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Research Article

GRAdient Cost Establishment (GRACE) for an Energy-Aware Routing in Wireless Sensor Networks

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In Wireless Sensor Network (WSN), the nodes have limitations in terms of energy-constraint, unreliable links, and frequent topology change. In this paper we propose an energy-aware routing protocol, that outperforms the existing ones with an enhanced network lifetime and more reliable data delivery. Major issues in the design of a routing strategy in wireless sensor networks are to make efficient use of energy and to increase reliability in data delivery. The proposed approach reduces both energy consumption and communication-bandwidth requirements and prolongs the lifetime of the wireless sensor network. Using both analysis and extensive simulations, we show that the proposed dynamic routing helps achieve the desired system performance under dynamically changing network conditions. The proposed algorithm is compared with one of the best existing routing algorithms, GRAB. Moreover, a modification in GRAB is proposed which not only improves its performance but also prolongs its lifetime.

1. Introduction

1.1. Overview. Advances in sensor technology, low-power electronics, and low-power radio frequency (RF) design have enabled the development of small, relatively inexpensive and low-power sensors, called microsensors, which can be wirelessly connected [1–3] to form a wireless sensor network (WSN). The sensor nodes (or simply nodes) are usually deployed randomly and densely in hostile environment. Depending on the environment, it may or may not be feasible to harness energy from ambient sources, such as solar power [4].

Sensor nodes collaborate to observe the surroundings and send the collected information back to the sink (a node responsible for collecting such information) in the case of any abnormal event.

WSNs find their applications in many diverse indoor and outdoor areas including medicine, security, factory automation, environmental monitoring, and condition-based maintenance [5]. In indoor settings, WSNs are already being used for condition-based maintenance of complex equipment in factories. In outdoor environment, these networks can monitor natural habitats, remote ecosystems, endangered species, and emergency situations.

In addition to sending the information to the sink, sensor nodes also perform complex computations for decision making within the network, either individually or in local clusters [6]. A major energy consumer in WSN is radio communication [3]. A comparison of the cost of computations to that of communication by Pottie and Kaiser [3] reveals that 3000 instructions can be executed for the same cost as the transmission of one bit over 100 m. An unlimited quantity of data is generated by the physical world, but wireless telecommunication infrastructure is finite. This leads to a burden on communication systems, computer networks, and human resources, which can be drastically reduced if raw data are processed at the source and the decisions conveyed [5]. Hence by performing the computations inside the network, communication payload may be reduced thus prolonging the network lifetime [6].

The wired networks, unlike wireless sensor networks, are not limited by energy, node failure, and lack of a centralized controller. It is, therefore, easier to design and model a real-time wired network system. However, due to inherent

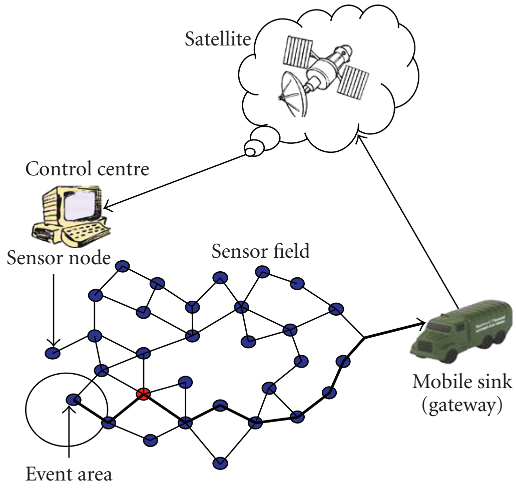


Figure 1: Wireless Sensor Networks.

problems of multihop wireless sensor networks, the design of a routing protocol, which is not only Quality of Service (QoS) and energy aware [7] but also supports real-time communication, is a challenging problem. Applications also set different delay requirements for the design of a routing protocol in WSNs. For instance, in surveillance applications, authorities need to be notified sooner about high-speed motor vehicles than slow-moving pedestrians. To support such applications, a real-time communication protocol must adapt its behavior based on packet deadlines. Hence, this implies that due to resource constraints of WSN platforms, a WSN protocol should introduce minimal overhead in terms of communication and energy consumption (Figure 1).

1.2. Literature Survey. A general data collection problem in a given sensor network refers to the problem of routing the data collected by the sensor nodes to the sink as efficiently as possible keeping in view the awareness of time and energy. However, most of the conventional routing protocols do not consider time deadlines, energy, or congestion at the forwarding nodes while routing a packet to its destination [7]. Therefore, no single routing protocol performs well in a complex real-world environment. If the impact of the above-mentioned characteristics is also added to the routing protocol designing problem, the situation is more intensified. In order to address these challenging issues, efforts have been made by the researchers around the globe. One such effort is to study the impact of energy utilization on the performance of WSN [8–11]. Several algorithms that lead to optimal connectivity topologies for power conservation have been proposed [12–17]. Later on these efforts were extended for more rigorous solutions. Flooding information [7, 18] through the network was considered a common way of ensuring real-time packet delivery. Nevertheless, this technique has extremely poor forwarding efficiency and results in lot of redundant transmissions, increased energy consumption, and thus decreased network lifetime.

A comparatively better approach had already been suggested in [19], where a set of disjoint paths is maintained from source to the destination over which the data are transmitted. This scheme, however, results in substantial energy overhead, suffers from cache pollution, and does not consider time constraint nature of the packets. Certain schemes like [20] require both GPS and GIS capability to find out the best route. Use of GPS-capable nodes is not recommended in sensor networks due to two reasons: firstly, it is too expensive in terms of power consumption to be used in power-aware networks. Secondly, it is subjected to failure when sensor nodes are deployed within some buildings, shades, tunnels, or caves [18].

In another real-time communication protocol, SPEED [21] achieves the goal of forwarding the packets closer to the destination and takes into account the presence of hot regions and congestion at forwarding nodes into its routing strategy. However, it does not take into account the energy of the forwarding nodes in order to balance the node energy utilization. Furthermore, the selection of region for forwarding data does not dynamically depend on the deadlines of the packets. SPEED also offers low reliability since it does not transmit any redundant data packets and uses a single route for data delivery. Meanwhile several other strategies were also proposed to choose an optimal path for real-time communication like minimal-load routing [22], minimal hop-routing, shortest-distance path routing [23], and so forth, but these strategies do not specifically support the stateless architecture and the energy constraints of the sensor networks.

Power Aware Chain (PAC) [24] protocol achieves a relatively better network lifetime and is fault tolerant. It is also scalable and does not require geographic information to build routing chains. However it is highly complex and involves too many control overheads which in turn enhances its memory requirements in densely populated networks. PAC assumes that all nodes are capable of reaching the sink node which may not be possible in randomly deployed sensor nodes.

Proactive Routing Protocol (PROC) [25] is another example of computationally expensive protocol and is used especially for real-time applications. Since it involves very high control overhead and requires high memory, its performance thus degrades like SPEED in densely populated networks.

Efficient And Reliable (EAR) [26] routing protocol also uses proactive approach to build routes and thus is suited for real-time applications. It routes the data reliably but dies out comparatively quicker due to energy depletion of the nodes around the hub (the node that collects the data from the network and forwards it to the base station). It also needs global identifiers which may not be feasible for large networks.

In GRAB [27], authors have focused on the problem of delivering messages from any sensor nodes to an interested client along a minimum-cost path in a large sensor network. Authors have presented a novel backoff-based cost field setup algorithm that searches for the optimal costs of all nodes to the sink with one single message overhead at each node. Once the field is established, the message, carrying dynamic cost information, flows along the minimum cost path in the cost field. Each intermediate node forwards the message only if it finds itself to be on the optimal path, based on dynamic cost states. The design does not require an intermediate node to maintain forwarding path states explicitly. It needs a few simple operations and has an ability to scale itself to any network size.

