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The Impact of Ambient Temperature on the Battery of a Sensor Node

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ABSTRACT

This paper focuses on the experimentally investigating the impact of ambient temperature on the discharging efficiency of the battery of a sensor node of the wireless sensor network (WSN). Experimental results have shown 5.137% improvement of battery lifetime at 15°C when the sampling interval is 0.2 seconds with data compression, but the improvement is 16.679% when the sensor node is operated at the optimum sampling interval of 0.62 seconds with data compression. However, the maximum improvement in the battery lifetime is recorded when the sensor field temperature is 35° C with optimum sampling interval.

Introduction

WSN technologies are influencing every domain of human interest. The culmination of this technology would result in the creation of a central nervous system to the planet Earth. As a result of this, any person through the internet access can get the dynamic information of any physical phenomenon of interest happening at any corner of the globe. This requires the placement of the sensor nodes in diversified environmental conditions of the earth. Figure 1 shows a typical architecture of a WSN.

A typical sensor node schematic is shown in Figure 2. Any sensor node has four important units viz. sensor unit, the communication unit, the processing unit, and power unit. The major power consumption of power is due to communication unit when it is in the transmitting mode. Normally, the power unit of the sensor node consists of non-rechargeable batteries. Thus, the lifetime of the batteries becomes the focal point for enhancing the lifetime of WSNs. Usually when the battery dies; still it has 20 % to 25% of unused energy. This is due to inefficient discharge of the battery. Therefore, this condition of the early death of battery is referred to as premature exhaustion of the battery. Premature exhaustion of the battery takes place because of rate capacity effect and recovery effect phenomenon that takes place in the battery. Further, the environment of the sensor field is also responsible for the early death of the battery. At colder conditions, the mobility of ions in the electrolyte of the battery decreases and it appears as increased internal resistance of the battery. A part of the useful power of the battery is wasted here. Hence, the cumulative effects of rate capacity effect, recovery effect, and environment of the sensor field have a detrimental influence on the lifetime of the battery thereby reducing the lifetime of wireless sensor network. The work presented in this paper focuses on the strategies to mitigate these effects to extend the lifetime of the WSN.

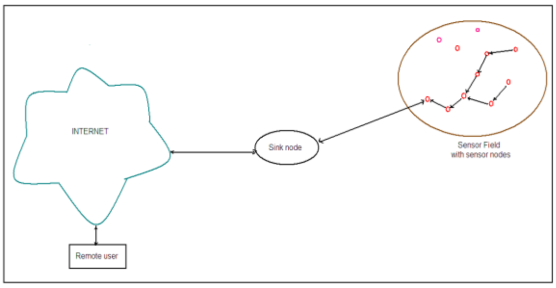

Figure 1. Typical WSN architecture.

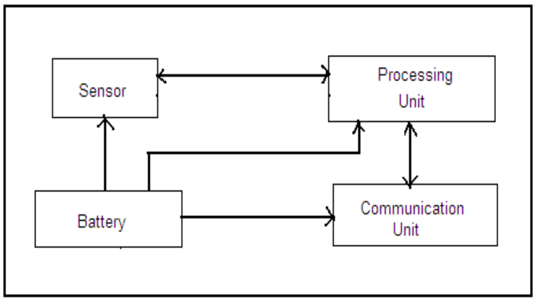

Figure 2. Schematic of a typical sensor node.

Related work

The work in [1] is related to the work presented in this paper. For the first time, it has been experimentally proved that the duty cycle, transmission power level and temperature of the sensor field have a direct impact on the lifetime of the sensor node. The results have shown that at higher transmission power levels the lifetime of the battery has been degraded. The important finding of the experiment was that the battery gets prematurely exhausted with 45% of the energy unused. It has also been proved that the discharging efficiency of the battery can be increased by decreasing duty-cycle and increasing sampling interval. Further, the authors have observed that the battery exhibits large variations in the energy delivered within the considered range of temperature and discharge currents.

