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Citation: Haq, Inam Ul, Javed, Qaisar, Ullah, Zahid, Zaheer, Zafar, Raza, Mohsin, Khalid, Muhammad, Ahmed, Ghufraan and Khan, Muhammad Saleem (2020) E2-MACH: Energy Efficient Multi-Attribute Based Clustering Scheme for Energy Harvesting Wireless Sensor Networks. International Journal of Distributed Sensor Networks, 16 (10). p. 155014772096804. ISSN 1550-1329

Published by: SAGE

URL: <https://doi.org/10.1177/1550147720968047>
<<https://doi.org/10.1177/1550147720968047>>

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E²-MACH: Energy efficient multi-attribute based clustering scheme for energy harvesting wireless sensor networks

International Journal of Distributed
Sensor Networks
2020, Vol. 16(10)
© The Author(s) 2020
DOI: 10.1177/1550147720968047
journals.sagepub.com/home/dsn


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Abstract

Internet of things have emerged enough due to its applications in a wide range of fields such as governance, industry, health-care, and smart environments (home, smart, cities, and so on). Internet of things-based networks connect smart devices ubiquitously. In such scenario, the role of wireless sensor networks becomes vital in order to enhance the ubiquity of the Internet of things devices with lower cost and easy deployment. The sensor nodes are limited in terms of energy storage, processing, and data storage capabilities, while their radio frequencies are very sensitive to noise and interference. These factors consequently threaten the energy consumption, lifetime, and throughput of network. One way to cope with energy consumption issue is energy harvesting techniques used in wireless sensor network-based Internet of things. However, some recent studies addressed the problems of clustering and routing in energy harvesting wireless sensor networks which either concentrate on energy efficiency or quality of service. There is a need of an adequate approach that can perform efficiently in terms of energy utilization as well as to ensure the quality of service. In this article, a novel protocol named energy-efficient multi-attribute-based clustering scheme (E²-MACH) is proposed which addresses the energy efficiency and communication reliability. It uses selection criteria of reliable cluster head based on a weighted function defined by multiple attributes such as link statistics, neighborhood density, current residual energy, and the rate of energy harvesting of nodes. The consideration of such parameters in cluster head selection helps to preserve the node's energy and reduce its consumption by sending data over links possessing better signal-to-noise ratio and hence ensure minimum packet loss. The minimized packet loss ratio contributes toward enhanced network throughput, energy consumption, and lifetime with better service availability for Internet of things applications. A set of experiments using network simulator 2 revealed that our proposed approach outperforms the state-of-the-art low-energy adaptive clustering hierarchy and other recent protocols in terms of first-node death, overall energy consumption, and network throughput.

Keywords

Internet of things, wireless sensor network, cluster head selection, energy harvesting, link statistics, signal-to-noise ratio

Date received: 7 March 2020; accepted: 22 September 2020

Handling Editor: Peio Lopez Iturri

Introduction

With the significant advancement in communication technologies during the last three decades, sensing devices are increasingly growing for application in numerous domains. In the field of network technology,

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wireless sensor networks (WSNs) have gained a significant consideration in research. The extraordinary development in WSN technologies helped in emerging a new paradigm of Internet of things (IoT) which is considered as one of the potential technologies for imminent prospect of ubiquitous and smart applications and services era.¹ IoT is a combination of technologies used for providing connectivity of many devices all the time and everywhere. The main working principle of IoT is to maintain cooperation and interaction between objects or things using wireless links to achieve ubiquitous communications.² The connected devices or things might be mobile phones, actuators, radio frequency identification (RFID) tags, or sensor nodes equipped with transceivers and a set of protocols for the propagation of sensing and control information.³ In this context, WSN is capable to provide services of ubiquitous computing in an IoT application domain.

WSN-based IoT have many interesting applications in many different areas such as scientific, commercial, civil, and military domains for continuous event detection and monitoring.⁴⁻⁷ Key responsibilities of IoT in different application domains include building management (smart home and office), security and surveillance, object tracking and monitoring, agriculture automation, environmental monitoring, healthcare, acoustic data gathering, and monitoring the natural or man-made crises, such as severe weather, earthquakes, and war field observations,^{8,9} as shown in Figure 1. In these domains, the IoT networks are improving the standard of life as well as contributing to the economic benefits of a society in general. Therefore, they are attracting substantial attention from universities, industries, governments, and researchers alike to develop new technologies and applications in different fields of life.

A typical WSN-based IoT setup is formed by a number of distributed and autonomous sensing devices or nodes, as shown in Figure 2. These devices are capable of sensing, processing, and transmitting information to other nodes, devices, or base station (BS) using wireless links. The sensor nodes are smaller in size; therefore, they are equipped with limited energy resource, for example, batteries. In most installations of WSNs in such IoT networks, it is difficult or costly to replace or recharge the node's battery as they are deployed in remote or harsh terrains. In addition to restricted energy supply, sensor nodes have limited computational and storage capabilities which needs to be addressed during the design of protocols for such networks.

The key challenge faced by sensing devices in IoT networks is limited battery-driven power supply,¹⁰⁻¹⁵ which not only restricts such network devices to provide services for a longer time but also affects the performance. In WSNs, the node's energy is consumed for sensing events, signal processing, computations, and data transmission. The later has a higher ratio of energy

utilization in an IoT node. Therefore, it is necessary for sensing devices to perform optimized data transmissions in order to utilize the limited energy resources more efficiently. Consequently, the achievement of efficient energy utilization in routing protocols of WSNs has been focused by numerous studies. A substantial amount of protocols have been proposed which tried to minimize energy utilization in data communication processes. There is still a gap for energy limitation and its efficient utilization in WSN and IoT networks. In addition, due to the nature and architectural structure, application domain, and working environment of sensor nodes, IoT devices are likely to be restricted to operate with short-range communication, frequent path losses, considerable node-to-BS delay, and low packet delivery ratio. These factors reduce the reliability of communication performed by the sensor nodes.

To deal with energy limitation, many routing protocols of different categories have been developed for WSN. The categories of routing protocols include plane routing, location-based routing, and hierarchal routing.^{11,12,16} Among them, hierarchical routing protocols are known as more energy-efficient due to their nature of structural organization.¹⁴ In these protocols, the network is logically segregated into multiple portions and each portion is called a cluster. Out of several nodes in a cluster, one node is designated as primary node called cluster head (CH), while remaining operates as normal nodes called members of the cluster. Each CH collects sensed information from respective member nodes, perform necessary aggregations on data, and send it to the BS directly or via other CH in the network. As CH nodes perform additional duties, that is, receiving packets from members, aggregating, and forwarding them to BS, hence they consume more energy. Therefore, a node performing CH role for longer time have high chance of quick energy depletion. Hence, to achieve balanced utilization of energy, the CH role is not fixed throughout and rotated to other nodes after some time period called "round." In each round, the selection algorithm selects a new CH on the basis of protocol policy. Selection of a stable CH is necessary to enhance energy efficiency and throughput, which consequently prolongs the network lifetime.

