Volume 10, Issue 4
August 2021

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

An Enhancement to Lifetime of Sensitive Nodes for Rare Event Detection in Cluster Based Wireless Sensor Networks

[1]Sundaravanan Jothiprakasam and [2]Senthil Murugan Boopalan

[1]Assistant Professor, Department of ECE, Thanthai Periyar Government Institute of Technology, Vellore, India

[2]Assistant Professor, Department of ECE, Thanthai Periyar Government Institute of Technology, Vellore, India

E-mail: sundaravanan@gmail.com

ABSTRACT

Wireless sensor networks find rapid deployment currently in various fields, especially in rare event detection. The major constraint for a wireless sensor node is its limited energy. The rare event should be monitored at periodic intervals and, at the same time, if detected, should be communicated within a specific period for further action. The sensor nodes should have an excellent long lifetime to periodically detect and transmit the sensed data to the base station or the sink node. There exists a protocol, namely the Statistical Data Collection Protocol, in which the lifetime of the sensor nodes is enhanced due to the lesser transmission of redundant data. Improved Statistical Data Collection Protocol is proposed in this paper, to further enhance the lifetime of sensor nodes, particularly the rare event detecting nodes. The simulation results show that the sensor nodes have enhanced lifetime from 9.08% to 25.23%, when compared to the Statistical Data Collection Protocol, with minimal detection delay.

Keywords: *Rare event detection, wireless sensor networks, energy consumption, lifetime enhancement*

1. INTRODUCTION

Several wireless sensor nodes form a network as Wireless Sensor Network (WSN) to achieve specific functionality. A non-rechargeable battery in many applications powers each of the wireless sensor nodes. The power and energy constraints of the sensor node play a vital role in deciding the protocols used over many layers of the WSN.

WSN finds applications in rare event detection in which the event of interest is of low probability and occurs very rarely during the period of observation. Wildfire monitoring is one such application, where the sensor nodes are used for sensing the entire forest area to detect any abnormal rise in temperature or detection of fire to be reported to the sink node or base station (BS) for further action to be initiated.

In WSN, clustered architecture is deployed in many environments in which the sensor nodes are organized into groups called clusters. In each cluster, one of the nodes is designated cluster head (CH), which is responsible for collecting the information from the other cluster members (CM) and for reporting to the sink or base station. The number of clusters should be optimal, as discussed in [1], to maximize the lifetime of the sensor networks. In the hierarchical clustering approach, the CH acts as a hot spot as it has to be in receive state for an extended duration of time than the CM nodes in a cluster. So, hotspot problem occurs at CH and network partitioning may occur due to faster depletion of the battery [2]. Several protocols have been developed for enhancing the lifetime of the network using clustered architecture. This paper is involved in proposing an improvement to the existing protocol for rare event detection in clustered architecture.

The survey in [3] was done on diverse hierarchical routing protocols. The protocols surveyed included Low Energy Adaptive Clustering Hierarchy (LEACH) and were extended to other routing protocols of WSN such as TEEN [4], APTEEN [5], PEGASIS [6], ELCH [7], and I-LEACH [8]. An Application-Specific Low Power Routing protocol (ASLPR)[9] was evolved to achieve energy efficiency and to enhance the lifetime of WSN. The features of proactive and reactive networks were incorporated in routing protocols for efficient data transmission[10].

Sensor nodes are highly constrained to energy consumption as they are battery-powered. A survey in [11] includes various energy conservation techniques to extend the lifetime of the nodes to reasonable times.

There are various lifetime enhancement techniques available in the literature for WSN. The survey in [12] presents various rare event detection techniques based on the various methods in the literature. A survey was done on different rare event detection techniques in [13], and the techniques include collaboration, duty cycling, energy harvesting, component deactivation, message suppression, and many more.

In message suppression [14], the number of messages transmitted is reduced significantly so as to reduce the power consumed by the radio transceiver. In PEGASIS, the nodes along the chain aggregate the data before transmitting the data to the next node. In LEACH, the CH receives the data from the CM nodes, aggregates them, and only transmits the aggregated data to the BS, while it suppresses the other data. [15][16] have addressed the platform to implement compressive sensing to WSN, in which the data is compressed.

A new ribbon structure was proposed in [17], in which only one-half of the nodes along the ribbon structure is active, reducing the number of packets transmitted to half in case of no rare event. The rare event detection delay is guaranteed in spite of increased lifetime. Recently Statistical Data Collection Protocol (SDCP) was proposed in [18] to