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The work in [2] has demonstrated energy minimization with Rate adaptation technique. The basis of their work was that the transmission energy can be significantly reduced by lowering transmission power and increasing the duration of the transmission.

In Sensor Surveillance system long lifetime is imperative [3]. Lifetime problem is mitigated in three steps which are computing the maximal lifetime of the surveillance system and a workload matrix by using the linear programming technique, decomposing the workload matrix into sequence of schedule matrices that can achieve the maximum lifetime and finally determining the sensor surveillance trees based on above obtained schedule matrices, which specify the active sensors and the routes to pass sensed data to the base station.

A set of distributed algorithms has been reported in the literature [4] with which a lifetime improvement of 10% to 20% have been expected.

Prolonging the lifetime of the wireless sensor network up to 6 times by the controlled sink movements have been reported in the literature [5].

Data aggregation coupled with optimal routing has resulted in maximizing the lifetime of the sensor network [6].

An approach has been reported in [7] for analyzing energy hole problem based on corona model. In this, sink organizes the sensors around it into dynamic infrastructure and position the disk into disjoint concentric sets termed as coronas.

Wireless sensor networks have opened new domains to distributed data acquisition. Such networks are prone to premature failure because some nodes deplete their batteries more rapidly than others due to workload variations, non-uniform communication, and heterogeneous hardware. Many-to-one traffic patterns further increase node power consumption. To mitigate this problem a novel battery allocation formulation has been reported in [8]. This formulation is based on cost-constrained heterogeneous battery allocation.

The lifetime of wireless sensor network can also be improved if each node does not need to send the data immediately. Instead, the node can store the data temporarily and transmit the same when the mobile sink node is at the most favorable location. Investigations in this direction have been reported in [10], where a framework that maximizes the lifetime of the WSN subject to the delay bound constraints was formulated and simulation results have exhibited a better lifetime than the existing models.

In impenetrable terrains and hostile zones, the best possible way to get the information about the various physical quantities is to deploy a large number of sensors. In such a scenario the lifetime extension becomes pivotal. To maximize the network lifetime in such conditions, two energy efficient approaches were investigated [11]. In this work, a two-tiered wireless sensor network where nodes are divided into clusters and nodes forward data to base stations through cluster heads is considered.

A query based wireless sensor system has been reported in the literature [12]. In query-based wireless sensor systems, a user would issue a query and expect a response to be returned within the deadline. While the use of fault tolerance mechanisms through redundancy improves query reliability in the presence of unreliable wireless communication and sensor faults, it could cause the energy of the system to be quickly depleted. Therefore, there is an inherent tradeoff between query reliability versus energy consumption in a query- based wireless system. In this paper, an adaptive fault-tolerant quality of service control algorithms based on hop-by-hop data delivery utilizing ‘source' and ‘path' redundancy, with the goal to satisfy the quality of service requirements while prolonging the lifetime of the sensor system was presented.

Research on maximizing the lifetime of heterogeneous wireless sensor networks happened at a slower pace. Inspired by ants, pheromone and heuristic information a new approach has been reported in the literature [13]. Based on pheromone and heuristic information, the ants seek an optional path on the construction graph to maximize the number of connected covers. The pheromone serves as a metaphor for the search experiences in building connected covers. The heuristic information is used to reflect the desirability of device assignments. This approach resulted in the maximization of the lifetime of heterogeneous WSNs.

A remarkable improvement in the lifetime of wireless sensor network was reported by replacing the single mobile sink node with multiple mobile sinks [14]. Many wireless sensor networks use a tree rooted at the sink as the underlying routing structure. The problem of maximizing the lifetime of wireless sensor network can be related to the routing structure. Delay is an important element in time-critical applications, and it is imperative to find the shortest path tree with the long lifetime.

A mathematical model based on this model has been reported in the literature [15] which has resulted in improvement in the lifetime of the network with dense node environment.

