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QoS-Aware and Heterogeneously Clustered Routing Protocol for Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSNs) have gained much attention in today's research domain for supporting a wide variety of applications including the multimedia applications. Multimedia applications that are regarded as the quality-of-service (QoS)-aware, delay sensitive, and bandwidth hungry applications, require enough energy and communication resources. WSNs being the energy-scarce network have now been designed in such a way that they can support these delay-sensitive and time-critical applications. In this paper, we propose an energy-efficient routing protocol for heterogeneous WSNs to support the delay sensitive, bandwidth hungry, time-critical, and QoS-aware applications. The proposed QoS-aware and heterogeneously clustered routing (QHCR) protocol not only conserves the energy in the network, but also provides the dedicated paths for the real-time and delay sensitive applications. The inclusion of different energy-levels for the heterogeneous WSNs also provide the stability in the networks while minimizing the delay for the delay-sensitive applications. Extensive simulations have been performed to validate the effectiveness of our proposed scheme. Our proposed routing scheme outperforms other state-of-the-art schemes in terms of the delay performances.**

***Index Terms*—Wireless Sensor Networks, energy efficiency, quality of service, real-time traffic.**

I. INTRODUCTION

Wireless sensor networks (WSNs) have gained much attention in the modern world because of their sensing capability. The micro-electro-mechanical system [1], [2] provides tiny low-power sensor nodes. The sensor nodes can sense, process, and then forward the data to other nodes for further investigation. The architecture of a tiny sensing node is shown in Fig. 1. Tiny sensing nodes can be applied to various fields to sense the required data. WSNs have found their way to many fields, such as health, industry, military, civil, and transportation systems [3], [4], [5], [6]. These sensing nodes have limited resources. Scarce resources with limited battery life demand from designers of tiny sensing nodes the design of energy-efficient platforms, operating systems, radio modules, and communication protocols for sensing nodes [7], [8].

WSNs have been extensively employed to sense the diverse kind of data. The various challenging applications of the WSNs as has been discussed in [9], [10], demand from sensor nodes to support the not only the energy-efficient communications paradigms but also the delay sensitive support. For this purpose, the energy-efficiency in WSNs have been regarded as the main motive for designing any communication protocol. The energy conservation in WSNs can be applied to various design patterns. The energy efficiency of WSNs can generally be classified into various approaches. Fig. 2 exhibits the classification of energy efficiency for various designs of WSNs.

The replacement or recharging of the batteries of sensor nodes incur a serious overhead. To overcome, this is issue different energy-conservation approaches at hardware and software platforms have been produced. Therefore, different energy conservation routing approaches are employed to conserve maximum energy in the system. Various energy-efficient routing protocols have been discussed in the literature [11], [12], [13], [14], [15]. Energy-efficient routing protocols can be classified into the following four types based on their energy conservation approaches [16], [17]:

Network Structure: The network layout becomes the basis for energy-efficient approaches. In network structure-based WSNs, the sensing nodes are clustered in such a way that nodes form the hierarchical layout. A flat network topology is also used by the routing protocols to conserve energy.

Communication Model: The sensing nodes communicate with one another through the exchange of packets or other negotiation messages. Different communication messages become the basis for the categorization of routing protocols for WSNs.

Reliable Routing: In this type of routing, the time-critical data are transmitted in such a way that quality of service (QoS) and energy efficiency are achieved within the network.

Topology Based: Routing protocols for mobile sensing nodes and location-aware sensing nodes are designed to save maximum energy. The network topology is usually focused on devising energy-efficient routing protocols for mobile sensing nodes.

Another classification of routing protocols for WSNs is based on the energy levels of sensing nodes. The nodes that are installed first seem to carry a lesser amount of energy than the nodes that are installed at a later stage. Thus, the sensing nodes are made to carry an unequal amount of energy. The initial energies of these sensing nodes are considered in designing energy-efficient routing protocols. WSNs with nodes that have an equal amount of energy are taken as homogeneous WSNs. Conversely, heterogeneous WSNs are networks in which the

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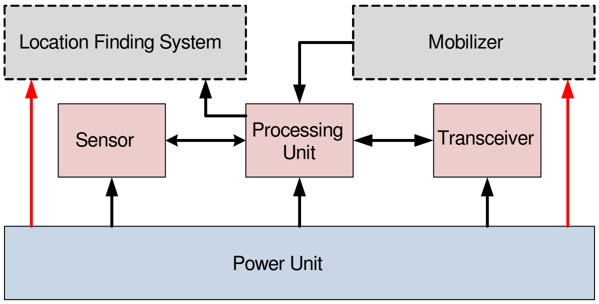

Fig. 1: The architecture of the sensor node consists of power unit, sensor, processing unit, transceiver, location finding system, and mobilizer

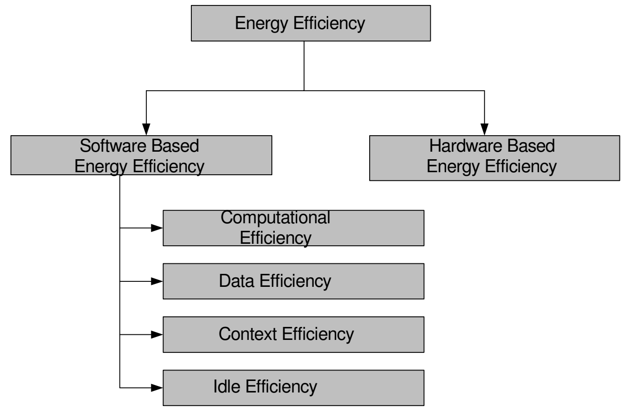

Fig. 2: Energy efficiency in WSNs can be classified into software-based energy-efficiency and hardware-based energy efficiency

sensing nodes have a different amount of energy [18], [19]. QoS-based energy-efficient routing protocols are needed for the transmission of time-critical data. Real-time applications (e.g., multimedia and time-critical queries) demand these efficient-routing protocols that provide minimum end-to-end delay, maximum load balancing, and fault tolerance. The QoS-based routing protocols proposed in [20], [21], [22] increase the network efficiency by prioritizing data packets.

