A Genetic-Algorithm-Based Optimized Clustering for Energy-Efficient Routing in MWSN

Getsy S Sara, S. Prasanna Devi, and D. Sridharan

With the increasing demands for mobile wireless sensor networks in recent years, designing an energy-efficient clustering and routing protocol has become very important. This paper provides an analytical model to evaluate the power consumption of a mobile sensor node. Based on this, a clustering algorithm is designed to optimize the energy efficiency during cluster head formation. A genetic algorithm technique is employed to find the near-optimal threshold for residual energy below which a node has to give up its role of being the cluster head. This clustering algorithm along with a hybrid routing concept is applied as the near-optimal energy-efficient routing technique to increase the overall efficiency of the network. Compared to the mobile low energy adaptive clustering hierarchy protocol, the simulation studies reveal that the energy-efficient routing technique produces a longer network lifetime and achieves better energy efficiency.

Keywords: Clustering, energy efficiency, genetic algorithm, mobile wireless sensor network, optimization, routing.

Manuscript received Apr. 30, 2012; revised Aug. 11, 2012, accepted Aug. 27, 2012.

This work was supported by the Junior Research Fellowship in Engineering and Technology, University Grants Commission (UGC), India, (F.10-01/2005 (SA-I), Development of Energy Efficient Routing Protocol (E^2RP) for Wireless Sensor Networks).

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http://dx.doi.org/10.4218/etrij.12.1812.0047

I. Introduction

Recent advances in wireless technology have led to the evolution of mobile wireless sensor networks (MWSNs), which use low-cost, low-power multifunctional sensor nodes equipped with mobilizers, such as springs, wheels, animals, or air, to achieve better targeting and data fidelity [1]. MWSNs have many applications in the 21st century, including smart city development, e-voting, intelligent traffic systems, and rescue operations in disaster areas [2]. However, as the mobile sensor nodes are low-powered devices, energy efficiency is one of the most crucial issues in designing the network, along with the challenges imposed by the mobility of nodes, among which are dynamic topology, dynamic clustering, and unknown positioning of nodes. Power optimization can be obtained by minimizing the active communication power required to transmit and receive the data packets or by reducing the power consumed during an inactive period, that is, a node's idle listening to the wireless medium for any possible communication requests from other nodes. It has also been observed that energy-efficient clustering models with optimum parameters help in minimizing the energy consumption through active communication [3].

Deng and others [4] proposed a mobility-based clustering protocol for MWSNs. A sensor node is elected as a cluster head based on its residual energy and mobility. The cluster head allocates each of its cluster members a time slot for data transmission in ascending order in a time division multiple access (TDMA) schedule based on the estimated connection time. The cluster member decides to join a cluster head by taking into account the estimated connection time, residual energy, node degree of the cluster head, and the distance between the sensor node and the cluster head. This protocol is found to have better adaptability to a highly mobile environment. TDMA scheduling makes the protocol complex, as new scheduling must be completed and broadcast to the members each time a node enters or leaves a cluster.

Nayebi and Sarbazi-Azad [5] designed a performance model of the low energy adaptive clustering hierarchy (LEACH) protocol for MWSNs. It investigates the effect of mobility on the LEACH protocol. The protocol applies a buffer zone to the transmission range of the nodes to increase the mobility tolerance. It is observed that the energy used for cluster joins, TDMA slot assignments, and sending data from cluster heads to base stations does not vary much. The selection of an optimal buffer zone and topology update interval is very important.

Roy and Das [6] proposed a QOS-based mobile multicast routing protocol, which determines near-optimal routes on-demand using the multiobjective genetic algorithm (GA). The algorithm provides the user with a set of Pareto optimal solutions and gives the user the flexibility to choose the best possible solution, depending on the specific application requirement.

In this paper, an analytical model of an energy-efficient media access control (MAC) protocol is designed, which allows us to derive the power consumption of a mobile sensor node. It considers the power consumption resulting from transmission and reception and also considers the power wastage resulting from collision and overhearing. A clustering algorithm is modeled based on the power consumption of the energy-efficient MAC model. The prime spotlight of this clustering algorithm is to achieve the energy efficiency optimization during the formation of the cluster head. This can be achieved by minimizing the number of cluster head changes. Frequent cluster head changes reduce the network's energy efficiency and, in turn, minimize the lifetime of the network. The near-optimal residual power and mobility below which a mobile node must give up its role of being the cluster head is derived. The GA optimization technique is employed here to find the near-optimal threshold for residual power. A hybrid routing protocol [7] is used for routing, which helps to increase the overall energy efficiency of the network.

This paper is divided as follows. Section II provides the design details of the system model. Section III discusses the simulation methodology and performance study of the proposed near-optimal energy-efficient routing protocol. Section IV concludes this paper. A glossary of the symbols used in the equations is given in the appendix.

II. System Model

Let us consider a set of mobile sensor nodes denoted by $S=\{S_1, S_2,\ldots, S_N\}$ (represented as the node's virtual ID, that is, VID), which is placed in an area of A m × A m. This area is further divided into square zones of size a m × a m. The total number of zones (Z) is calculated as

$$Z=\frac{A\times A}{R^2_{\text{Max}}}, \quad (1)$$

in which R_{Max} represents the maximum transmission range of the sensor node.