Volume 10, Issue 4
August 2021

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

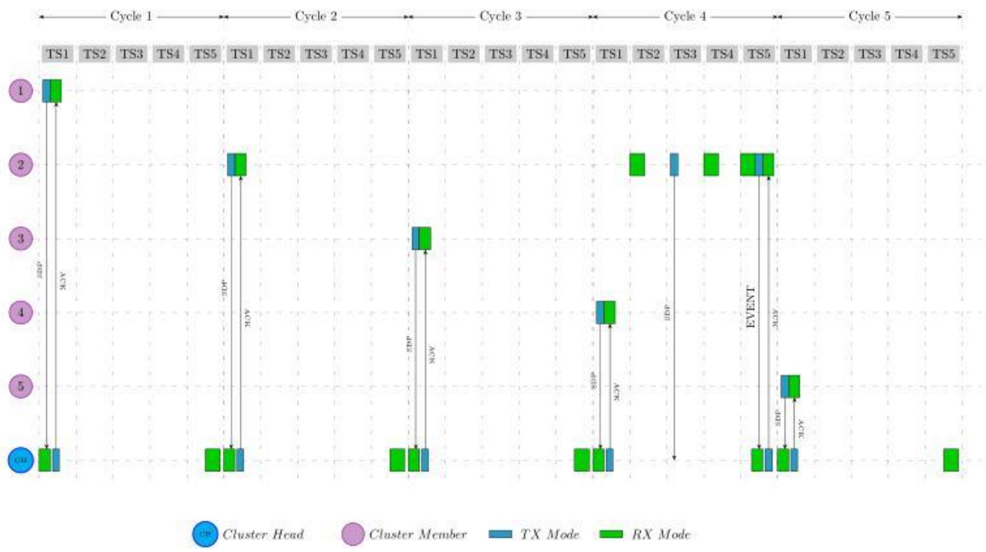

Fig. 1 SDCP data collection with rare event

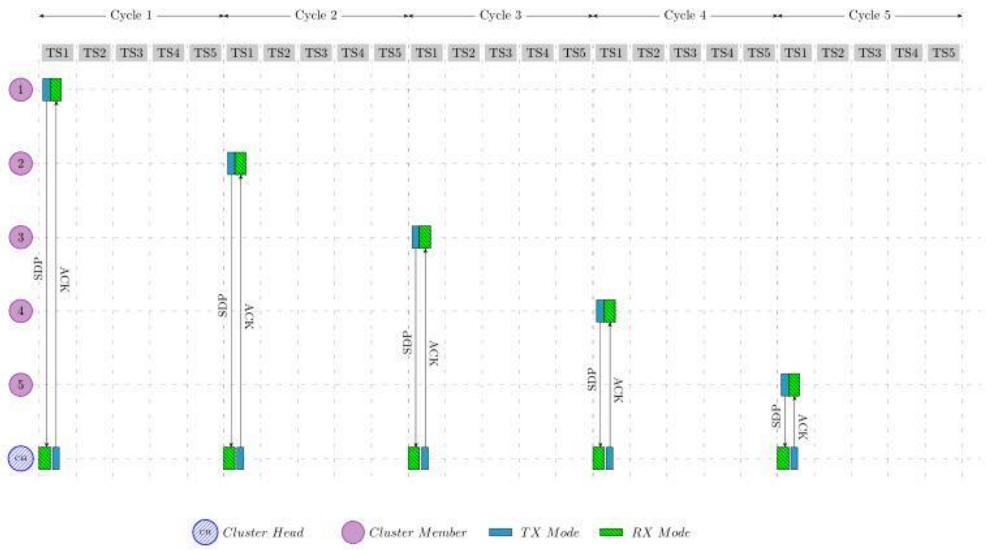

Fig. 2 Data collection in I-SDCP

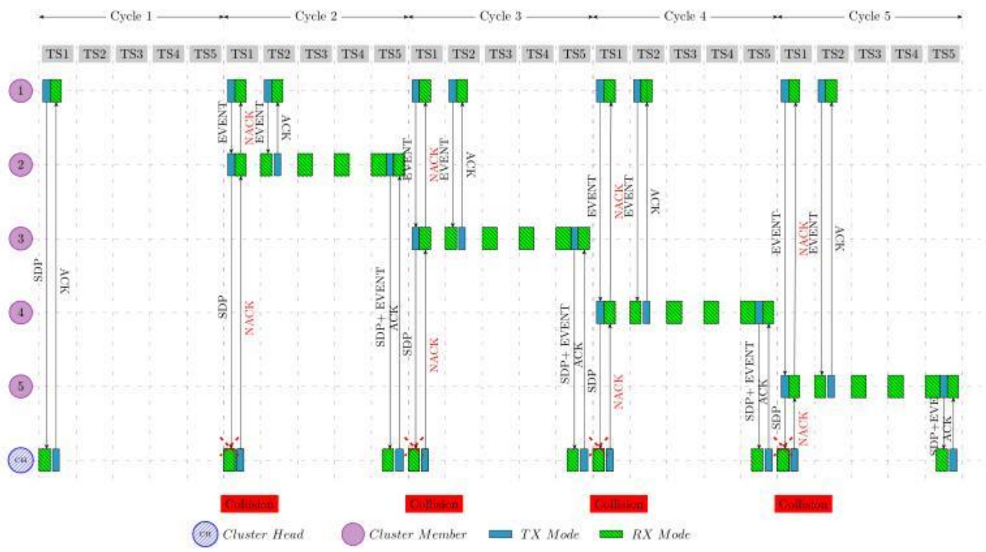

Fig. 3 Rare event detection in I-SDCP

enhance the network lifetime, at the same time maintaining the rare event detection delay. Various techniques for network lifetime enhancement like message suppression, duty cycling, component deactivation are used in SDCP. Further, SDCP was proposed for cluster based network topology to detect rare events with guaranteed delay.

The remainder of the paper is organized as follows. Section 2 briefly discusses the working of SDCP protocol in different modes along with its advantages and drawbacks. The problem statement is given in section 3. In section 4, the Improved Statistical Data Collection protocol (ISDCP) is proposed along with its different operation modes. Section 5 discusses the performance evaluation of ISDCP, which also includes the simulation results of the proposed protocol. Section 6 concludes the ISDCP along with the future scope.