The challenging applications of WSNs such as defined in [9], [10] compel the researchers to design routing protocols to support the various applications. The multimedia application which are the delay sensitive and bandwidth hungry applications also require the QoS-aware and energy-efficient routing protocols. The main motivations of our work has been discussed as follow:

- Multimedia applications are the delay sensitive and bandwidth hungry applications. They require enough network resources. For this purpose, qos-aware and energy - efficient routing protocols are designed.
- To avoid the delay in transmitting the delay sensitive traffic. The dedicated paths or paths with high priority are required for communicating the real-time traffic.
- The tiny senor nodes are installed with very limited energy resources. Therefore, this also compel the need of energy-efficient routing and communication schemes to conserve the maximum energy in the system.
- The energy-nodes with fluctuating energy levels in the heterogeneous WSNs also need to be adjusted to achieve the stability in the network.

In this paper, we propose an energy-efficient QoS-aware and heterogeneously clustered routing (QHCR) protocol for the transmission of real-time and non-real-time traffic. The concept of heterogeneity is employed to provide energy-efficient routing protocols for heterogeneous WSNs. Sensing nodes with different amounts of initial energies are categorized into four energy levels. Nodes belonging to each energy level are clustered with nodes belonging to the same energy level. QHCR protocol adopts multipath routing techniques that use several alternative routing paths from a source to a destination. The multipath approach also provides dedicated paths for real-time traffic. The best and shortest paths are selected on the basis of the new metric, which is based on the initial energies of the sensing nodes and other link metrics. These link metrics consider the traffic load and packet delivery ratio. The different energy levels with the clustered approach and the inclusion of multipath provide energy efficiency, QoS, load balancing, fault tolerance, and reliability in the WSNs. The main contribution of our paper can be summarized as follows:

- The concept of a hybrid energy level for heterogeneous WSNs is introduced in our paper. The hybrid energy level contains sensing nodes with fluctuating energy, and these nodes were not considered in previous studies.
- Considering the heterogeneity of the WSNs, cluster heads (CHs) are given a new parameter called the cost value (C_v) . The introduction of the (C_v) results in a more optimal clustering in heterogeneous WSNs compared with the other clustering approaches used in the literature.
- shortest path to the destination, i.e., the CH and the base station (BS), is selected based on the routing metric called the path metric P_{metric} . The P_{metric} is the novel metric that uses the combination of initial energy, expected transmission count, inverse expected transmission count, and minimum loss. The introduction of the P_{metric} in combination with the (C_v) and the hybrid energy level makes the QHCR energy efficient and delay tolerant for time-critical traffic

The rest of the paper is organized as follows: Section 2 presents the related work, and Section 3 discusses the energy consumption model. In Section 4, the heterogeneous network model is explained, and Section 5 presents the proposed scheme. The simulations results are detailed in Section 6, and Section 7 concludes the paper.

II. Related Work

Energy-efficient clustering routing protocols have gained much attention in WSNs. In these protocols, the sensing nodes are divided into smaller groups called clusters. One of the nodes in a cluster is assigned with more duties of communication than other nodes. This special node is called the CH, and the other nodes are referred to as member nodes. Member nodes send their sensed data to the CH. Then, the CH

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performs some type of data aggregation and then forwards that data to the BS. The whole clustering process classification is illustrated in Fig. 3. Different energy-efficient clustering protocols have been discussed in the literature [23], [24], [25]. The following discusses some clustered and QoS-aware routing protocols, their main contributions, and some of their limitations.

The equalized cluster head election routing protocol (ECHERP) [26] is based on balanced clustering. In the QHCR protocol, optimal clustering is introduced with the help of various linear systems. The Gaussian problem solving approach is commonly used for the balanced election of CH. The ECHERP improves a networks lifetime and stability compared with other conventional clustering routing protocols of WSNs. However, a limitation of this protocol is the non-supportive behavior for real-time traffic. ECHERP does not consider QoS-sensitive applications.

A heterogeneous WSNs based reinforced barrier-coverage approach has been proposed in [27]. In this scheme, the data related to the penetration from any intruder is forwarded to the base station (BS) with less delay. Through the creation of base graph, a novel approach has been discussed to transmit the delay sensitive traffic. However, as compared to our proposed approach, this technique does not consider the sensor nodes with fluctuating energy. In our scheme, the sensor nodes with fluctuating energy has been considered in the hybrid energy-level.

The energy-efficient and QoS-aware routing (EEQR) [28] protocol addresses both issues (energy efficiency and QoS). In the EEQR protocol, network traffic is prioritized on the basis of traffic content. A combination of static and mobile sink is devised to provide multi-paths for real-time traffic. The end-to-end delay is minimized by prioritizing network traffic. This approach enhances the network lifetime and stability of homogeneous WSNs. However, the EEQR protocol is limited by the fact that it does not address the heterogeneity of a network. Its performance usually drops when a heterogeneous network environment is used to ensure the QoS in WSNs.

Priority-based application-specific congestion control clustering (PASCCC) [29] is another clustering approach to ensure QoS in WSNs. PASCCC minimizes congestion through the efficient scheduling mechanism of CH. The packets of distant nodes are given higher priority by the CH than the packets of nearby nodes. This routing approach integrates the mobility feature of a sensing node. PASCCC also considers the heterogeneity of a network. However, the main limitation of PASCCC is that it does not address the delay for non-real-time traffic. Non-real-time packets suffer more in this routing approach, and thus the overall network throughput is affected.

In [30], an efficient QoS-aware data reporting approach is proposed to ensure the minimum end-to-end delay in clustered WSNs. The combinatorial approach is used to provide the intra-cluster data reporting control (Intra DRC) and inter-cluster data reporting control (Inter DRC). Congestion within the cluster is avoided using the Intra DRC, while the Inter DRC prioritizes the network traffic and assigns dedicated paths for real-time traffic. The minimization of end-to-end delay is the main contribution of this approach. However, as compared to our routing scheme, this clustering scheme do not consider the heterogeneity of the sensor nodes. The real-time, delay sensitive, and time-critical applications have been transmitted with less delay, but the stability of the network has also not been taken into account in this study.

The QoS-based adaptive route optimization and load balancing ROL [31] routing approach addresses the QoS-related applications of WSNs. ROL protocol employs the link metrics that can be modified according to the network traffic priority. It enhances network robustness and network lifetime.