Let $X=\{X_1, X_2,\ldots, X_M\}$ denote the mobile sensor nodes in zone X. All the nodes within the zone should be able to communicate with the zone head (ZH) X_j, and it is assumed that all nodes in the network know the sink's VID.

1. Zone Head Election

During the initial setup, the node that initiates a communication in the zone is elected as the ZH. It broadcasts its VID to all the nodes within its transmission range. Nodes that are within the zone area become the zone members. They send the JOIN_MSG_MEM to the ZH to become the zone members. They communicate with the ZH periodically, updating their residual energy and mobility factor. A new node entering a zone area broadcasts a registration strobed preamble (RSP). Upon receiving an RSP, the ZH sends its VID to the node. As the RSP does not include the intended receiver address, it differs from the strobed preamble. Any node intending to leave the zone sends the LEAVE_MSG to the ZH. Gateway nodes are those nodes whose transmission range covers a minimum of two zones. They send the JOIN_MSG_GW to the ZH to become the gateway nodes. The mobility factor is given by the mean zone change rate for a period T, as calculated in (16). When the residual power of the ZH goes below the predefined threshold value, $P_{\text{Res-th}}$, and the mobility goes above the predefined threshold value, M_{th}, it searches for a new node to take up the responsibility. The node that has the maximum residual power and minimum mobility factor is elected as the next ZH. The existing ZH transfers its data to the new ZH and then broadcasts the new ZH's VID to all other nodes in the zone. It then quits its role as the ZH and becomes a member of that zone.

2. Clustering Algorithm

1. Divide the network area into square zones of equal area.
2. The total number of zones (Z) is calculated as
$$Z=\frac{A\times A}{R^2_{\text{Max}}}.$$
3. The node that first starts a communication in a zone X is elected as the ZH of that zone initially. Let (x_{Xc}, y_{Xc})

be the center point of the zone X and let (x_{mc}, y_{mc}) be the center point of the neighboring zones.

4. ZH broadcasts its VID and location (x_{Xj}, y_{Xj}) to its neighbors.
5. The neighbor node with the location at (x_{Xi}, y_{Xji}) checks

if $\sqrt{(x_{Xj}-x_{Xi})^2+(y_{Xj}-y_{Xi})^2} \le a/2$,

send JOIN_MSG_MEM to the ZH;

else if $a/2 \le \sqrt{(x_{Xj}-x_{Xi})^2+(y_{Xj}-y_{Xi})^2} \le a$,

if $\sqrt{(x_{Xi}-x_{Xc})^2+(y_{Xi}-y_{Xc})^2} \le a/2 \ \&\& v_t^{Xi}=0$,

send JOIN_MSG_GW to the ZH;

else if $\sqrt{(x_{Xi}-x_{mc})^2+(y_{Xi}-y_{mc})^2} \le a/2 \ \&\& v_t^{Xi}>0$,

send LEAVE_MSG to the ZH and broadcast RSP;

end if;

end if;

3. MAC Model

A mobile sensor node can either be in an active mode or sleep mode. In the sleep mode, the sensor node consumes minimal energy. During sleep, the node turns off its radio and sets a timer to wake it later. The sensor unit senses the event even when the radio unit is in sleep mode and stores it in the processing unit. The radio wakes up after a predetermined time, and then the node notifies the event to the ZH by sending the strobed preamble [8]. The strobed preamble consists of a series of short preamble packets with small pauses between each packet, during which the transmitting node pauses to listen to the medium. The short preamble packet consists of the node's VID, the data generation time, and the intended receiver's VID. Upon waking up, the intended receiver sends an early acknowledgement (EACK) packet back to the sender during these gaps. The neighboring nodes look at the target ID in the short preamble packet and go back to sleep immediately upon realizing that they are not the intended recipients. The sender waits for a data interframe spacing (DIFS) period and then sends the request-to-send (RTS) packet. A new node entering the zone sets its NAV_{RTS} and goes back to sleep for its specified duration. The receiver then sends the clear-to-send (CTS) packet after waiting for a short interframe spacing (SIFS) time. All other nodes trying to communicate with the receiver node go into the sleep mode upon receiving the CTS packet. Then, the sender starts transmitting the data to the receiver. Upon receiving the data packets, the receiver sends an acknowledgement packet and the process continues. The RTS-CTS mechanism is used to avoid the hidden terminal problem, which occurs due to the dynamic nature of the network. Figure 1 illustrates the timing diagram of the communication model. We study the performance of the energy-efficient MAC protocol, and the average round-trip time (RTT) per packet is estimated and compared with XMAC and low-power listening (LPL). The XMAC [8] is a low-power MAC protocol for WSNs that employs a shortened preamble approach for reducing excess energy consumption at nontarget receivers while retaining the advantages of LPL and simplicity. In the LPL operation [9], when a node wants to send data, it first sends a preamble. All the nodes in the network probe the channel at every t_i seconds of sleep. Upon finding the preamble, the receiver remains in the wake state and communication takes place, which helps in reducing idle listening time and