2. RELATED WORK

In this section, the SDCP proposed in [18] is briefed to have a better understanding of the enhancement. SDCP is proposed for cluster based network topology with cluster head and cluster members in each cluster. Various types of energy efficient MAC protocols have been proposed in the literature [19]. SDCP proposed a cross-layered approach for energy efficiency with modified MAC for rare event propagation. In one round of data collection in a cluster containing N cycles, where N is the number of CM nodes in the cluster. Each cycle is divided into N time slots (TS) in which the last time slot is split up into two periods in which the last period is called the additional time slot. The sensor nodes remain in an active state for a very small period in a TS and switch to sleep mode during the rest of the period to conserve energy. In the absence of rare event, only one node transmits its Statistical Data Packet (SDP) to CH in its first time slot. Instead of all the nodes reporting data to CH in all cycles, only one node after another reports to CH in different cycles. For the data collected between two transmissions, the sensor nodes calculate the statistics of significance and transmit in the SDP along with the current sample.

The CH remains in receive mode in the first time slot and in the additional time slot at the end of each cycle. The node detecting rare event also has to remain in receive mode for N-1 TS and transmits the rare event packet twice during a cycle. The node detecting rare event interacts with the other nodes and sends its rare event data to the CH towards the end of the cycle in the additional time slot. SDCP incorporates quick loop mode to avoid excessive energy consumption by the node that had detected the rare event. SDCP incorporates quick loop mode in which the CH and the node detecting the rare event for a certain number of consecutive cycles gets its event communicated to the CH confined to the timeline without affecting the other nodes by communicating in predetermined TS.

A single round of data collection in SDCP, when a rare event is detected during a cycle is illustrated in Fig. 1. In the absence of a rare event, the scheduled nodes transmit the SDP to CH in cycles 1, 2, 3 and 5. In these cycles, the CH node remains in receive mode for two periods, one during the reception and during the other period, times out not receiving any packet. In cycle 4, Node 1 detects the rare event. Node 4 transmits its SDP during time slot 1. Having detected the rare event, Node 1 switches to receive mode during time slots 2, 4 and 5 and transmits its rare event during TS3 and also in the additional TS. Again the Node 1 retransmits its rare event packet during the additional time period of time slot 5, which is received and acknowledged by the CH.

The rare event of interest like wildfire has a low probability of occurrence during the lifetime of a wireless sensor node. Hence, the network traffic is to be maintained at a minimum level but should also be capable of detecting the event and reporting within the delay constraint. The SDCP differs from other cluster based protocols in collecting data from each of the CM once in N cycles instead of each cycle, which enhances the lifetime. However, the node detecting rare events drains out excessive energy during the additional receive periods despite its significance.

3. PROBLEM STATEMENT

Sensor nodes are placed in a field to detect rare events forming a network. The occurrence of the event to be detected is very low and may or may not happen during the lifetime of the sensor node. Cluster based topology is used in the field in a self-organizing manner wherein the sensor nodes in a cluster are covered within the transmission radii of each other to incorporate SDCP. The data from each of the CM nodes is received in a cycle and in a round-robin fashion over a period of many cycles. When a sensor node detects a rare event, the sensitive node consumes higher energy due to the additional transmit and receive durations in the entire cycle. In spite of the node's significance for event detection in further cycles, the lifetime of the significant node is left in high-risk scenario. The problem is to reduce the energy spent by the sensitive node for communicating the detected rare event within the same cycle, thereby extending the lifetime of the node of significance.

3.1 Energy Consumption Model

The energy model considered for evaluation is similar to that of the models used in [9][17]. For each node, the sensor subsystem, transceiver subsystem and microcontroller subsystem are considered for the calculation of power and energy. The sensor subsystem remains in either of sense mode or idle mode based on whether it is sensing the parameter or not. The radio transceiver subsystem remains in one of the three states – transmit, receive or idle state. The microcontroller subsystem remains in an active state whenever the sensor subsystem and the transceiver subsystem is not in the idle state. Further, during computation, the microcontroller subsystem is active and remains in idle or sleep state or low power state during the rest of the time to conserve power and energy. Let α, β, γ and τ be the duration for transmission, reception, sensing and entire data collection cycle respectively. Pmcu_active, Pmcu_idle denote the power consumed by the microcontroller unit during active state and idle state. Ptrx_tx, Ptrx_rx, Ptrx_sleep denote the transceiver power consumption during transmission, reception and sleep states respectively. Ps_sensor and Ps_idle indicate the power consumed by the sensor while sensing and in idle mode.

The total power consumed by a sensor node is

$$Power_{Node} = P_{mcu}+P_{sensor}+P_{trx}$$

The total energy consumed by a sensor node over a period τ is

$$E_{Node} = (\alpha+\beta+\gamma)P_{mcu\_active}+(\tau-\alpha-\beta-\gamma)P_{mcu\_idle} + \gamma P_{sensor\_sense}+(\tau-\gamma)P_{sensor\_idle} + \alpha P_{trx-tx}+\beta P_{trx-rx}+(\tau-\alpha-\beta)P_{trx-sleep}$$

4. PROPOSED PROTOCOL - IMPROVED STATISTICAL DATA COLLECTION PROTOCOL (I-SDCP)

SDCP reports higher lifetime than the other cluster based protocols. In the improved lifetime, the node detecting the rare event spends more energy throughout the cycle, making it more vulnerable to failure in spite of its significance, i.e., for example, a cluster with 15 CM nodes, the node detecting rare event needs to be in receive mode for 13 TS. The significant node detecting rare event is to be active in all the time slots for many cycles before entering into the quick loop mode of SDCP. Also the CH remains in receive mode for the second time even when there is no rare event detected. Also in SDCP, the size of the cluster is reduced to a lesser area with all the nodes within transmission radii of each other. The first two drawbacks provide ample opportunity to improve the lifetime of the sensor nodes and thereby the network for rare event detection, for which the Improved Statistical Data Collection Protocol (ISDCP) is proposed in this section.