One important reason for the decrease in the lifetime of the wireless sensor network is an unbalanced distribution of the data among the sensor node. Mitigating this problem has resulted in an improvement in the lifetime of the wireless sensor network, which has been reported in the literature [16]. In this work, the authors introduced special nodes called mobile agent. They have designed an energy prediction strategy which enabled mobile agents to know about the remaining energy of all sensors in their clusters. Based on this strategy they have proposed a solution for energy dissipation problem.

One important reason for the decrease in the lifetime of the wireless sensor network is an uneven distribution of the data among the sensor node. Mitigating this problem has resulted in an improvement in the lifetime of the wireless sensor network, which has been reported in the literature [17]. In this work, the authors introduced special nodes called mobile agent. They have designed an energy prediction strategy which enabled mobile agents to know about the remaining energy of all sensors in their clusters. Based on this strategy they have proposed a solution for energy dissipation problem.

In non-time-critical applications of wireless sensor network applications with a mobile sink can reduce the energy consumption resulting in prolonging the network lifetime of wireless sensor network [18].

A sensor network cannot carry out its task after the nodes energy is exhausted. Thus a sensor's lifetime is the duration of the time when it begins to generate the first data packet to the time when it generates the last data packet that is deliverable to the sink. When one sensor is out of operation or a few sensors are partitioned from the sink, the rest of the network can still work, as long as useful data generated by other sensors can reach the sink. Therefore the lifetime of a sensor network includes the lifetime of all sensors that produce useful data. Research in this direction has been reported in the literature [19].

A novel approach called Intra-route and Inter-route coordination to prolong the sensor network lifetime under the end-to-end delivery delay constraints has been reported in the literature [20]. Their work focused on two important aspects. First, the Intra-route coordination module that allows the nodes on the same route to balance their nodal lifetimes through adjusting the MAC-Medium access control behaviors collaboratively. Second, the Inter-route coordination module that balances the nodal lifetimes across different routes via adjusting the communication routes.

A novel approach called Intra-route and Inter-route coordination to prolong the sensor network lifetime under the end-to-end delivery delay constraints has been reported in the literature [21].

In order to prolong the sensor network lifetime, the popular approach is to construct a load-balanced routing tree routed at the base station for data gathering. However, this may result in a long routing path from some sensors to the base station. This situation may not suit to some mission-critical applications that require all sensed data to be received by the base station with minimum delay. A work focused in this direction to construct a routing tree such that the network lifetime is maximized while keeping the routing path between each sensor and the base station minimized has been reported in the literature [22].

A distributed refinement algorithm [23] was devised that dramatically improves on the load balancing for the routing tree produced by the top-down algorithm. They have demonstrated using simulations that network lifetime achieved around 85% of the optimum.

By intuition, significant extensions of wireless sensor network lifetime can be achieved by adding spare nodes. The spares are ready to be switched on when any primary node uses up its energy. Research work in this direction has been reported in the literature [24].

In wireless sensor networks, transmission and reception of data packets are considered as the chief source of energy consumption. Due to lack of energy consumption management, there will be quick depletion of the energy resources of the nodes near the sink. In the most of the routing algorithms, the periodical choice of the optimal path and the energy problem of the nodes near the sink have the substantial impact on the lifetime of wireless sensor networks. As a result of these two problems, the network will be partitioned and the wireless sensor network would not be able to perform its intended critical function. Work in this regard has been reported in the literature [25].

Further, work presented in [26] proposed a method to find the optimum value for sampling interval to achieve optimum performance of WSN. Also, they have experimentally investigated the effects of the environment [27] on the performance of the wireless sensor node.