Recently, energy acquisition technology called energy harvesting is incorporated in sensing devices for managing energy utilization. It enables the network to convert solar, thermal, or mechanical vibrational energy in surrounding into usable electric power for sensing devices.¹⁷ The energy harvesting characteristics have ensured the additional supply of energy to nodes up to some extent; however, it still has some complexities.¹⁸ Energy harvesting from environmental sources is insufficient in many cases to solve the limited energy problem of nodes completely. This is because energy

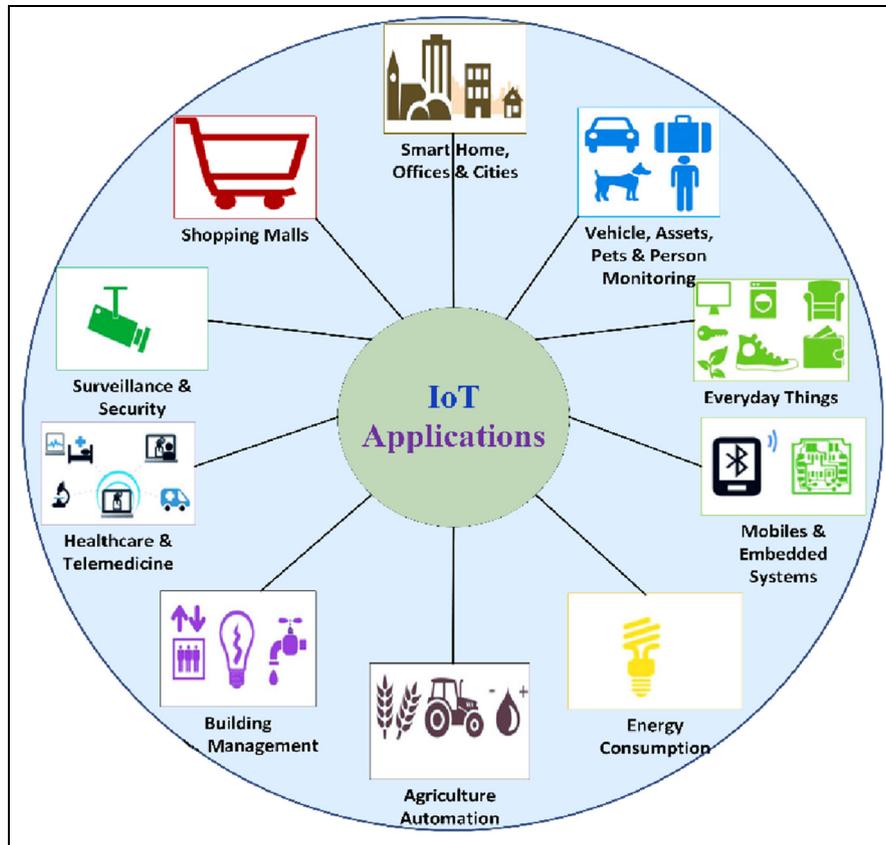


Figure 1. Categories of IoT applications.

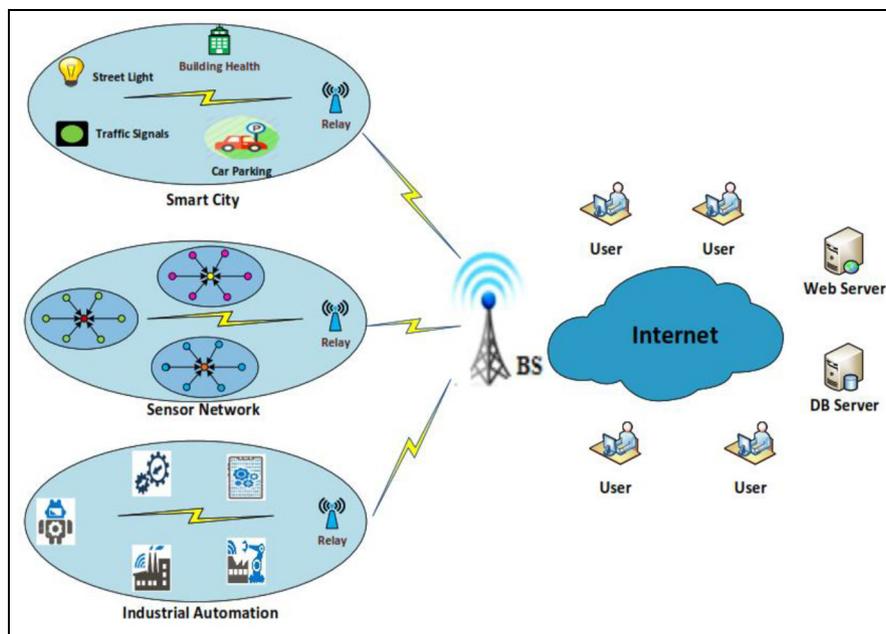


Figure 2. Architecture of a typical IoT network.

harvesting depends on surrounding environmental conditions which are inclined to change over time;

therefore, the harvesting efficiency does not remain constant throughout the network lifetime.¹⁹ Although

energy harvesting techniques cannot provide unlimited energy to a sensor node; however, still it is a better option for the enhancement of network lifetime provided, it is utilized in combination with energy optimal routing techniques in WSNs.²⁰

Hierarchical routing protocols divide the network into clusters to deal with energy limitation in WSNs. In clusters, a CH node plays a vital role in the transmission of data from member nodes (source) to BS (destination); therefore, it needs to be reliable and energy-efficient. For this purpose, a variety of clustering algorithms have been proposed in literature since 2000. In most of these protocols, CH selection is based on current node's energy, the average distance between CH and member nodes, the density of neighboring nodes, distance from BS, and rate of energy harvesting in rechargeable networks. Although the consideration of these parameters contributes to increase network lifetime, they do not consider other important factors that ultimately affect the performance and energy utilization of sensor nodes which includes path losses and weaker links between sensor nodes which causes re-transmissions of packets. In the result of packet re-transmissions, the transmitting nodes consume more energy and experience increased end-to-end delay that ultimately affects the overall network lifetime and throughput. Furthermore, as WSNs operates in harsh environments where noise in the region is common which causes degradation in the quality of links between nodes and frequent path losses. Therefore, link quality is another important parameter for reliable and efficient communication as it can further improve the overall lifetime with maximized throughput of the network.

While taking the above-mentioned characteristics into consideration, a clustering mechanism is required that ensures efficient utilization as well as conservation of the node's energy with enhanced throughput and minimized end-to-end delay. Therefore, this study proposes an energy-efficient and reliable CH selection scheme for energy harvesting aware WSNs. The proposed energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs (E²-MACH) primarily concentrates on enhancing network lifetime by assigning CH role to best suitable nodes in different clusters. The selection criteria of this scheme ensure efficient utilization of the node's energy, minimum path losses between member nodes and CH, reduced re-transmissions. and achieving maximum throughput. CH is selected on the basis of the node's current status of energy, energy harvesting rate, neighboring density, and link quality which is measured in terms of noise in links. The first three parameters ensure balanced utilization of energy. while the last one helps to restrict the selection of nodes which exhibit re-transmission and delay due to weaker links with the surrounding nodes.

Weaker links are mainly caused by noise in the region. For this purpose, along with other parameters, the signal-to-noise ratio (SNR) of wireless links is considered for nodes while selecting a CH. In this manner, an optimal CH is selected which demonstrates better utilization of energy, preserves energy by reducing re-transmissions of packets, minimizes end-to-end delay, and enhances throughput. These characteristics collectively ensure the reliable delivery of data packets and improved network lifetime. The proposed scheme, E²-MACH, was assessed with simulation experiments in network simulator 2 (NS2). Our results show that E²-MACH outperformed the existing techniques in terms of energy utilization, network stability, overall throughput, and network lifetime.

The rest of this article is organized as follows: section "Related work" presents the literature study of some state of the art and recent techniques related to the subject. Section "Model construction" discusses the models for energy consumption and energy harvesting by sensor nodes. Section "Proposed scheme" describes the details of the proposed scheme along with the simulation details; results and discussion and comparison with existing schemes are given in section "Performance evaluations and results analysis." Finally, section "Conclusion and directions for future work" presents the conclusion of the proposed scheme with some future directions.

Related work

WSNs face many challenges and require to prolong the network lifetime, reduced transmission delay, and reliable communication with a high rate of data delivery. These requirements are associated directly or indirectly with energy utilization of sensor nodes. WSNs usually operate in crucial applications such as dealing with sensitive information in real time; therefore, they should communicate BS with lesser delay, high efficiency, and minimum utilization of energy. To achieve these goals, many clustering techniques have been proposed in the literature,^{5-7,15,21-26} including solutions for traditional as well as energy harvesting enabled WSNs. Some state of the art and recent studies are discussed below.

Heinzelman et al.²⁷ proposed the low-energy adaptive clustering hierarchy (LEACH). This scheme performs the random distribution of clusters, in which every node can get a chance to become the CH due to the rotating role of CH. The selection of CH is based on a predefined probability for the rotation of head role among sensor nodes in order to prevent fast battery draining if selected. The remaining nodes in a cluster, that is, member nodes are connected to their respective CHs in such a way that they use minimal energy for reaching it. After CH selection, it receives the

information from its member nodes using assigned time slots defined by the time division multiple access (TDMA) schedule. LEACH was the first hierarchical routing protocol and showed great improvement in the performance of WSNs. On the basis of LEACH, there were a number of protocols proposed in the literature to overcome its shortcomings.