4.1 Data Collection In ISDCP

In ISDCP, the cluster based network topology is maintained for detecting rare events. For each round, there are N cycles, in which each of the CM nodes transmits its Statistical Data Packet (SDP) to CH in the first time slot. The SDP contains the statistics of the entire data collected by the sensor nodes between successive transmissions. The data from the CM is acknowledged by the CH and the nodes switch to sleep mode for the remaining period of the cycle, in the absence of no rare event as shown in Fig. 2. The CH is active for only one TS instead of two TS in SDCP. The CH remains in active state only in the first TS and does not remain in receive mode during the additional TS.

4.2 Rare Event Mode

In this mode, a rare event is detected by one or more nodes. First, the case of rare event detection by a single node is considered in Fig. 3, in which the packet exchange diagram for a single round of data collection is illustrated. If the node detecting rare event is scheduled for transmission in the first TS of the cycle, then it transmits its SDP along with the current sample value indicating the rare event to the CH. In the other cycles, the node detecting rare event transmits its packet for rare event in the same TS, while the other scheduled node transmits its SDP to the CH node. The CH node experiences a collision and sends a negative acknowledgement (NACK) to the CM nodes. If the time duration for the packet is too less to cause collision, the CH waits for a possible rare event data packet before sending the ACK or NACK at all instances. When the CH experiences collision, it schedules itself for an additional receive slot towards the end of the cycle. The regularly scheduled node of that particular cycle switches to receive mode for the remaining time slots in the cycle to collect the rare event data from the other nodes. The time slots from 2 to N are scheduled for the remaining CM nodes in case of a rare event, one in a time slot. The CM node that detected rare event transmits its rare event packet in its TS, which is received and acknowledged by the original CM node scheduled for first TS in that cycle, which again transmits the consolidated rare event packet in the last additional TS. The process of consolidation of rare events is shifted from the node detecting rare event in SDCP to the other nodes in ISDCP, significantly reducing the energy drain of the critical node.

In Fig. 3, during cycle 1, node 1 is the scheduled node to transmit SDP and also the node detecting rare event. Node 1 transmits the rare event detected through SDP to CH in cycle 1. In cycle 2, node 1 and node 2 transmit their packets at the same time and cause a collision at the CH. The CH transmits its NACK packet, which is received by both nodes 1 and 2. CH reschedules itself for another reception towards the end of cycle 2. Having received NACK packet, node 2 remains in receive state for all the remaining TS in the current cycle. Node 1 sends its rare event packet in TS2 to node 2 and node 2 sends the acknowledgement packet back to node 1. In TS3 to TS5, the node 2 times out, having not received any packet. During the later part of TS5, node 2 transmits the consolidated rare event packet to CH, which acknowledges with an ACK packet. In this rare event mode, the rare event is detected by the CH within the same cycle without any additional delay. Similar is the case during the other cycles of the same round.

Fig. 3 shows the packet exchanges for the condition when the rare event is detected by more than one node in a single round of data collection. Rare event detection by multiple nodes is illustrated in Fig. 4, in which nodes 2, 3, and 4 are considered to be detecting rare events. When nodes 2, 3, and 4 having detected rare event, send the rare event packet in the first time slot along with SDP of node 1, the collision occurs at the CH, which then transmits NACK. Node 1 in the first cycle will remain in receive mode for the remaining time slots and receive the rare event packet from the detected nodes in TS2, TS3 and TS4. After aggregating all the rare event packets with the SDP, the scheduled node will transmit the consolidated data packet to the CH in the additional time slot and it is received by the CH. Similar packet transmissions take place during the other cycles.

4.3 Quick Loop Mode

The quick loop mode of ISDCP is similar to that of SDCP in which the only difference is that the CH does not remain in receive state during the additional time duration of the last time slot. The sensor node detecting rare event for M consecutive cycles, enter into quick Loop mode where M is configurable. In the quick Loop mode, the CH remains in receive mode for the rare event packet in the time slots, when the node will transmit its rare event packet without any collision, thus making the significant data to be received at the

