Connectivity Re-establishment using Adjustable Sensor Nodes for Self-organization of Wireless Sensor Networks in the Presence of Dumb Nodes

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In this work, we propose a scheme, named *CoRAD*, for the re-establishment of lost connectivity using adjustable communication range sensor nodes in the presence of dumb nodes in stationary wireless sensor networks (WSNs). A sensor node is termed as "dumb" [Misra et al. 2014], when it can sense its surroundings, but cannot communicate with its neighbors due to shrinkage in communication range attributed to adverse environmental effects such as rainfall, fog, and high temperature. These nodes behave normally following the resumption of favorable environmental conditions. Therefore, the presence of dumb nodes in a network gives rise to lost connectivity between the nodes, which are *temporary* in nature, and, thus, are distinct from the traditional isolation problem considered in stationary WSNs. The mere activation of intermediate sleep nodes cannot guarantee re-establishment of connectivity, because there may not exist neighbor nodes of the isolated nodes. On the contrary, the increase in communication range of a single sensor node may make it dead quickly. Including this, a sensor node has maximum limit of increase in communication range that may not be sufficient to re-establish connectivity. Therefore, we propose a price-based scheme that helps the network to self-organize and re-connects the isolated nodes by activating some intermediate sleep nodes. The scheme increases the communication range of nodes, when there is no neighbor node in the reduced communication range. The scheme also deactivates the additional activated nodes and reduces the increased communication range, when the dumb nodes resume their normal behavior, on the return of favorable environmental conditions. To implement the proposed scheme *CoRAD* it is required to construct the network using GPS enabled adjustable communication range sensor nodes. Simulation results show that the proposed scheme exhibits improved performance over the existing topology management schemes such as LETC [Torkestani 2013], and A1 [Rizvi et al. 2012], in such scenarios with respect to the number of activated nodes, message overhead, and energy consumption.

Categories and Subject Descriptors: C.2.2 [**Wireless Sensor Networks**]: Environmental Effect, Reliable Data Gathering

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Additional Key Words and Phrases: Dumb Node, Environmental effect, Connectivity, Dynamic Shrinkage, Adjustable Sensor Nodes

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1. INTRODUCTION

Recent advancement of low-cost and efficient integrated electronic devices has had considerable impact on the realization of WSNs, which are presently used in wide range of applications such as security, surveillance, disaster management, military, health care, and environment monitoring [Akyildiz et al. 2002b]. Due to the limited range of communication of sensor nodes, WSNs use multi-hop path from a source node to the base station, where one or multiple nodes cooperate as intermediate nodes during this communication. Connectivity is one of the major considerations of wireless multi-hop networks [Akyildiz et al. 2002a]. A connected network has at least one path between every pair of nodes in the network. Cooperation and collaboration between sensor nodes is an important factor for establishing connectivity between nodes and proper functioning of the network. Misbehaviors, attacks, and faults are the major challenges to be overcome for promoting cooperation and collaboration between sensor nodes. A faulty sensor node can create congestion in the network, may not cover its sensing area, drop its received packets, or mis-route them [Herbert et al. 2007; Bagci et al. 2014]. The possible effects of misbehavior of a sensor node include packet dropping, modification of routing information or packets, misrepresentation of network topology, and misleading of nodes [Misra et al. 2009; Misra et al. 2010; Drozda et al. 2007; Mukherjee et al. 2013]. An external attacker can reduce the availability of network resources, and can break the integrity and confidentiality of a network. All these effects are factors contributing to the degradation of network performance [Abduvaliyev et al. 2013].

In this work, we have considered a specific type of misbehavior, termed as *dumb* behavior [Misra et al. 2014]. A sensor node behaves as dumb, when cannot communicate due to shrinkage in communication range, typically due to the onset of adverse environmental effects, and thereafter at a later point in time resume communication, when favorable environmental conditions return. These dumb node continue to sense, whereas they cannot communicate the sensed data to the other nodes. Consequently, the dumb behavior of sensor nodes induces variable network connectivity, creates communication hole, results in loss of information, and isolate the network. To handle the adverse effects of dumb nodes in the network, and alleviate network performance, the network topology is reconstructed using GPS enabled adjustable communication range sensor nodes [Chen et al. 2007; Mir and Ko 2008], which vary in their communication range, at the cost of additional energy expense, when required. We also consider log-distance path loss propagation model for the channel characteristic. When sensor nodes start to behave as dumb and become isolated, dumb nodes optimally increase the communication range and activate the intermediate sleep nodes to re-establish connectivity with the network. In this manner the adverse effects of dumb node in the network are moderated. A scheme for *Connectivity Re-establishment using Adjustable Sensor Nodes in the Presence of Dumb Nodes* (*CoRAD*) has been proposed to address the above problem.