Qing et al. proposed distributed energy-efficient clustering (DEEC),²⁸ a clustering-based routing protocol to enhance energy efficiency in WSNs by distributing the energy utilization in a heterogeneous environment. DEEC assume multi-levels of energy for sensor nodes that can take different values. The DEEC selection criteria for CH consider the ratio of residual energy of a node to the average energy of all nodes in the network. By this approach, the protocol ensures balanced utilization of energy to achieve prolong lifetime. However, DEEC uses an estimation technique for calculating network average residual energy which is inconsistent in reality. This inconsistency, however, leads to the weakness of DEEC in practical application scenarios.

Stable election protocol (SEP)²⁹ is another development in routing protocols which extends the state of the art LEACH. SEP assumes a heterogeneous level of energy for sensor nodes. In this scheme, the network nodes are categorized as advanced and normal nodes. Nodes in the earlier category are provided with high initial energy, while the latter is provided with a lesser amount of energy as compared to advanced nodes. The probability factor for electing a node is configured for each individual node and based on its initial energy. Each node then calculates its probability for CH selection. In this manner, the high energy nodes have a greater chance to become CH as compared to the normal nodes. By this approach, the normal nodes get a chance to consume less energy by avoiding to take CH responsibility and thus achieves better performance in terms of network lifetime.

Kumar et al. proposed energy-efficient heterogeneous clustering (EEHC)³⁰ and energy-efficient clustering and data aggregation (EECDA)³¹ protocols for energy efficiency in clustered networks. These schemes assume heterogeneous nodes which are categorized into three groups: superior, advanced, and ordinary nodes. EEHC uses weighted probability function for the election of CH which is based on the residual energy of the individual node. EECDA combines the idea of energy-efficient clustering presented in EEHC with data aggregation to further enhance the performance which includes the lifetime and stability of the network. Along with efficient clustering, this protocol also determines a data transmission route consisting of nodes with the maximum amount of remaining energy.

Energy centric cluster-based routing (ECCR)³² is a recent protocol which introduced a new parameter called as node rank. Node rank is used for CH selection

which is calculated by combining values of distance from member nodes and node's residual energy. ECCR primarily focuses on minimizing energy utilization by reducing control messages in the CH selection process and routing. Besides the primary function of data aggregation and forwarding packets, the head nodes also provide assistance in CH selection in the next round by sharing the rank information of member nodes. In this manner, the transmission of control messages is reduced which is used by each node to share its local information with other nodes in each round. In first round, the high ranked node is identified from cluster member table (CMT) and elected as CH, whereas in subsequent rounds, the former CH shares the rank information. In a particular round of ECCR, CH of previous round can get selected again in the immediate round.

Purkar and Deshpande³³ recently proposed a protocol called energy-efficient clustering protocol to enhance performance of heterogeneous wireless sensor network (EECEP-HWSN) for heterogeneous WSNs. This protocol introduced a new parameter called node quality index (NQI), which is calculated by combining the node's real time parameters such as initial energy, residual energy, and hop counts for reaching BS. CH is selected on the basis of NQI, to achieve energy efficiency in heterogeneous networks. The NQI is formulated through different index modeling techniques used for the database system. This scheme inherits the LEACH²⁷ policy for CH selection in first 50 rounds, while uses NQI value for the remaining rounds. To reduce internal overhead for network management, the nodes population density is considered and the network is partitioned into four different zones which are controllable as compared to the arbitrary size of the network.

Malathi et al.³⁴ proposed a clustering protocol called hybrid unequal clustering with layering (HUCL), which focuses on the enhancement of network lifetime. This protocol uses unequal clustering approach with minimum overhead of cluster formation. This protocol considers both static and dynamic clustering with better performance compared to other dynamic methods. A similar approach was followed by Gupta et al.³⁵ in their proposed protocol, energy aware distributed unequal clustering (EA-DUC) which follows an energy-aware and distributed clustering mechanism. This protocol is based on HUCL with some improvements. The protocol constructs smaller size clusters in surroundings of BS, whereas in other regions of the network, clusters are formed with the larger size. With a defined cluster, a competition radius is used which is calculated on the basis of the node's energy.

An energy-neutral clustering³⁶ protocol was proposed for WSNs with energy harvesting capabilities. It defines a group of CHs in a cluster so that multiple

CHs can be selected for sharing the heavy traffic load. Multiple CHs in a cluster reduces cluster re-formation frequency and control messages overhead. In this protocol, the convex optimization technique is used for determining the optimal number of clusters for maximum information gathering. The aim of this protocol was to enhance the network's lifetime and to achieve maximum data delivery at BS.

Chelbi et al.³⁷ proposed a new routing protocol based on a clustering mechanism for WSNs composed of energy harvesting nodes as well as ordinary nodes. The proposed mechanism incorporates scheduling and clustering modules based on optimization technique—particle swarm optimization (PSO) and fuzzy C-mean (FCM), respectively. In clustering module, the proposed protocol aims to solve the problem of the early death of CH due to extra workload by introducing a number of energy harvested nodes into the network, which performs as CH and balance energy utilization. Furthermore, the protocol focuses on the efficient and correct deployment of energy harvested nodes to achieve the design goals.

Heterogeneous node sensor (HNS)³⁸ is another clustered routing scheme proposed for heterogeneous WSN with energy acquisition from mechanical vibrations in the surrounding. For CH selection, this algorithm considers residual energy and currently supplied energy of sensor nodes. The network is composed of two types of nodes, ordinary and advanced. Advanced nodes are equipped with energy harvesting functions while normal nodes do not. For each category of nodes, protocol maintains separate threshold calculating function in CH selection procedure. The self-recharge coefficient is maintained for every advanced node. The advanced nodes with higher self-recharge rate get a high probability to become a CH. In this way, the protocol claims balanced utilization of energy by network nodes.

To achieve efficient utilization of energy in large-size networks, an energy-efficient multistage routing protocol (EE-MRP)³⁹ was introduced which consists of CH selection, cluster formation, and data transmission phases. The proposed scheme divides the field into three logical regions called (S1, S2, and S3). Regions S1 and S3 are clustered, while S2 is left non-clustered. S2 is the central region of the network among these stages. Clustered regions use a CH, while non-clustered region uses a forwarder node for data communication to BS. For clustered regions, the static cluster formation approach is followed which is performed by BS. Upon completion of cluster formation, the CH is selected on a probability basis like LEACH algorithm.²¹ For CH replacement EE-MRP checks the energy level of CHs with a predefined threshold value, if it is greater than that, the CH remains unchanged for the next round

until its energy level become lower than the threshold limit. When the energy of a CH becomes lower than the threshold limit, the protocol mark such CHs as retired which cannot get a chance to become CH again. In this way, the unnecessary energy consumption in CH selection process of such nodes is restricted. In the data communication phase, the CHs in stage S1 directly send their data to BS, while the forwarder node in stage S2 also sends its data directly to BS. In contrast, all CHs in stage S3 transmit their data to forwarder node in S2 and it then sends the gathered data to BS.

Han et al.⁴⁰ proposed CHSES—a clustered protocol for heterogeneous WSNs with solar energy supply nodes. This algorithm was proposed on the basis of HNS³⁸ and SEP²⁹ algorithms. The protocol considers two types of nodes, one with energy harvesting capability while the other one is a traditional normal node. These nodes are deployed with different energy levels which increase the probability of advanced nodes to become CH. In CH selection, two different threshold functions are maintained for both types of nodes. The threshold for advanced nodes is influenced by the residual energy and self-recharge state of nodes, where the ordinary node's threshold is only dependent on residual energy. For advanced nodes, protocol calculates the sum of residual energy and harvested energy in each round and compares it with an initial energy of nodes to find the nodes with maximum residual energy and harvesting rate. Such nodes have a high probability of selection as CH.