Proposed approach

In the proposed method, a thorough experimental investigation is carried out to understand the effects of temperature on the lifetime of the sensor node which is one of the environmental parameters. Generally, batteries are designed to operate normally over a range of temperatures. However, exceeding this range would result in premature exhaustion of the battery. Further, the arbitrary selection of sampling interval of the WSN put more stress on the battery. In the colder sensor field environments and when the sensor node is transmitting, the battery would be discharged in a manner which results in premature exhaustion of the battery. This is due to Rate capacity effect and Recovery effect of the battery. In the present work, lifetime and power dissipated by the sensor node at different temperatures are analyzed and a data compression technique along with optimum sampling interval is used to mitigate the increased power dissipation at the lower temperature of the sensor field to extend the lifetime of the sensor node.

Experimental setup

The sensor node is designed and fabricated with three sensors viz., temperature sensor, accelerometer and light sensor. These sensors are interfaced to the microcontroller. Further, the sensed signals of sensors are conditioned by LM324. The microcontroller used in the present work is PIC18F252 made by Microchip. It is a 28 pin controller. Further, it is high-performance equipped with enhanced flash memory and a 10 bit analog to digital converter. Sensed physical quantity by the sensors, which is in the analog form, is converted to digital by the microcontroller. In the present work, the resolution of analog information is set to 4.88mV. USART of the microcontroller is set at 9600 baud rate while transmitting the data to the receiver node or sink node. Timer ‘1’ of the microcontroller is used for measuring the sampling interval. A 20MHz crystal oscillator is used for the microcontroller. Sink node or receiving node acts as the master node, through which the sampling time of the slave node or sensor node is controlled. Each sensed physical quantity is converted into two-byte digital data. Since there are three sensors, there will be six bytes of the sensed information. The distance between the sensor node and the sink node is fixed to 30 meters. Three lithium-ion batteries with specifications of 2200mAh, 3.7V each is used to energize the sensor node. The microcontroller is energized with regulated five volts using IC 7805 regulator which is further given to IC 2941 to improve the supply efficiency of IC 7805 and this output is finally given to the microcontroller.

CC2500 Transceiver from Texas Instruments is used to provide the wireless communication between the sensor node and the receiver node. The CC2500 is a low-cost 2.4 GHz transceiver designed for very low-power wireless applications. The circuit is intended for the 2400-2483.5 MHz ISM (Industrial, Scientific, and Medical) and SRD (Short Range Device) frequency band. The RF transceiver is integrated with a highly configurable baseband modem. The modem supports various modulation formats and has a configurable data rate up to 500 KBaud. Also, CC2500 provides extensive hardware support for packet handling, data buffering, burst transmissions, clear channel assessment, link quality indication, and wake-on-radio.

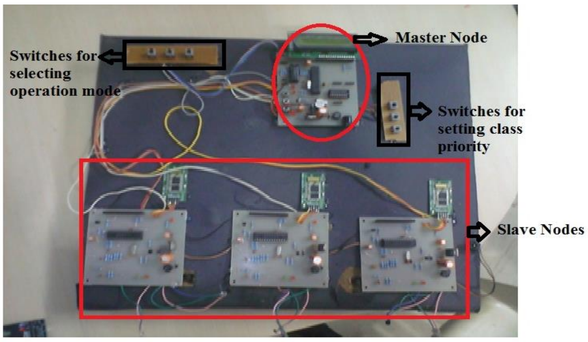

Figure 3. Circuits of sensor or slave nodes and sink node or master node.

It is energized with +3.3 volts supply. Receiver node also consists of CC2500 to receive the data bytes from the sensor node and it is so configured to change the sampling interval of the sensor node as required by the experiment. The output of the receiver node is connected to the computer through USB port to record the results of the experiment. The experimental setup is as shown the Figure 3.