1.1. Motivation

Connectivity between nodes is an important consideration for enabling multi-hop wireless sensor networks. Shrinkage in communication range attributed to adverse environmental conditions such as fog, rainfall, and high temperature leads to the manifestation of sensor nodes as dumb. Due to the initiation of this behavior, sensor nodes get isolated from the network and do not participate in the network functionality *temporarily*, while they continue their sensing operation without sending the sensed information to the sink. Consequently, communication holes are created *dynamically* in the network. It may be stressed that these holes are dynamic in nature, and are distinct from the holes identified in the existing sensor network (e.g. [Ahmed et al. 2005], [Yu et al. 2007]). They can get created or removed during the network operation thereby increasing/decreasing the size of the holes in the network. The problem is interesting as the effect is not permanent. It is temporary because with the resumption of favorable environmental conditions the nodes continue to perform their normal operations. Therefore, this behavior is considered as a misbehavior, and it can pose inimical effects on the network performance, which need to be addressed adequately. The adjustment of the communication range of a single node to re-establish connectivity of a large number of co-located disconnected nodes may not be desirable, because the energy of a node depletes so quickly that it becomes dead rapidly. So, there should be a "balance" to optimally adjust the communication range of nodes and activate some of the selected sleep nodes for uniform distribution of additional energy consumption among nodes, which, in turn, increases the lifetime of a network. As dumb behavior is dynamic in nature, with the return of favorable environmental conditions, the nodes that had increased their communication ranges need to decrease them. The additional nodes, which were activated to re-establish connectivity, need to return to the sleep state, to reduce the additional energy consumption of the network.

1.2. Contribution

In this work, we have constructed the network using adjustable range sensor nodes, which can change their communication range at the cost of additional energy expenditure. In this connectivity re-establishment process, it is undesirable to depend on a single sensor node and adjust its communication range to re-establish connectivity. By doing so, the energy consumption of the node increases faster, which, in turn, makes the node die sooner. Further, any node has a maximum limit upto which its communication range may be increased. Even by increasing its range upto that limit, it may not still be possible to re-establish connectivity. Therefore, we need to optimize the adjustment of communication range of sensor nodes. Additional node activation is required to balance the energy consumption of sensor nodes and enhance the lifetime of the network. We outline the overall *contributions* of this work as follows.

— Propose a price-based optimization mechanism, named *CoRAD*, for the re-establishment of connectivity of nodes, which are temporarily isolated due to the dynamic shrinkage in communication range, on the onset of adverse environmental effects.
— On the resumption of favorable environmental conditions, the increased communication range needs to be reduced to normal, and the additional activated nodes are required to be sent back to the sleep state. A solution is proposed to address this issue.
— Theoretical characterization of the proposed scheme *CoRAD*.
— Simulation based performance evaluation and comparison with other existing topology management protocols.

1.3. Organization

The rest of the paper is organized as follows. Section 2 describes the related work done in this area. Section 3 describes the problem addressed in this paper. Sections 4 and 5 model the overall system and propose a solution for the given problem. We describe the simulation setup and analyze the results in Section 6. We conclude our work in Section 7, while giving directions on how it can be extended in the future.