By reviewing the related work, it is clear that existing clustering techniques uses one or more parameters such as current energy, distance from BS, and location of the node, for CH selection criteria^{27–40} to ensure energy efficiency and prolong network lifetime. However, none of them considers quality of the link and energy gain rate by a node in CH selection process, which potentially contributes to the enhancement of energy utilization, network lifetime, and reliability of packets delivery. This research work proposed a novel clustering method described in section “Proposed scheme,” to addresses the above-mentioned parameters.

The comparative analysis of the above-mentioned schemes with respect to different characteristics is shown in Table 1.

Model construction

In the development of the proposed clustering protocol (E²-MACH), the operating environment is provided by different working models which include network model, energy consumption model, and energy harvesting model. These models are briefly discussed in this section.

Table 1. Comparative analysis of clustered routing protocols for WSN.

Protocol name	Energy efficiency (low/medium/high)	Network lifetime (low/medium/high)	Energy harvesting (yes/no)	Consideration of link statistics (yes/no)	End-to-end delay (low/medium/high)	Energy consumption (low/medium/high)	Network throughput (low/medium/high)	Network type (homogeneous/heterogeneous)
LEACH ²⁷	Medium	Medium	No	No	Medium	High	Low	Homogeneous
DEEC ²⁸	Medium	Medium	No	No	Medium	High	Low	Heterogeneous
SEP ²⁹	Medium	Low	No	No	Medium	Medium	Low	Heterogeneous
EEHC ³⁰	Low	Medium	No	No	Medium	Medium	Low	Heterogeneous
EECDA ³¹	Medium	Medium	No	No	Medium	High	Low	Heterogeneous
ECCR ³²	Medium	High	No	No	Low	Medium	Medium	Homogeneous
EECPEP ³³	Medium	Medium	No	No	Medium	High	Medium	Heterogeneous
HUCL ³⁴	Low	Medium	Yes	No	Medium	High	Medium	Homogeneous
ENC ³⁶	Medium	Medium	Yes	No	Medium	Medium	High	Homogeneous
HRP ³⁷	Low	Low	Yes	No	Low	Low	Low	Heterogeneous
HNS ³⁸	High	High	Yes	No	High	Medium	Low	Heterogeneous
EE-MRP ³⁹	Medium	Medium	No	No	Low	Medium	Low	Homogeneous
CHSES ⁴⁰	Medium	Medium	Yes	No	High	Medium	Low	Heterogeneous

LEACH: low-energy adaptive clustering hierarchy; DEEC: distributed energy-efficient clustering; SEP: stable election protocol; EEHC: energy-efficient heterogeneous clustering; EECDA: energy-efficient clustering and data aggregation; ECCR: energy centric cluster-based routing; EECPEP: energy-efficient clustering protocol to enhance performance; HUCL: hybrid unequal clustering with layering; HNS: heterogeneous node sensor; EE-MRP: energy-efficient multistage routing protocol; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; ENC: energy neutral clustering; HRP: hybrid routing protocol.

Sensor network model

In the proposed scheme, the nodes are provided with energy harvesting capabilities for WSN. The nodes are equipped with energy acquisition units and connected to a BS which have unlimited energy supply. In this setup, each node gets a chance to operate as CH as well as a normal member node. In addition to the above characteristics, the network follows some assumptions listed below:

1. The network consists of homogeneous nodes which are equipped with energy acquisition capabilities.
2. The initial energy of all sensor nodes is at the same level.
3. Sensor nodes are randomly deployed in two-dimensional plane.
4. The BS and deployed sensor nodes are fixed once deployed.
5. The transmission power of network nodes is adjustable as per requirements.
6. Each node has a unique ID, certain storage, and data fusion capabilities.
7. Sensor nodes can share their location information with BS and other nodes

Energy consumption model

Various energy consumption models were proposed for radio communication in literature, for example, Heinzelman et al.²⁷ and Kumar et al.³¹ This research undertaking, however, has followed the “first-order radio model”²⁷ due to its relevancy and simplicity with the proposed scheme.

The total consumed energy E_{Total_Con} in data transmission, reception, and aggregation is estimated by equation (1)

$$E_{Total_Con} = E_T + E_R + E_{Agg} \quad (1)$$

where E_T and E_R are the energy consumption in transmission and reception of data packets, respectively, while E_{Agg} shows the energy required for integrating received data by a node.

Energy consumed by transmitter and receiver for operating electronics and amplifier circuitry is represented by E_{Te} and E_{Re} , respectively. Based on the distance between transmitting and receiving nodes, free-space or multi-path attenuation model is used. If the distance d is equal or less than d_0 , free-space model (ϵ_{fs}) is adopted; otherwise, multi-path attenuation (ϵ_{ms}) model is adopted. Equation (2) expresses the total amount of energy consumed in transmitting k -bit data packet over a distance d

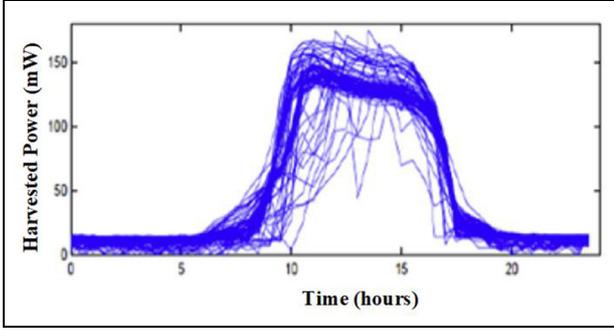


Figure 3. Rate of energy harvesting by a sensor node.⁴¹

$$E_T(k, d) = \begin{cases} k(E_{T_e} + \varepsilon_{fs}), & d \leq d_0 \\ k(E_{R_e} + \varepsilon_{ms}), & d > d_0 \end{cases} \quad (2)$$

The energy consumed by a node in receiving and aggregating k -bit data packet is expressed in equations (3) and (4), respectively.

$$E_R(k) = k \times E_{R_e} \quad (3)$$

and

$$E_{Agg}(k) = k \times E_{R_e} \quad (4)$$

Energy harvesting model

Sensor nodes with energy harvesting capabilities can acquire energy from its surroundings. The availability of harvesting energy varies in time. The acquired energy by a sensor node i in a given round r is stored in the node's power storage, that is, batteries, which is denoted by $E_{Har}(i, r)$. To predict the amount of harvested energy by a sensor node, there is a commonly used prediction model called “*exponentially weighted moving average*” (EWMA).⁴¹ EWMA assumes solar energy as harvesting source for sensor nodes. EWMA records the measurements for harvested power by a node on 24 h basis, as shown in Figure 3. It is assumed by the proposed scheme that sensor nodes can use the solar energy as harvesting source on 24 h basis. Due to its simplicity and relevancy with the proposed scheme, we use the simplified energy harvesting model,⁴² which is derived from EWMA⁴¹ prediction model, as shown in Figure 4. The energy model of a sensor node is expressed in equation (5)

$$E_{Curr}(i, r) = E_{Curr}(i, r-1) + E_{Har}(i, r-1) \quad (5)$$

where $E_{Curr}(i, r)$ is the total current energy of node i at the start of the round r , while $E_{Har}(i, r-1)$ is the amount of harvested energy by a node in previous round the $(r-1)$, which is given by equation (6)

$$E_{Har}(i, r-1) = HR_i \times \Delta t \quad (6)$$

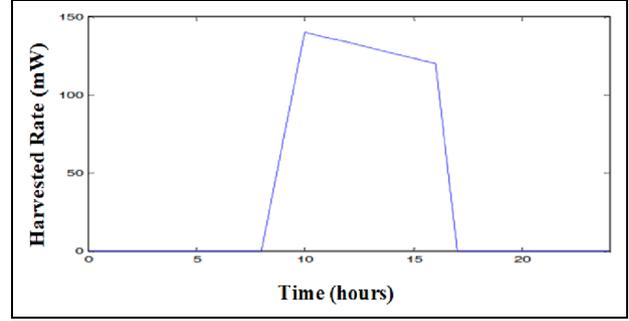


Figure 4. Simplified model for energy harvesting.⁴²

where HR_i is the rate at which a node i acquired energy from external sources during previous round and Δt is the time duration of a round. HR_i is defined by equation (7)

$$HR_i = rand(EH_{min}(r-1), EH_{max}(r-1)) \quad (7)$$

Equation (7) calculates the energy harvesting rate of a node i in the previous round $(r-1)$ and it is a random variable between lowest ($EH_{min}(r-1)$) and highest ($EH_{max}(r-1)$) amount of harvested energy with uniform distribution.