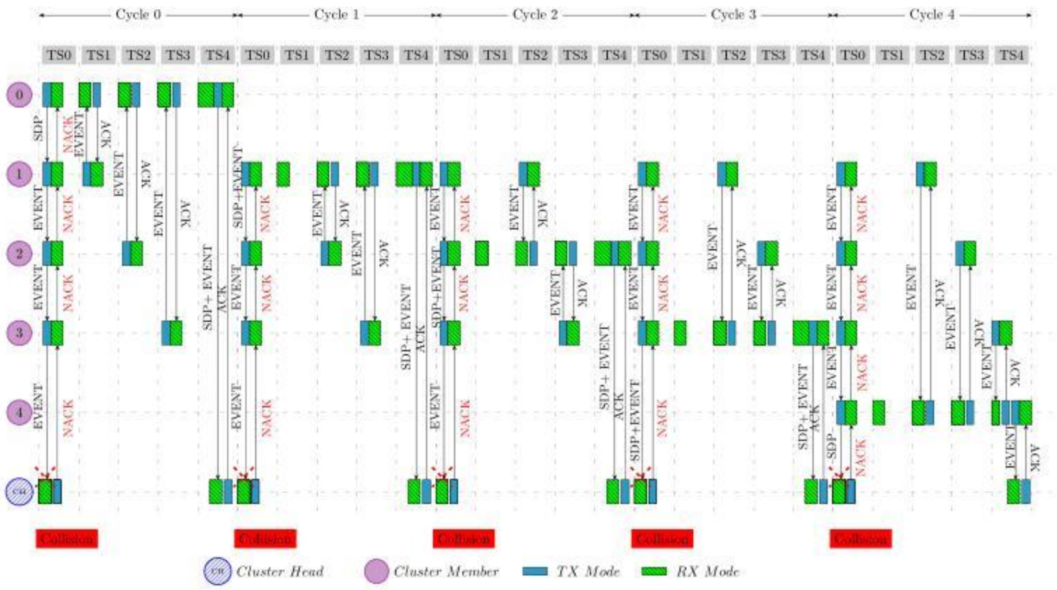

Fig. 4 Rare event detection by three nodes in I-SDCP

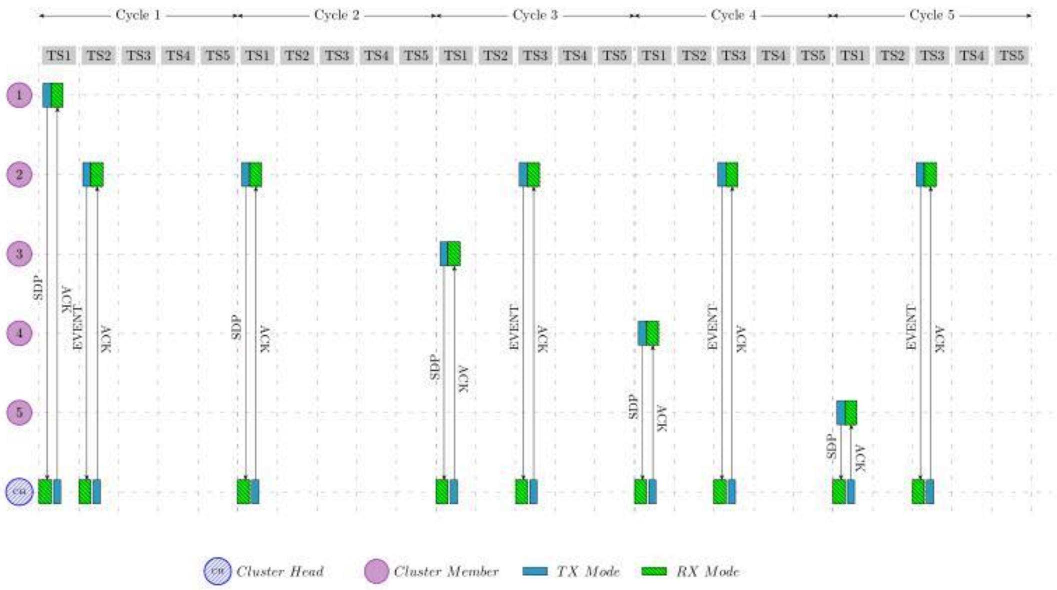

Fig. 5 Quick loop mode in I-SDCP

CH without any additional overhead. Fig. 5 shows the packet exchange diagram for quick Loop mode in ISDCP when CH listens for the rare event packet and acknowledges for the rare event packet promptly to the CM node. The quick loop mode is maintained in ISDCP so that the nodes other than the one detecting rare event be relieved of the additional load to transmit rare event packets. Also, quick loop mode reduces the energy drain for the node detecting rare events to transmit once during any cycle instead of two.

5. PERFORMANCE EVALUATION

5.1 Energy Consumption

The ISDCP is proposed to enhance the lifetime of the WSN over SDCP, reducing the load of the sensitive node that has detected the rare event for reporting. Using the energy consumption model in Section 3.1, the improvement in energy consumption for ISDCP over SDCP is analyzed as follows. To make the analysis simpler, the energy consumption due to the sensor subsystem is ignored due to the minimal and constant value in both SDCP and ISDCP.

Cluster Head

In SDCP when there is no rare event, the cluster head switches to receive state twice during a single cycle, one time during the first TS and again during the last TS. In the first TS, the CH also transmits acknowledgement to the sensor node reporting statistical data packet. In ISDCP, the load of the CH is reduced to almost half in which the CH receives the statistical data packet and transmits the acknowledgement only

Volume 10, Issue 4
August 2021

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

in the first TS in the absence of rare event. The energy savings of the CH node during a single cycle in ISDCP compared to SDCP, when no rare event is detected is given as follows:

$$E_{CH_{Savings}} = \beta^{**}[P_{trx_{rx}} + P_{mcu_{active}} - P_{trx_{idle}} - P_{mcu_{idle}}]$$

where β** is the timeout duration in receive mode for SDCP. When a node detects a rare event, there is no change in energy consumption for the CH node except for the fact that the CH transmits a NACK packet in ISDCP instead of ACK packet in the first TS. During the additional time slot, CH receives and acknowledges the rare event packet.