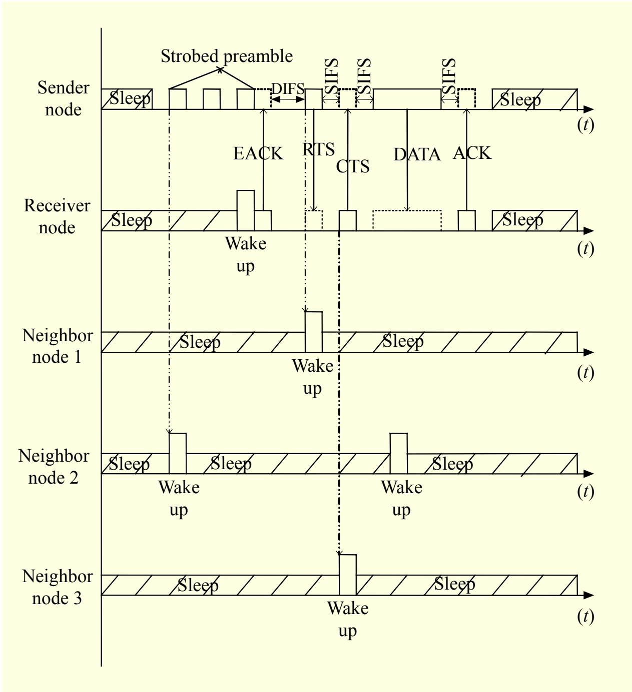

Fig. 1. Timing diagram of communication model.

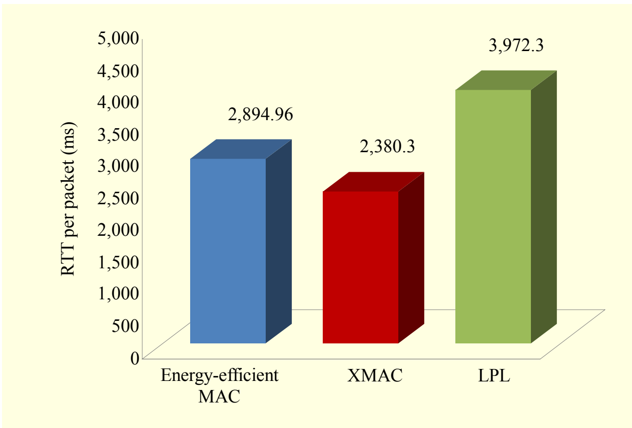

Fig. 2. Average RTT per packet.

thereby energy consumption. However, as the load increases, the collision of preambles becomes a significant waste due to the hidden terminal problem.

Figure 2 shows the average RTT per packet for energy-efficient MAC, XMAC, and LPL [9]. The RTT is estimated as the length of time it takes for a packet to be sent plus the length of time it takes for an acknowledgement of that packet to be received. A four-hop network with a preamble time of 500 ms is considered. The approximate delay incurred by LPL, XMAC, and the energy-efficient MAC is 4 s, 2.4 s, and 2.9 s, respectively.

It is observed that as the mobility of nodes and the collision of packets due to the hidden terminal problem are considered in the analysis of the energy-efficient MAC, the average RTT per packet is higher than it is in XMAC. However, the energy-efficient MAC protocol reduces the delay that occurs due to the overall collisions in the network and thereby reduces the latency of the entire network (Fig. 6).

4. Power Consumption Model

Let us consider that, at time t, X_i is the node that is trying to transmit data to its ZH X_j. The node initializes its RF circuit as soon as it detects an event [10]. Assume that the node takes P_{RF} amount of power to initialize the RF circuit. The power required to transmit a packet by node X_i to ZH X_j is calculated as follows.

The expected amount of power to be consumed to send a packet is

$$P_{\text{Tx}}^{XiXj} = \left[P_{\text{RF}} + \left(\frac{\{(P_{\text{Tx}} \times S_{\text{p}}) + (P_{\text{Rx}} \times S_{\text{al}})\} \times (R_{\text{L}} + R_{\text{S}})}{(R_{\text{L}} - S_{\text{p}})} \right) \right] + \begin{bmatrix} P_{\text{idle}} \times \{DIFS + (3 \times SIFS)\} + P_{\text{Tx}} \times (L_{\text{RTS}} + L_{\text{DATA}}) \\ + P_{\text{Rx}} \times (L_{\text{CTS}} + L_{\text{ACK}}) \end{bmatrix} + \begin{bmatrix} (M-1) \times \{P_{\text{idle}} \times (DIFS + (2 \times SIFS) + L_{\text{CTS}}) \\ + (P_{\text{Tx}} \times L_{\text{RTS}})\} \end{bmatrix}, \tag{2}$$

in which the first line on the right-hand side of (2) represents the power required to initialize the RF circuit of node X_i, the sum of the preamble power and the power per EACK listen multiplied by expected preamble listen iterations required (for strobed preamble usage) [8]. The second line corresponds to the power spent by the node for transmitting the data, and the third line calculates the power consumed in case of collision. Any node that initiates communication should have power greater than P_{Tx}^{XiXj}.