Results and discussions

In the experiment, the power dissipated by the sensor node is recorded at different temperatures of the sensor field in which the node is placed with respect to the sampling interval. Results are shown in Figure 4 and Figure 5 When the temperature of sensor field is 15°C, the power dissipated by sensor node is 0.9 watts at the sampling interval of 0.2 seconds. However, when the data compression is applied, the power dissipation is reduced to 0.8watts. This corresponds to 11.11% reduction in the power consumed by the sensor node. From the graph, it is evident that as the sampling interval is gradually increasing, the power dissipated by the sensor node is decreasing. Therefore, it can be said that the battery is stressed more at lower sampling intervals. Further, when the sampling interval is made equal to its optimum value of 0.62 seconds, the power dissipated by the sensor node without applying data compression is reduced to 0.47 watts from 0.9 watts. This corresponds to a reduction of 47.778% in power dissipated by the sensor node. The chief reason for the maximum reduction in the power dissipated by the sensor node is that the recovery effect of the battery is circumvented when the sampling interval is at its optimum value of 0.62 seconds.

Figure 5 shows the graph of the lifetime of the sensor node with respect to the sampling interval. When the sampling interval is 0.2 seconds, the lifetime of the sensor node is 554 minutes. The lower lifetime is both because of a relatively colder environment of the sensor field as well as the non-optimum sampling interval. Colder sensor environment results in decreased mobility of the ions in the battery that manifests as increased internal resistance of the battery. Thus, a part of the power drawn from the battery by sensor node will be consumed by the internal resistance. The sampling interval of 0.2 seconds results in recovery effects of the battery. To improve the lifetime, the data about the physical environment sensed by sensor node is compressed which results in sensor node lifetime of 584 minutes. This corresponds to 5.299% improvement. There is a gradual improvement in the lifetime as the sampling interval is increasing. The improvements are 8.581% at 0.3 seconds, 9.61% at 0.35 seconds, 11.445% at 0.4 seconds, 12.728% at 0.45 seconds, 15.044% at 0.5 seconds, 15.226% at 0.55 seconds, 15.096% at 0.6 seconds. However, when the sampling interval is 0.62 seconds, which is the optimum sampling interval, the improvement in the lifetime of the sensor node is 16.679%.

Figure 6 and Figure 7 shows the graphs of power dissipation versus sampling interval and lifetime versus sampling time respectively at 25^{o}C. The effect of the increase in sensor field temperature has resulted in reduced power dissipation and improvement in the lifetime of the sensor node. For instance, at the sampling interval of 0.2 seconds, the power dissipated is 0.79 watts as compared to 0.9 watts at 15^{o}C. This corresponds to 22.22% decrease in the power dissipation. And the lifetime has increased to 581.3 minutes as compared to 554 minutes at 15^{o}C. it corresponds to 4.696% improvement in the lifetime. Data compression has resulted in an improvement of 2.679% in the lifetime. However, when the sensor is operated at optimum sampling interval, the improvement in its lifetime is 16.05%.

Figure 8 and Figure 9 shows the graphs of power dissipation and lifetime with respect to the sampling interval at 35^{o}C. Graphs exhibit the same trend as others. However, at optimum sampling interval, sensor node has the lowest power dissipation of 0.33watts and the highest lifetime of 736.8 minutes. This corresponds to an improvement of 20.29%. Also, the power dissipated by the sensor node has decreased by 64.935%. This is the temperature of the sensor field where the battery has yielded optimum performance at 15^{o}C.

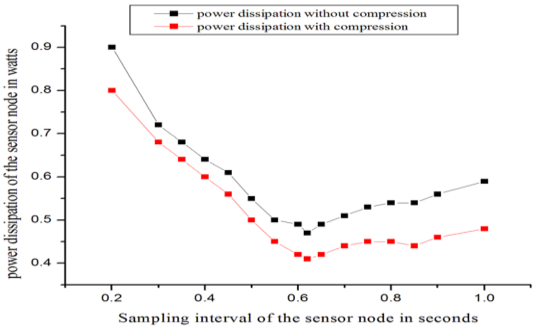

Figure 4. Graph shows power dissipation versus sampling time at 15^{o}C.

