Quality of Service-Based Cross-Layer Protocol for Wireless Sensor Networks

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Abstract—Sensor nodes in wireless sensor networks (WSN) are used for perceiving, monitoring, and controlling a wide range of applications. Owing to the small size of sensor nodes and limited power sources, energy-saving is critical for ensuring network longevity. Protocols in different layers consume energy for their function. It is possible to significantly reduce energy usage by implementing energy efficiency measures in the protocol design. Most protocols in the literature focus on the energy efficiency of individual layers. Recent studies have shown that cross-layer designs (CLD) are more energy-efficient than individual layer designs. Therefore, this article proposes a novel quality of service-based cross-layer (QSCL) protocol design by combining the IEEE 802.15.4-based MAC protocol in the data link layer and the LEACH-based routing protocol in the network layer to minimize energy consumption (EC). The dynamic duty cycle of the IEEE 802.15.4 protocol was modified based on the amount of data present in the node, which minimizes the EC of the data-transfer mechanism. The cluster head (CH) selection of the LEACH-based protocol was modified by considering the average residual energy (ARE) and distance of the nodes into account. This helps preserve the energy in the CH, thereby extending the lifespan of the network. Simulation results show that the proposed QSCL protocol outperformed existing protocols in terms of quality of service (QoS) parameters.

Keywords—clustering, cross-layer design, energy consumption, energy efficiency, MAC layer, network layer, network lifetime, quality of service (QoS), wireless sensor networks

1 Introduction

Sensor nodes in a WSN work together to monitor and control various applications. Due to their compact size, low power usage, and inexpensive cost, they find application in all aspects of our lives. These wireless sensor nodes are becoming increasingly popular in the Internet of Things (IoT) applications [1]. Considering the vast range of applications, sensor nodes equipped with tiny batteries must consume less power to maximize energy savings and extend their lifespan. Increasing the lifespan of a WSN reduces the cost of replacement or re-deployment [2][3].

The communication in WSN goes through different layers. These layers are stacked as shown in Figure 1. Each layer in this stack has a specific operation to perform. These layers are the application layer (APL), transport layer (TPL), network layer (NWL), data link layer (DLL), and physical layer (PYL) [4][5]. Apart from these layers, power, connection, and task management are the three management planes passing through each layer. These planes distribute tasks, connections, and power between nodes to increase the efficiency and lifespan of a network [6]. Each layer is comprised of a set of protocols that consume energy to function. According to a literature survey, cross-layer techniques use much less energy than individual-layer approaches [7]. Given the limited power and computational capabilities of sensor nodes, CLD has been chosen as an alternative to standard layered approaches [8]. As per the literature survey, the network and DLLs consume most of their energy owing to the nature of their operations. The proposed cross-layer protocol design combines these two layers to achieve energy efficiency [9].

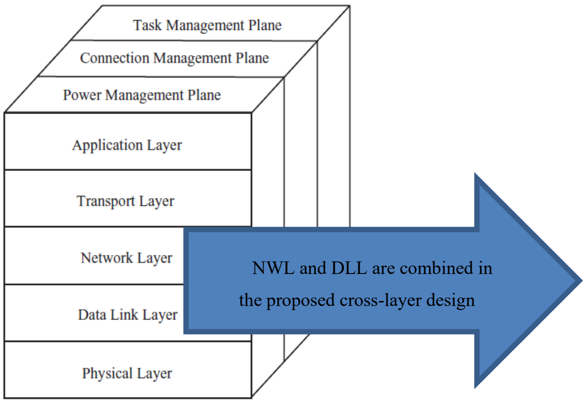

Fig. 1. WSN protocol stack [6]

When numerous sensor nodes are randomly deployed in remote regions such as forests, multi-hop communication is used. Therefore, an energy-efficient multi-hop routing protocol is desirable for the NWL [10]. Cluster-based protocols were found to be the most effective [11]. Sensor nodes in cluster-based networks self-organize into clusters. There are many clusters in a typical WSN, as shown in Figure 2. Each cluster contained a CH and a few cluster member (CM) nodes. Data is received by each CH from the CM nodes and processed before being sent to the sink node for further processing. LEACH-based protocols are widely used in cluster-based networks for energy-efficient applications [12].

In LEACH-based protocols, the operations are performed in rounds. Each round begins with the formation of clusters and ends with the transmission of data. Figure 3 shows the setup and steady-state phases of the complete round. In the steady-state phase, CHs collect data from their CM nodes and deliver them to the sink for further processing [13][14][15]. Depending on the quantity of data to be delivered, the duration of each round may vary. When performing these tasks, the CH uses relatively more energy than the CM nodes. Therefore, CH energy depletes faster than the energy of CM nodes in the cluster [2]. This study proposes a method for balancing the residual energy (RE) of all network nodes based on the RE of the nodes and their distance from the sink.

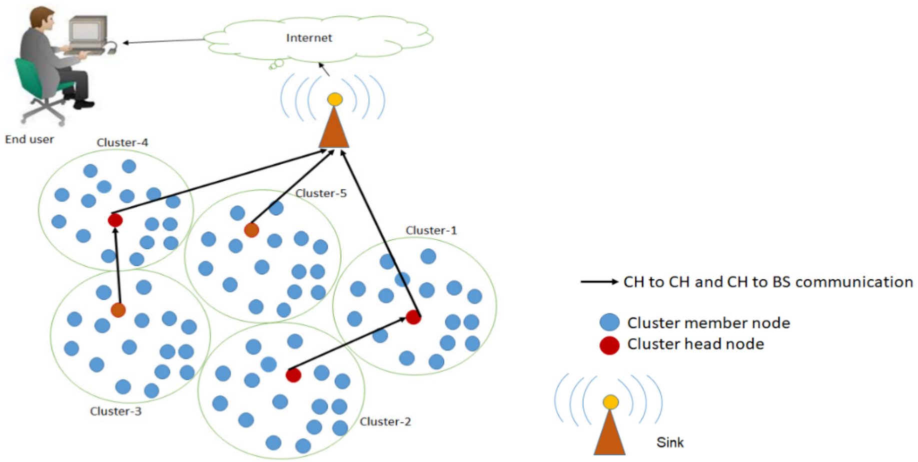

Fig. 2. Cluster structure of WSN [6]

The DLL consists of two sublayers: medium access control (MAC) and logical link control (LLC). Among these two, the MAC layer requires more energy for its transceiver operation. Therefore, an energy-efficient MAC scheme is essential to minimize the EC associated with transceiver events, such as wake-up, sleep, retransmissions, and control packet transfers detailed in Section 3.1.