In [28, 29], Local Update-based Routing Protocol (LURP) and Sensor Networks With Mobile Access (SeNMA) protocol have been presented for WSNs with mobile sinks, respectively. In LURP, as the sink node moves, it only broadcasts its location information within a local area rather than broadcasting among the entire network. The node presents in that local area, communicating their data to the sink dissipating lesser energy as compared to communicating the same data from a distant location. This scheme also decreases the probability of collisions in wireless transmission. One major drawback of this protocol is that the sink broadcasta its location information to the entire network, whenever it goes outside the destination area. So if the network is large, the sink has to broadcast its location information to all of the sensor nodes in the entire network, which takes a lot of time and consumes a large portion of the available bandwidth. In SeNMA, an airplane acts as a mobile sink, which is not a practical approach. The reason is that the sensor nodes have resource constraints like limited energy and low transmitting ability. However, a ground vehicle as a mobile sink is a practical approach in many WSN applications [30].

Chen et al. [31] have recently proposed a routing protocol, named STEER (Spatial-Temporal relation-based Energy-Efficient Reliable routing protocol) which uses a distributed framework for routing data from source to the sink. In traditional approaches, a path is usually established before the data transmitted. This degrades the performance of a routing protocol that does not work in a highly dynamic environment. In a dynamic environment, usually the path (or set of links, or next hop nodes) chosen at an earlier time may not work well during data transmissions after a while. In STEER, a packet is broadcast first and the node closest to the sink among all those neighbors that receive the packet will be chosen as the next hop relay nodes in a distributed manner. However this approach is not bandwidth-efficient as a node broadcasts the data to each of its neighbors and thus uses most of the bandwidth.

From the above discussion, it can be concluded that the main problems in using conventional protocols are [32] the following:

(i) the size of processor and required memory are too large;

(ii) the bandwidth required is too high;

(iii) the protocols are not energy usage aware.

These problems lead to an interesting debate on the fundamental limits of wireless sensor network. The debate starts with the basic question of what the maximum sustainable throughput and the maximum lifetime of a network are. The answers to these and similar other questions are of great importance to both the theoretical and practical aspects of wireless sensor networking research.

As discussed earlier, a lot of work has been done in addressing the above issues in WSNs. However every listed piece of work either discusses only one issue from the above two issues and ignores the other one completely or gives lesser importance to one or both of them. Our research thus finds its directions to the theoretical underpinnings and design principles for an energy-efficient routing strategy that can ensure sustainable higher throughput in WSN with prolonged lifetime. In addition, the aim of this work is to find a dynamic way to maintain an efficient routing structure with minimal overhead.

Organization of the rest of the paper is as follows. Section 2 discusses the proposed strategy, GRACE, in detail. Section 3 presents various modes of operation involved in updating procedure of status information in routing tables of sensor nodes. Section 4 presents simulation results considering various performance metrics, which are usually used to evaluate the performance of routing strategy in a wireless sensor network. Section 5 proposes a modified and improved version of GRAB protocol. Finally, Section 6 concludes the paper and discusses the future work.

2. Proposed Routing Strategy—GRAdient Cost Field Establishment (GRACE)

The drawbacks and shortcomings of the routing strategies discussed in Section 1.2 were properly dealt with implementing better broadcast routing approaches. The resulting improved routing strategy thus presents good results and outperforms the previous routing approaches published in literature so far.

2.1. GRACE System Model

2.1.1. Model Assumptions. We randomly deploy a large number of sensor nodes in a monitoring area, which sense the data and send it to the control center via stationary sink. We make the following assumptions in the present study.

(i) To simplify the energy analysis, the time for sending a certain amount of data is assumed to be the same as the time for receiving the same amount of data.

(ii) The distance from the different nodes to the sink is ignored as we are dealing with the number of hops instead of propagation delay which is usually based on the physical distance from source to the sink.

(iii) All sensor nodes are assumed to be homogeneous; therefore the energy consumption for sensing is the same to each sensor node.

2.1.2. Stochastic Model. As we know that the radio pattern is largely random, there are certain other factors which are also random; but once we pick a particular value of a parameter for an experiment, it becomes deterministic. For example, the value of transmission power can be a uniformly distributed random variable and can be varied from [max, min], but in order to start an experiment we pick a particular power value. This value remains constant till the end of the experiment. Hence, for an entire process, the value of transmission power can be selected randomly from its domain; therefore the process is called as random process or stochastic process.

We can apply same procedure to the weather conditions and other environmental factors. After completing the experiments at different parameter values, the entire process becomes a random process and we can apply statistical techniques on it. Figure 2 shows a set of index random variables which combine to form a whole random process. It is also called a set of samples or a set of sample paths or realization. Here we take different data samples $X(t, S_1), X(t, S_2), \ldots, X(t, S_n)$ from each of different sensor nodes $S_1, S_2, S_3, \ldots, S_n$ after a specific time interval $t_1, t_2, t_3, \ldots, t_n$. The collection of data points from different sensor nodes at each time t_n is represented by a random variable X_n as shown in Figure 2. Associated with each of these random variables is a probability mass function (pmf) or a probability density function (pdf). Therefore if there are n index random variables: $x_1, x_2, x_3, \ldots, x_n$, then for each random variable x_n, there is an associated pdf $f_{Xn}(x)$. In addition, there is a joint pdf corresponding to all of these pdfs. In other words, in order to represent the entire random process which consists of a set of index random variables $x_1, x_2, x_3, \ldots, x_n$, we should have a joint pdf $f_{(x_1,x_2,x_3,\ldots,x_n)}$ which can represent or characterize the entire random process. We can get this joint pdf by summing up each of these individual pdfs.

The joint probability density function is given by

$$f_{x_1,x_2,x_3,\ldots,x_n} = f_{x(t)}(x). \tag{1}$$

The mean, variance, autocorrelation, autocovariance, and correlation coefficient values of the Random Process (RP) can be obtained from (2), (3), (4), (5), and (6), respectively:

(i) Mean:

$$m_{x(t)} = \int_{-\infty}^{+\infty} f_{x(t)} x \, dx, \tag{2}$$

(ii) Variance:

$$\begin{aligned} \operatorname{var}[x(t)] &= \int_{-\infty}^{+\infty} \left(x - m_{x(t)}^2\right) f_{x(t)} x \, dx, \\ \operatorname{var}[x(t)] &= E[x^2(t)] - E^2[x(t)], \end{aligned} \tag{3}$$

(iii) Auto Correlation:

$$R_{x(t_1,t_2)} = E[x(t_1)x(t_2)] = E[x_1 x_2], \tag{4}$$

(iv) Auto Covariance:

$$C_{x(t_1,t_2)} = R_{x(t_1,t_2)} - m_{x(t_1)} m_{x(t_2)}, \tag{5}$$

(v) Correlation Coefficient:

$$\rho_{x(t_1,t_1)} = \frac{C_{x(t_1,t_2)}}{\sqrt{C_{x(t_1,t_1)}}\sqrt{C_{x(t_2,t_2)}}}. \tag{6}$$

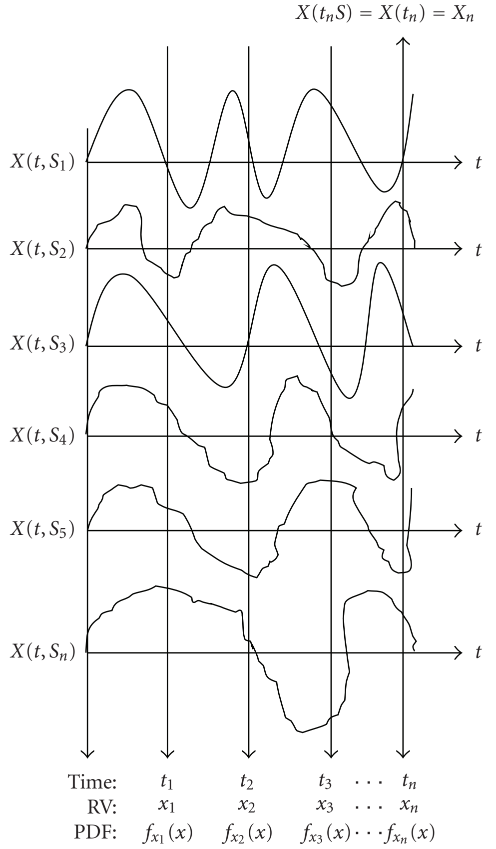


Figure 2: Random Process.