2. RELATED WORK

A key problem in WSNs is the establishment of connectivity between sensor nodes, so that sensed information can be sent from the source to the sink while collaborating with other nodes. Co-operation and collaboration among sensor nodes are major issues of concern for the proper functioning of a sensor network. Shrinkage in communication range is a major challenge affecting successful co-operation and collaboration among the nodes in these network, which, in turn, degrades the performance of the network. Misra and Jain [Misra and Jain 2011] proposed a self-organizing and self-healing Policy Controlled Self-Configuration mechanism for Unattended Wireless Sensor Networks (PCSSN) scheme for topology management and maintenance. In this scheme, they used the redundancy property of a densely deployed sensor network and activated only those nodes that reduce the energy consumption of the network. They designed node activation policies based on Markov Decision Process (MDP) to activate minimum number of nodes such that the application fidelity does not get affected. In these policies, during the construction and maintenance of topology, the authors did not consider the isolation of nodes due to the shrinkage in communication range. Zhang and Hou [Zhang and Hou 2005] proved that for full coverage and connectivity, communication range should be twice the sensing range. They proposed a fully decentralized and localized algorithm, named Optimal Geographical Density Control (OGDC), for finding and activating a minimum subset of nodes, which ensures coverage and connectivity between them. In their algorithm, the authors did not consider shrinkage in communication range due to the presence of adverse environmental conditions, in which case nodes may not satisfy the constraint. The communication range of sensor nodes is required to be twice the sensing range, and thus may not provide full coverage and connectivity in the network. Khelifa *et al*. [Khelifa et al. 2009] developed a new monitoring mechanism to guarantee strong connectivity in WSN. At any time instant, this mechanism detects the critical nodes that represent articulation points for monitoring sensor connectivity. These articulation points connect portions of the network. Hence, a self-organization mechanism was developed to increase the degree of connectivity in their vicinity, thereby increasing fault tolerance. Dini *et al*. [Dini et al. 2008] proposed a method for repairing a split network. They used mobile nodes by finding their proper position, so that the connectivity between the sensor nodes can be reestablished. However, this method may not be useful when the deployed area of WSN is non planar, i.e., the presence of any obstacle creates disturbance in the movement of mobile nodes. Senel *et al*. [Senel et al. 2011] proposed a spider-web based approach with the help of minimum spanning tree to reconnect the partitioned network, where the partitioning is formed due to the damage of the sensor nodes. In this work, they deployed relay nodes to reconnect the partitioned network, which are permanently deployed. However, the works of Khalifa *et al*. [Khelifa et al. 2009], Dini *et al*.[Dini et al. 2008], and Senel *et al*. [Senel et al. 2011] cited above only considered the connectivity issues, which are permanent, and took measures for mitigating the permanent node isolation problem. They did not consider temporary node isolation occurring due to external environmental factors.

Anastasi *et al*. [Anastasi et al. 2004] showed how the performance of a sensor node is affected under adverse environmental conditions. Such conditions cause permanent or temporary wireless link failure [Paradis and Han 2007]. Additionally, temperature affects the signal strength of a wireless communication link and the transmission power of sensor nodes [Bannister et al. 2008] [Nadeem et al. 2010] [Boano et al. 2010]. Foanimokun and Frolik [Fanimokun and J.Frolik 2003] and Misra *et al*. [Misra et al. 2011] explored the connectivity issues of a sensor network. In their experiments, they mainly used a low-cost environmental sensing network. Bonvoisin *et al*. [Bonvoisin et al. 2012], adopted a two-level approach for developing a computational model based on life-cycle assessment (LCA) and energy modeling. They first explored WSN infrastructure and its life-cycle and presented the environmental impacts on the assessment model in detail. From the review of the existing literature, it can be infered that environmental effects have inimical effects on the communication of sensor nodes, due to which shrinkage in communication range occurs.

Rajagopalan and Varshney [Rajagopalan and Varshney 2009] investigated the problem of probabilistic connectivity of WSNs in the presence of channel fading. They developed a mathematical model to evaluate the probabilistic connectivity of sensor networks, which incorporates the characteristics of wireless channels, multi-access interference, network topology, and propagation environment. They presented an analytical framework for the computation of the node isolation probability and network connectivity under different channel fading models. Ruiz *et al*. [Ruiz et al. 2004] proposed and evaluated a failure detection scheme using a management architecture for WSNs, called MANNA. This can provide self-configuration, self-diagnostic, and self-healing, and some of the self-managing capabilities automatically in event-driven WSNs. Dhurandher *et al*. [Dhurandher et al. 2009] considered misbehaving nodes based on QoS and reputation to find a secure path for routing. In these works, the authors considered that sensor nodes exhibit misbehavior or faulty behavior due to attacks by malicious external entities, node failure, or malfunctioning. However, these works did not consider temporary behavior, when a sensor node can sense, but cannot transmit its sensed information to others due to the shrinkage in communication range, when adverse environmental effects prevail as misbehavior, as was considered in [Misra et al. 2014; Roy et al. 2014a; Roy et al. 2014c; Roy et al. 2014b].

Jose *et al*. [Jose et al. 2011] proposed the Adjustable Range of Transmission (ART) protocol to balance the energy consumption among sensor nodes based on their positions and using long-hop communication. This protocol helps in routing information to the base station using small number of longer-hop communication. This has been achieved by adjusting transmission range power based on the position of nodes in the network. Mao *et al*. [Mao et al. 2011] minimized the total energy cost of forwarding data to the sink in a WSN by selecting and prioritizing the forwarding list. They proposed the Energy Efficient Opportunistic Routing (EEOR) scheme, in which the transmission ranges of all the sensor nodes are either fixed or are dynamically adjustable. However, the above-cited works only considered permanent change in communication range and for this they adjusted the communication range to establish connectivity between nodes. They did not consider the adjustment of communication range due to temporal variation in the environment.