Cluster Member

The energy consumption of the CM nodes is the same as that for SDCP, in the absence of rare event. When the cluster contains N CM nodes and if a node detects rare event other than the node scheduled in first TS, the energy consumed by the rare event CM node in a SDCP cycle is given by

$$E_{CM_{SDCP}} = [(N-2)\beta^{**} + 2\beta][P_{trx\_rx} + P_{mcu\_active} + 2\alpha[P_{trx-tx} + P_{mcu-active}] + [\tau - (N-2)\beta^{**} - 2\beta - 2\alpha] * [P_{trx-idle} + P_{mcu-idle}]$$

The energy consumed by a sensor node in an ISDCP cycle, when it detects rare event is

$$E_{CM_{ISDCP}} = 2\alpha[P_{trx\_tx} + P_{mcu\_active}] + 2\beta[P_{trx\_rx} + P_{mcu\_active}] + [\tau - 2\beta - 2\alpha] * [P_{trx\_idle} + P_{mcu\_idle}]$$

The savings in energy consumption for the sensitive node due to ISDCP over SDCP is

$$E_{CM_{Savings}} = (N-2)\beta^{**}[P_{trx\_rx} + P_{mcu\_active} - P_{trx\_idle} - P_{mcu\_idle}]$$

The energy savings for ISDCP is dependent on two parameters N and β**. If there are more number of CM nodes in a cluster, the efficiency of the ISDCP is increased due to the presence of (N-2) term for receive duration. Further, this energy conservation of the critical node is distributed to all the other cluster members equally, thereby increasing the reliability of the WSN for reporting the rare event within the same cycle.

5.2 Other parameters

Any node that had detected the rare event, transmits the event data and the value reaches the CM within the same cycle of data collection. The time delay for the rare event communication to CH is maintained as that of SDCP without any additional delay.

Scheduling the sensor nodes is similar to SDCP, with no additional complexity for any of the modes of ISDCP.

The ISDCP can be scaled to any network size provided that the cluster is formed in such a manner that all the CM nodes are inside the transmission area of every other sensor

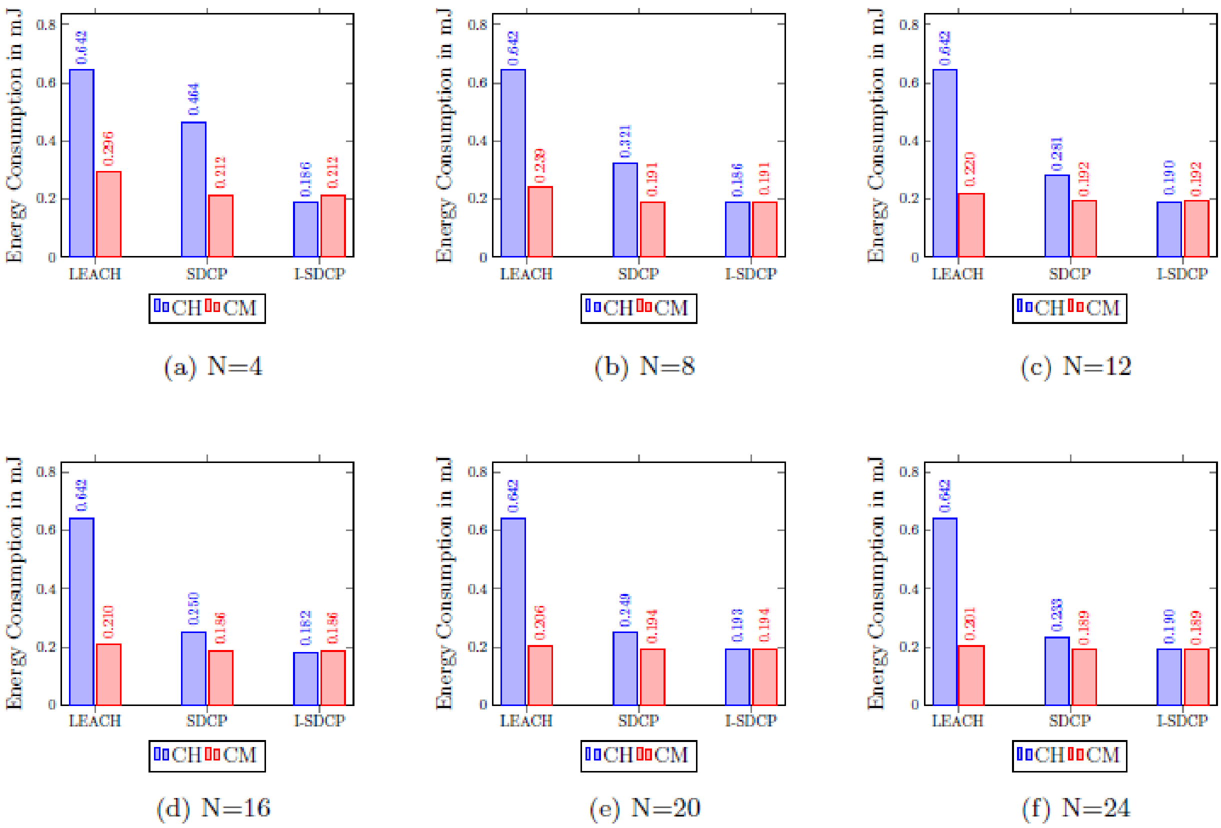

Fig. 6 Energy expenditure for the nodes in 5 minutes with different cluster size after 5 minutes