We are dealing with an event-based WSN system where the sensor nodes activate whenever an event occurs. These events occur according to a random process with a rate denoted as λ. Hence we collect the data X each time an event occurs. Let $X(t)$ be the total data collected till time t, as shown in Figure 3:

$$X(t) = \sum_{i=0}^{n} x(i). \tag{7}$$

The probability that the total data collected till time t, $X(t)$, equal to j is given by

$$P[X(t) = j] = \sum_{n=0}^{\infty} P\left[X(t) = \frac{j}{N(t)} = n\right] P[N(t) = x]. \tag{8}$$

Here X_n is a poison process, and therefore

$$\sum_{n=0}^{\infty} P\left[X(t) = \frac{j}{N(t)} = n\right] = \frac{n^j}{j!} \exp^{-n}. \tag{9}$$

Hence, (8) becomes

$$P[X(t) = j] = \sum_{n=0}^{\infty} \frac{n^j}{j!} \exp^{-n} \frac{(\lambda t)^n}{n!} \exp^{-\lambda t}. \tag{10}$$

2.1.3. GRACE Parameters. Each sensor node is defined by a infovalue pair. These infovalue pairs have already been

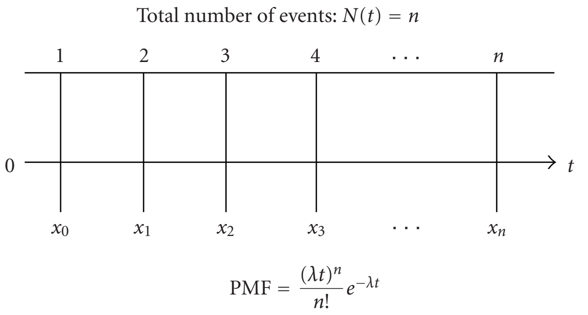


Figure 3: Poisson Process.

discussed in our previous work [33] and are discussed here again briefly.

Energy of Node, $I_{E,i}$. In order to increase the lifetime of WSN, low-energy nodes are avoided in routing. This is achieved by maintaining the following attribute for each node:

$$I_{E,i} = \frac{P_i^0}{P_i}, \tag{11}$$

where P_i is the remaining battery power and P_i^0 is the starting battery power. From the above formula, we can conclude that we should avoid those paths which contain nodes having high value of $I_{E,i}$.

Link Cost, I_L. The proposed strategy uses link costs that reflect the communication energy consumption rates at the two end nodes. The aim of the strategy is to maximize the lifetime of the network by carefully defining link cost as a function of receiving and transmission power using that link. The transmission-value is set initially same for all the nodes. The link cost between nodes u and v can be measured as follows:

$$I_{L,u-v} = \frac{P_{t,u}}{P_{r,v}}, \tag{12}$$

where $P_{t,u}$ is the transmission power of node u and $P_{r,v}$ is the received power of node v. For convenience in use, we will represent $I_{L,u-v}$ as I_L from now onward.

Intuitively, a link that has high value of I_L means that there exist more chances of packet drop and more transmission energy would be required to overcome the hindrances of the path. So we can conclude that we should avoid such links that have higher values of I_L.

2.2. Phases of GRACE

2.2.1. Setup Phase Algorithm. Most of the WSNs routing strategies are data-centric. In data-centric strategies, sink sends interest packets to the area in the sensor field where it wants to collect the data. However in our strategy, which is more generalized as compared to the above mentioned approach, the sink initiates the setup phase for the entire WSN. In the setup phase, a cost propagates throughout the sensor field. This cost field is established using the advertisement packet.

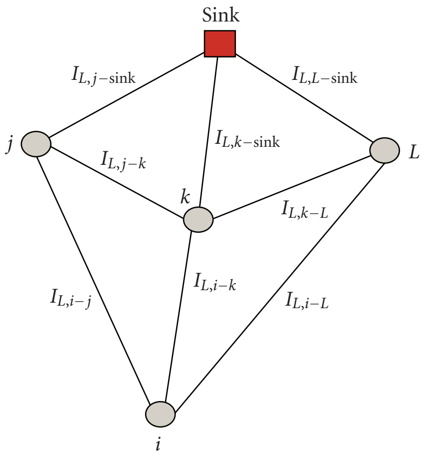


Figure 4: Cost Field Establishment.

(i) Let $C_{i\text{-Sink}}$ be the cost of the path which heads to the sink from the ith node.

(ii) Let C_{ij} be the cost of the path which heads to the sink via jth node from the ith node.

(iii) Let A_i be the advertisement packet broadcasted by ith node to its immediate neighbors.

The cost field propagation is better understandable by an example. As shown in Figure 4, nodes j, k, and l are the immediate neighbors of the ith node. We can define the cost fields and advertisement packets as follows,

$$\begin{aligned} A_j &= C_{j\text{-Sink}} + I_{E,j}, \\ A_k &= C_{k\text{-Sink}} + I_{E,k}, \\ A_l &= C_{l\text{-Sink}} + I_{E,l}, \\ C_{ij} &= A_j + I_{L,i-j}, \\ C_{ik} &= A_k + I_{L,i-k}, \\ C_{il} &= A_l + I_{L,i-l}, \\ C_{i\text{-Sink}} &= \min\left(C_{ij}, C_{ik}, C_{il}\right). \end{aligned} \tag{13}$$

Initially $C_{\text{node-Sink}}$ is set to infinite for all the nodes in the sensor field. The sink initiates the setup phase by broadcasting the advertisement packet containing the cost $A_{\text{Sink}} = 0$ to all of its immediate neighbors. When a node receives the advertisement message with the cost, it stores the cost in its routing table. Then it calculates the link cost $I_{L,\text{node-Sink}}$, as described in (12). Thus, a node's routing table contains cost **C** received from each of its immediate neighbors along with the neighbors' id. Now, the receiving node (say i) picks the smallest **C** value from its routing table, adds its own $I_{E,i}$ cost in it, and broadcasts this final value A_i to all of its immediate neighbors. Also, the receiving node considers the smallest value node as the relay node to send data back to the sink. The similar algorithm is running on other nodes and this process continues till the last node of the sensor field. Once the setup phase is completed, the steady-state phase is performed to find the best path.

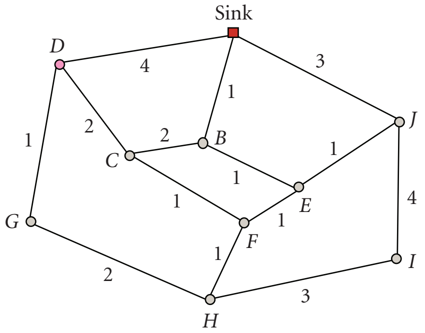


Figure 5: Example Scenario.

2.2.2. Steady-State Phase Algorithm. After the completion of the setup phase, the source node sends the data to that particular node which has the smallest cost **C** value in its routing table. The receiver then forwards the data to that node having the smallest cost **C** value in its routing table and the same process continues till the data reach to the sink. In order to update the status information of sensor nodes, we propose different modes of operations that will be discussed in detail in Section 3.

2.3. An Example Scenario of the Proposed Strategy. The setup and steady-state phases can be better understandable if we take an example. Let us take an example network as shown in Figure 5. The energy levels and the link costs are calculated using (11) and (12), respectively. First the *SINK* node broadcasts the advertisement message to nodes B, D, and J. This advertisement message contains the cost $A_{\text{Sink}} = 0$. Nodes B, D, and J receive the message, calculate their respective link costs $I_{L,B\text{-Sink}}$, $I_{L,D\text{-Sink}}$, and $I_{L,J\text{-Sink}}$, and then add their link costs to A_{Sink} to form $C_{B\text{-Sink}}, C_{D\text{-Sink}}$, and $C_{J\text{-Sink}}$, respectively. Nodes B, D, and J store these information in their routing tables, as shown in Table 1. After a certain period of time, which depends on these costs as discussed in [27], the nodes select the minimum cost $C_{x\text{-Sink}}$ from their routing tables, add their own energy cost I_E in it, and broadcast it to all of their immediate neighbors (In the figure node B broadcasts its advertisement A_B to nodes A, C, and E. Node D broadcasts its advertisement A_D to nodes A, C, and G. Node J broadcasts its advertisement A_J to nodes A and I). The same procedure also runs at nodes G, C, E, and I. This process goes on one after the other according to their intervals, till the last node of the sensor field establishes its routing table. After the setup phase, steady-state phase begins. We take node H as a source node. Now node H looks for the node in its routing table which has the smallest cost **C**. In our case, it is node F; so node H sends the data to node F. Same decisions for forwarding data are made on other nodes. In this way data reach the sink with minimal routing overhead.