Nutrient-flow-based distributed clustering (NDC) is an optimization criteria used by the ROL to achieve load balancing in hierarchical routing protocols. The use of various link metrics and NDC incurs an overhead on network traffic. The excessive congestion of ROL protocol affects real-time traffic and does not minimize the end-to-end delay

The cluster chain weight metrics (CCWM) [32] protocol accounts for the service parameters for achieving QoS and energy efficiency in the network. The CCWM protocol provides the balance cluster with the formation of optimal CH. The weight metric is commonly used to select appropriate CH. Load balancing and flexibility are provided by balanced clustering. The CCWM protocol also gives local clustering and a novel approach for data transmission, thus making it an energy-efficient routing approach for WSNs. However, the CCWM protocol does not support heterogeneous WSNs. The end-to-end delay is also not addressed in the case of real-time traffic. The simulation results show that our proposed scheme outperforms this scheme in network stability period, throughput, and delay. This is due to the inclusion of dedicated paths in our proposed scheme.

Multi-constrained QoS multi-path (MCMP) routing [33] is an energy-efficient routing protocol for WSNs. Data are delivered to the sink through multipath routing. The MCMP protocol minimizes the end-to-end delay and enhances network lifetime and stability. The QoS support is achieved by the optimization approach called linear integer programming. In the MCMP protocol, real-time traffic is transmitted to the sink through the path with the minimum number of hops. This approach introduces a congestion problem in some cases and renders the protocol less efficient during peak hours. This issue has been resolved with certain modifications in the protocol in its advance versions. Another limitation of this approach is that it does not address the heterogeneity of a network. Real-time and non-real-time traffic in heterogeneous WSNs is not supported by the MCMP protocol.

Authors in [34], have proposed a clustering scheme for the heterogeneous WSNs. In this scheme, the concept of sun nodes with static clustering scheme has been introduced to conserve the energy in the system. The sleep-awake cycle enables the tiny sensor nodes to conserve the maximum energy while improving the network life time. However, in this scheme the transmission of the multimedia applications with delay sensitive data has not been considered. Also, the heterogeneous WSNs do not include all the sun nodes in clustering scheme to take the clustering scheme.

Achieving energy efficiency and QoS in heterogeneous WSNs for tiny sensing nodes is a challenging task. The min-

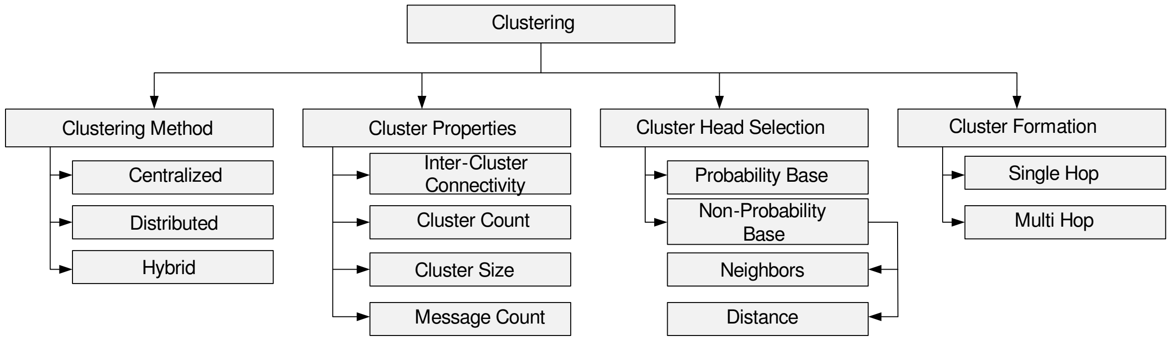

Fig. 3: Clustering in WSNs can be achieved by considering clustering method, clustering properties, cluster head selection procedure, and cluster formation

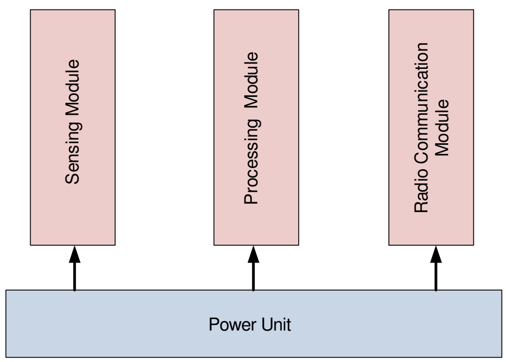

Fig. 4: Sensor node with three main modules.

imization of end-to-end delay and transmission delay, and the achievement of load balancing for lowpower sensing modules require a balanced and reliable energy-efficient routing approach. In the QHCR protocol, the limitations of various QoS-aware energy efficient routing protocols are addressed using different link metrics and by assigning different dedicated paths for real-time and non-real-time traffic. Heterogeneous WSNs show an increased network lifetime and throughput with the implementation of the QHCR protocol.

III. Energy consumptions Model

The energy consumption models discussed in [35], [36] consider energy consumption only by radio communication module. However, in this study, we use the energy consumption model suggested in [37]. This energy consumption model encompasses the energy consumed by all the modules involved in this heterogeneous WSNs. The energy consumed by the radio communication, processing, and sensing module are usually taken into consideration by our proposed scheme. The energy consumption by the following three modules is actually the overall energy consumption by the sensing node:

1) Sensing module.
2) Processing module.
3) Radio communication module.

Fig. 4 illustrates the sensor node with the three modules and a power supply. The sensing module conducts a sensing operation that can be broadly classified into three operations, namely, signal modulation, conversion of analog signal to digital, and signal sampling. The sensing module senses the data and then forwards them to the processing module. Then, the processing module performs the processing of data and controls the sensing and communication module. The radio communication module performs wireless communication. Its main components are the receiving and transmitting antenna and amplification units. The total energy consumed by the three modules is the sum of the energy consumed by the individual module. The total energy T_{EN} is given by Eq. (1).

TABLE I: State descriptions

Sign	Description
$1 \rightarrow 0$	Switched OFF
$0 \rightarrow 1$	Switched ON
$1 \rightarrow 1$	Switched ON
$0 \rightarrow 0$	Switched OFF

$$T_{EN} = S_{EN} + P_{EN} + W_{EN} \tag{1}$$

where S_{EN}, P_{EN} and W_{EN} are the energy consumption of the sensing module, processing module, and wireless communication module, respectively.