The expected amount of power needed to receive a packet is given as

$$P_{\text{Rx}}^{Xi} = \left[P_{\text{RF}} + \left[\frac{(R_{\text{s}} \times P_{\text{slp}}) + (R_{\text{L}} \times P_{\text{idle}})}{(1 - \{1 - P_{\text{d}}(t)\}^{(R_{\text{L}} + R_{\text{s}})})} \right] \right] + \begin{bmatrix} (P_{\text{Rx}} \times S_{\text{p}}) + (P_{\text{Tx}} \times R_{\text{a}}) + [P_{\text{Rx}} \times (L_{\text{RTS}} + L_{\text{DATA}}) \\ + P_{\text{idle}} \times 3 \times SIFS + P_{\text{Tx}} \times (L_{\text{ACK}} + L_{\text{CTS}}) \end{bmatrix} + \left[(M-1)\{(P_{\text{idle}} \times 2 \times SIFS) + (P_{\text{Tx}} \times L_{\text{CTS}})\} \right]. \tag{3}$$

The first part of the RHS of (3) represents the amount of power consumed for RF initialization and the amount of power consumed during the preamble arrival. It is calculated as the product of the expected iteration for a preamble to arrive and the sum of the listen cycle energy and the sleep cycle energy. The second part of (3) represents the amount of power consumed during the reception of a data packet, and the third line represents the power consumption owing to collision during reception at the receiver node. The probability of receiving a packet in a given interval of time is $P_{\text{d}}(t)$. It is chosen as an interpolation table of exponentially spaced entries, ranging between 10^{-4} and 10^{3} expected packets per second. The optimal instantaneous estimate of $P_{\text{d}}(t)=k/n$, in which k packets arrive over a period of $(n\times t)$, which is modeled as a Bernoulli process of n trials [8].

The expected amount of power needed to overhear is

$$P_{\text{Ov}}^{Xi} = \left[P_{\text{RF}} \right] + \left[\left\{ \frac{(R_{\text{s}} \times P_{\text{slp}}) + (R_{\text{L}} \times P_{\text{Rx}})}{(1 - \{1 - P_{\text{d}}(t)\}^{(R_{\text{L}} + R_{\text{s}})})} \right\} \times (\delta) \right] + \left[\{P_{\text{Rx}} \times L_{\text{RTS}} + P_{\text{idle}} \times DIFS\} \times (\Delta) \right]. \tag{4}$$

If δ=1, then the neighbor node transmits a strobed preamble; else δ=0. If Δ=1, then the neighbor node transmits a control packet; else Δ=0. The first part of (4) gives the RF initialization power of node X_i; the second part explains the power consumed by node X_i trying to overhear a neighbor's preamble during X_i's wake up time; and the third part explains the power consumed by overhearing a control packet by node X_i.

Each node performs a low duty cycle operation, that is, listening and sleeping when no event occurs [11]. During this period, the node remains inactive. The expected amount of power that a node consumes during this period is calculated as

$$P_{\text{inactive}}^{Xi} = P_{\text{idle}} \times \left[\frac{T_{\text{listen}}}{T_{\text{ci}}} \right] + P_{\text{slp}} \times \left[\frac{T_{\text{slp}}}{T_{\text{ci}}} \right], \tag{5}$$

$$T_{\text{ci}} = T_{\text{listen}} + T_{\text{slp}}. \tag{6}$$

The total power consumed by a node for a time T is

$$P_{\text{Total}}^{Xi} = \frac{\begin{Bmatrix} (N_{\text{Tx}}^{Xi} \times P_{\text{Tx}}^{XiXj}) + (N_{\text{Rx}}^{Xi} \times P_{\text{Rx}}^{Xi}) \\ + (N_{\text{Ov}}^{Xi} \times P_{\text{Ov}}^{Xi}) + (P_{\text{inactive}}^{Xi} \times T_{\text{inactive}}^{Xi}) \end{Bmatrix}}{T}, \tag{7}$$

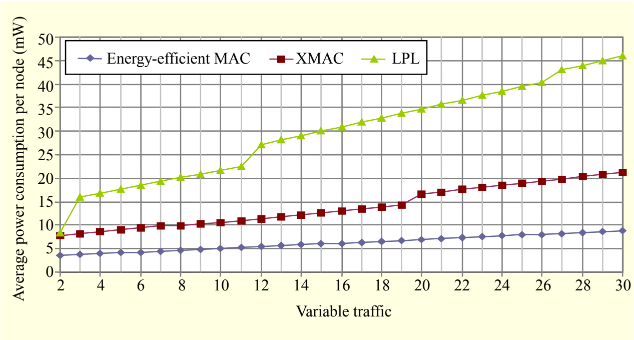

Fig. 3. Power consumption per node against variable traffic in network.

where

$$T_{\text{active}}^{Xi} = T_{\text{Tx}}^{Xi} \times N_{\text{Tx}}^{Xi} + T_{\text{Rx}}^{Xi} \times N_{\text{Rx}}^{Xi} + T_{\text{Ov}}^{Xi} \times N_{\text{Ov}}^{Xi}, \quad (8)$$

which leads to

$$T_{\text{inactive}}^{Xi} = T - T_{\text{active}}^{Xi}. \quad (9)$$

The residual power at node X_i during time T is

$$P_{\text{Res}}^{Xi} = \frac{\left[P_{\text{Init}}^{Xi} - P_{\text{Total}}^{Xi}\right]}{T}. \quad (10)$$

The residual power of a node is the difference between the expected battery capacity of a sensor node and the total power consumed by the node for a time period T.