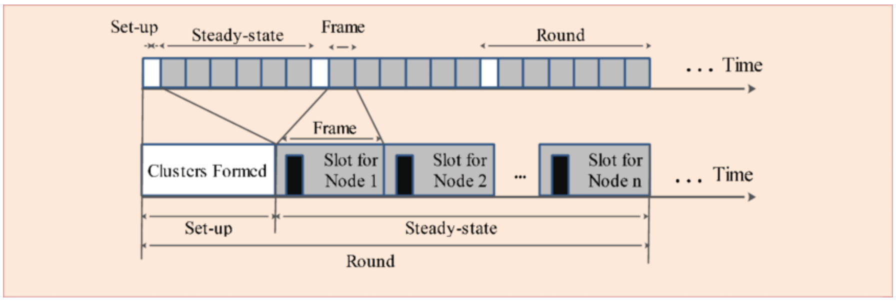

Fig. 3. Set-up and steady phase of one round in LEACH-based protocols [12]

Quality of service (QoS) is a measure of the performance of the WSN. Some of the parameters often used in WSNs as a measure of QoS are network lifetime, energy efficiency, packet delivery ratio (PDR), end-to-end delay (EED), and routing overhead (ROH).

- ***Network lifetime*** is the duration (measured in rounds) to which network nodes remain alive.
- ***Energy consumption (EC):*** Sensing the environment, listening and waiting for the channel, sending and receiving messages, and sleeping are all activities that require energy from a sensor node [1]. The EC of a sensor node per second can be calculated using Equation (1).

$$E_{cons} = E_{cd} + E_{lw} + E_{Tr} + E_{Re} + E_{sl} \ (Joules/sec) \tag{1}$$

Here, E_{cons} is the EC of a node per second, E_{cd} is the energy utilized to sense and collect data, E_{lw} is the energy used for listening and waiting for the channel, E_{Tr} is the energy used to transmit messages, E_{Re} is the energy used to receive the messages, and E_{sl} is the energy used during the sleep state.

- ***Residual energy (RE):*** It is defined as the amount of energy remaining in a node. This can be calculated by subtracting consumed energy (E_{cons}) from the initial energy (E_{init}) of the node using Equation (2)

$$RE = E_{init} - E_{cons} \ (Joules/sec) \tag{2}$$

- ***Packet delivery ratio (PDR):*** It is defined as the ratio of data packets received (DPR) at the sink node to the total number of packets transmitted from the source nodes (PTS) [14][15][16]. We used Equation (3) to calculate the PDR.

$$PDR = \frac{Number\ of\ DPR\ at\ sink}{Number\ of\ PTS} \tag{3}$$

- ***Routing overhead (ROH):*** It is the ratio of routing packets to data packets [5][14]. This can be calculated using Equation (4)

$$ROH = \frac{Number\ of\ routing\ packets}{Number\ of\ data\ packets} \tag{4}$$

Keeping in mind the necessity of energy conservation in WSN, we propose a QSCL protocol that combines the NWL and MAC layer to reduce EC. The following is a summary of the contributions of our research:

- The proposed QSCL protocol effort is to extend the network's lifespan. This protocol combines IEEE 802.15.4-based data transfer with a LEACH-based routing method.
- The IEEE 802.15.4 CSMA/CA outperforms other MAC protocols in terms of EC, EED, and PDR for WSN applications. This MAC protocol was selected for the QSCL design. By doing this, the EC during data transmission is significantly decreased [13].
- We proposed a CH selection procedure based on the nodes' RE and maximum probable distance at the network layer [7]. This reduces the EC for routing.
- We compared the performance of the proposed QSCL protocol with the existing "Energy-efficient cross-layer approach for wireless body area networks (EECLW-BAN)" and "Energy-efficient cross-layer (EECL)" protocols using simulation results. Simulation studies showed that the proposed QSCL outperforms the current

protocols by extending the lifespan of the network. Moreover, this technique improves the PDR and reduces the ROH [17].

In the remainder of this article, studies related to CLD [6][7] are discussed in Section 2. Section 3 describes the design of the proposed cross-layer protocol. Section 4 compares the QoS parameters of the proposed and existing cross-layer protocols. The conclusions are presented in Section 5 and Section 6 contains the references.

2 Related work in cross-layer design for the WSNs

To maximize energy efficiency, the majority of WSN protocols proposed in the literature focus primarily on the design of specific layers, such as the PYL, DLL, NWL, TPL, and APL. Because each of these protocols was designed to enhance the performance of a specific layer, they were not tuned to enhance overall network performance. The design of protocols by combining layers significantly improves the overall network performance by reducing energy usage [7][8]. Given the limited power and computational capabilities of sensor nodes, CLD has been chosen as an alternative to the standard layered approaches [9].

Numerous studies have been conducted to understand the EC of cross-layer protocols designed using the MAC and network layers. Among these, Zhang et al. [7] proposed a CLD based on the modified LEACH and S-MAC protocols. Because of the communication overhead in S-MAC, this protocol was unable to improve EC to a greater extent. Bahbahani et al. proposed a CLD using modified LEACH and TDMA protocols [12]. This protocol reduced the EC, but PDR was not improved. Cerli et al. proposed a CLD based on modified LEACH and CSMA protocols [17]. This protocol reduced the EC, but the PDR was not improved. Janbakhsh et al. proposed a CLD based on the modified LEACH and S-MAC protocols[18]. This protocol increased ROH due to the communication overhead in S-MAC. Deepak et al. [19] proposed a CLD based on modified LEACH and CDMA protocols. The EC is not significantly reduced in this protocol. The modified LEACH and CSMA/CA protocols that were proposed by Amutha et al. as the basis for CLD [20]. This protocol reduced the EC, but the PDR was not improved. Utilizing modified LEACH and TDMA, Chandravathi et al. [21] proposed CLD. The CH selection proposed in this paper reduced the EC; however, the PDR was not improved. Babber et al. [22] proposed a CLD that used modified versions of the LEACH and S-MAC protocols. This protocol could not reduce the EC due to more communication overhead in S-MAC.

From the existing cross-layer protocols, we have selected two recent protocols to assess the performance of the proposed protocol. EECLWBAN using the hybrid protocol [17] and an EECL for WSNs [18] are the two protocols that were chosen.

The existing EECLWBAN protocol combines an on-demand data transmission technique at the MAC layer with LEACH-based routing at the network layer. On-demand data transfer is used to send data from CMs to their CH and from CHs to the sink node. The LEACH-based hybrid protocol is used for energy-efficient route selection [17]. In this strategy, slots are solely assigned to active nodes and not to idle nodes. The CHs are selected based on their random probability, irrespective of their distances from the sink and their RE. In this approach, the setup phase requires more time than the steady-state phase. This allows less time for data transfer and, therefore, the PDR is reduced. The CH selection consists of merely the random probability of the node, which can select nodes with lower RE. This results in a further decrease in the node's RE. Additionally, frequent CH selection and cluster creation reduce the network's longevity.

The existing EECL protocol [18] takes the nodes' leftover energy into account while selecting the CHs. The EECL protocol combines an S-MAC-based data transfer with LEACH-based routing in which the CH selection procedure incorporates the remaining energy of nodes to reduce EC. However, the CH selection does not include the distance of the node from the sink. In addition to synchronization overhead, S-MAC data transmission involving request to send (RTS), clear to send (CTS), and acknowledgement (ACK) is costly in terms of energy usage and delay [23].