3. Modes of Operation for Updating Status Information

We propose various modes of operation for updating status information of the sensor nodes in the WSNs. The performance of any routing strategy depends on the use of any particular mode. In this section, we present the behavior of our proposed routing strategy under the operation of these modes. These modes of operation are given as follows

(1) Single Setup (SS) Alone Mode,

(2) Unicast Acknowledgement Mode,

(3) Broadcast Acknowledgement Mode,

(4) Correction Mode (starting from the sink),

(5) Correction Mode (starting from the intermediate node).

The setup phase will be run at start and information update will be made according to the operation of these modes. The plots showing the behavior of these modes on the performance of the network would consequently be used for choosing the best mode of operation for the information update procedure.

3.1. Single Setup (SS) Alone Mode. In this mode of operation, the setup phase runs only once at the startup. Thus later on using this mode, there is no mechanism to update the status information of sensor nodes. This leads to the continuous usage of a routing path till any of the node in the path dies. We take a network, deployed in an area of 50 m × 50 m as an example to illustrate various modes of operations.

3.2. Unicast Acknowledgement Mode. Since every node has cost factors of its neighbor nodes, it selects node for routing data that has minimum cost. Later on, this cost factor is updated in such a way that the receiving node sends an acknowledgement to the sender whenever it receives the data. This acknowledgement comprises of one extra byte, showing the current minimum cost factor of the receiver node. Thus, the updates propagate in the sensor field by sending acknowledgments for the received data. Figure 6 shows the Unicast Acknowledgement Mode.

3.3. Broadcast Acknowledgement Mode. One major drawback of the acknowledgement phase is that only the sender knows about the updated status information of the receiving node. In order to prevent from it, the receiving node can broadcast the acknowledgement along with its updated status information to all of its immediate neighbors. In this way, a node can inform all of its neighbors about its updated status information. Figure 7 shows the Broadcast Acknowledgement Mode.

3.4. Correction Mode (Starting from the Sink). Whenever a node sends data packet to another node, it keeps the packet ID in its buffer. Similarly, every node gets a list of all the packet IDs it receives. Whenever a packet reaches the sink, sink sends the acknowledgment to the node from which it receives the packet. That node then broadcasts the acknowledgement containing its updated status information to all of its neighbors along with data packet IDs. The packet ID will help recognize the corresponding node among the

Table 1: Energy Levels of Nodes at some time after the deployment of the Network.

ID	A	B	C	D	E	F	G	H	I	J
I_E	0	2	3	4	5	6	7	8	9	10

Table 2: Cost Fields.

ith Node	Neighbor jth Node	A_j	$I_{L,i-j}$	C_{ij}	$C_{i\text{-Sink}}$	$I_{E,i}$	A_i
B	Sink	0	1	1	1	2	3
	C	8	2	10			
	E	9	1	10			
D	C	8	2	10	4	4	8
	Sink	0	4	4			
	G	16	1	17			
J	E	9	1	10	3	10	13
	Sink	0	3	3			
	I	26	4	30			
C	D	8	2	10	5	3	8
	B	3	2	5			
	F	15	1	16			
E	J	13	1	14	4	5	9
	B	3	1	4			
	F	15	1	16			
F	E	9	1	10	9	6	15
	C	8	1	9			
	H	22	1	23			
G	H	22	2	24	9	7	16
	D	8	1	9			
H	I	26	3	29	16	8	22
	G	16	2	18			
	F	15	1	16			
I	H	22	3	25	17	9	26
	J	13	4	17			

neighbors which took part in carrying that packet. This process will continue till the source node, which originated the data packet, get the corrected cost of the path used in carrying its data. Storing packet IDs gives an extra burden to the node memory. In order to minimize this burden, node will use a specified memory for packet ID storing on FIFO basis. Consequently, in case of congestion in a particular region of the network, node will lose the packet ID from its memory and hence will stop broadcasting for not allowing an increase in the congestion. Figures 8(a) and 8(b) show the Correction Mode (Starting from the sink).

3.5. Correction Mode (Starting from the Intermediate Node). Sometimes the packet is lost or dropped at some intermediate node. In this case the correction mode will not be initiated as the packet is not reached at the sink. Therefore there must be a mechanism which initiates the correction operation at any intermediate node, so that the updated cost field is propagated along the entire path. Correction operation starting from the intermediate node is a solution for it. Figures 9(a) and 9(b) show the Correction mode (Starting from the intermediate node).

Table 3: Parametric values used in Simulations.

Parameters	Value
Number of nodes	250
Initial energy	100 J
Communication Range	10 m
Sensor field size	$50 \times 50\,\text{m}^2$
Data rate	40 kbps
Simulation Time	1500 units

4. Results and Discussion

4.1. Simulation Setup. To investigate the performance and the scalability of the proposed protocol, we generate a sensor network comprising of 100 nodes and carry out extensive simulations in Matlab 6.0 in order to validate the proposed routing strategy under different modes of operation. Our sensor field's dimension is 0.0025 Kilometer Square. The numerical values chosen for our simulations can be seen in Table 3.

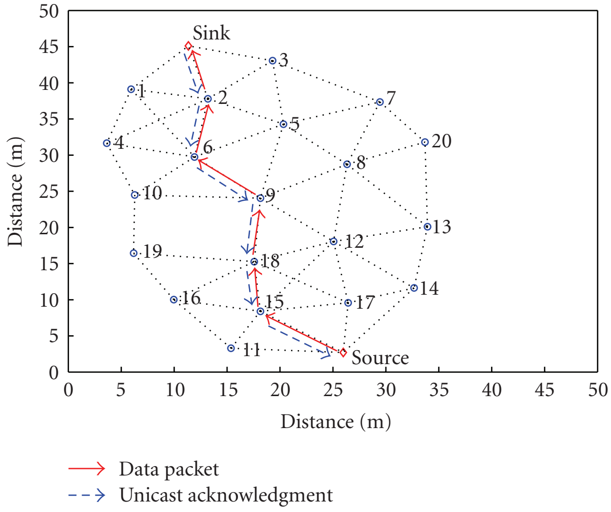


Figure 6: Unicast Acknowledgment Mode.

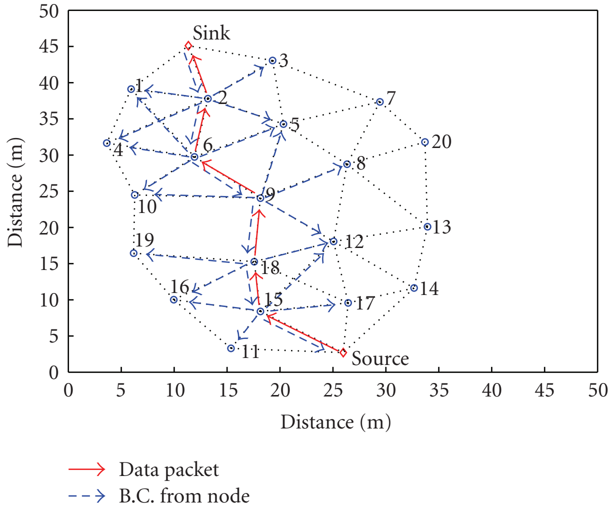
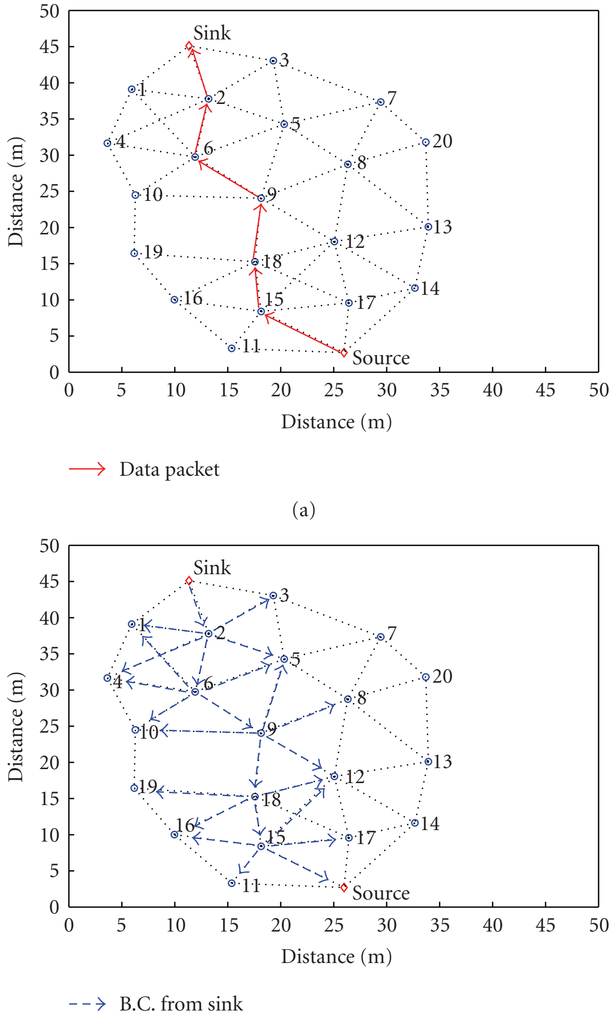