Figure 3 shows the power consumption per node versus the variable traffic of the energy-efficient MAC, XMAC, and LPL when used in an MWSN. XMAC and the energy-efficient MAC consume less power than LPL consumes because the receiver sends an EACK packet as soon as it wakes up, effectively truncating the preamble. However, as mobility is involved, a hidden terminal problem occurs in the MWSN, which leads to a higher rate of collision in XMAC. This is taken care of by the energy-efficient MAC; hence, the average power consumption is minimized here.

5. Mobility Model

The random waypoint mobility model [12] is considered for our design. This is a simple and stochastic mobility model that can describe the random movement of a mobile sensor node. A node chooses a destination randomly in a given area and moves with a certain speed to this point. It also waits for a pause time before moving to the next destination point. The movement of a node from its starting point to its next destination point is called "a transition." The random variable representing the Cartesian coordinates of the destination point that a node X_i chooses in its movement period t is denoted by vector

$$\{P_t^{Xi}\}_{t \epsilon T} = P_0^{Xi}, P_1^{Xi}, P_2^{Xi}, P_3^{Xi} \ldots. \quad (11)$$

The complete movement process of the node X_i is given as [10]

$$\{P_t^{Xi}, v_t^{Xi}, T_{\text{p},t}^{Xi}\}_{t \epsilon T}, \quad (12)$$

in which v_t^{Xi} represents speed at time t and $T_{\text{p},t}^{Xi}$ represents the pause time at destination P_t.

The transition length is the Euclidean distance that a node travels during one movement period between two points. The expected transition length within a square of size A m×A m is given by [12]

$$E(L) = 0.5214 \times A. \quad (13)$$

The transition time is defined as the time it takes for a node to move from one point to the next point. The expected transition time is calculated as [12]

$$E(T) = \frac{1}{v_t^{Xi}} \times E(L); \;\; v_{\min} \le v_t^{Xi} \le v_{\max}. \quad (14)$$

For a given time T, let z denote the number of times the node changes its zones. For a regular n×n grid, the expected number of zone changes that occur within a transition is given by [13]

$$E(z) = \frac{2 \times (n^2 - 1)}{3n}. \quad (15)$$

The mean zone change rate is

$$\lambda^{Xi} = \frac{E(z)}{E(T)} \times T. \quad (16)$$

6. Optimizing Parameters

The GA optimization technique [14] is used here to find the residual power threshold, $P_{\text{Res-th}}$. GAs are computerized search optimization algorithms, which follow the principles of natural genetics. Variables are represented as binary-coded strings of ones and zeros. The fitness function is derived from the objective function and then used in successive genetic operations. Each string is evaluated to find the fitness value. The entire population operates by three main operators, namely, reproduction, crossover, and mutation. The reproduction operator is a selector operator that selects good strings in a population and forms a mating pool. New strings are then formed in the mating pool by exchanging information among the strings during crossover with a probability P_c. The mutation operator changes the ones to zeros, and vice versa, with a small mutation probability P_m [15].

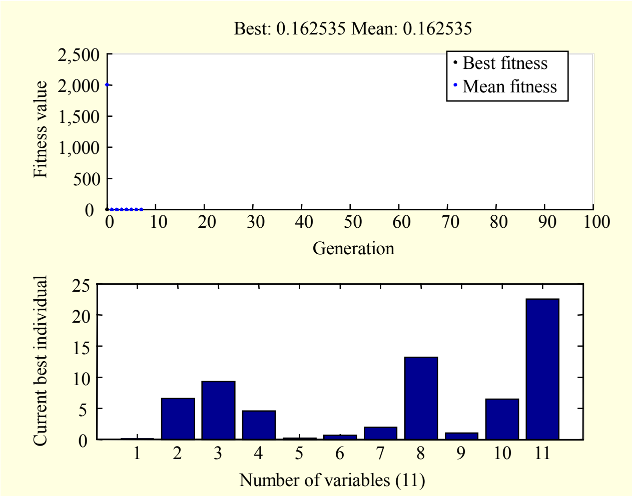

Fig. 4. GA optimized residual power output.

A. General Framework of GA

Choose an initial population of random solution.
Evaluate fitness of each solution
While termination criterion is not satisfied do
Select parents;
Perform parents' recombination;
Perform offspring mutation;
Evaluate fitness of offspring
End.

Our goal is to find the minimum residual power below which a node becomes incapable of being the ZH.

B. Optimal Residual Energy

Minimize P_{Res}^{Xi}, subject to constraints

1. $N_{\text{Tx}}^{Xi} + N_{\text{Rx}}^{Xi} + N_{\text{Ov}}^{Xi} \le N,$
2. $\{(x_{Xj} + v_t^{Xj}\text{Cos}\,\theta_{Xj}t - x_{Xi} + v_t^{Xi}\text{Cos}\,\theta_{Xi}t)^2$
   $+(y_{Xj} + v_t^{Xj}\text{Sin}\,\theta_{Xj}t - y_{Xi} + v_t^{Xi}\text{Sin}\,\theta_{Xi}t)^2\} \le R_{\text{Max}}^2,$
3. $P_{\text{Total}}^{Xi} \le P_{\text{Init}}^{Xi}.$

The first constraint specifies the maximum number of communications that a node can get involved in. The second constraint indicates that, for a node to be within the zone, the distance between the ZH and the node should be less than or equal to the square of the maximum transmission range of a node. The third constraint signifies that the total power consumed at any time T is always less than the expected battery capacity of the node at that time.