Proposed scheme

In this research study, an “energy efficient multi-attribute based clustering scheme for energy harvesting WSN” is proposed which addresses the issues of

- Instability of selected CHs caused by limited energy.
- Path loss between member nodes and CHs due to weaker links caused by the presence of noise in regions.

To address the above-mentioned issues, the proposed scheme primarily focuses on the increasing network lifetime, minimization of end-to-end delay, and maximization of network throughput. To achieve these goals, the scheme follows a clustering approach and selection of proper and suitable node as CH. The CH selection criterion considers parameters that ensure balanced energy utilization and reliable connectivity between member nodes and CHs. These parameters include residual energy of node, rate of energy harvesting, neighborhood density of a node, and the node's link quality in terms of SNR. Measurement of residual energy and energy harvesting rate of a node follows the model described in sections “Energy consumption model” and “Energy harvesting model,” respectively. To select the best node for the CH role, a weighted election value (EW) is used, which is calculated by a

weighted function for each eligible node. A node within each cluster having the highest EW value is selected as CH in a particular round. The working of the proposed protocol is divided into different phases described in this section.

Deployment phase

Working of the proposed protocol starts with the deployment phase in which all sensor nodes are randomly deployed in a targeted field. These nodes are homogeneous in terms of the initial supplied energy, storage capacity, and processing capabilities. Furthermore, to ensure additional supply of energy, each sensor node is equipped with energy harvesting capability. Upon the successful deployment using network model described in section ‘‘Sensor network model,’’ BS broadcasts a begin message (*Begin_Msg*) to sensor nodes N , where N is the set of all sensor nodes $\{N_1, N_2, N_3, \dots, N_n\}$. On reception of *Begin_Msg*, each node measures its distance from the BS based on the power of the signal received and enters into the next phase.

Initialization phase

Initialization phase starts with the transmission of a *Hello* message by all nodes to each other in its communication range using carrier-sense multiple access with collision avoidance (CSMA/CA) access method in order to avoid collision in shared medium. In response to the received *Hello* message, each node transmits a *Reply* message. It comprises some useful information such as source node id (ID_s), destination node id (ID_d), distance from BS ($Dist_{BS}$), and initial energy (E_{init}). The *Hello-Reply* messages are exchanged to achieve four goals at each node level. These include updating neighbor tables and calculation of distance $dist(N_s, N_d)$ from source node (N_s) to the destination node (N_d) within communication range, the neighbor density DN_i , and average signal-to-noise ratio (SNR_i). The definition of the above-mentioned parameters is given below.

Distance calculation. Distance between source (N_s) and destination (N_d) nodes are calculated using Euclidean distance given by equation (8)

$$dist(N_s, N_d) = \sqrt{(X_{N_s} - X_{N_d})^2 + (Y_{N_s} - Y_{N_d})^2} \quad (8)$$

Node density calculation. Node density represents the set of nodes residing in the neighborhood of a node i and denoted by DN_i . It is calculated by equation (9)

$$DN_i = \cup_{i \neq j} \{j | dist(i, j) < tx_{range}\} \quad (9)$$

where tx_{range} is the communication range of node i and $dist(i, j)$ is the distance between node i and j .

SNR calculation. SNR is a metric for quantifying the behavior of a link by determining the strength of a signal. It is the ratio of actual signal strength to environmental noise strength defined by equation (10)

$$SNR = \frac{Power_{Signal}}{Power_{Noise}} \quad (10)$$

Due to the wide and dynamic range of received signals, they are also expressed in logarithmic decibels scale. The actual signal and environmental noise in decibels (dB) are expressed by equations (11) and (12), respectively

$$Power_{Signal, dB} = 10 \log_{10}(Power_{Signal}) \quad (11)$$

and

$$Power_{Noise, dB} = 10 \log_{10}(Power_{Noise}) \quad (12)$$

Another representation of SNR in decibels is given in equation (13)

$$SNR_{dB} = 10 \log_{10}(SNR) \quad (13)$$

Using equation (10), SNR in decibels can also be expressed as given in equation (14)

$$SNR_{dB} = 10 \log_{10}(Power_{Signal}/Power_{Noise}) \quad (14)$$

Once the initialization is completed, the nodes in each cluster enter into the CH selection phase.

Cluster formation phase

Two approaches are commonly in use, for cluster formation in cluster-based routing protocols, that is, dynamic cluster and static cluster formation. The dynamic cluster formations take place by a random selection of CHs in whole network field. Once a CH is elected, the remaining member nodes are registered with nearest CHs. By this approach, however, there are high chances of non-uniform CHs distribution in the field. As a result, some portions of network field may get less number of CHs than others. In such a situation, sensor nodes in portions having lesser CHs are likely to expire earlier because the CHs in these regions become overloaded by providing services to more member nodes.

To take these issues in consideration, the proposed protocol follows the static formation of clusters in which the BS divides the entire network into various sub-regions, and then in each region, CHs are selected by the given criteria. This strategy ensures even distribution of CHs and hence balanced energy utilization

which contributes to overall efficiency and prolongs the network lifetime.

To divide network into clusters, BS assigns region IDs to each sensor node based on their location information. They are restricted to join only the CHs in its own region upon selection. If a region has more than one selected CHs, the member nodes will join the CH at a minimum distance from it. The CH selection strategy within a region is presented in the next section.

CH selection phase

For the selection of best suitable node as CH, four parameters are considered including current energy (E_{Curr}), rate of energy harvesting (HR), neighbor node density (DN), and ratio of the actual signal and noise in it, that is, SNR of a node. These parameters are combined in a weighted function to compute the election weight (EW) of a node. The node with highest EW is selected as CH in the region.

Election weight EW_i for a node i is calculated differently in first round and subsequent rounds defined by equation (15). The protocol detail is given below

$$EW_i = \begin{cases} DN_i \times \gamma_1 + SNR_i \times \gamma_2, & \text{if } r = 1 \\ DN_i \times \gamma_1 + SNR_i \times \gamma_2 + E_{Curr} \times \gamma_3 + HR_i \times \gamma_4, & \text{if } r > 1 \end{cases} \quad (15)$$

where $\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 = 1$ and are called the weight parameters. The weight parameter ($\gamma_1, \gamma_2, \gamma_3, \gamma_4$) can be adjusted according to the network requirements. DN_i , SNR_i , $E_{Curr}(i, r)$, and HR_i represent the neighbor density, average signal-to-noise ratio, current energy at round r , and energy harvesting rate of node i and defined by equations (9), (10), (5), and (7), respectively.

CH selection in first round. In first round ($r = 1$), EW of a node is calculated by considering only the neighbor density DN and SNR of that sensor nodes. Other two parameters, that is, $E_{Curr}(i, r)$ and HR_i , are not considered at first round. In homogeneous networks, the level of initially supplied energy of all deployed nodes is the same, whereas energy harvesting rate of nodes cannot be determined correctly before the beginning of the very first round. Therefore, in first round, all nodes are eligible for CH competition.

CH selection in other rounds. In subsequent rounds ($r > 1$), eligibility of nodes is checked first and only eligible nodes are allowed to take part in the CH selection competition. Node eligibility is influenced by its current energy level. Nodes having current energy (E_{Curr}) greater than a certain threshold of energy, called election threshold (E_{TH}), are allowed to participate in CH selection. All other nodes wait for CH selection and

then join the selected CH in its cluster. For CH selection, EW calculation involves computations of different parameters which need transmission of some control messages. Therefore, restricting low-energy nodes from CH selection competition ensures the preservation of energy in such nodes that may be consumed in message exchanges for EW calculations. Moreover, being normal nodes, such nodes consume less energy and get a chance to harvest more energy during the round for enhancing their energy level and become eligible in future rounds. This process reduces the chance of early death of the nodes. Furthermore, the eligibility criterion ensures selection of high energy nodes as CHs which helps in constructing stable clusters.

