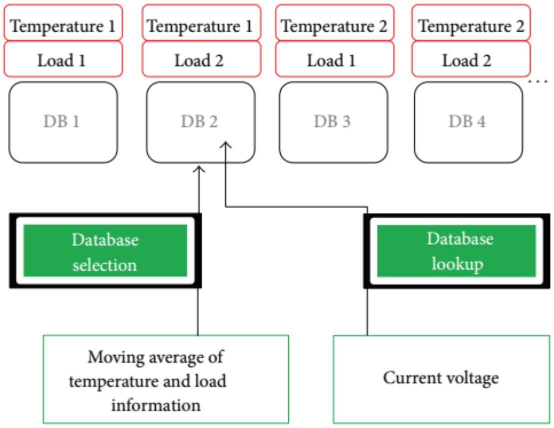

Fig1. The residual battery energy estimation scheme [13]

Fig1. summarizes the estimation scheme discussed earlier. This scheme embeds a database into a sensor system to estimate the residual battery energy that changes according to the voltage, temperature and load. When residual-energy information is needed, a sensor system senses the voltage information and calculates the moving averages of load and temperature and then performs a lookup to find the residual energy with the voltage value in the corresponding DB (database).

A better model is developed in [14] which is able to work with 5 different routing protocols i.e. bellman ford, RIP, DSR, AODV and DYMO. The energy consumption of the proposed battery model with above mentioned different routing protocols was found out and compared with the energy consumption of these protocols when employed with other battery models. Apart from energy consumption, a significant improvement was observed for other QoS parameters like average jitter, packet delivery, throughput and end to end delay. It is also concluded that DYMO protocol comes out to be the most energy efficient.

Similarly a scheduling algorithm called the energy balance algorithm is presented in [15] to make a decision as to which batteries have to be operational based on residual energy. Based on this scheduling algorithm, an energy consumption model of a node based on zigbee protocol is given in which various parameters such as working current, voltage, time duration of data sending and receiving are used to establish energy consumption of a node.

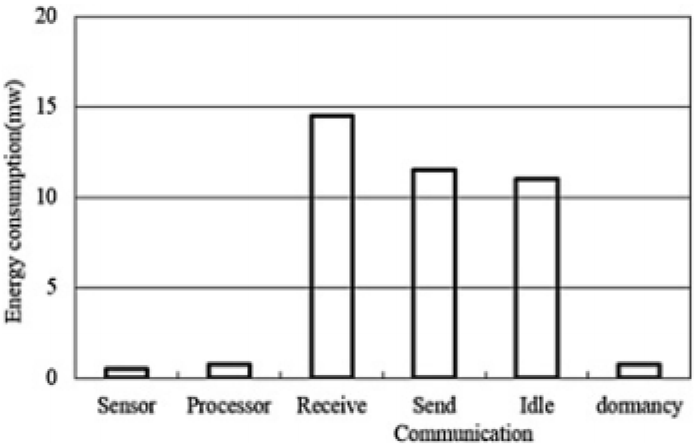

Figure 2: Energy consumption of each unit in a node [15]

This algorithm works in real-time, considers the healing energy of the battery and calculates the energy consumption of the network. This energy consumption battery model is termed as KiBam (Kinetic Battery Model).

A theoretical model based on simple finite automata is presented in [16] which is then used for simulation and generation of ML-MAC (multilayer media access control) protocol.

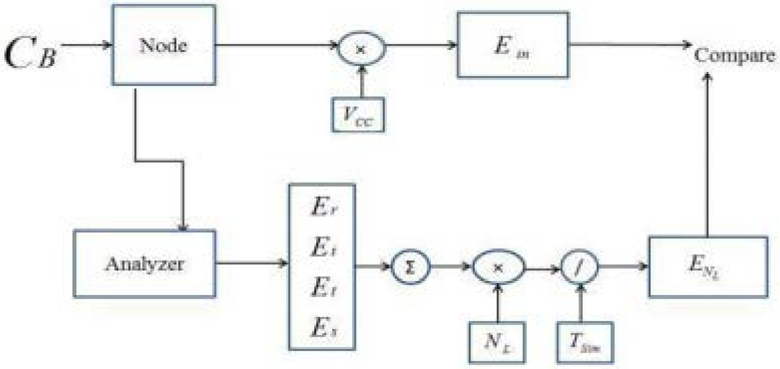

Figure 3: Energy Analysis model for ML-MAC [16]

This energy model ensures better performance by setting duty cycles for each node which helps to manage the ON and OFF times. After evaluating the duty cycle of each node of the network, the network lifetime is calculated afterwards. The duty cycle must not be too low or high for it will decrease the contention period and increase the energy consumption respectively. Hence an optimal value of duty cycle is found out that will maximize the network lifetime. So battery conservation is achieved by this type of energy model.