Sensors usually switch off their sensing module after sensing the data to conserve energy [37]. However, energy is still consumed during switching from ON state to OFF state, and vice versa. $S_{1\rightarrow 0}$ and $S_{0\rightarrow 1}$ are the energy used during transitions from ON to OFF and from OFF to ON, respectively. $S_{1\rightarrow 1}$ is the energy used by the sensing operation. Table I presents the transition of different states and their descriptions. The overall energy consumption by the sensing module is defined as

$$S_{EN} = S_{1\rightarrow 0} + S_{0\rightarrow 1} + S_{1\rightarrow 1} \tag{2}$$

In Eq. (1), P_{EN} is the combination of energy use by the current processor state and its state transition. Eq. (3) expresses the energy consumption of the processing module.

$$P_{EN} = P_{cpu-state} + P_{cpu-change} \tag{3}$$

where $P_{cpu-state}$ is the energy used in each state, and $P_{cpu-change}$ is the energy required to transition from one state to another. The energy consumption of the processing module is the combination of the processor state energy and the processor state transition. The three major states of a processor, namely, idle, run, and sleep, consume energy in their state transition. The energy consumption of the processing module can also be written as follows:

$$P_{EN} = \sum_{k=1}^{q} W_{cpu-state(k)} X_{cpu-state(k)} + \sum_{l=1}^{r} Y_{cpu-change(l)} Z_{cpu-change(l)} \tag{4}$$

where $W_{cpu-state(k)}$ is the energy consumed in state k, $X_{cpu-state(k)}$ is the time duration that a processor remains in state k, $Y_{cpu-change(l)}$ is the occurrence or frequency of the new state l, $Z_{cpu-change(l)}$ is the energy dissipation during the state transition of l, $k = 1, 2, 3...q$ is the current state, q is the number of the states, $l = 1, 2, 3, ..r$ is the kind of state transition, and r is the total number of state changes.

The energy consumption of the radio communication module W_{EN} is based on the radio model given in [38]. Energy consumption by the wireless module when the b number of bits is transmitted over the distance D is given by Eq. (5).

$$W_{EN} = W_{Tran/Rec}(b, D) = \begin{cases} bC_{en} + b\epsilon f(D)^2 & D < Do \\ bC_{en} + b\epsilon m(D)^4 & D > Do \end{cases} \tag{5}$$

where C_{en} is the energy consumption by the transmitting and receiving circuits, ϵf and ϵm are the amplification factors for free space and multipath propagation, Do is the distance factor so that $Do = \sqrt{\frac{\epsilon Af}{\epsilon Am}}$. W_{EN} is either the transmission energy or the reception energy so that W_{Tran} is the transmission energy consumed during the sending of b number of bits over the distance D, and W_{Rec} is the energy consumed during the receiving of b number of bits. This energy-model takes into consideration the energy-consumption from all the aspects. As compared to the other energy models, this energy model provides the more realistic energy distribution in the heterogeneous WSNs.

IV. Network Model

In heterogeneous WSNs, the sensing nodes usually have different amounts of energy. Some nodes have more energy than other nodes. These nodes can be classified into different energy levels because of the differences in their initial energies. In the QHCR protocol, a heterogeneous network model consists of 100 nodes with 4 different energy levels with an area of $400m \times 400m$. The four energy levels are categorized into low, medium, high, and hybrid energy levels. Heterogeneous WSNs are clustered by dividing the sensing nodes into different levels with respect to their energy. In [39], the two levels are used to optimally cluster the heterogeneous nodes, whereas three levels are used in [37]. In our network model, we use a fourth level called the hybrid energy level. The hybrid level considers the energy of nodes that do not fit into the already defined two or three energy levels of the sensing nodes. Moreover, the nodes with energy that keeps fluctuating during various rounds for CHs elections can be accommodated into the hybrid energy level. To obtain a more efficient clustering, four energy levels with their sensing nodes are shown in Fig. 5.

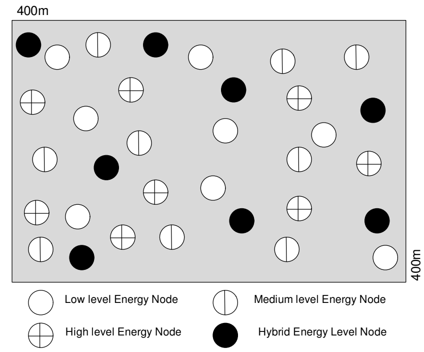

Fig. 5: Four energy level nodes and their random distributions

The nodes with low energy level have En energy in the low energy level. However, the medium energy level nodes with fraction r_1 have x times more energy than the low energy level nodes. The high energy level nodes with the fraction r_2 have y times more energy than the low energy level node, and the hybrid energy level nodes of fraction r_i have z times more energy than the low energy level nodes.

The energy in the hybrid energy level nodes is defined in Eq. (6) as follows: (6):

$$HB_{EN} = mr_i En(1 + z) \tag{6}$$

where $i = Lowenergylevel \leftrightarrow Highenergylevel$ In Eq. (7) the initial energy of the high energy level nodes is given by

$$H_{EN} = mr_2(1 - r_3)En(1 + y) \tag{7}$$

In Eq. (8) the energy of the medium energy level nodes is defined as

$$M_{EN} = mr_1(1 - r_2)En(1 + x) \tag{8}$$

Eq. (9) shows the energy of the low energy level nodes:

$$L_{EN} = m(1 - r_1)En \tag{9}$$

where in above (6), (7), (8), and (9). The total energy E_T of the all nodes in the four energy levels is given in Eq. (10) and (11):

$$E_T = HB_{EN} + H_{EN} + M_{EN} + L_{EN} \tag{10}$$

$$E_T = (mr_i En(1 + z)) + (mr_2(1 - r_3)En(1 + y)) + (mr_1(1 - r_2)En(1 + x)) + (m(1 - r_1)En) \tag{11}$$

The proposed network model consisting of four energy levels seems to have $r_1(x + r_2)(y + r_i z)$ times more energy than the single-level homogeneous network consisting of tiny sensing nodes. To make our routing operation smoother, we make the following assumptions:

- Sensing nodes are not mobile nodes.
- CH has to receive and send data all the time.
- Network packets are of the same size.
- BS is far away from the sensing nodes and is static in its position.
- Transmission of data is highly sensitive to delay and loss.

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- Sensing nodes have different amounts of energy from each other.

These assumptions help to design an energy-efficient and QoS-aware routing approach for WSNs.