Once the value of EW is calculated by all eligible nodes, it is communicated with all other nodes in their transmission range. Every node compares its own EW with received values. The nodes with maximum EW mark itself as CH for current round in the current cluster. The selected CHs then broadcast an advertisement message, whereas in response, all other nodes in its vicinity send a join request to the CH. The pseudo-code and flowchart of proposed scheme E^2 -MACH are shown in Algorithm 1 and Figure 5, respectively.

Performance evaluations and results analysis

This section presents the performance evaluation of proposed scheme by discussing simulation results. The validation of this scheme is done through comparison of results with some recent protocols proposed in the literature.^{27,33,39,40}

Evaluation parameters

The evaluation and comparison with other schemes are carried out on the basis of multiple parameters whose brief description is given below.

Number of alive nodes. It is the number of nodes in the targeted network which have not yet exhausted in terms of energy and are able to continue with the network operations. A number of alive nodes at different stages of network operations indicate the remaining network lifetime.

Number of dead nodes. These are the nodes whose energy is completely depleted and are not able to continue further network operations. This number is recorded with respect to different rounds. The number of dead nodes indicates the expiration rate of sensor nodes and the remaining lifetime of the network in a particular round.

Algorithm 1. E²-MACH algorithm pseudo-code

Definitions:

- 1: N : Set of total nodes in the network
- 2: DNi : Neighbor density of node i
- 3: $SNRi$: Average signal-to-noise ratio of node i
- 4: HRi : Harvesting rate of node i
- 5: M : Set of clusters in the network
- 6: EWi : Election weight of node i
- 7: $ECurr$: Current energy of a sensor node
- 8: ETH : Election threshold for node's energy
- 9: CH : cluster head

Deployment Phase:

10: All sensor nodes deployed in the field

11: BS broadcast begin a message to all

 $N = \{N1, N2, N3, \dots, Ni\}$ nodes

Initialization phase:

12: for all sensor nodes Ni do

13: Calculates distance from BS

14: Broadcast hello and replay messages in comm range

15: Calculate distance from other nodes in comm range

16: Calculate DNi by equation (9)17: Calculate $SNRi$ by equation (10)

18: end for

Cluster formation phase:

19: M clusters are formed based on node's location

20: Assigned respective cluster ID to each node

Cluster head selection phase:

21: for all nodes Ni do

22: if round == 1 then

23: Calculate EWi for first round by equation (15)

24: else if round > 1 then

25: Calculate ($ECurr$) by equation (5)26: if $ECurr > ETH$ then27: Compute EWi for other than first rounds by equation (15)

28: else

29: Block participation for CH competition in current round

30: $Ni.status \leftarrow$ member node

31: end if

32: end if

33: if round == 1 or Ni is eligible then34: Broadcast EWi in the cluster35: Compare EWi with received EWj of other nodes36: if EWi is Max then37: $Ni.status \leftarrow$ CH

38: Broadcast Adv. message to member nodes

39: Wait for member nodes to join

40: else

41: $Ni.status \leftarrow$ member node

42: Wait for Adv. message from CH

43: end if

44: end if

45: end for

46: for all Nodes Ni do47: if $Ni.status ==$ member node then

48: Send join request to current CH

49: Receive response and update its CH id

50: else if $Ni.status ==$ CH then

51: Register member nodes and update member table

52: end if

53: end for

54: Go to data transmission

Stability period. Time period starting from the initialization of a network till the death of its first node is called the stability period of the network. The network with high stability period exhibits high throughput and performance.

Network lifetime. Time period between the initialization of sensor nodes and death of the last node in the network is called lifetime of network. Higher number of rounds signifies the longest lifetime of a network.

Energy consumption. The energy consumed by each node is determined by residual energy of sensor nodes in different rounds. It signifies the amount of harvested and consumed energy by a sensor node in a particular round.

Simulation parameters setting

The simulation of the proposed scheme is performed in NS2 on a 64 bit Ubuntu 18.6 operating system. The network simulation scenario uses a square area of $100 \times 100 \text{ m}^2$, where 100 sensor nodes are deployed randomly. The location of BS was fixed outside the deployment area. Every node is supplied with an initial energy of 0.5 J and recharging solar energy model described in section "Model construction," is used for the nodes. In real environments, the recharge rates are random and influenced by the weather and time. For simulating better energy acquisition, simplified energy harvesting model as illustrated by equation (7) is shown in Figure 4. Other simulation parameters are listed in Table 2.

Simulation results and analysis

The LEACH, EECPEP-WSN, CHSES, and EE-MRP protocols were simulated in the NS2 tool under the same network parameters to conduct experiments on homogeneous WSN. Differences between the performance of the above listed protocols and the proposed scheme E²-MACH were identified by comparing their simulation results. The performance comparison conducted in terms of the number of dead as well as surviving nodes, residual energy of nodes, and other indicators. The rest of this section is dedicated to the description of performance analysis of the proposed scheme in terms of network lifetime, energy consumption, and network throughput.

Network lifetime. Network lifetime is signified by the number of dead nodes as well as alive nodes in different cluster rounds. This number increases and decreases

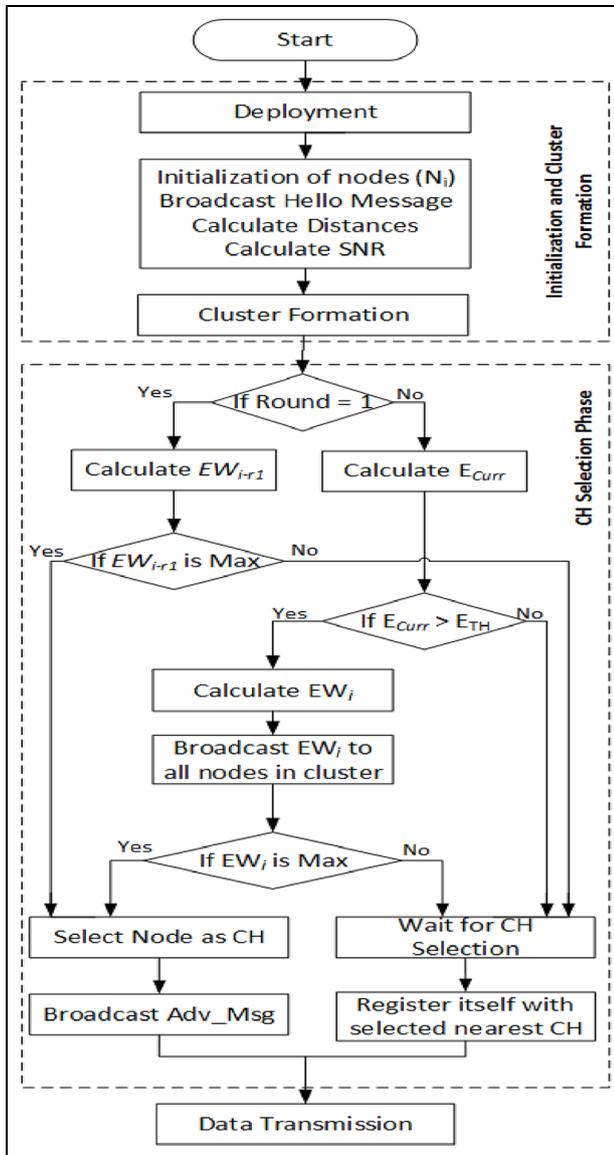


Figure 5. E²-MACH scheme flowchart.

with the passing number of rounds, respectively. The residual energy of sensor nodes in different schemes gradually decreases as the rounds progress; therefore, the number of dead nodes increases which affect the network lifetime. It can be observed in Figure 6 that the first node in LEACH dies at 745th round, while in other protocols it became dead beyond 1000th round. However, the first node dies in EE-MRP and EECPEP at 1180th and 1389th rounds, respectively.