With the existing EECLWBAN and EECL protocols, data transfer and CH selection cost a greater amount of energy with a lower PDR. The proposed QSCL protocol uses a new data transfer method based on IEEE 802.15.4 at the MAC sublayer and an efficient routing algorithm based on LEACH at the NWL to minimize EC.

3 Proposed quality of service-based cross-layer (QSCL) protocol

The proposed QSCL protocol design has been distributed into three phases, each of which is described in this section. The flow of the proposed model is shown in Figure 4.

Phase 1: Selection of the most appropriate MAC protocol for CLD [24].
Phase 2: Implementation of the IEEE 802.15.4-based data transfer scheme.
Phase 3: Implementation of the proposed CH selection and CLD.

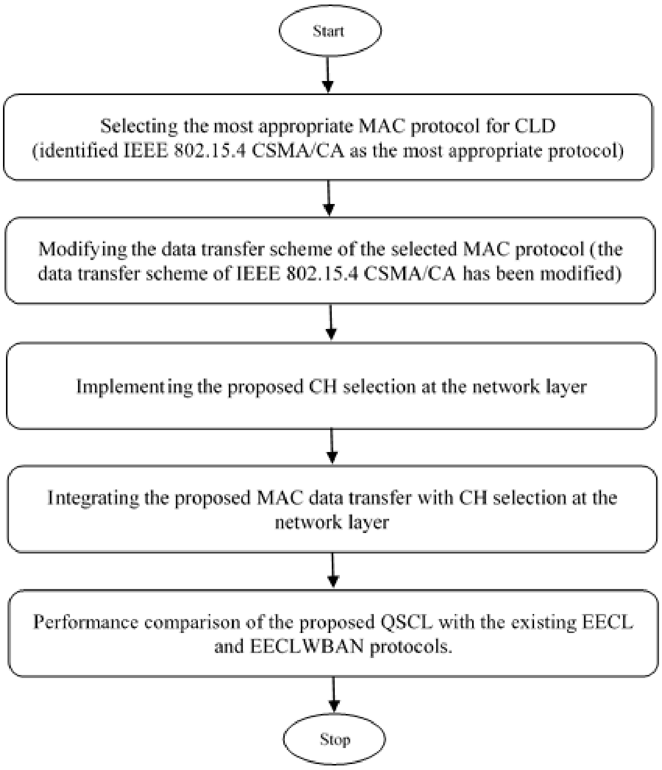

Fig. 4. Flow of the proposed model

3.1 Phase 1: Selection of the most appropriate MAC protocol for CLD

It is important to minimize the elements that affect the energy efficiency of the transceiver in a WSN. To achieve this, wake-up times, collisions, and retransmissions must be reduced. Finding an appropriate MAC protocol that reduces these values is critical [25]. To do this, the S-MAC, B-MAC, X-MAC, L-MAC, and IEEE 802.15.4 MAC protocols were chosen for comparison [24][26].

The B-MAC was designed in response to the increased EC of the S-MAC protocol owing to the communication overhead packets [27]. Therefore, from the identified protocols, excluding S-MAC, all other protocols were used for the comparative analysis. Simulations were run to determine which one could reduce EC when used in CLD. In order to compare the performance of protocols, the EC, RE, and received packet count are utilized as metrics [24].

Depending on the network configuration, the 802.15.4 permits two types of channel access mechanisms for the MAC sublayer: Beacon mode and non-beacon mode. In light of our scenario's high volume of traffic, we opted for a non-beacon mode of network operation. In this mode, CSMA-CA is un-slotted. Each time a device wishes to send data frames or commands, it awaits the conclusion of a random backoff period before sensing the channel. If the device detects that the channel is vacant, it sends the data;

otherwise, it waits for a random period before trying to access the channel again. Table 1 shows the simulation parameter settings that are used for the comparison of MAC protocols [28].

Four source nodes, a gateway node, and a server node make up the network being used to compare these MAC protocols. Finding an appropriate MAC protocol that maximizes data packet count while decreasing EC was a primary objective of the simulation [24][29][30]. The simulations were repeated ten times and the average of the results was used for the comparative analysis. Simulation results are discussed in the following sections.

Table 1. Simulation parameters used for the comparison of MAC protocols [24][28]

Parameters	Values
Message Length	10 bytes
Preamble duration of the transmitter	0.0001sec
Transmitter Power	2.24mW
B-MAC Specific	
Slot duration	0.025sec
Header Length	1 byte
X-MAC Specific	
Sensor slot duration	0.25sec
Gateway slot duration	0.1sec
Header Length	24 bits
L-MAC Specific	
Number of slots	8
Slot duration (identified from simulation)	50ms
IEEE 802.15.4 Specific	
Backoff method	Exponential
Maximum number of extra back offs	4
Base unit for all backoff calculations	0.00032 sec
Number of backoff periods of the initial contention window	2
Minimum backoff exponent	3
Maximum backoff exponent	5
Clear channel assessment detection time	0.000128 sec

Energy consumption (EC) comparison - The EC of these protocols is shown in Figure 5. The average EC is 0.359485 J for B-MAC, 0.987638 J for the X-MAC, 0.2852 J for the L-MAC, and 0.132777 J for the IEEE 802.15.4 MAC. As shown in Figure 5, the average EC of the IEEE 802.15.4 protocol is lower than that of the other protocols used in the comparative analysis [24].

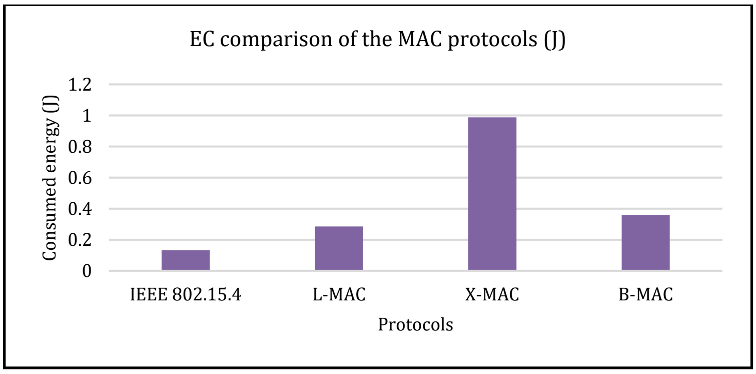

Fig. 5. EC comparison of the MAC protocols

Received data packets count comparison - The data packets received for the different MAC protocols with a simulation time of 100s are shown in Figure 6. As illustrated in Figure 6, IEEE 802.15.4 receives more packets than the other protocols.