Figure 7: Broadcast (B.C) Acknowledgment Mode.



(a)

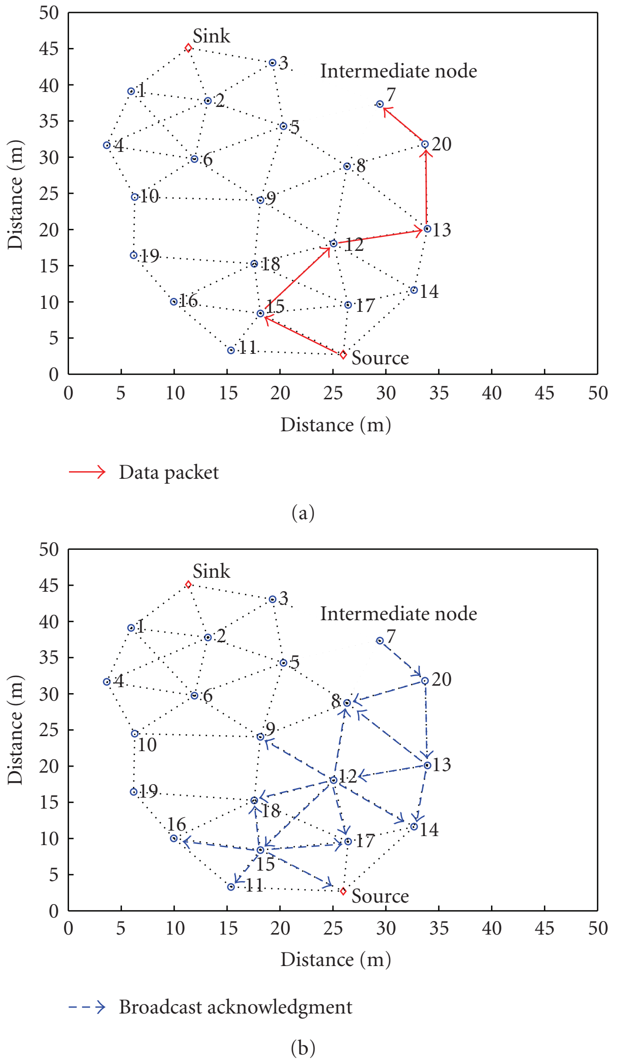
(b)

Figure 8: Correction Mode (Starting from the sink). (a) Data Packets. (b) Acknowledgment Packets.

4.2. Performance Metrics. A set of performance metrics is used for evaluating the performance of the proposed strategy. One point that should be kept in mind is the degree of goodness or badness of the results. It is clear that it depends on the working life of the network. A network having only one established path from the source to the sink is much better than the network that has got large number of disconnected nodes scattered in the field. This takes us to the strategy that utilizes the network nodes on a uniform balanced manner. Another criterion that promises the reliability and useability of the network is preventing the nodes from dying till a large number of nodes die out collectively. The collective death of a large number of nodes will ensure a reliable data delivery and network operation for a specified time. This time would thus give us a prediction about the safe operation of the network. The use of network beyond this time would make its operation unreliable and unpredictable. The figures show the result obtained under various scenarios and modes of operation.

4.2.1. Network Lifetime (in Terms of Node Failures, f). It shows how much time the network will alive. In Figure 10, number of alive nodes is plotted against simulation time units. It can be seen that the correction mode from intermediate node has the lowest working life while the broadcast acknowledgement mode has the highest working lifetime, thus keeping a large number of nodes alive with high data rate and reliable data delivery. The reason of this difference in results is that setup phase with the broadcast acknowledgement uses the nodes evenly in terms of energy utilization, while the other approaches like GRAB [27] do not ensure a balance utilization of nodes.

In Figure 11, we draw a bar graphs of the node failure, f (in percentage) versus time elapsed. It is also clear from that when first node dies, single setup with unicast acknowledgement mode has longer time elapsed, while the single setup mode and GRAB [27] have the lowest time elapsed. This is due to the fact that in case of single setup mode, which is based upon the initial nodes' status



(a)

(b)

FIGURE 9: Correction Mode (Starting from the intermediate node). (a) Data Packets. (b) Acknowledgment Packets.

information, it continuously uses a path till any of the nodes in the path dies. While in case of GRAB [27], the setup phase will not run till the occurrence of any event.

4.2.2. Network Energy Left, e. It shows the amount of energy left, e, in the alive nodes whether connected or disconnected in the network with the passage of time. Figure 12 shows plots of the network energy versus simulation time. From the figure, it is clear that use of single setup mode outperforms the others if energy consumption is considered. This is due to the fact that the setup phase runs only at the startup and no acknowledgment and correction is done at later times. Although this mode is good in the energy consumption sense but as a result of not using acknowledgement and correction, it loses data reliability as compared to other nodes.

4.2.3. Data Reliability, μ. It shows the success ratio of the data packets, that is, the number of data packets received by the

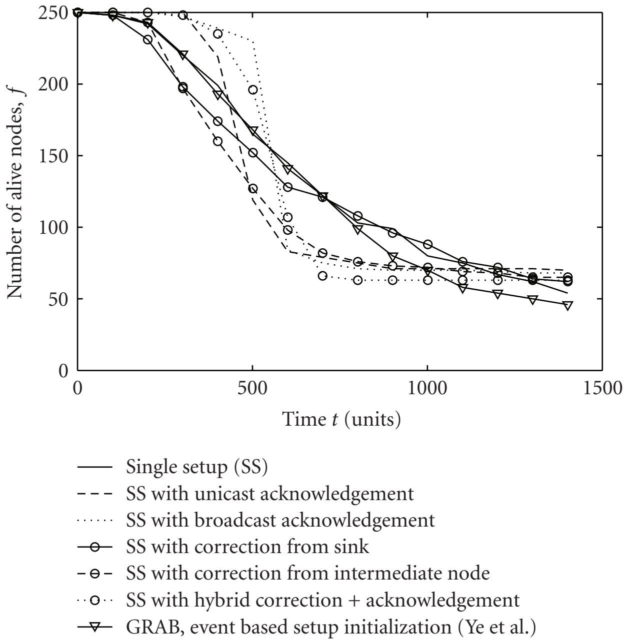


FIGURE 10: Network Lifetime: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