Due to energy harvesting ability in CHSES and E²-MACH, consumed energy is recovered up to a certain level and hence they perform better than other protocols. Table 3 shows that first node dies in CHSES at 1506th round, while in E²-MACH, it persists until 1680th round due to optimized clustering. The analysis in Figure 6 clearly shows that 50% of nodes were died

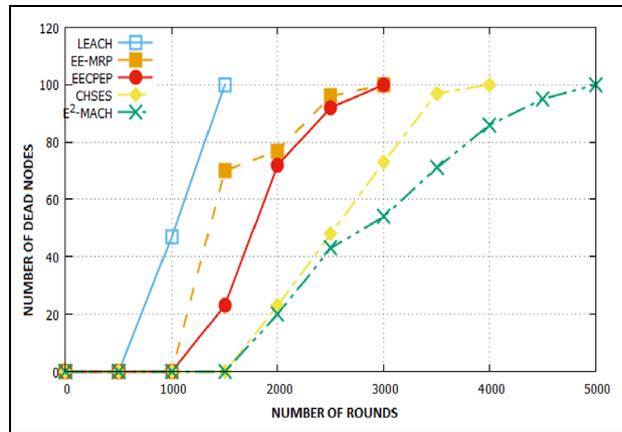


Figure 6. Comparison of number of dead nodes over rounds.

for LEACH, EECPEP, and EE-MRP at round number 1053, 1703, and 1440, respectively. In the meanwhile, the protocols with energy supply show a lesser death rate of sensor nodes and lasts for longer time as compared to non-energy harvesting schemes. The CHSES and proposed protocol continued its operations until round number 4000 and 5000, respectively.

Number of surviving nodes. The number of surviving nodes at different cluster rounds is another metric to gauge the network lifetime. The result comparison for the number of alive nodes of proposed protocol with other existing schemes is shown in Table 4 and Figure 7.

The results clearly show that the number of surviving nodes in our proposed protocol (E²-MACH) is comparatively high. The number of alive nodes in LEACH is about 80% in 450th round which persists till 1000th round and then sharply decreased and ultimately reached to 0% in approximately 1500th round. EE-MRP continued with 100% alive node till 1000th round; however, in the next 1000 rounds, it decreased sharply to approximately 10% of the total nodes. In the next 500 rounds, the number of alive node became 0%. The node death rate of EECPEP was considerably slower than LEACH and EE-MRP but as overall performance, it also reached to the level of 0% in the 3000th round.

In contrast, due to energy supply and optimal clustering mechanism, the sensor nodes of CHSES and E²-MACH protocol survived for a longer time. Both of these protocols performed with 100% nodes till 1600th round. After this point, the number of alive nodes in CHSES gradually decreased at a faster rate compared to E²-MACH and eventually it reached to the level of 0% at 4000th round. However, E²-MACH continued its operations till 5000th round due to link statistics consideration for clustering mechanism.

Table 2. Network parameters for simulation.

Parameters	Meaning	Value
$M \times M$	Sensor node's deployment area (m)	$100 \times 100 \text{ m}^2$
N	Total sensors	100
E_i	Initially supplied energy	0.5 J
ET	Circuit loss in transmission	50 nJ/bit
ER	Circuit loss in reception	50 nJ/bit
ϵ_{mp}	Free-space amplifier's consumption factor	10 pJ/bit/m^2
ϵ_{fs}	Multi-path attenuated amplifier's consumption factor	$0.0013 \text{ pJ/bit/m}^2$
E_{int}	Energy consumed in data integrations	5 nJ/bit/signal
L	Data packet length (bits)	4000 bits

Table 3. Number of dead nodes at different cluster rounds.

S. No	Protocol name	First node death at (round)	Number of nodes become dead at different number of cluster rounds										
			500 rounds	1000 rounds	1500 rounds	2000 rounds	2500 rounds	3000 rounds	3500 rounds	4000 rounds	4500 rounds	5000 rounds	
1	LEACH	745	0	47	100	100	100	100	100	100	100	100	100
2	EE-MRP	1180	0	0	70	77	96	100	100	100	100	100	100
3	EECPEP	1389	0	0	23	72	92	100	100	100	100	100	100
4	CHSES	1506	0	0	0	23	48	73	97	100	100	100	100
5	E^2 -MACH	1680	0	0	0	20	43	54	71	86	95	100	100

LEACH: low-energy adaptive clustering hierarchy; EE-MRP: energy-efficient multistage routing protocol; EECPEP: energy-efficient clustering protocol to enhance performance; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; E^2 -MACH: energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs.

Network residual energy. The comparison of network average residual energy with respect to time (in seconds) is shown in Figure 8. In parameter setting for simulation, 0.5 J energy is assigned to each node which in total make 50 J for 100 nodes. It is clearly shown in the figures that energy dissipation of the proposed protocol is less than all other schemes.

In LEACH and EE-MRP, the energy consumption rate is high and hence their residual energy reaches to the lowest level of 0 J in round number 3000 and 4000, respectively. EECPEP scheme comparatively performs better than LEACH and EE-MRP whose residual energy declined at a slower rate and become 0 J in 7000th round. However, in CHSES and proposed protocol (E^2 -MACH), residual energy of sensor nodes shows even slower declination due to the addition of harvested energy during rounds. This condition shows that the energy acquisition of sensor nodes can enhance the network lifetime. As shown in Figure 8, CHSES continues until 10,000th round, while the proposed protocol outperforms the CHSES due to optimized clustering and efficient utilization of energy by selecting multi-parametric based CHs.

The experimental results of different protocols for network average residual energy are shown in Table 5. The comparison with LEACH, EE-MRP, EECPEP,

and CHSES clearly shows that E^2 -MACH has better energy utilization and runs for a longer time than other schemes. This is due to its use of the best CH selection strategy based on four different parameters which play significant role in the preservation and optimized energy utilization.

Network throughput. The throughput in a communication system is defined as the total number of successfully delivered packets at the destination point. The comparison of throughput of the proposed protocol with other schemes under discussion is depicted in Figure 9. This clearly depicts that most of the algorithms experience the same throughput in first 1000 rounds and gradually increases with approximately the same rates. The reason of this is that initially there are either no or less number of dead nodes in the network.

However, after 1000th round, considerable differences were recorded in the throughput value of different algorithms. Some of them gradually increased with different rates, while others maintain almost the same throughput value. The throughput value for LEACH protocol did not increase significantly after 1000th round. Furthermore, EE-MRP was able to manage an increase in throughput until 2000th. After 2000th

Table 4. Number of alive nodes at different cluster rounds.

S. No	Protocol name	Number of surviving nodes at different number of cluster rounds											
		Or	500 rounds	1000 rounds	1500 rounds	2000 rounds	2500 rounds	3000 rounds	3500 rounds	4000 rounds	4500 rounds	5000 rounds	
1	LEACH	100	100	53	0	0	0	0	0	0	0	0	0
2	EE-MRP	100	100	100	30	23	4	0	0	0	0	0	0
3	EECPEP	100	100	100	77	28	8	0	0	0	0	0	0
4	CHSES	100	100	100	100	52	27	3	0	0	0	0	0
5	E ² -MACH	100	100	100	100	80	57	46	14	5	0	0	0

LEACH: Low-energy adaptive clustering hierarchy; EE-MRP: energy-efficient multistage routing protocol; EECPEP: energy-efficient clustering protocol to enhance performance; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; E²-MACH: energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs.

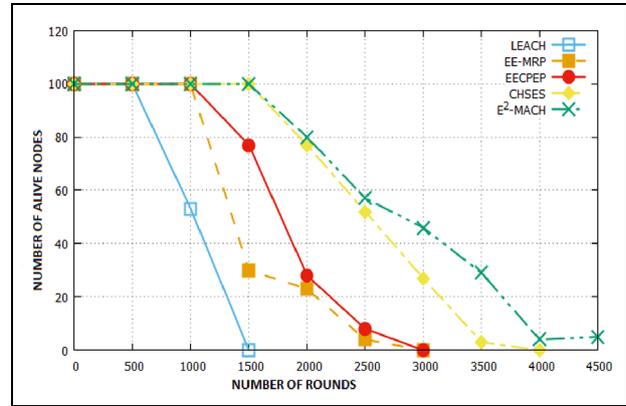


Figure 7. Comparison of number of alive nodes over rounds.