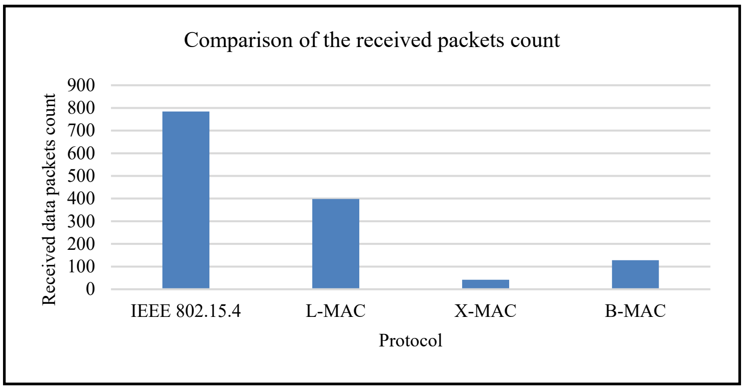

Fig. 6. Comparison of the received packets count

End-to-end delay (EED) comparison - The EED for the selected protocols are listed in Table 2. The EED of the B-MAC range was 40-1500 ms, 280-1320 ms for X-MAC, 100-400 ms for L-MAC, and 2-5 ms for IEEE 802.15.4. Compared to the other protocols, IEEE 802.15.4's EED is very low [24].

Table 2. End-to-end delay of MAC protocols

Parameters	MAC protocols performance comparison			
	IEEE 8802.15.4	***L-MAC***	***X-MAC***	***B-MAC***
End-to-end delay (ms)	2 - 5	100 - 400	280 - 1320	40 - 1500

Observations - IEEE 802.15.4 outperforms other protocols in terms of energy efficiency, EED, and packet delivery. Therefore, this protocol was chosen for the QSCL protocol design [24]. The proposed IEEE 802.15.4-based data-transfer scheme is described in Section 3.2.

3.2 Phase 2: Implementation of a proposed IEEE 802.15.4-based data transfer scheme

This section describes the novel data-transfer scheme developed for the proposed QSCL protocol using a modified IEEE 802.15.4-based protocol. After the formation of clusters, CM nodes send their sensed data to their CHs. The CH performs data fusion and then transmits to the sink either directly or via nearby CHs. Each CM node in the cluster selects whether or not to transfer data to the CH based on the proposed data transfer. This decision is based on the number of times the node has already sent data. The node makes this decision by selecting a random number (RN) between 0 and 1. If the RN is less than the packet delivery threshold ($pd_{threshold}$), the node sends data [31].

The proposed IEEE 802.15.4-based data transfer is a non-beacon-enabled method that uses un-slotted CSMA/CA. In this mode, devices are permitted to send data packets as required. Using a $pd_{threshold}$ and a RN generated by a node [32], the probabilities of channel access and successful transmission are assessed. Only when the condition is satisfied, the transceiver is switched on to perform the data transfer. If not, it will be in the OFF state. The ON state of the transceiver maintains the active status of the node, whereas the OFF state of the transceiver places the node in a sleep state. Consequently, the duty cycle is modified according to the availability of data [28].

Following the proposed IEEE 802.15.4-based data transfer, each time a device intends to send data frames or commands; it awaits the conclusion of a random backoff period before sensing the channel. If the device detects that the channel is not in use, it transmits the data; otherwise, it waits for an indeterminate amount of time before attempting to access the channel again. This technique reduces the collision rate [28].

The proposed data transfer scheme, shown in Figure 7, involves the following steps.

- Selection of a $pd_{threshold}$ value to facilitate dynamic data transfer
- Selection of an optimum value for maximum retry (max-retry)
- Data transfer using a modified MAC scheme

Simulations were performed to select the appropriate $pd_{threshold}$ and max-retry values. They are implemented as shown in Figure 7 in the proposed data-transfer scheme after determining the appropriate values for these parameters. The $pd_{threshold}$ and max-retry values, which provided better performance in terms of the stable network lifetime (SNL), RE, and PDR parameters, were selected for implementation in the proposed MAC data transfer scheme. Having larger SNL, RE, and PDR makes the network more efficient. However, obtaining a higher PDR along with a higher SNL and RE in the WSN is dependent on the below factors.

- The likelihood of successfully accessing a medium decreases as the number of nodes contending for channel access rises. This results in a decrease in PDR performance.
- EC increases as data transmission increases. Obtaining a higher PDR while maintaining higher SNL and RE is always a challenge.

The modified MAC scheme begins the data transfer by initializing the number of retries, max-retries, and $pd_{threshold}$. As long as the number of retries is less than the max-retry, nodes that are ready to send data, create an RN and compare it with the $pd_{threshold}$. If the RN is less than the $pd_{threshold}$, the data transfer is successful; otherwise, the nodes retry the new RN. This operation is repeated until the node reaches its maximum retry value. Data transmission fails if RN is greater than the $pd_{threshold}$ in all attempts. Thus, the implementation of RN and $pd_{threshold}$ in MAC data transfer enables collision-free dynamic data flows in the network. The dynamic data transfer adjusts the active sleep period of each node according to the amount of data. Thus, the QoS performance has been improved in comparison to existing protocols [29][33][34].

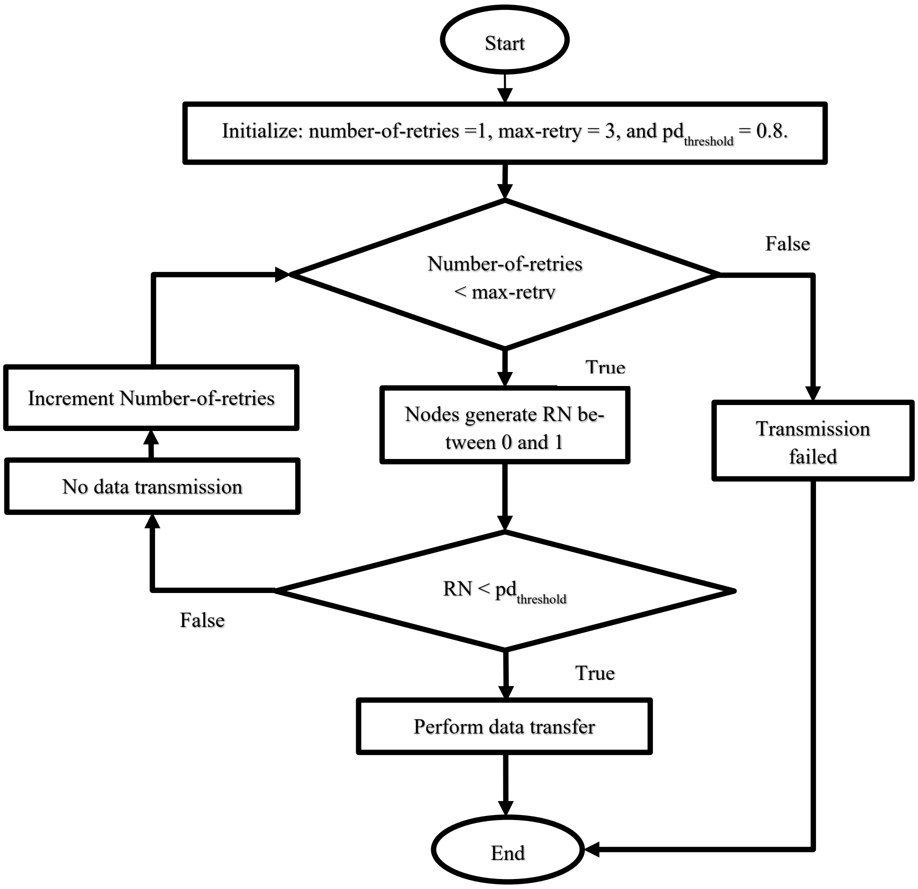

Fig. 7. Proposed data transfer scheme for the QSCL protocol

Selection of $pd_{threshold}$ value - To select an appropriate value for the $pd_{threshold}$, simulations were run with the parameters specified in Table 3. MATLAB was used for the simulations. The IEEE 802.15.4 asynchronous CSMA protocol simulation was performed using the communications ToolboxTM library for the ZigBee® protocol available in MATLAB [35].