V. Proposed Protocol

Features of clustering and intra-cluster communications at each energy-level enables the proposed QHCR protocol to conserve the maximum energy. The entire communication becomes energy efficient because of the multipath transmission links to the CH. The implementation of QoS-related parameters within the cluster makes the QHCR protocol more QoS aware and energy efficient. Time-critical data are provided with less delay with the implementation of the pathmetric (P_{metric}). QoS is achieved with the implementation of a cost value (C_v) and P_{metric}. C_v is used for the election of CH at each energy level and P_{metric} is used for intra-cluster communication to minimize the delay. The whole operation of the QHCR protocol is divided into multiple phases. The details of each phase are given below

A. Information gathering phase

In this phase, neighbor-related information of the tiny sensor nodes involved in the network is gathered by every node at each energy level. For this purpose, every node is equipped with a global position system (GPS), which then starts sending and receiving broadcast messages to and from other nodes belonging to a particular energy level. After receiving the broadcast message, other nodes respond to acknowledge the message. The collision has been minimized be employing the carrier sense multiple access/collision avoidance (CSMA/CA) [40]. The CSMA/CA protocol not only prevents collision in the network and hinders the two nodes from sending the broadcasts at the same time. After the exchange of broadcast messages, every node maintains the neighbor table. Information on the neighbor table is related to the number of neighbor nodes, their initial energy, and their distance from the BS or from each other. All sensing nodes update the BS after exchanging the information with one another. QHCR is centralized routing protocol. In centralized routing protocols, BS gathers all information of a network regarding the number of nodes, relative distance of nodes, and their initial energy [41]. The BS has the database of the whole network. This information is then used to elect the CH, which has been explained in the next subsection. The information-gathering phase is periodically repeated after every round (a round is a some specific time interval after which a new CH is selected) to collect the latest information on the sensing nodes used in the WSNs. The end of information gathering phase then leads to the CH election phase.

B. CH election phase

The CH election process occurs at each energy level. Cost value (C_v) is used for the election of CH at each energy level. The C_v value depends on the average distance of a node from the BS or from its neighbor, the initial energy of each particular energy level, and the number of nodes at that level. The information of average distance to the BS, total number of nodes, and initial energy information is provided by the BS. At every energy level, a node with a minimum value of C_v is elected as the CH. There will be only one CH for each energy level. There will be also four CHs in our proposed scheme. A node whose residual energy falls below a certain level will be then replaced with other CH with low value of (C_v) . Each level then becomes a separate cluster with multiple nodes. C_v can be calculated by the following Eq. (12):

$$C_v = \frac{D_{avg} \times W_d}{(M_r \times W_m) \times (En \times W_e)} \tag{12}$$

where D_{avg} is the average distance of every node from another neighbor, M_r is the number of nodes at each energy level or cluster, En is the initial energy of a particular energy level, and W_d, W_m, W_e are the weights of each criterion. The criteria are the average distance, the number of nodes, and their initial energy. The value of each weight assigned to this criterion is between 0 and 1. This weight is then used to prioritize criteria. The average distance of a node from its neighbors (D_{avg}) can be calculated as follows in Eq. (13):

$$D_{avg} = \frac{S_{dt}}{N} \tag{13}$$

where S_{dt} is the sum of all the nodes distance, and N is the neighbor distances of all nodes. The C_v values for the hybrid energy level nodes, high energy level nodes, medium energy level nodes, and low energy level nodes are given in Eqs. (14), (15), (16), and (17), respectively:

$$C_v(HB) = \frac{D_{avg} \times W_d}{((mr_i)W_m) \times ((En(1+z)) \times W_e)} \tag{14}$$

$$C_v(H) = \frac{D_{avg} \times W_d}{((mr_2(1-r_3))W_m) \times ((En(1+y)) \times W_e)} \tag{15}$$

$$C_v(M) = \frac{D_{avg} \times W_d}{((mr_1(1-r_2))W_m) \times ((En(1+x)) \times W_e)} \tag{16}$$

$$C_v(L) = \frac{D_{avg} \times W_d}{((m(1-r_1))W_m) \times (En \times W_e)} \tag{17}$$

The C_v of an energy level suggests that nodes with a longer distance will have a larger value of C_v. In this case, the nodes with a larger value of C_v have a minimum chance of becoming the CH. Conversely, nodes with a greater number of neighbors or with more energy have a smaller value of C_v . The nodes with a smaller value of C_v have more chances of becoming the CH. The CH with an optimum number of member nodes conserves the energy in the system by receiving the data from member nodes and then performs data aggregation. Redundancy in the data is minimized during data aggregation. This data aggregation conserves the energy in the system as the redundant data is suppressed from transmitting to the BS.

After the information-gathering and the CH election phases, every node at each energy level sets its C_v to a certain particular value. The node whose C_v is lower than the other nodes at a particular energy level elects itself as the CH. The

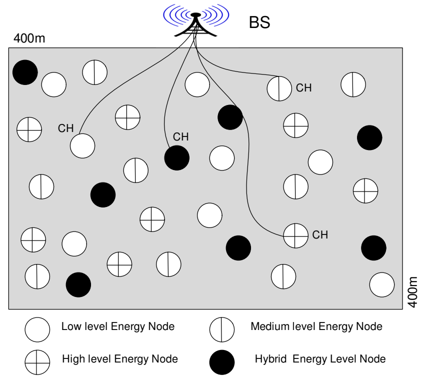

Fig. 6: Four energy level nodes with their cluster heads.

CH then forwards the message to other nodes in its radius range. The formation of CH at each energy level and its communication with the BS is illustrated in Fig. 6.

C. Node association phase

CHs are elected at each energy level. The elected CHs then start transmitting the broadcast messages to other non-CHs nodes. If the non-CHs nodes do not receive any broadcast message from any CH, they elect themselves as CHs. After electing CHs, the broadcast message is sent to each member node. The broadcast message carries the following information:

- The broadcast message contains the duration of count time (T_c). T_c is the time duration between two regular updates. In the WSNs, the sensing nodes regularly update the BS with a regular update after each T_c . These updates include the required sense data, node energy, and number of neighbors.
- User-related queries are tagged with attribute (A). CH sends the attribute-related information to each member node. Sometime users are more interested in obtaining specific information rather than the whole sensed information. These user-related queries are differentiated by attributes.
- Time division multiple access (TDMA) scheduling information for data transmission is also assigned by the CH. The TDMA-related information is forwarded to non-CH nodes by the CH.

The nodes in any of the four energy levels after electing CHs start transmitting the sensed data to the BS. However, some member nodes may be at a longer distance from the CH in a cluster. Therefore, to enhance network responsiveness and to make the timely availability of time-critical data nodes at a longer distance and behind other sensing nodes, data are sent indirectly to the CH through another node. This intra-cluster communication is discussed in the next subsection.