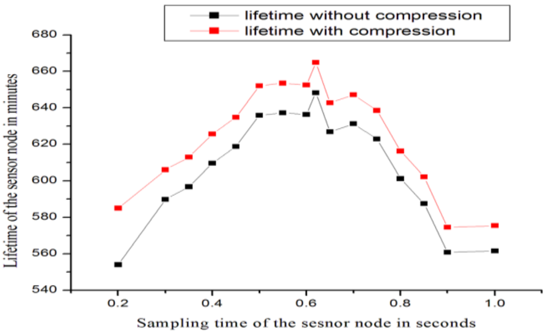

Figure 5.Graph shows lifetime versus sampling interval at 15^{O}C.

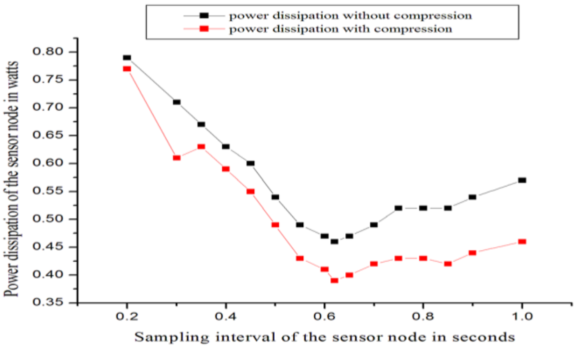

Figure 6.Graph shows power dissipation versus sampling interval at 25^{o}C.

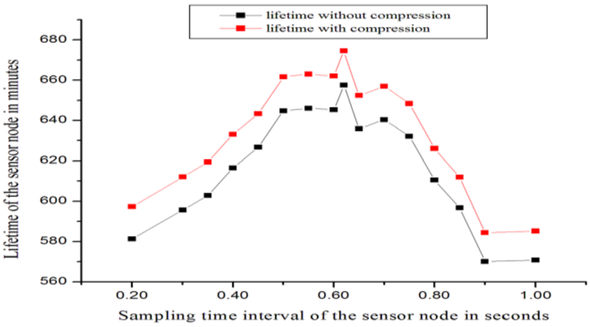

Figure 7.Graph shows lifetime versus sampling interval at 25^{O}C.

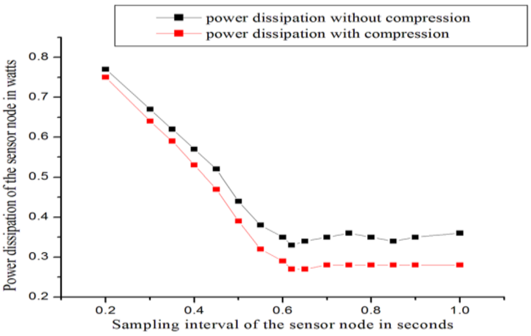

Figure 8.Graph shows power dissipation versus sampling time at 35^{o}C.

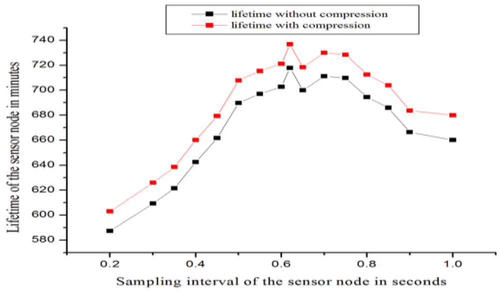

Figure 9.Graph shows lifetime versus sampling interval at 35°C.

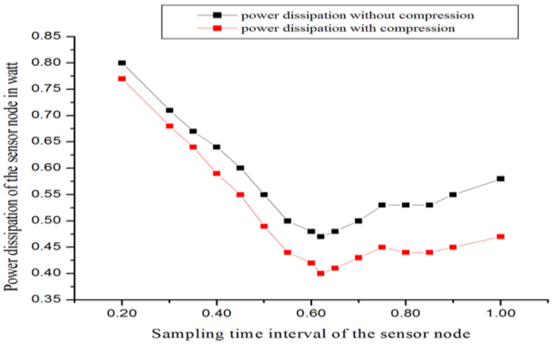

Figure 10.Graph shows power dissipation versus sampling time at 45°C.