Table 3. Simulation parameters [18]

Parameter	Values
Simulation Area (x, y)	100 meters x 100 meters
Sink Location (x, y)	50 meters x 50 meters
Initial Energy of nodes	0.5 Joules
E_{TX} & E_{RX}	$50 * 10^{-9}$ J
Energy Spent for data aggregation	EDA=$5*10^{-9}$ J
Data packet size	4000 bytes
Hello packet size	100 bytes
Radio Range	RR = 0.5*Area.x*√2 meters

From Figure 8, it can be observed that RE gradually decreased as $pd_{threshold}$ increased from 0.0 to 0.8 and there was a significant decrease after 0.8. An increase in the $pd_{threshold}$ above 0.8 leads to a significant decrease in RE, and therefore, $pd_{threshold}$ = 0.8 was chosen.

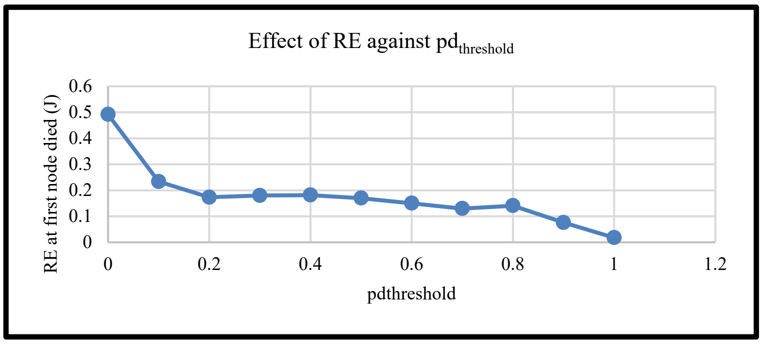

Fig. 8. Effect of RE against $pd_{threshold}$

Selection of optimum value for max-retry - To identify the optimum value for max-retry, simulations were run with values ranging from two to ten. The chosen retry value is incorporated into the proposed data transfer scheme, as shown in Figure 7. The max-retry parameter is set to the value that provides the most consistent network performance in terms of SNL. Simulations were conducted for 100-500 nodes and the average results were used for the SNL performance analysis.

Stable network lifetime (SNL) - This was measured in rounds. This is defined as the number of rounds in which all nodes remain alive before the first node dies. The simulations were run with the number of retries ranging from two to ten, and the number of rounds for which all nodes (100%) remained alive was calculated, as shown in Figure 9. The results show that the number of rounds was higher for retry three. In other words, the SNL for a retry value of three was higher. The retry and corresponding round numbers for which all nodes are alive are shown in Figure 9. Because max-retry three has a long SNL, it was found to be optimal for the proposed data transfer scheme [34].

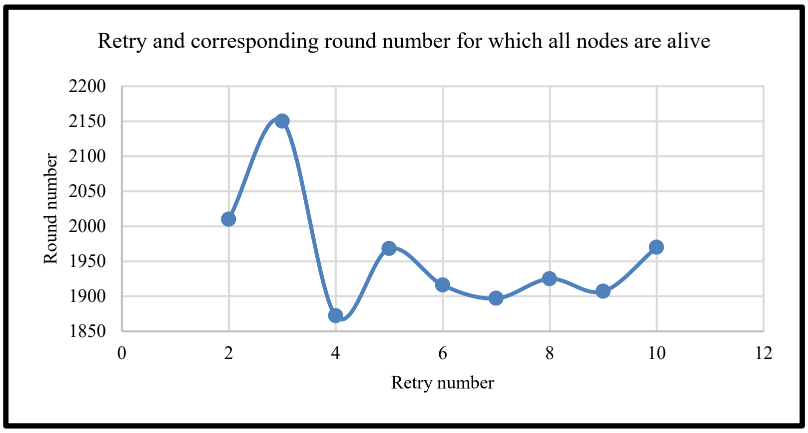

Fig. 9. Retry and corresponding round number for which all nodes are alive

3.3 Phase 3: Proposed CH selection and cross-layer design (CLD)

This phase describes the proposed CLD, which combines the CH selection mechanism proposed in this section with the MAC scheme proposed in phase 2. The subsequent sections detail the proposed CH selection, cluster construction, and CLD procedure.

QSCL is a cross-layer protocol that is located in the network layer. As shown in Figure 10, it collects the data frames from the MAC sub-layer and passes them via the most energy-efficient path to the sink. QSCL transmits data using the energy-aware probabilistic distance method. Collaboration at the network layer facilitates the identification of energy-efficient routes to conserve energy.

The proposed data transfer scheme and routing scheme are integrated into the CM and CH nodes. The advantages of the proposed QSCL design are that it reduces EC and avoids packet loss during data transfer. The cross-layer architecture of the QSCL protocol is shown in Figure 10. The following subsections describe the QSCL design to achieve these advantages [24][36].

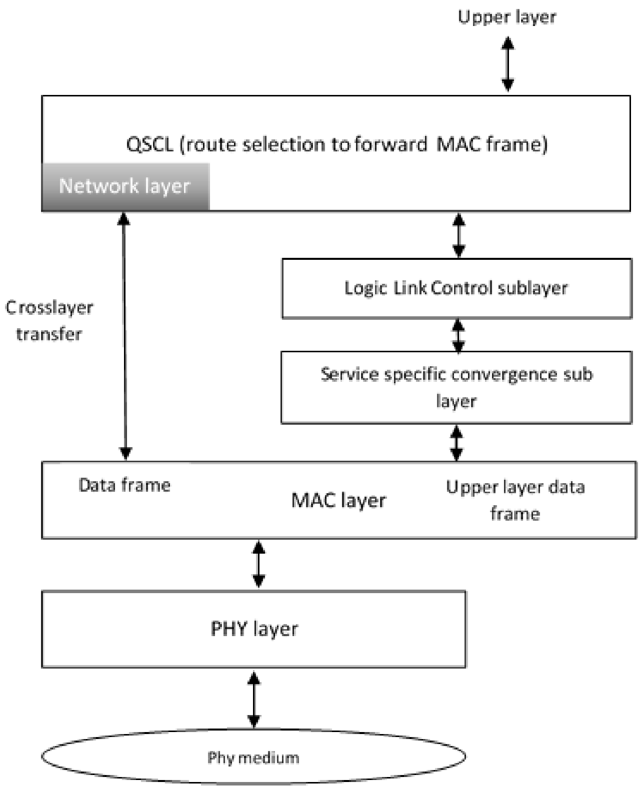

Fig. 10. Cross-layer architecture of QSCL protocol

Proposed CH selection mechanism at the network layer - Figure 11 illustrates the proposed CH selection process. The CH selection process began at the start of each round, and only nodes with RE higher than the ARE of the network participated. The ARE of a network with 'n' nodes can be determined using Equation (5), where RE_i is the RE of node i [16]:

$$ARE = \frac{1}{n} \sum_{i=1}^{n} RE_i \tag{5}$$

Random numbers between 0 and 1 are generated by the nodes participating in the CH selection process. The generated RN is compared to the probability (P_i) calculated using Equation (6). Nodes with RN less than the calculated P_i are eligible to become CHs in that round. The probability of a node becoming a CH is calculated using Equation (6), which is based on its maximum probabilistic distance from the sink. The distance of sensor node 'i' from the sink node is indicated by d_i [16]:

$$P_i = 1 - \frac{d_i}{max\,(d_i)} \tag{6}$$

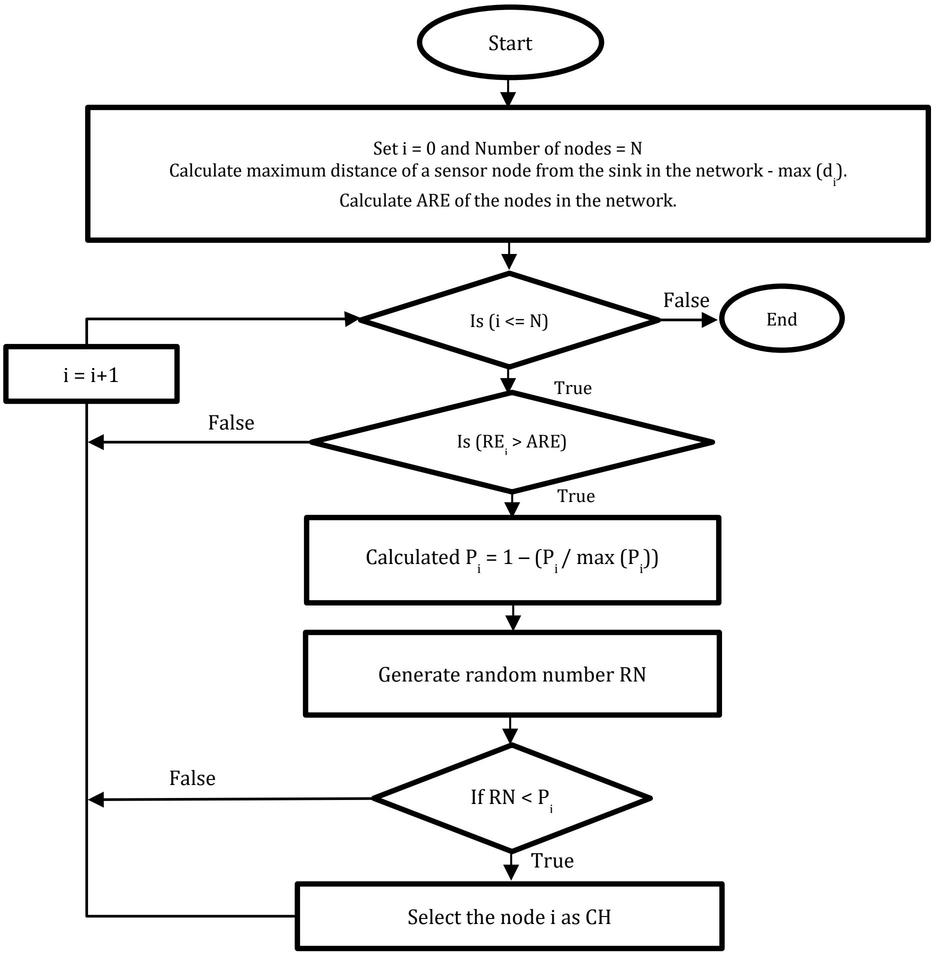

Fig. 11. Proposed CH selection mechanism [34]

In the proposed CH selection using maximum probabilistic distance and ARE, the following procedures are carried out:

- At the start of each round, each node in the network updates its RE to the sink node.
- The sink node calculates the networks' ARE and sends it back to all the nodes in the network.
- Each node compares its RE to the ARE it has received.
- Only nodes with RE values greater than ARE will be eligible for distance calculation in that round.
- The maximum distance max (d_i) and probable distance (P_i) are determined for the eligible nodes.
- The nodes with the highest P_i will be chosen as CH for the current round.
- This is repeated for each round.

Example cluster scenario:

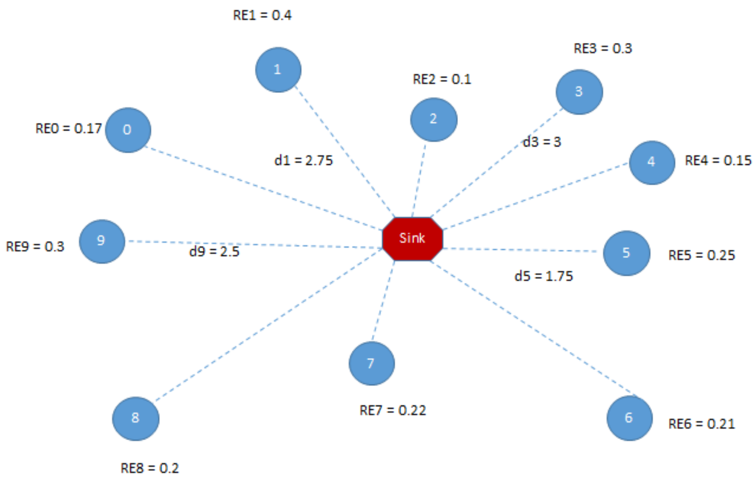

Fig. 12. A WSN with random deployment of nodes around a sink node

Figure 12 shows an illustrative scenario for the proposed CH selection procedure. In this example, ten sensor nodes are randomly distributed around a sink node. The RE and the Euclidean distance to the sink node are also indicated for each node.

- Each of the ten nodes transmits RE data to the sink node.
- Using these data, the sink node calculates the ARE value as 0.23joules.
- RE is greater than ARE for nodes 1, 3, 5, and 9, and so the Euclidean distance using Equation (7) is determined just for these nodes. Table 4 summarizes the calculated distances.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{7}$$

Table 4. Calculated distances between nodes and sinks

Node_id	Euclidean distance from a node to sink $d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$	Order based on max (d_i)
1	$d_1 = 2.75$	2
3	$d_3 = 3.00$	1 (higher)
5	$d_5 = 1.75$	4
9	$d_9 = 2.50$	3

- As can be seen from Table 4, the distance between node 3 and sink ($d_3 = 3$) is greater than other distances. Therefore, max (d_i) = 3. Thus, the node at the maximum distance is calculated.
- The probability of these nodes is calculated to identify the node having the maximum P_i to select it as CH for the current round using Equation (6).