D. Intra-cluster communication

The non-CH nodes which are at longer distance from the CH and BS usually consumes much energy while transmitting its data to the CH. In this case, nodes at a longer distance use other intermediate nodes for forwarding the data to a CH or BS or to other sensing nodes. As many nodes lie between the sending node and the CH or BS, the selection of best path for sending the data with less delay is the main focus of the QHCR protocol. Within each cluster, nodes at a longer distance from the CH or BS use the pathmetric (P_{metric}) and find all available paths to the CH or BS. Through the P_{metric} , a sensing node can compute the path to its destination. The P_{metric} is given by Eq. (18):

$$P_{metric} = En_r + ETX_p + InvETX_p + ML_p \tag{18}$$

where En is the initial energy of any of the four energy levels, r is the node at a specific energy level, ETX_p is the expected transmission count [42] of a path P, $InvETX_p$ is the inverse expected transmission count [43], and MLp is the minimum loss [44]. The P_{metric} values for the hybrid, high, medium, and low energy level nodes are given by Eqs. 19, 20, 21, and 22, respectively.

$$\begin{aligned} P_{metric}(HB) = mr_3 En(1+z) + \\ ETX_p + InvETX_p + ML_p \end{aligned} \tag{19}$$

$$\begin{aligned} P_{metric}(H) = mr_2(1-r_3)En(1+y) \\ +ETX_p + InvETX_p + ML_p \end{aligned} \tag{20}$$

$$\begin{aligned} P_{metric}(M) = mr_1(1-r_2)En(1+x) \\ +ETX_p + InvETX_p + ML_p \end{aligned} \tag{21}$$

$$\begin{aligned} P_{metric}(L) = m(1-r_1)En + ETX_p + \\ InvETX_p + ML_p \end{aligned} \tag{22}$$

where ETX_p , $InvETX_p$, and ML_p are given by Eqs. (23), (24), and (25), respectively.

$$ETX_p = \sum_{x \epsilon p} \frac{1}{sd(x) \times ds(x)} \tag{23}$$

$$InETX_p = \sum_{x \epsilon p} sd(x) \times ds(x) \tag{24}$$

$$ML_p = \prod_{x \epsilon p} sd(x) \times ds(x) \tag{25}$$

where $sd(x) \times ds(x)$ is the packet delivery ratio on the link $x$of path p from source to destination $(sd(x))$ and from destination to source $(ds(x))$.

The sensing nodes send the route request messages to other nodes to find the link information. Other nodes respond with the rout reply message to the received route request messages. Upon reception of the route reply messages, the source node finds the direction of its path to the destination. The next hop is selected, and the whole path to the destination is selected using the P_{metric} . The exchange of route request and reply messages continues until the multipaths to the destination are selected. According to a previous study [45], multipath communication provides load balancing, minimization of end-to-end delay, flexibility, reliability, and fault tolerance. The

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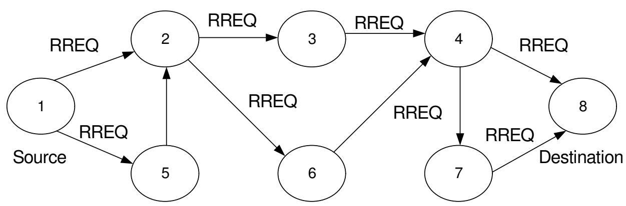

Fig. 7: Availability of the multipath and exchange of route request (RREQ) messages.

availability of the multipath and the relative exchange of route request messages between sensing nodes are shown in Fig. 7.

In the QHCR protocol, the sensing nodes exchange the triggered updated messages through $Hello$ messages, whenever certain topological changes occur. With the help of these triggered updates, the sensor nodes respond to the topological changes more frequently, and makes the proposed QHCR protocol sensitive to the topological changes. Therefore, the sensing nodes do not wait for the cluster round to terminate and update the topology table. However, the sensing nodes exchange the triggered updates whenever extensive topological changes occur in the network. Although energy is consumed during this process, it adds more reliability in the transmission of time-critical data. Therefore, the QHCR protocol is applied to gain the most reliable and flexible WSN. Energy consumption during the transmission of $Hello$ packets and the network control packets (C) is expressed as follows:

$$E_p = E_{Hello} + E_C \tag{26}$$

where E_p is the energy consumption during the transmission of different packets. The C packets are actually the topology control packets. The sensing nodes send the triggered updates $(C - t)$ during the transmission of time-sensitive data to gain QoS in the clustered topology of WSNs. In addition to triggered updates, the default updates $(C - d)$ are also sent to keep the whole network layout updated every 10 s of the time interval. The following Eqs. (27), (28), (29), and (30) for the energy consumptions of different packets are presented:

$$E_p = E_{Hello} + E_{C-t} + E_{C-d} \tag{27}$$

$$E_{Hello} = \frac{\tau Alive}{\tau Int} \sum_{\forall r \epsilon s} \sum_{\forall q \epsilon s_n} \tag{28}$$

$$E_{C-t} = \int^{\tau Alive} \sum_{\forall r \epsilon s} \sum_{\forall q \epsilon s_n} \tag{29}$$

$$E_{C-d} = \int^{\tau Alive} \sum_{\forall r \epsilon s} \sum_{\forall q \epsilon s_n} \tag{30}$$

where $\tau Alive$ represents the alive nodes, and it is actually the network lifetime. The transmission of packets consumes the energy that affects the network lifetime of a network. τInt is the time interval during which the $Hello$ packets are transmitted, s_n is the neighbor node, s is the network node,

TABLE II: Simulation parameters

Parameter	Value
Transmit power	20mW
Receive Power	15mW
Idle power	10mw
Transmitter electronics $W_{Tran}C_en$	50nj/bit
Receiver electronics $W_{Rec}C_en$	50nj/bit
Transmission range	24 m
Max buffer size	256 k-bytes
Buffer threshold	1024 bytes
Simulation time	1000s
Number of nodes	100
Area of Network	$400m \times 400m$