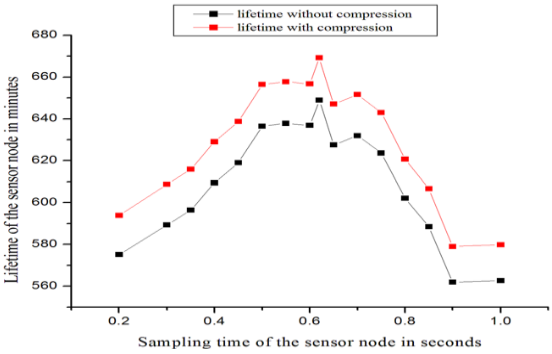

Figure 11. Graph shows lifetime versus sampling interval at 45°C.

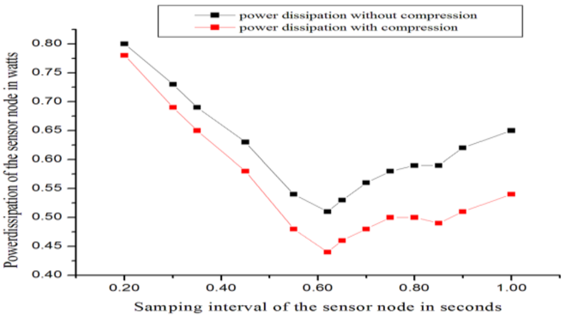

Figure 12. Graph shows power dissipation versus sampling time at 55°C.

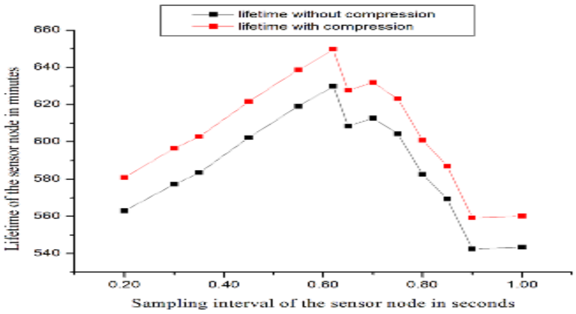

Figure 13.Graph shows lifetime versus sampling interval at 55°C.

Figure 10 and Figure 11 shows the graphs of power dissipation and lifetime of the sensor nodes with respect to the sampling time at 45°C. At optimum sampling interval, the improvement in the lifetime of the sensor node is 14.069%.

Figure 12 and Figure 13 shows the graphs of power dissipation and lifetime with respect to the sampling interval. At optimum sampling interval, the improvement in the lifetime of the sensor node is 13.258%.

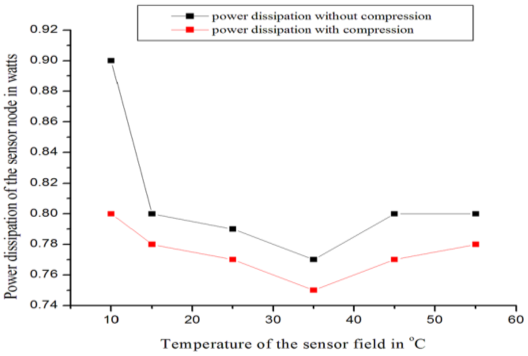

Figure14.Graph shows power dissipation versus temperature at sampling interval of 0.2seconds.