ITEE Journal
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ISSN: - 2306-708X

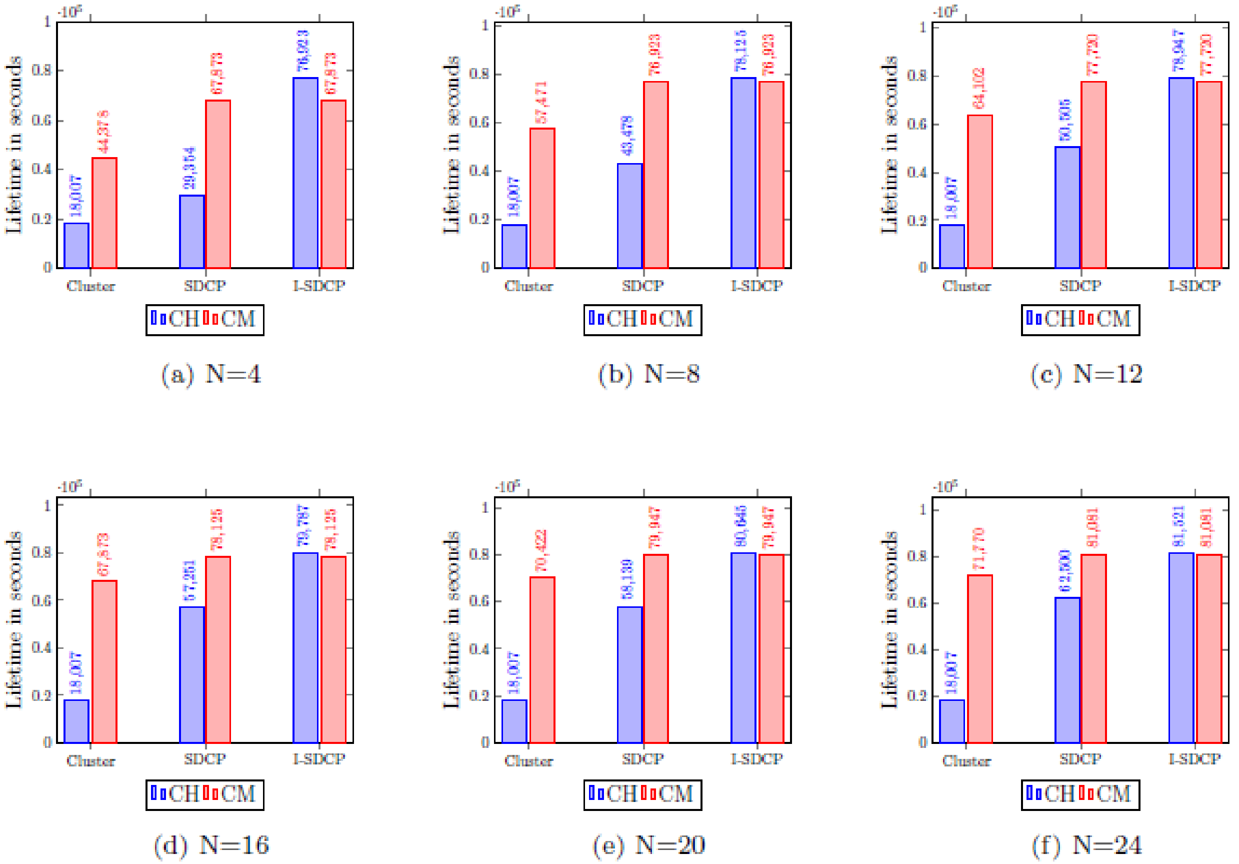

Fig. 7 Timeline in seconds for the first node failure within a cluster for initial energy 50J

node within the cluster. The number of clusters, node density, and communication range are decided by the application requirements based on the sensing intervals and latency requirements. Hierarchical implementation is also feasible for ISDCP.

Time synchronization is critical for the implementation of ISDCP as the rare event mode is based on the collision sensed by the CH. To avoid any false negatives, the CH is scheduled to be in the receive mode for a constant period of time, considering the timing offsets expected of other nodes based on the worst-case analysis. The ACK and/or the NACK packets from the CH act as beacon signals for the CM nodes that require synchronization.

5.3 Simulation results

The Castalia software, an OMNET++ based simulator is used for verifying the proposed ISDCP. The simulation is carried out in a field of 50 m*50 m area. The initial energy of all the sensor nodes is set to 50 J. Results from various experiments are verified for the implementation of ISDCP. The simulations were carried out for different parameters like variation in the number of clusters, variation in transmission power of radio transceivers.

In the first experiment, the effectiveness of ISDCP is compared with LEACH, SDCP and their energy consumption details are given in Fig. 6. The energy expenditure of CH and CM nodes is plotted after 5 minutes of network time. The ISDCP provides better result for all the cluster sizes and the results for ISDCP shows improvement with increased cluster size.