- Table 5 indicates the probability of nodes becoming CH. As shown in Table 5, node 5 has a higher probability (P_i) of becoming CH for the current round.
- Thus, the distances d_i and max (d_i) are used to select the CHs for the current round.

Table 5. Probability of nodes becoming a CH

Node_id	Probability (P_i)
1	0.08
3	0.0
5	0.42 (higher)
9	0.17

Proposed QSCL protocol design - The proposed QSCL protocol design begins each round with a setup phase and ends with a data-transfer phase. The setup phase includes the selection of CHs and cluster formation using the proposed LEACH-based technique outlined in Section 3.3. During the steady-state phase, the CM nodes send data to the CH using the proposed IEEE 802.15.4-based data transfer mechanism described in Section 3.2 [16]. The CH performs data fusion and then transmits to the sink either directly or via nearby CHs. Each CM node in the cluster selects whether or not to transfer data to the CH based on the proposed data transfer. This decision is based on the number of times the node has already sent data. The node makes this decision by selecting a RN between 0 and 1. If the RN is less than the $pd_{threshold}$, the node sends data [31].

4 Comparison of QoS parameters of the proposed QSCL protocol with the existing EECL and EECLWBAN protocols

4.1 Simulation environment

A comparison of the proposed QSCL protocol performance against existing EECLWBAN [17] and EECL [18] protocols is presented in this section. We implemented the CH selection and data transfer schemes of QSCL, EECL, and EECLWBAN in separate modules and conducted the simulations by varying the number of nodes from 100 to 500. Then the average of the results is used for the performance evaluation. The simulation parameters are listed in Table 3. The simulation was set up with a sink in the center of a random distribution of sensor nodes. Sample simulation screenshots with 100 nodes are shown in Figure 13. After deployment, the nodes remain static in their positions.

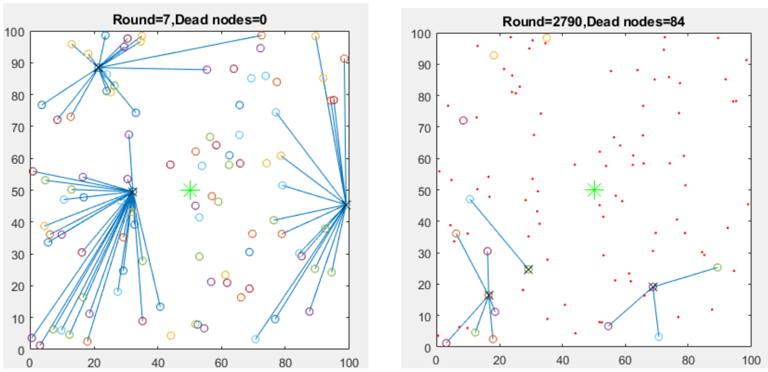

Fig. 13. Sample simulation screenshot at different rounds

4.2 Simulation results and comparative analysis

Network lifetime analysis - Network lifetime can be evaluated by counting the number of alive or dead nodes in each round. In this section, we compare surviving nodes at the end of each round.

As shown in Figure 14, for SNL, all nodes were alive for 198, 63, and 19 rounds for the proposed QSCL, existing EECL, and EECLWBAN protocols, respectively. The round numbers corresponding to 80 percent of the nodes remaining alive were used to compare the three protocols' reliable network lifetime (RNL). The RNL of the QSCL, EECL, and EECLWBAN are 572, 396, and 24 rounds respectively as shown in Figure 14 [16].

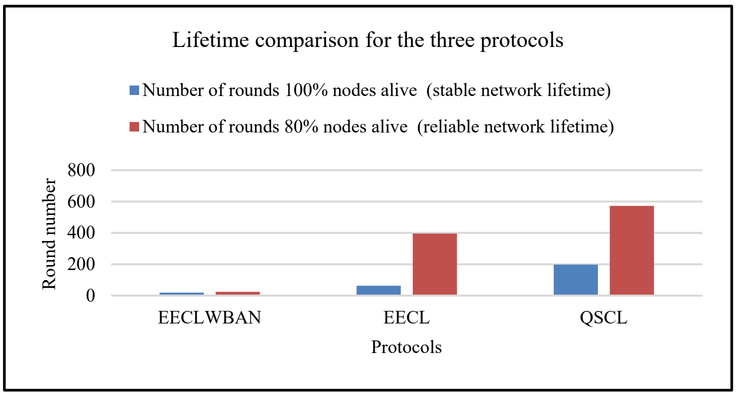

Fig. 14. Lifetime comparison for the three protocols (in rounds)

Residual energy (RE) - The RE of the proposed and existing protocols is shown in Figure 15. It can be observed from the graph that 50% RE exists up to 615 rounds in the proposed QSCL protocol, compared to 469 rounds for the EECL protocol and 271 rounds for the EECLWBAN protocol. The RE of the networks becomes zero in 3,157 rounds in the case of the proposed QSCL protocol, compared with 2,545 rounds in the EECL protocol and 1,592 rounds in the EECLWBAN protocol.

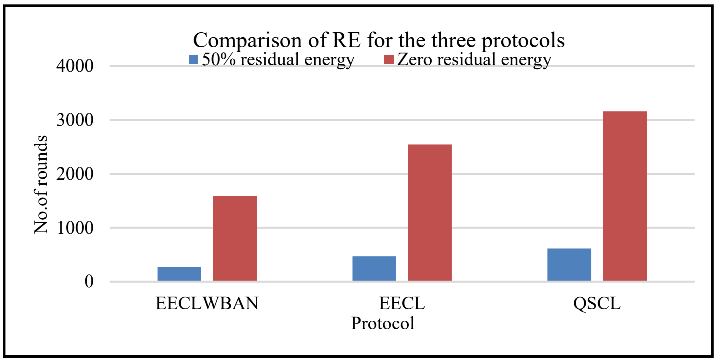

Fig. 15. Comparison of RE for the three protocols (in rounds)

Data packets dropped (DPD) - Figure 16 shows a comparison of the DPD of the proposed and existing protocols. The results indicate that zero packets are dropped in the proposed QSCL for up to 199 rounds, 64 rounds for EECL, and 20 rounds for EECLWBAN respectively.