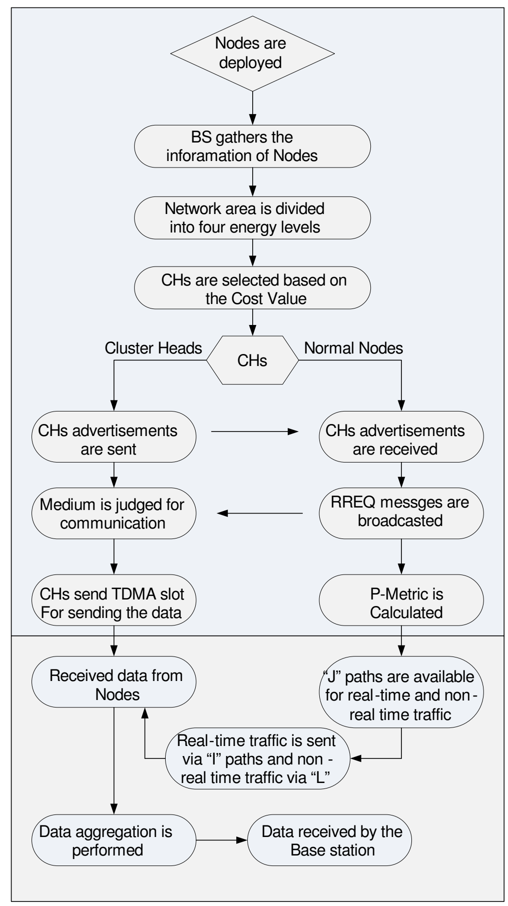

Fig. 8: Flowchart of the QHCR protocol

and r is the one specific node in the network that has to send the packets in the network.

After the different paths are computed by the P_{metric} , the best path is selected from the available paths. The path with the largest value of the P_{metric} is selected for the transmission of real-time, delay sensitive, and bandwidth hungry (multimedia) data to the destination. In the QHCR protocol, not only the energy conserved by the clustering of the whole network, but real-time traffic is also sent with less delay. The P_{metric} provides the multipaths. Our proposed scheme selects the separate path for real-time and nonreal- time traffic.

The P_{metric} provides the J paths for the transmission of data. The QHCR protocol selects the I paths for sending

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real-time traffic and the L path for transmitting non-real-time traffic. The transmission of real-time and non-real-time traffic over the I and L paths is expressed as Eqs. (31), (32), respectively:

$$I = \frac{R_T}{R_T + NR_T} J \tag{31}$$

$$L = \frac{NR_T}{R_T + NR_T} J \tag{32}$$

where (R_T) is real-time traffic and (NR_T) is non-real-time traffic. The I and L paths are the combination of J paths so that $J = I + L$. These J paths are caused by the multipaths present in our network topology. All the I paths are dedicated for the real-time traffic. These are the paths with high priority and less delay, where the L paths are all dedicated for the non-real-time traffic. By using the dedicated paths, our proposed scheme also minimizes the network congestion and achieves the load balancing in the networks.

The QHCR protocol conserves the energy in the system and minimizes the delay for real-time and non-real-time traffic by providing dedicated paths. The detailed flowchart of our proposed QHCR protocol is presented in Fig. 8.

VI. Performance evaluation of the QHCR protocol

In this section, we have evaluated the performance of the proposed QHCR protocol. The extensive simulations are performed using MATLAB to validate the results. In our simulations, we use 100 sensor nodes with various energy levels. Out of these 100 nodes, 35 are hybrid , 28 are high, 20 are medium, and 17 are low energy nodes. The network area of $400m \times 400m$ is used for the sensing operation. Different simulation parameters are given in Table II. The larger area with 100 nodes is used to ensure the sensing operation for larger areas as in the case of larger industrial units. We compare the performance of the QHCR protocol with those of the ECHERP, PASCCC, and CCWM protocols. Network lifetime, stability period, throughput, energy consumption, and end-to-end delay are used in the comparative analysis.

A. Network life time

Network lifetime can be defined as the time period between the installation of the first node to the death of the last node. At the start of each round, energy of every node is calculated and based on that energy, the sensing nodes are grouped into different energy levels. Therefore, if the energy of any node decreases, then at the next round of CH election, that node will be a part of low energy level than its present energy level. In this way, when a node dies, that node will ultimately not be considered for the election of the CHs in the next round. And through the CHs advertisements, the information of dead node is also deleted from the database of the other neighbor nodes. As shown in Fig. 9, the QHCR protocol has a more improved network lifetime than the ECHERP, PASCCC, and CCWM protocols. This enhancement is due to the optimal clustering and presence of the C_v value. Real-time traffic is provided with a dedicated path for its transmission that enhances the network lifetime. In the QHCR protocol, the first node dies after 2750 rounds and the last node after 4300 rounds. In other routing protocols under consideration, the energy of the sensing nodes decreases at an early stage as compared to our proposed scheme. In the case of ECHERP, the first node dies after 1300 rounds and the last node after 2800 rounds. This improvement in network lifetime is due to the efficient energy conservation approach employed by the QHCR protocol.

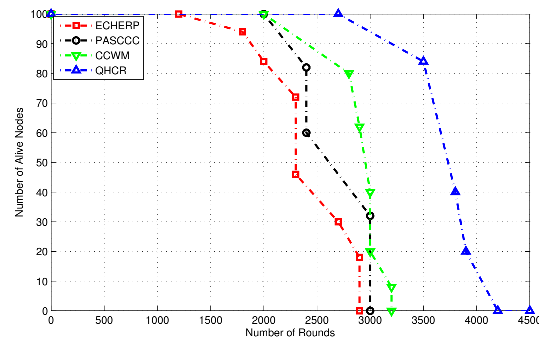

Fig. 9: Network life time

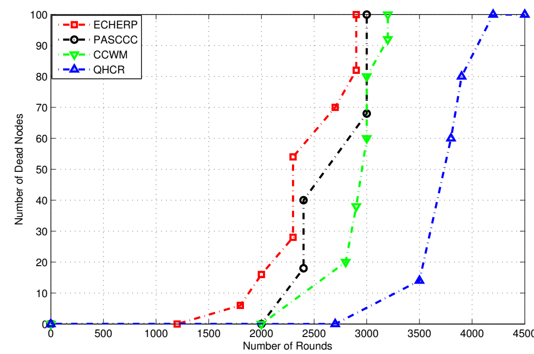

Fig. 10: Network stability period

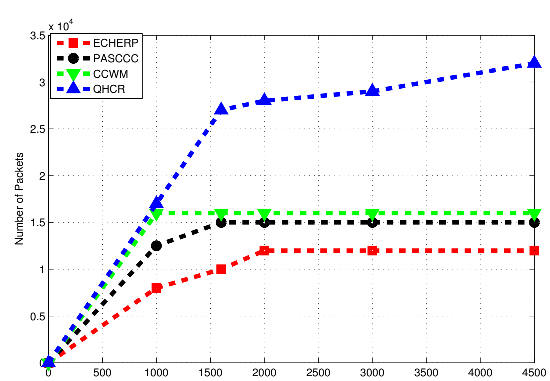

Fig. 11: Network throughput

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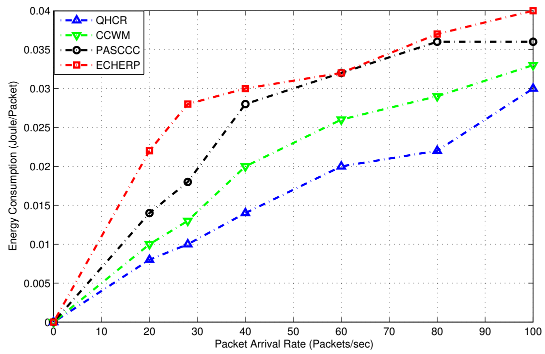