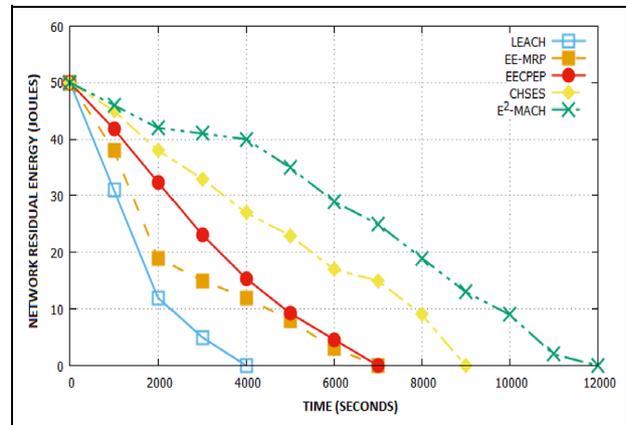


Figure 8. Comparison of network residual energy (in Joules).

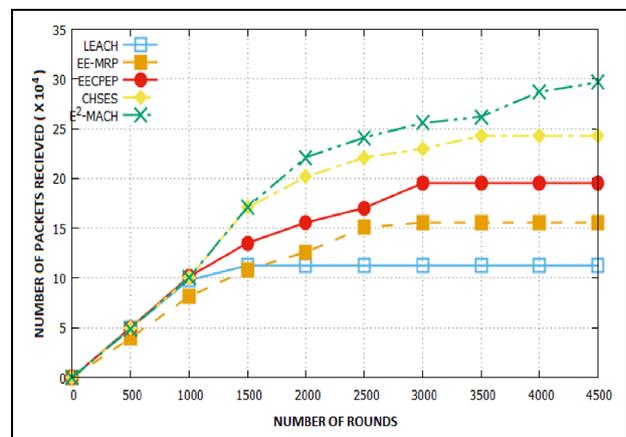


Figure 9. Comparison of overall network throughput.

round, the increase was insignificant. For EECPEP, it was gradually increasing till 3000th round after which it converged at a constant rate. However, during this time, the network throughput of CHSES and the

Table 5. Network average residual energy in different cluster rounds.

S. No	Protocol name	Average network residual energy in Joules with respect to time in seconds													
		0 s	1000 s	2000 s	3000 s	4000 s	5000 s	6000 s	7000 s	8000 s	9000 s	10,000 s	11,000 s	12,000 s	
1	LEACH	50	31	12	5	0	0	0	0	0	0	0	0	0	
2	EE-MRP	50	38	19	15	12	8	3	0	0	0	0	0	0	
3	EECEPEP	50	41.8	32.4	23.1	15.4	9.25	4.62	0	0	0	0	0	0	
4	CHSES	50	45	38	33	27	23	17.2	15	9	0	0	0	0	
5	E ² -MACH	50	46	42	41	40	35	29.4	24.9	19	13	9	2	0	

LEACH: low-energy adaptive clustering hierarchy; EE-MRP: energy-efficient multistage routing protocol; EECEPEP: energy-efficient clustering protocol to enhance performance; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; E²-MACH: energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs.

Table 6. Network throughput (number of received packets) in different cluster rounds.

S. No	Protocol name	Network throughput at different number of cluster rounds										
		0 round	500 rounds	1000 rounds	1500 rounds	2000 rounds	2500 rounds	3000 rounds	3500 rounds	4000 rounds	4500 rounds	
1	LEACH	0	50,123	97,834	112,562	112,562	112,562	112,562	112,562	112,562	112,562	112,562
2	EE-MRP	0	39,893	81,332	108,473	125,923	150,745	155,250	155,250	155,250	155,250	155,250
3	EECEPEP	0	50,153	101,323	135,163	155,733	170,397	195,644	195,644	195,644	195,644	195,644
4	CHSES	0	49,325	99,897	170,653	201,590	221,000	229,952	243,109	243,109	243,109	243,109
5	E ² -MACH	0	48,992	100,045	171,302	221,190	241,206	255,652	262,143	287,020	296,541	

LEACH: low-energy adaptive clustering hierarchy; EE-MRP: energy-efficient multistage routing protocol; EECEPEP: energy-efficient clustering protocol to enhance performance; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; E²-MACH: energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs.

proposed protocol was still increasing at a considerably high rate.

However, CHSES algorithm throughput remained constant after 3000th round because of differences between consumed energy and acquired energy by a sensor node. In contrast, the proposed protocol exhibits the increasing rate of throughput with respect to cluster rounds, which indicate that the network lifetime has effectively enhanced, balances the energy utilization, and increases network reliability with high throughput. Table 6 presents the detailed values of packets received at BS at different rounds by different protocols.

Network stability period. The stability period of a network is the time period between the initialization of a network and the death of its first node. To ensure overall network operations with efficient data transmission for a longer time, the stability period of a network is very important. Simulation results, as shown in Figure 10 and Table 7, depict that the stability period of the proposed protocol is highest among the protocols being analyzed. In E²-MACH, the network completed 1680 rounds before the death of its first node which makes

Table 7. Number of rounds in stable period of network.

S. No	Protocol name	Network stability cycle in cluster rounds First node die at round
1	LEACH	745
2	EE-MRP	1180
3	EECEPEP	1389
4	CHSES	1506
5	E ² -MACH	1680

LEACH: low-energy adaptive clustering hierarchy; EE-MRP: energy-efficient multistage routing protocol; EECEPEP: energy-efficient clustering protocol to enhance performance; CHSES: clustered protocol for heterogeneous WSNs with solar energy supply; E²-MACH: energy-efficient multi-attribute-based clustering scheme for energy harvesting WSNs.

the protocol clearly shows better performance compared to other protocols in question.

The results of the evaluations show that the proposed protocol is efficient than other protocols according to the respective criteria. However, it should be noted that proposed method broadcasts considerable amount of messages in different phases, that is, cluster

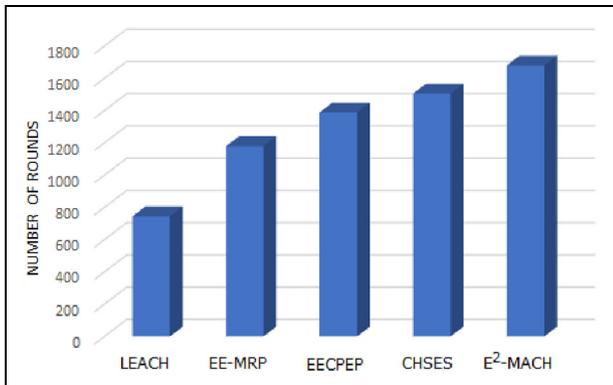


Figure 10. Network stability period in terms of rounds.

formation and CH selection. Consequently, the proposed method experiences extra message broadcasting overhead than other methods.

Conclusion and directions for future work

The key challenges in designing routing protocols for WSNs are efficient utilization of sensor's energy and a lifetime of the network. In this prospect, an important issue is to achieve maximum stability period in order to enhance packets delivery rate at BS in a reliable manner. In the proposed clustering protocol, the CH selection is based on a formulated parameter, that is, EW, which depends on various characteristics of sensor nodes such as current energy, rate of energy harvesting, number of neighbor nodes, and quality of the link in terms of environmental noise in its surrounding. The first three parameters ensure balanced energy utilization and energy preservation of a sensor node. In addition, the last parameter ensures the avoidance of weaker links for communication between nodes. This feature reduces path losses and packet drops during data transmissions. It also contributes to energy preservation by reducing the re-transmission of dropped packets. This approach leads to improvement in overall residual energy in the network and helps in enhancing the stability and throughput of the network for the maximum time period.

As stated earlier in this article, the protocol proposed in this research work aimed to be designed for WSNs with static sensor node once deployed. As a direction for future work, the proposed protocol can be extended to facilitate the moving sensor nodes and IoT devices in a mobile environment. Furthermore, additional quality of service (QoS) parameters, such as fault tolerance and message broadcasting overhead, should be minimized in the proposed protocol.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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