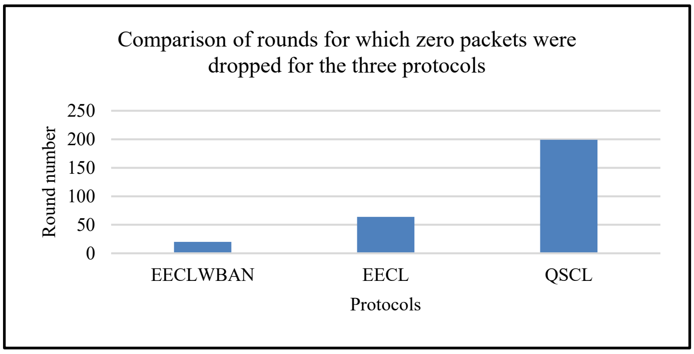

Fig. 16. Comparison of rounds for which zero packets were dropped for the three protocols

Routing overhead packets (ROH) - These are control packets used across the network to keep track of the connections between the nodes. The overhead packets in a network can also differ depending on the routing protocol used. This affects the energy efficiency and the latency of the network. A good protocol should have a low ROH to reduce EC and latency [16].

Figure 17 shows a comparison of the average ROH packets for the proposed and existing protocols. The proposed QSCL protocol has an average overhead of 1,554, which is significantly lower than that of the existing EECL protocol (1,743). However, it was greater than 763, which is the value obtained for the EECLWBAN protocol.

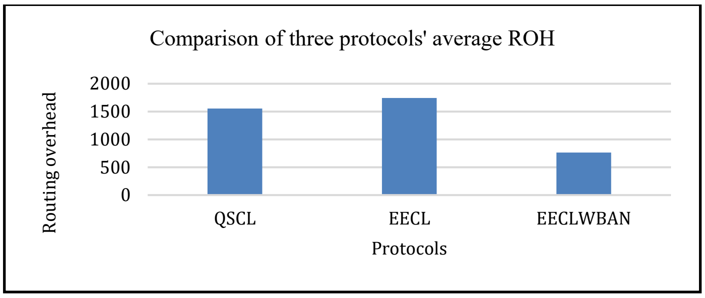

Fig. 17. Comparison of three protocols' average ROH

Packet delivery ratio (PDR) - The PDR was calculated using Equation (3). The average PDRs for the proposed QSCL, existing EECL, and EECLWBAN protocols were 81.398 percent, 79.421 percent, and 70.242 percent, respectively. As shown in Figure 18, the average PDR of the QSCL protocol is 1.977% higher than that of the EECL protocol and 11.156% higher than that of the EECLWBAN protocol [14][15][16].

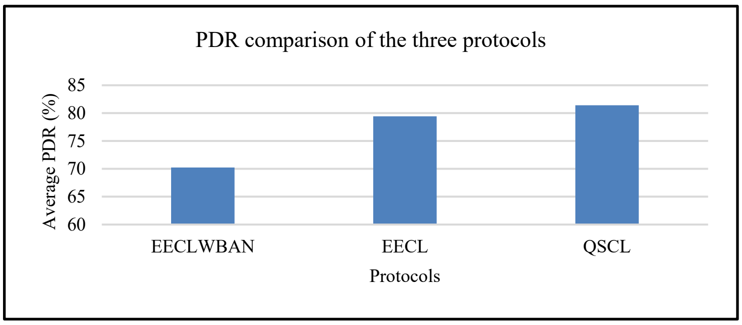

Fig. 18. PDR comparison of the three protocols

4.3 A comparison of the QSCL, the EECL, and the EECLWBAN protocols

Table 6 compares the QSCL, EECL, and EECLWBAN cross-layer protocols by their lifetimes, number of alive nodes, RDP counts, ROH counts, and PDR values.

The proposed QSCL protocol has an SNL that is 10.42 times longer than that of the EECLWBAN protocol and 3.14 times longer than the EECL protocol. The RNL of the proposed QSCL protocol is 23.83 times longer than that of the EECLWBAN protocol and 1.44 times longer than that of the EECL protocol.

Table 6. Comparison of existing and proposed protocols

Parameters	Protocols		
	EECLWBAN	***EECL***	***QSCL***
Stable Network Lifetime (up to round) (100% nodes alive)	19	63	198
Reliable Network Lifetime (up to round) (80% nodes alive)	24	396	572
50% of residual energy (up to round)	271	469	615
Zero residual energy (up to round)	1592	2545	3157
Zero packets dropped (up to round)	20	64	199
Average routing overhead (in packets)	763	1743	1553
Average packet delivery ratio (%)	70.242	79.421	81.398

It can be observed that 50% RE exists up to 615 rounds in the proposed QSCL protocol, compared to 469 rounds for the EECL protocol and 271 rounds for the EECLWBAN protocol. In the proposed QSCL protocol, it takes 3,157 rounds for the RE of the networks to reach zero. In the EECL protocol and the EECLWBAN protocol, it takes 2,545 rounds and 1,592 rounds, respectively.

The proposed QSCL protocol did not drop any packets until round 199. However, the existing EECL protocol began to drop packets after 64 rounds, while the EECLWBAN protocol began to do so after 20 rounds. This increases the proposed QSCL protocol's PDR.

The proposed QSCL protocol has an average overhead of 1553, which is significantly lower than that of the existing EECL protocol (1743). The average PDR of the proposed protocol is 1.977% higher than that of the EECL protocol and 11.156% higher than that of the EECLWBAN protocol.

4.4 Limitation and future scope

Due to hardware implementation challenges such as cost and number of sensors, our work was limited to simulations. In the future, the proposed approach may be implemented in hardware as well. In the designed model, only two layers are included. Cross-layer designs may in the future incorporate more than two layers concurrently. Improving energy efficiency by extending this concept to all layers is the future scope. In the developed model, only static networks were considered for cluster formation and data transport. This strategy could be used on mobile networks in the future.

5 Conclusion

In a WSN, sensor nodes equipped with tiny batteries consume less power to increase their energy efficiency and lifespan. A WSN uses a layered framework to organize its protocols. Among all the layers, the network and data link layers consume most of the energy owing to the nature of their operation. In terms of energy efficiency, the cross-layer protocols outperformed the individual-layer protocols. Therefore, this article proposes a cross-layer protocol design that combines these two layers, which significantly reduces energy usage. In the NWL, the proposed QSCL protocol is a modification of the LEACH protocol, whereas in the MAC layer it is a modification of the IEEE 802.5.4 CSMA/CA protocol. The simulation results shown in Table 6 indicate marked improvements in the lifetime, RE, ROH, and PDR in the proposed QSCL protocol compared with the EECLWBAN and EECL protocols. The proposed QSCL protocol extends the SNL by 135 rounds compared with the EECL protocol. With existing techniques, the ROH is reduced at least 1.12 times and the PDR is increased by at least 1.977%. Modifications to the network layer CH selection and MAC layer data transfer in the proposed QSCL protocol contribute to an overall increase in WSN QoS performance.

Significant improvements have been made to the ability to route packets at the NWL in the proposed QSCL protocol. This is accomplished by enhancing the energy efficiency of the CH selection process, which is the primary energy consumer at this layer. In addition, the improved data transport technique at the MAC layer helps to conserve energy. PDR with reduced ROH is cost-effective for long-term remote monitoring applications such as intruder detection in deserted regions, animal habitat monitoring, and forest fire detection, among others. Thus, the proposed CH selection improved the network's communication architecture, and the reduced EC at the MAC layer for data transfer paved the way for the development of several IoT-based applications.

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