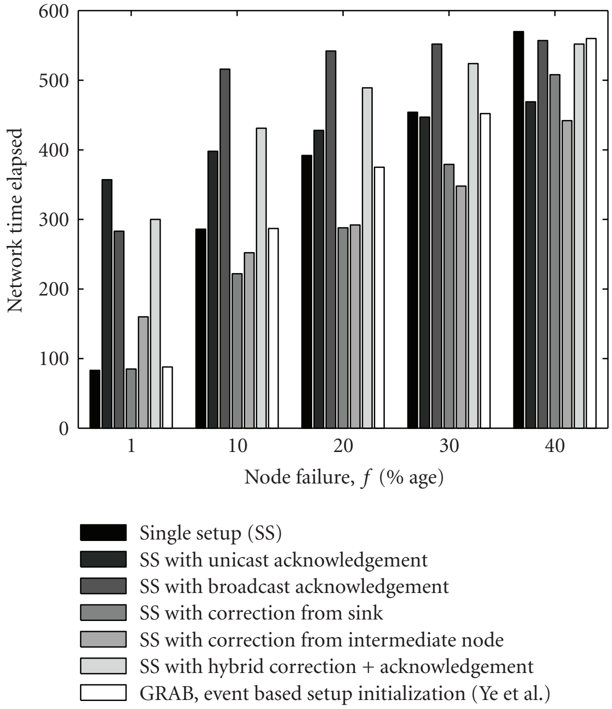


FIGURE 11: Node Failure in Percentage: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

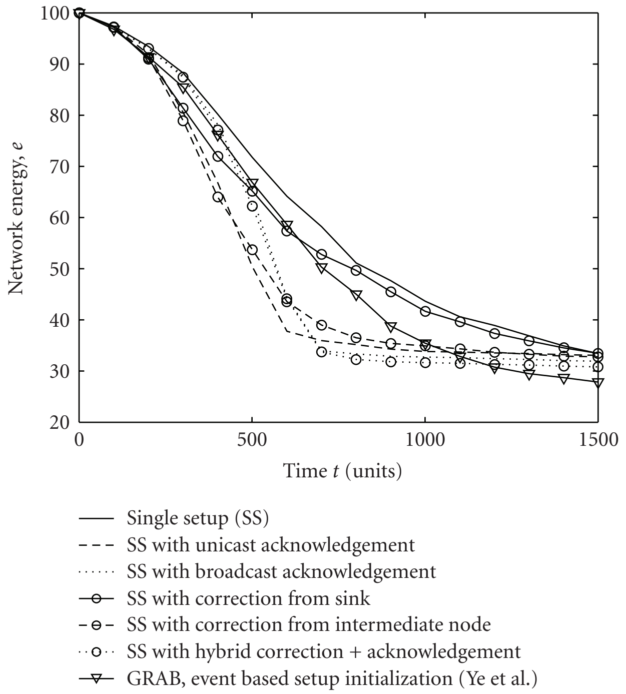


Figure 12: Network Energy Left: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

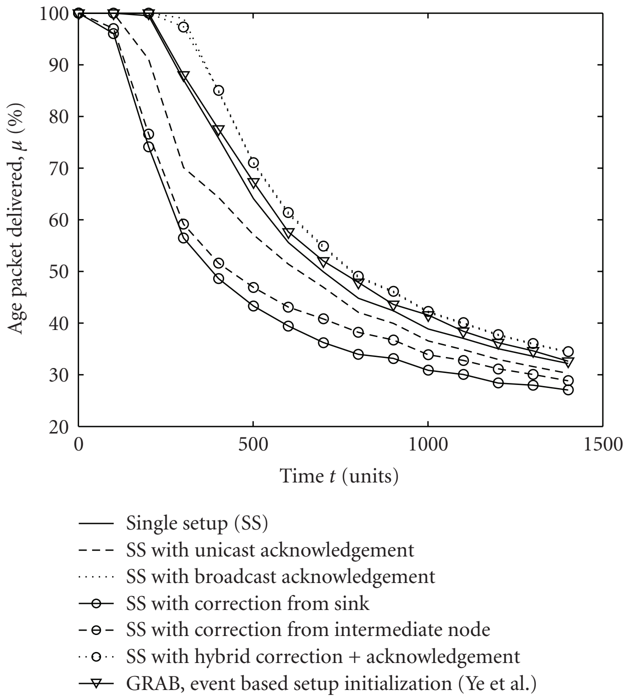


Figure 13: Data Delivery in Percentage: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

sink out of the total number of data packets generated by the source. In Figure 13 one aspect of data reliability comparison is shown, where the plots represent the percentage data delivery with respect to simulation time. It is clear from the figure that the hybrid approach and the single setup with broadcast acknowledgement have high data reliability. This is due to the fact that the status information of the sensor nodes is updated frequently, in these modes of operation.

Another aspect of data reliability comparison is shown in Figure 14, where the plots show interval-based data delivered to the sink after a specified time interval (e.g., after each 100 seconds in our case); we note down the number of data packets received at the sink. It can be noted from the plots that initially the single setup with broadcast acknowledgement mode has the highest percentage of delivered packets to the sink but cannot keep its pace at later times and degrades its performance due to bulk node failures.

Discussing the last aspect of data-delivery performance comparison, the packet received by the sink have been plotted against the packets sent by the source. Figure 15 shows that the single setup with broadcast acknowledgement mode has large number of packets received. The reason is obvious that in the single setup with broadcast acknowledgement mode status information of the sensor nodes is updated frequently and thus nodes are evenly utilized.

4.2.4. Collective Performance Metric, $\beta = (f \times \mu \times e)$. The Collective Performance Metric, β, can be used to reflect the network energy left, reliability, and the node

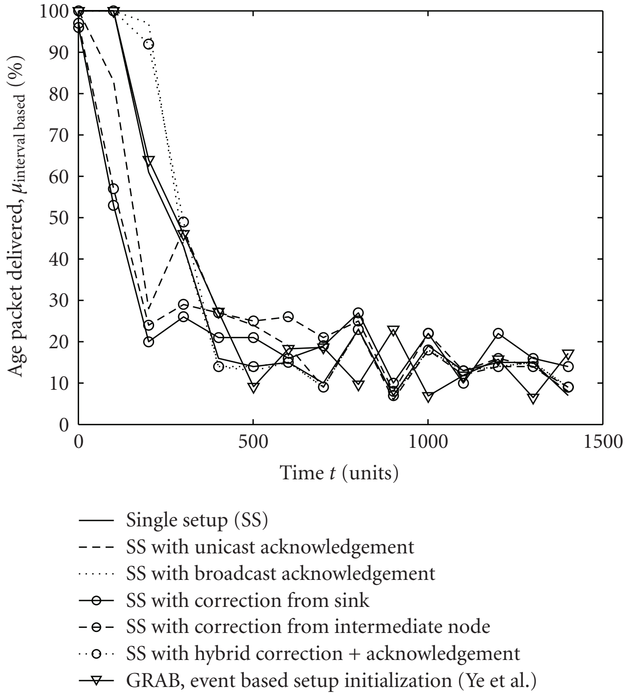


Figure 14: Interval-based Data Delivery in Percentage: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

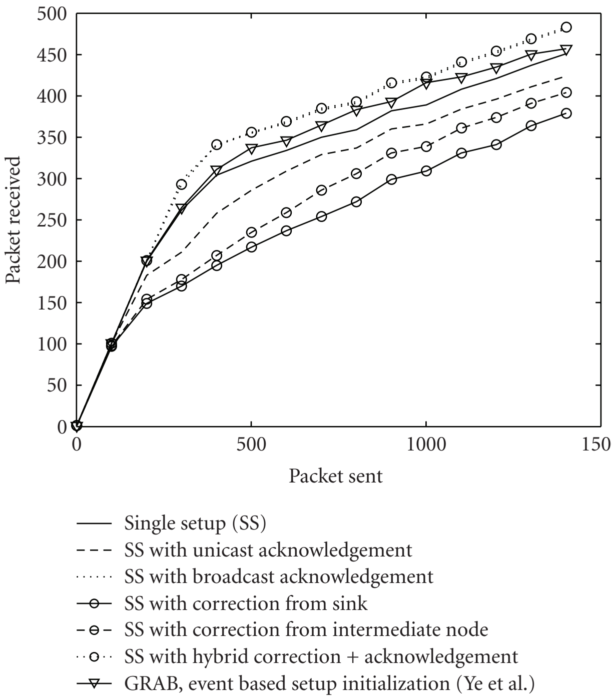


Figure 15: Packet send versus Packet Received: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