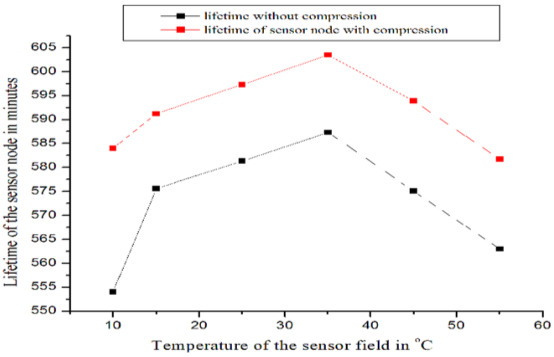

Figure 15.Graph shows lifetime versus temperature at sampling interval of 0.2 seconds.

Figure 14 and Figure 15 shows the graphs of power dissipation and lifetime of the sensor node with respect to the sensor field temperature. Maximum lifetime improvement is observed at 35° C, which is 8.202% with data compression and is 5.67% without compression.

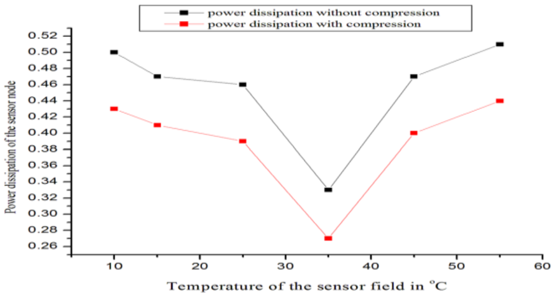

Figure 16.Graph shows power dissipation versus temperature at sampling interval of 0.62 seconds.

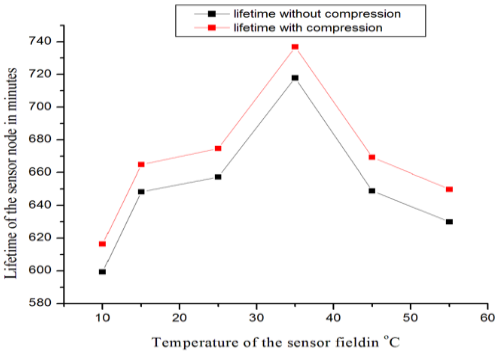

Figure.17 Graph shows lifetime versus temperature at sampling interval of 0.62 seconds.

Figure 16 and Figure 17 shows the graphs of power dissipation and lifetime of the sensor node with respect to the temperature at the optimum sampling interval of 0.62 seconds. The improvement in the lifetime at 35^{o}C is 24.81% with data compression and 22.82% without data compression as compared with their values at the sampling interval of 0.2seconds. Parameter improvement with the proposed strategies is shown in Table 1.

Table.1 Parameter improvement at 15^{o}C.

.	Arbitrary sampling interval of 0.2 seconds	Optimum sampling interval of 0.62 seconds	% improvement as compared with uncompressed values
Power dissipated without compression in watts	0.9	0.47	47.778
Power dissipated with compression in watts	0.8	0.41	54.444
Lifetime without compression in minutes	554	648.3	14.546
Lifetime with compression in minutes	584	664.9	16.679

Conclusions

In this work, an experimental investigation is carried out to understand the impact of environmental conditions on the sensor field on the sensor node lifetime. From the results obtained it is evident that at colder environmental conditions, the power dissipated by sensor node increases and vice versa. Further, it leads to premature exhaustion of the battery and thus the lifetime of the sensor gets reduced. The strategy of data compression is adapted to the data generated by the sensor node about the physical phenomenon being sensed to extend the lifetime of the sensor node. Huffman compression algorithm with the compression ratio of 28% is used. The maximum improvement obtained in the lifetime is 5.137% at an arbitrary sampling interval of 0.2 seconds when the sensor field temperature is 15^{o}C. However, when the sensor node is operated at optimum sampling interval, the lifetime has increased to 16.679%. Thus the strategy of data compression along with the optimum sampling interval mitigates the premature exhaustion of the battery. Further, the experimental results have shown that at 35^{o}C, the performance of the battery is optimum. The improvement in the lifetime is 24.81% as compared to when the sensor field temperature is 15^{o}C.

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