Each chromosome is represented as a fixed length list in which each gene represents a variable, such as number of transmissions, number of receptions, number of times overheard, velocity, direction of mobility, or location coordinate of the node. Since it is a constrained minimization problem, the objective function is replaced with a penalized function represented as

$$\rho_{\text{Res}}^{Xi} = P_{\text{Res}}^{Xi} + p. \tag{17}$$

The initial penalty specifies an initial value of the penalty parameter that is used by the nonlinear constraint algorithm. The fitness function is defined as

$$F(Ch_{Xi}) = \frac{1}{(1+\rho_{\text{Res}}^{Xi})}. \tag{18}$$

This fitness function is to be minimized, and it involves the residual power. The aforementioned constraints are checked for each chromosome during the evolutionary process. During the reproduction process, high-quality chromosomes are selected based on their fitness values. We simulate using the roulette wheel, stochastic uniform, and tournaments selection methods. All of these selection mechanisms have the same purpose of creating more copies of the individuals with higher fitness than those with lower fitness. However, the selection mechanisms differ in the manner in which they allocate copies to the fittest individuals. Different selection mechanisms work well under different situations. The appropriate method has to be chosen for the specific problem to increase the optimality of the solution. We have adopted the roulette wheel scheme because it is simple, effective, and yields the most near-optimal minimal residual power, as shown in Table 1.

The strings selected are then used in the crossover operation. We have adopted the heuristic crossover scheme, which uses the fitness value of two parent chromosomes to determine the search direction [13].

Offspring 1=best parent + r× (best parent–worst parent), (19)
Offspring 2 = best parent, (20)

in which r is a random number between 0 and 1.

Heuristic crossover employs a user defined parameter q to determine the number of tries to find an r that results in a feasible chromosome; else, the worst parent is chosen as the offspring. Then, a coin is flipped for a probability of P_c = 0.8, 0.9, 0.95 to check whether a crossover is desired or not. If the outcome of the coin flipping is true, then the crossover is performed and the new strings are placed in the intermediate population; otherwise, the old strings are placed in an intermediate population for a subsequent genetic operation. It is observed from Table 1 that for P_c = 0.8, a better value for minimum residual power is obtained. We have adopted the adaptive feasible mutation with a user defined mutation probability. This alters one or more gene values in a

Table 1. Results summary: at the end of 100 s.

P_c	Selection model		
	Roulette wheel	Stochastic uniform	Tournament
0.95	0.162553	0.162537	0.16258
0.90	0.162537	0.16254	0.16256
0.80	0.162535	0.16254	0.16254

chromosome from its initial state, which results in an entirely new gene value, thereby arriving at a better solution than was previously possible. This has prevented the population from stagnating at any local optimum. The adaptive feasible mutation randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. The feasible region is bounded by the constraints and inequality constraints. A step length is chosen along each direction so that linear constraints and bounds are satisfied.

We have performed tests for several instances with different durations using MATLAB [16]. In this paper, an instance with 30 mobile sensor nodes and 4 zones is shown. The initial penalty is set to 10, and the penalty factor is set to 100. We have used the "stall generation" condition to stop the execution of GA in our work. The "Pareto distance" is used as the convergence criteria. The "iterative history" is used to determine the Pareto distance. The fitness value for generations and the near optimal values of the variables used are shown in Fig. 4. The solution is charted in Table 1.

From the solution, we can choose the near-optimal residual power at which a ZH must give up its role as 0.162535 W.

C. Optimal Mobility

Maximize v_t^{Xi}, subject to constraints

1. $\lambda^{Xi} < 1$,
2. $v_t^{Xi} <= 1.38$.

The first constraint dictates that the mean zone change rate has to be less than 1, and the second constraint specifies that the maximum permissible speed of a node is 1.38 m/s. From the studies done by Bettstetter and others [12] and Hyytia and Virtamo [13] and through repeated simulation, the near-optimal mobility for the ZH is chosen as 0.2 m/s.

7. Routing Model

The hybrid routing protocol is used for routing, and it uses a modified version of the ad-hoc on-demand multipath distance vector (AOMDV) [17] routing protocol for reactive routing. Nodes periodically update their mobility factor and residual power to the ZH. Upon detecting an event, the source node generates the data announcement (DA) packet, which is made up of the strobed preamble. Many of the sensor nodes in a zone may detect the event simultaneously and try to send the DA packet to the ZH using intrazone routing [18]. Upon waking up, the ZH verifies the data generation time and sends an EACK to the node with the latest data generation time. Then, it checks whether the destination (sink) is within its zone. If so, the data is sent proactively to the destination. Otherwise, the data is forwarded by the ZH via the gateway nodes to the other zones using the multipath reactive routing technique called interzone routing [18]. Rather than choosing the entire available multipath to be stored in the routing table, a few of the best paths are selected based on the maximal nodal residual energy. The routing request (RREQ) message contains the following fields:

<Source address, source sequence no., broadcast ID, advertised hop count, destination address, destination sequence no., residual power-path (*n*)>

The routing reply message contains the following fields:

<Source address, destination address, sequence number, advertised hop count, maximum residual power, lifetime>

The advertised hop count of a node X_i for a destination represents the maximum hop count of the multiple paths for the destination available at X_i. When the intermediate ZH receives an RREQ message from a gateway node, it checks whether the sequence number specified in the RREQ message is greater than the node's sequence number [19]. If so, it adds its residual power to the existing residual power along the path. By this method, it is possible to achieve the value of maximum residual power in the specified path. The reverse paths are set up as the RREQ travels from a source to various destinations. The paths in the route list are sorted by the descending value of residual power. The shortest path is initially chosen as the routing path by the source node. Upon route failure, the data packets are forwarded via the path with the maximum residual power.