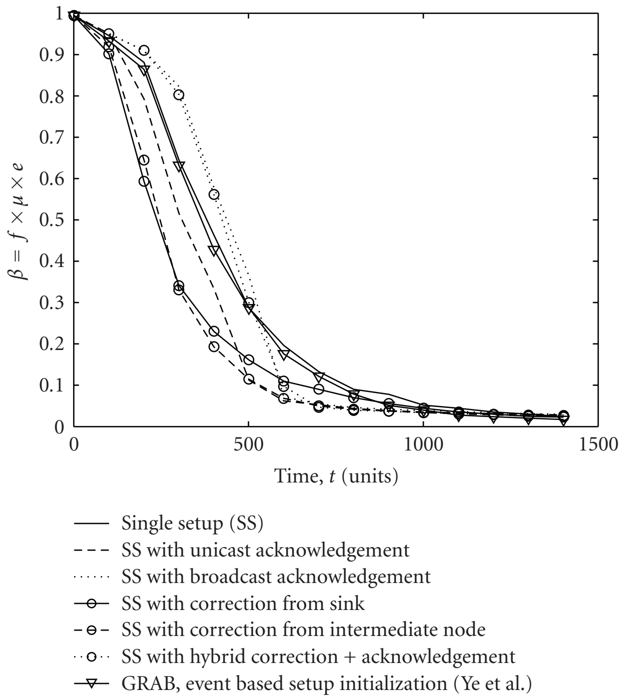


Figure 16: Collective Performance Metric, β: SS Alone, SS with Unicast, SS with Broadcast, SS with Correction from Sink, SS with Correction from Intermediate Node, SS with Hybrid Mode and GRAB, an event-based setup initialization (Ye et al. [27]).

failures (Figure 16). It is clear from Figure 23 that the hybrid approach and the single setup with broadcast acknowledgement have high value of this metric. This is due to the fact that the status information of the sensor nodes is updated frequently.

5. Modified GRAB

GRAB [27] strategy discussed in Section 1 is based on dynamic cost information which is used to find an optimal path from source to the sink. It ensures a robust data delivery using unreliable sensor nodes. However, each packet is forwarded over multiple paths, which increases the probability of data delivery of packets to the sink on one hand, but results in high bandwidth consumption, and increased redundancy and more interference, on the other hand. Although these demerits are the results of a tradeoff for reliable data delivery, yet a slight modification in the GRAB strategy can also assure its energy-efficient use with no significant loss in data delivery. The proposed modification is to decrease the number of broadcast messages. This can be done either through setup phase with acknowledgement or with the introduction of setup phase with correction. Both approaches have been discussed in Section 3. It has been observed there that these approaches in the routing strategy result in less bandwidth consumption and efficient energy utilization. Figures 17, 18, 19, 20, 21, 22, and 23 show the resulting improvements in GRAB [27] with the introduction of the proposed modifications. A comparison of the performance of the modified GRAB with that of the simple GRAB [27] can be well visualized simply by observing how node failures and packet losses affect the network lifetime and packet delivery in a wireless sensor network.

Figure 17 shows the resulting pattern of alive nodes after the introduction of broadcast acknowledgement strategy in GRAB. It is clear from the figure that a large number of nodes die out almost at the same time in modified GRAB, whereas simple GRAB exhibits worst performance as some nodes that remain alive in simple GRAB find themselves disconnected from the rest of the network nodes. The reason is that in simple GRAB, nodes die out at a constant interval of time due to which existence of some alive nodes does not prevent the network to fall into a not-connected state. Figure 18 also shows that the modified GRAB with the inclusion of broadcast acknowledgement strategy keeps the network alive for a relatively longer period of time. Figure 19 elaborates that simple GRAB leaves behind a large amount of energy which remains unutilized till the death of the whole network. A good routing strategy should residue as little amount of energy as possible. GRAB [27] can also be modified with the inclusion of hybrid strategy, that is, a combination of the correction and acknowledgement strategies, discussed in Section 3. Figure 20 shows a significant improvement in the delivery of successful packets when GRAB is used with the hybrid of correction and acknowledgement strategies. When the time exceeds 1400 units, the percentage of packets delivery goes down to its minimum value in simple GRAB

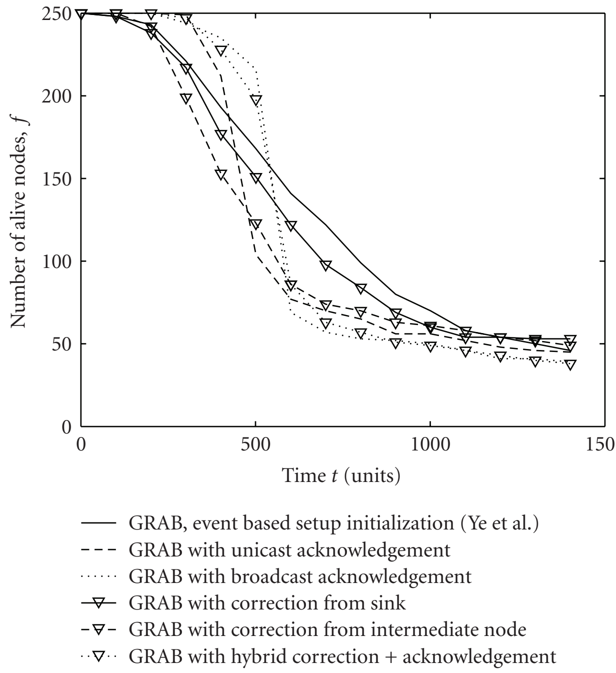


Figure 17: Network Lifetime: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

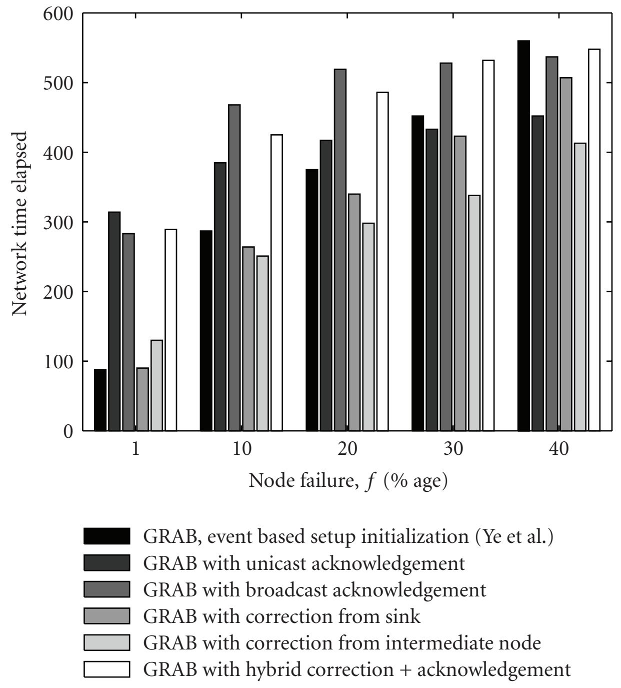


Figure 18: Node Failure in percentage: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

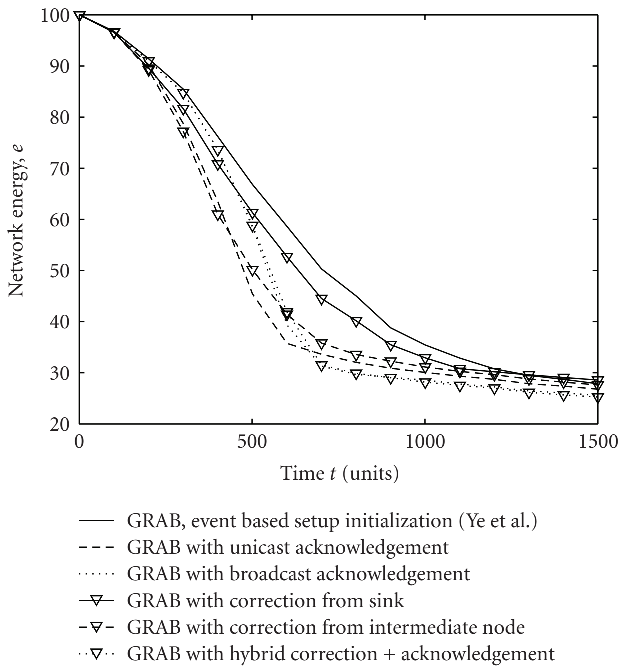


Figure 19: Network Energy Left: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