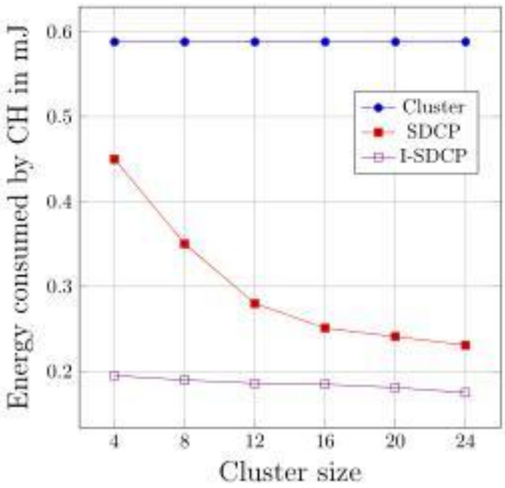

Fig. 8 Comparison of energy consumption of CH nodes for different cluster sizes

Fig. 7 presents the lifetime of the nodes under static clustering, SDCP and ISDCP. In static clustering, the same cluster is maintained throughout the entire period of the simulation without CH re-election to verify the effectiveness of ISDCP. The energy consumption of CH is compared with different protocols for different cluster sizes after 5 minutes of activity with no rare event as indicated in Fig. 8. The ISDCP

Table 1 Energy consumption of nodes detecting rare event for different cluster sizes for initial energy 50J

Cluster Members N	Energy after N rounds (mJ)		% Reduction in Energy	Lifetime in seconds		% Increase in Lifetime
	SDCP	ISDCP		SDCP	ISDCP	
4	105.72	96	9.19	60536	66034	9.08
8	452.04	384	15.05	56632	66291	17.06
12	1042.21	864.01	17.1	55267	66458	20.25
16	1876.21	1536.01	18.13	54578	66668	22.15
20	2954.05	2400.01	18.76	54163	67113	23.91
24	4275.73	3456.01	19.17	53886	67480	25.23

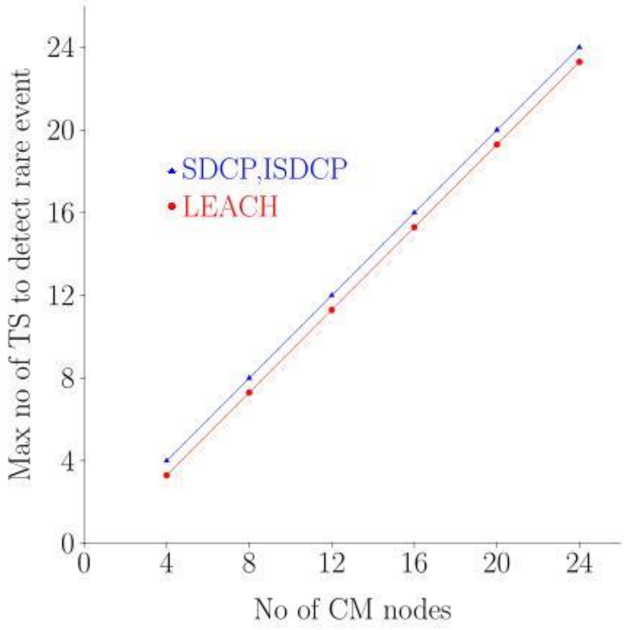

Fig. 9 Rare Event Detection Delay

performs better than other protocols for all the cluster sizes and the results improve with an increase in the cluster size. The plots indicate a better lifetime for ISDCP compared to SDCP and cluster.

Another set of experiments were conducted to verify the load on the nodes detecting a rare event in both SDCP and ISDCP. In this experiment, the same node is made to detect rare events from the first cycle without entering into quick loop mode with an initial energy of 50J.

The lifetime of the sensitive node for different cluster sizes and round lengths is reported in

Table 1. It is inferred from the table that the node detecting rare event in ISDCP provides an extended lifetime in the range of 9.08% to 25.23% compared to SDCP. Fig. 9 indicates the rare event detection delay for different cluster sizes. The figure indicates a minimal delay compared to LEACH for both ISDCP and SDCP due to the additional time slot towards the end of the cycle for collecting rare events by the CH node.

6. CONCLUSION

In this paper, ISDCP is proposed for rare event detection in cluster based networks to reduce the energy consumption of the nodes detecting rare events. The proposed protocol is evaluated against LEACH and SDCP and is found to have an enhanced lifetime than the other protocols. The overhead of CH is also reduced in the proposed protocol. Also, the additional overhead of CM that has detected rare events for transmitting the event within the cycle is distributed among the other CM nodes. The latency of the proposed protocol is maintained the same as that of SDCP. Further extension can be carried out in finding the optimal number of clusters based on the coverage constraints.

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AUTHOR PROFILES

Sundaravanan Jothiprakasam received his B.E from Bharathiyar University, M.E from Sathyabama University and Ph.D from Anna University. He is working as Assistant Professor in the Department of Electronics and Communication Engineering at Thanthai Periyar Government Institute of Technology, Vellore. He has more than 10 years of industry experience and 8 years of academic experience. His research interest includes Wireless Sensor Networks, Embedded Systems.

Senthil Murugan Boopalan received his B.E from Madras University and M.E from Anna University. He is working as Assistant Professor in the Department of Electronics and Communication Engineering at Thanthai Periyar Government Institute of Technology, Vellore. He has more than 17 years of teaching experience. He is currently pursuing his research in the field of Sensor Networks and Signal Processing.