III. Simulation Analysis and Performance Study

The simulation setup is designed based on the application scenario in which a human rescue team is operating in an earthquake hit area. We have simulated the proposed protocol for MWSN in the OMNET++ (4) network simulator [20].

The simulation parameters are set up based on the specification of IRIS motes [21]. A mobile sensor network comprising 30 sensor nodes, each with a transmission range of 30 m, is randomly distributed in an area of 60 m × 60 m. The total network area is divided into four zones, each an area of

Table 2. Simulation parameters.

Parameter	Value
Battery capacity	2,850 mAh
Transmission power	68 mW
Receiver power	45 mW
Idle power	54 µW
Sleep power	2.7 µW
Initialization power	10 mW
Duration of sender preamble	0.26 ms
Duration of sender EACK	0.3 ms
Duration of receiver listen	0.3 ms
Duration of receiver sleep	0.26 ms
Packet size	1,000 bits
RTS, CTS, ACK size	64 bits
Data rate	250 kb/s

30 m × 30 m. The nodes are made to move using the random waypoint mobility model with a maximum speed of 1.38 m/s and pause time of 0.1 s. The simulation time is set to be 100 s and 1,500 s, and the performance of the protocol is evaluated and compared with the mobile LEACH protocol (M-LEACH). The simulation parameters are shown in Table 2.

We measure the packet delivery ratio, average end-to-end packet delay, power consumption along the routing path, and network lifetime for energy-efficient routing and M-LEACH.

It is observed from Fig. 5 that the packet delivery ratio is degraded as the mobility increases due to the link error probability in both protocols. Energy-efficient routing shows an improved packet delivery ratio because link breakages are minimized owing to fewer cluster head changes and gateway nodes with lesser residual power do not take part in the communication. The impact of the mobility of nodes is reduced due to the availability of multiple routes in the routing table. Alternate routes are immediately assigned if a link is found to be broken.

Figure 6 shows that the end-to-end delay of the energy-efficient routing is smaller when compared to M-LEACH as the probability of route rediscovery is much smaller. Collisions due to the hidden terminal problem are avoided, and control overheads are minimized.

Figure 7 demonstrates the average power consumption during the routing process, which mainly occurs due to transmissions from ZHs to zone members, gateway nodes of two different zones, and gateway nodes to the ZHs. In energy-efficient routing, the control overhead and wastage of bandwidth are comparatively smaller. Energy-efficient

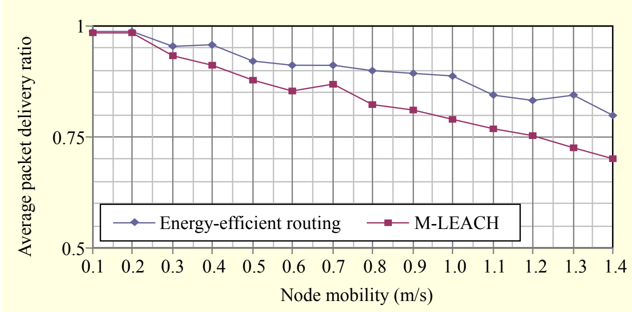

Fig. 5. Average packet delivery ratio against node mobility.

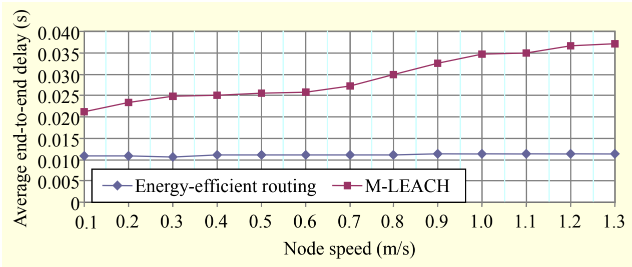

Fig. 6. Average end-to-end delay per packet vs. node speed.

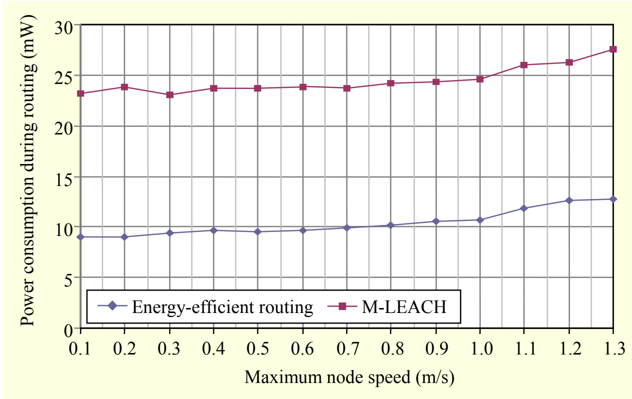

Fig. 7. Average power consumption for routing a packet against node speed.