A novel method for WSN lifetime estimation is introduced in [17] which functions on combined firmware images and models the difficult behavior of batteries. This method overcomes two main limitations over other methods that firstly rely on theoretical methods or high level protocol implementations and most often overlook low level constraints such as drivers, hardware etc.

which have a major effect on network lifetime and secondly they use an ideal battery model which overestimates the network lifetime due to its constant voltage and and linear nature. The method is divided into four main steps i.e. Firmware design, firmware emulation, lifetime prediction and lastly design iteration. Network lifetime was increased by a factor of three in one of the case studies using this method without compromising on performance.

An analytical framework providing closed form expressions for residual energy and lifetime prediction of wireless sensor nodes is introduced in [18] and is termed as SAVE (Stochastic Analysis and aVailability of energy). SAVE models a wide variety of input factors, including channel characteristics, different energy sources and harvesting policies, link layer parameters (e.g., error control and duty cycling) and various data traffic generation models. Residual energy distribution of various harvesting nodes is derived using semi- Markov models

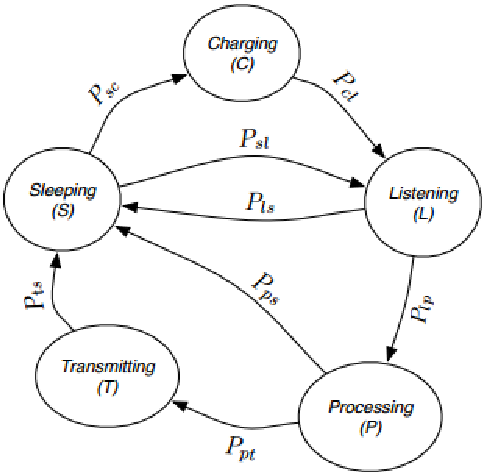

Figure 4: Semi Markov chain of a harvesting sensor node [18]

The functions of the harvesting sensor node is modeled as a semi-Markov chain consisting of (i) charging (C), (ii) sleeping (S), (iii) listening (L), (iv) processing (P), and (v) transmitting (T) operational states, which are represented in Fig. 4. This type of modeling ensures better energy conservation for a battery and increase in network lifetime.

A hierarchical approach is proposed in [19] to construct a continuous energy map of a sensor network. This method consists of a topology discovery and clustering phase, followed by an aggregation phase when energy information collected is abstracted and merged into energy contours in which nodes with similar energy level are grouped into the same region. The topology of the monitoring tree is restructured periodically to distribute energy cost among all nodes fairly, which helps to reduce the impact of the monitoring scheme on the lifetime of the sensor network.

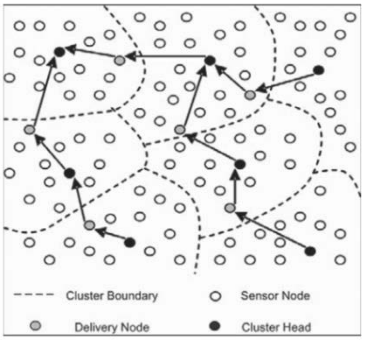

Figure 5: Topology discovery [19]

Table1 : Comparison of different residual battery models

Battery model	Advantage	Disadvantage
Residual battery energy estimation	Better than linear model	Limited scope of application
Service Life Estimator model	Can work on different protocols	Calculation complexity
KiBam	Works in real time	Increased overhead
ML-MAC energy model	optimizes duty cycles	Decreased throughput
Lifetime estimation model	Considers low level constraints	Number of iterations required
SAVE model	Ensures better energy conservation	Algorithm complexity (Markov chains)
Hierarchical Approach	Reduces impact of monitoring scheme	Increased packet latency

III. Conclusion

The energy management in wireless sensor networks has become a major hurdle in the further development of wireless sensor networks. Hence it is imperative that this hurdle must be removed in order to improve the network lifetime. Therefore a number of residual battery models have been studied and surveyed which help to achieve this aim of battery conservation. All the schemes discussed above have modeled the residual energy of the battery and has tried to conserve the network energy by optimizing the various network parameters. While some battery models optimize the battery life while maintaining the network performance, others maximize the residual battery life by rescheduling the duty cycles of the sensor nodes. In this way, the network life span can be increased considerably thus eliminating the need for redeployment of sensor nodes.

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