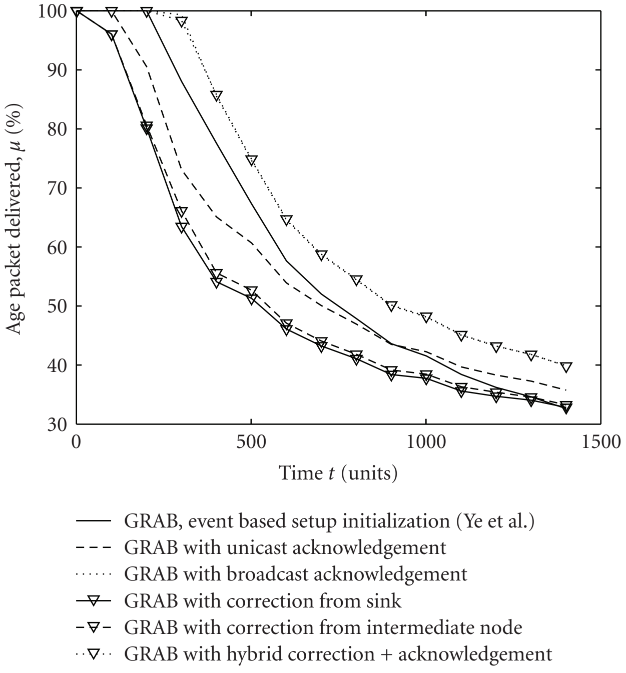


Figure 20: Data delivery in Percentage: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

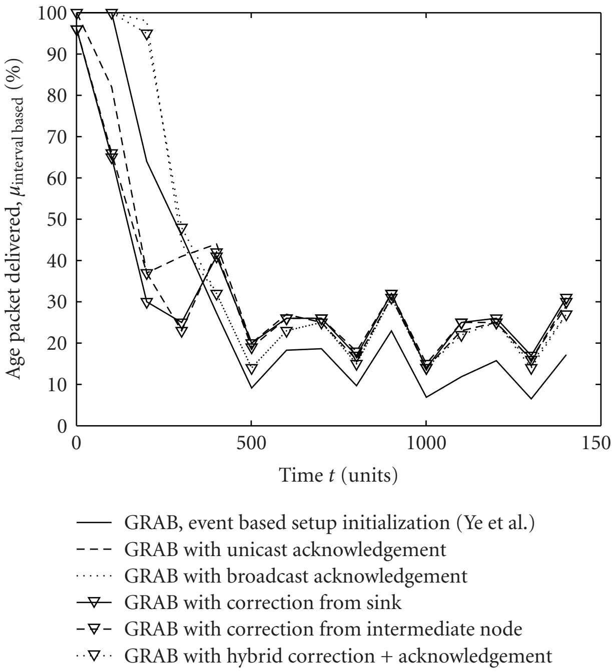


FIGURE 21: Interval-based Data delivery in Percentage: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

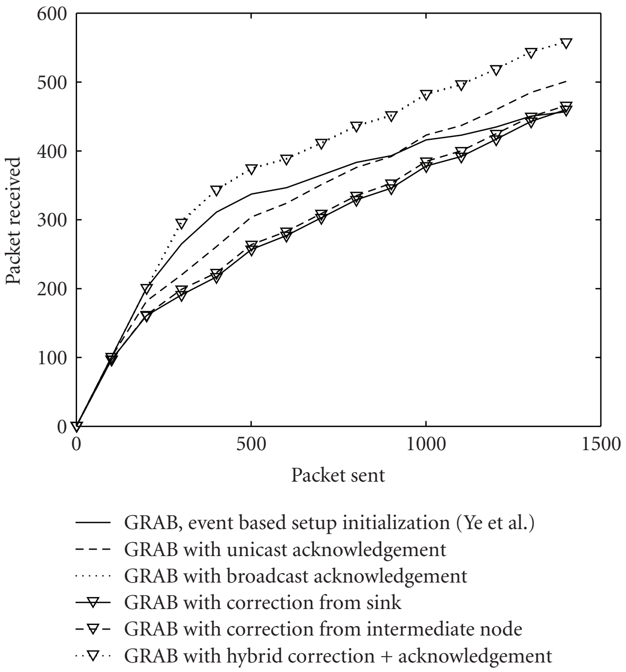


FIGURE 22: Packet Send Vs. Packet Received: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

but GRAB with hybrid correction and acknowledgement strategy still keeps a higher rate. This is because the updated cost information is propagated along the entire path even in the case of packet loss at some intermediate nodes. Thus the packets that reach their destinations successfully rise percentage of packet delivery.

Figure 21 shows interval-based data delivered to the sink after a specified time interval (e.g., after each 100 seconds in our case). After noting down the number of data packets received at the sink, it can be seen that GRAB with broadcast acknowledgement results in the highest percentage of interval based packets delivered to the sink. In Figure 22, GRAB with hybrid correction and acknowledgement strategy results in the highest ratio of packets received to packets sent, while GRAB with correction from sink results in the lowest ratio of packets received to packets sent. Performance comparison on the basis of combined metric has been given in Figure 23. It shows the impact of all of the considered performance parameters. It is clear from Figure 23 that GRAB with hybrid mode and GRAB with broadcast mode show the highest performance among all other modification modes of the GRAB.

6. Conclusions and Future Work

In this paper, we have proposed an energy-aware routing strategy based on GRAdient Cost Establishment (GRACE) for Wireless Sensor Networks. The proposed routing strategy outperforms the existing ones with an enhanced network

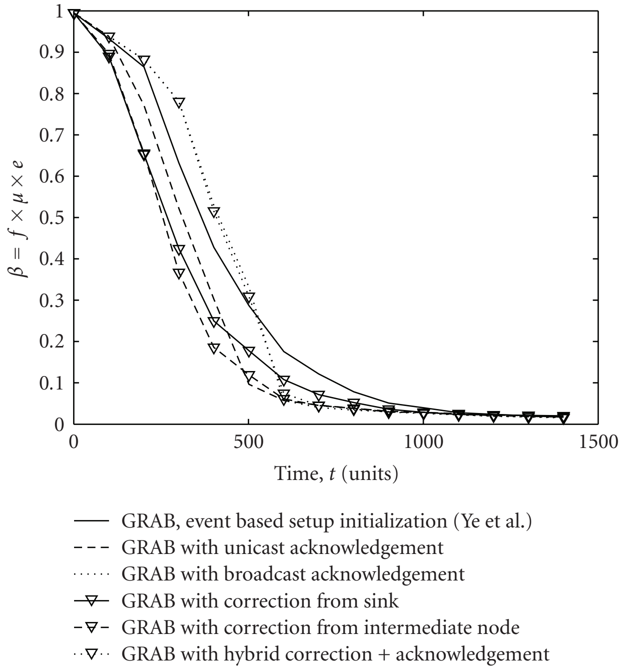


FIGURE 23: Collective Performance Metric: GRAB, an event-based setup initialization (Ye et al. [27]), GRAB with Unicast, GRAB with Broadcast, GRAB with Correction from Sink, GRAB with Correction from Intermediate Node, and GRAB with Hybrid Mode.

lifetime and more reliable data delivery. A setup mechanism governing the GRACE scheme has also been discussed in detail. Various modes of operation for updating status information of the sensor nodes have been indicated. Moreover, some performance metrics have been set to evaluate the performance of WSNs. A comparison of the proposed strategy, GRACE, with a well-known event-based cost field establishment scheme, GRAB [27], has been given which shows a better performance of GRACE over GRAB. Some modifications have also been suggested in the GRAB scheme, which improve the performance of GRAB with respect to bandwidth efficiency and network life time. The proposed research work can be extended to a cost-based globally gradient setup mechanism which reduces the number of broadcast messages made by the sensor nodes during cost field establishment procedure. Since the density of nodes affects the number of broadcast messages, therefore the proposed strategy GRACE can be modified in accordance with the density of nodes in the vicinity of sink in order to improve the lifetime of the sensor' network.

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