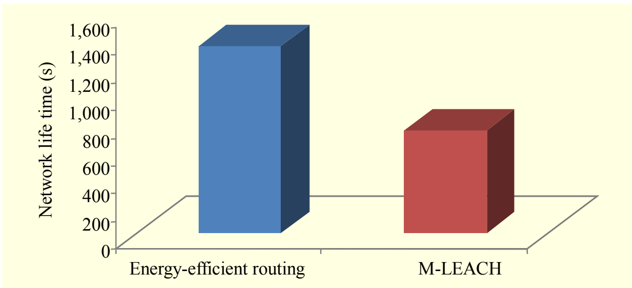

Fig. 8. Network lifetime.

routing also avoids route rediscovery for each route break. Communication between two zones is via gateway nodes, which reduces the control traffic produced by the periodic flooding of routing information throughout the entire zone. The energy consumption during transmission is reduced by the EACK packet sent by the receiver as soon as it wakes up.

Figure 8 compares the network lifetime of energy-efficient routing with that of M-LEACH. Network lifetime is defined as the time at which the first node dies. It is observed that using energy-efficient routing almost doubles the network lifetime achieved using M-LEACH. Nodes with higher mobility and lesser residual power are not involved in the communication, thereby increasing the network lifetime. Since alternate routes are available in the routing table, connectivity of the entire network is assured even if there are link breakages due to node mobility. The mean residual power of energy-efficient routing is higher than that of M-LEACH. The nodes are awake only if there are events occurring, which means that sleep time increases. Hence, the network lifetime is enhanced in energy-efficient routing.

IV. Conclusion

In this paper, we designed an analytical model of a MAC protocol, which is used to evaluate the power consumption of a mobile sensor node. Based on this, a clustering technique was devised in which the near-optimal thresholds for residual power and mobility to establish a ZH was determined using the optimization technique. A hybrid routing protocol in which a modified AOMDV protocol was employed for reactive routing between zones was used as the near-optimal routing technique, and its overall performance was evaluated. It was observed through extensive simulation that the energy-efficient routing technique outperforms M-LEACH in terms of packet delivery ratio, average end-to-end delay, and energy efficiency. The results showed that the network lifetime of the MWSN is doubled by using energy-efficient routing compared to using M-LEACH. Therefore, this protocol can better adapt to a power-stressed and mobile network.

Appendix

Glossary of symbols.

Symbols	
$A*A$	Total area of the MWSN
$a*a$	Area of a zone
R_{Max}	Maximum transmission range of a node
T	Total simulation time
N	Total no. of nodes in the network
P_{Tx}^{XiXj}	Power required to transmit one data packet from node X_i to X_j
P_{RF}	Power required initializing the sensor node
$P_{Tx}, P_{Rx}, P_{idle}, P_{slp}$	Transmission power, reception power, idle power , sleep power, respectively
S_p, S_{al}, R_L, R_s	Duration of sender preamble, sender acknowledgement, receiver listen, receiver sleep, respectively
DIFS & *SIFS*	Duration of data interframe spacing & short interframe spacing
$L_{RTS}, L_{CTS}, L_{DATA}, L_{ACK}$	Duration of RTS, CTS, data & acknowledgement packets, respectively
M	Average no. of required transmission attempts for a packet
P_{Rx}^{Xi}	Power consumed in receiving a data packet by node X_i
$P_d(t)$	Probability of receiving a packet in a given interval
R_a	Duration of receiver early acknowledgement
P_{Ov}^{Xi}	Power consumed in overhearing other nodes' packets by node X_i
$P_{inactive}^{Xi}$	Power consumed when node X_i is inactive
T_{listen}	Idle listening time of a node when no event is taking place in the zone
T_{slp}	Sleep time of a node
T_{ci}	Check interval
$N_{Tx}^{Xi}, N_{Rx}^{Xi}, N_{Ov}^{Xi}$	During time T, no. of packets transmitted by node X_i to X_j, received packets by node X_i overheard packets by node X_i, respectively
$T_{Tx}^{Xi}, T_{Rx}^{Xi}, T_{Ov}^{Xi}$	Time taken by node X_i to transmit data, receive data, overhear data, respectively
$T_{active}^{Xi}, T_{inactive}^{Xi}$	Time period during which node X_i was active and inactive, respectively
P_{init}^{Xi}	Expected battery capacity of the node at any time T
v_t^{Xi}	Speed at time t
$T_{p,t}^{Xi}$	Pause time at destination
v_{min} & v_{max}	Minimum speed & maximum speed of a node, respectively
$[x_{Xi}, y_{Xi}]$	Position of node X_i
$[x_{Xj}, y_{Xj}]$	Position of ZH X_j
θ_{Xi}	Direction of node X_i
θ_{Xj}	Direction of ZH X_j
p	Penalty factor
ρ_{Res}^{Xi}	Penalized function

Acknowledgements

We would like to thank Dr. K. Suryaprakasa Rao and the anonymous reviewers for providing constructive suggestions and feedback that improved the quality of the paper.

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