Fig. 12: Average energy consumption

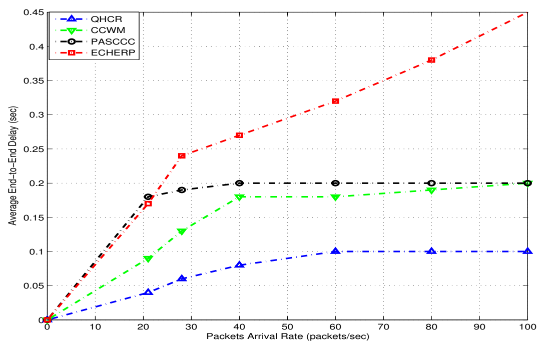

Fig. 13: End-to-End delay

B. Stability period

Stability period can be defined as the period before the first node dies in the network. Fig. 10 illustrates the stability period. The QHCR protocol shows significant improvement in the stability period as compared to the ECHERP, PASCCC, and CCWM protocols. This improvement in the stability period is due to the energy conservation approach of the QHCR protocol. In the proposed protocol, the first node dies after 2750 rounds, whereas in other routing protocols, the first node dies at an early stage in the network. The first node dies after 1300 rounds in the ECHERP protocol, after 2000 rounds in the PASCCC protocol, and after 2100 rounds in the CCWM protocol. This increase in stability period in the QHCR protocol is due to the optimal transmission of data over multiple links and the minimization of distance between the CH and member nodes. The enhancement in the stability period is also due to the introduction of the hybrid energy-level. The sensor nodes with the fluctuating energy are usually accommodate by the hybrid energy level.

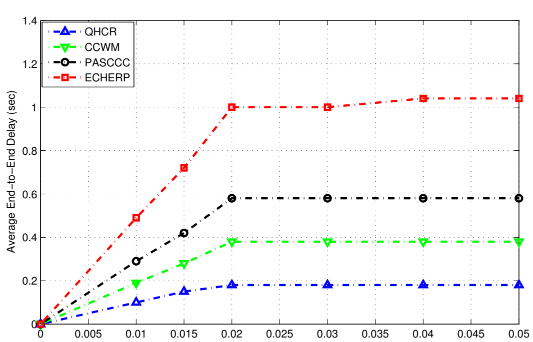

Fig. 14: Packet delay in case of node failure

C. Throughput

Throughput performances are presented in Fig. 11. Throughput is defined as the number of packets sent to the BS. Improvements in the throughput are achieved by the QHCR protocol but not by the ECHERP, PASCCC, and CCWM protocols. This improvement is due to the minimization of end-to-end delay and the availability of multipaths. The availability of multipaths enables more numbers of packets to be transmitted to the BS. The increased in the throughput is also due to the smooth transmission of the real-time and non-real-time traffic on the dedicated links by avoiding any bottlenecks in the networks.

D. Average energy consumptions

The average energy consumption in the QHCR protocol is illustrated in Fig. 12. The QHCR protocol has better energy efficiency than the other routing protocols of WSNs under consideration. This energy conservation is due to the optimal clustering of heterogeneous networks. The C_v metrics for CH election and the P_{metric} for the minimization of distance makes QHCR protocol more energy efficient than the ECHERP, PASCCC, and CCWM protocols.

E. Average end-to-end delay

Real-time or the delay sensitive traffic such as multimedia applications are given the dedicated path for its transmission in the QHCR protocol. The availability of dedicated paths for real-time and non-real time traffic minimizes the end-to-end delay. The exchange of route request messages for the reception and transmission of timely data makes our proposed scheme less susceptible to delay. In this way, the time-critical data are sent without delay, and user queries are attended with a rapid response. The minimization of delay in the QHCR protocol compared with the ECHERP, PASCCC, and CCWM protocols is illustrated in Fig. 13.

F. Average delay due to node failure probability

The ratio of node failure affects the average delay in the network. The average delay in case of node failure probability is presented in Fig. 14. As compared to the other protocols, our proposed QHCR protocol has better performance and less delay in case of node failure. The simulations results show that the ECHERP protocol is more sensitive to node failure than the QHCR protocol and that the QHCR has less delay for both real-time and non-real-time traffic. The simulation results show that QHCR protocol has better performance than the PASCCC and CCWM protocols.

VII. Conclusion and Future Work

In this paper, we have proposed a novel quality-of-service (QoS)-based routing approach for heterogeneously clustered wireless sensor networks (WSNs). The real-time traffic is transmitted with less delay by dedicated paths. To achieve the QoS in heterogeneous network, nodes of four energy levels with different initial energies are used. A cost value (C_v) is employed to achieve the optimum clustering in each energy level. In our proposed QoS-aware and heterogeneously clustered routing (QHCR) protocol, sensing nodes which are at longer distance from cluster head (CH) used other sensing nodes as an intermediate nodes to transmit the packets. Multiple paths are provided with the help of path metric (P_{metric}). This P_{metric} used initial energy of sensing nodes from different energy levels, expected transmission count (ETX), inverse expected transmission count $(InvETX)$, and minimum loss (ML). The real-time and non-real-time traffic is then transmitted over different paths with less delay. QHCR protocol minimizes the end-to-end delay, transmission delay and congestion. It also provides load balancing, fault tolerance, flexibility and reliability in a heterogeneous WSNs. Simulations results shows an improvement in network life time, stability, throughput and minimization in end-to-end delay. In future, we intent to incorporate the energy-harvesting feature in our proposed routing approach for heterogeneous WSNs. The energy-harvesting feature will help in conserving the energy from some renewable energy source.

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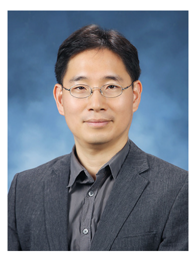

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