Synthesis: A review of the existing literature reveals that authors of the existing works considered different types of misbehaviors, faults, connectivity issues, and environmental effects. Misra *et al.* [Misra et al. 2014] has considered this behavior of sensor nodes and termed this behavior as dumb behavior. They have characterized and studied the effects of this behavior of sensor nodes on the performance of a WSN. The dumb behavior of sensor nodes can be classified as a kind of misbehavior, because of its detrimental effect on the network performance. Roy *et al.* [Roy et al. 2014a; Roy et al. 2014c; Roy et al. 2014b] has detected node exhibiting the dumb behavior in a WSN. But authors of the existing literatures has not considered re-establishment of connectivity of temporarily isolated nodes due to dumb behavior with the network with the network. In this work, we used adjustable communication range sensor nodes to re-establish connectivity among the isolated nodes in the network for improving its degraded performance.

3. PROBLEM DESCRIPTION

The dumb behavior [Misra et al. 2014] arises due to the sudden onset of environmental phenomena such as fog, rainfall, and high temperature. If the transmission range shrinks due to these phenomena, then a node can, at certain times, sense its physical surroundings, but cannot communicate with its neighbors.

We have considered two types of nodes in the network – (a) normal-behaved, and (b) dumb. Further, all the sensor nodes are considered to be inhomogeneous, which implies that each node has the same capabilities of sensing, but can adjust its communication range. Table I lists all the notations used in this work.

Table I. Notation Table

Notation	Description
Ψ_n	Normal behavior of a node
Ψ_d	Dumb behavior of a node
r_c^{ne}	Communication range of a node to an active neighbor node
d_{min}	Distance to the nearest active neighbor node
ne	List of active neighbor nodes
R	Maximum specified fixed communication range of a sensor node
$r_c(t)$	Communication range at time instant t
$\mathcal{E}_i^r$	Residual energy of neighbor node n_i
$\mathcal{E}_m^r$	Maximum residual energy
$\mathcal{R}_i^l$	Received signal strength of neighbor node n_i
$\mathcal{R}_m^l$	Maximum received signal strength
φ_i	Distance from a node n_i to the line joining between *BEGIN* and *STOP* node
υ_i	Distance between a node n_i and the *STOP* node
$\mathcal{L}_{uv}$	Distance between a pair of *BEGIN* and *STOP* nodes
$\mathcal{D}_i^e$	Effective distance of a node n_i
$\mathcal{H}_i^c$	Hop-count of a node n_i from the *BEGIN* node
$\mathcal{H}_m^c$	Maximum hop-count
Γ_i^e	Energy level of a node n_i
Γ_m^e	Maximum energy level of a node
ω_i	Worth function of node n_i
ς_i	Cost function of node n_i
σ_i	Selection constraint of node n_i
b_i	Benefit function of node n_i
b_i^c	Cumulative benefit of node n_i
t_{rep}	Estimated time for receiving REPLY packet
t_{rpt}	Estimated time for repeating the algorithm

Let, R be the specified fixed communication range of sensor nodes. In Fig. 1, let, d_{min} [Misra et al. 2014] be the distance from Node X to its nearest active neighbor Node Y. We have,

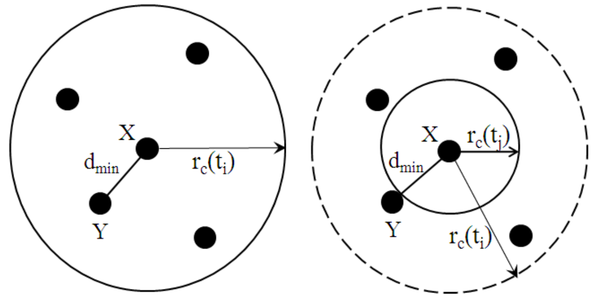
$$d_{min} = min(r_c^{ne}) \quad \forall ne \tag{1}$$

Definition 1. *Normal Behavior: A sensor node, which can sense the physical phenomena in its surroundings and transmit the sensed data during its entire lifetime is termed as normal-behaved node (Refer to Fig. 1(a)). Such behavior is denoted by Ψ_n. Mathematically [Misra et al. 2014],*

$$\Psi_n = \begin{cases} 1, & (0 < d_{min} \leq r_c(t_i) \leq R) \quad \forall t_i \\ 0, & otherwise \end{cases} \tag{2}$$

Definition 2. *Dumb Behavior: A sensor node that can sense the physical phenomena in its surroundings, but cannot transmit the sensed data at a certain instant of time, due to the presence of adverse environmental condition such as temperature, fog, or rainfall, but transmit at different instants of time, with the resumption of favorable environmental condition, is termed as a dumb node [Misra et al. 2014] (Refer to Fig. 1(b)). Such behavior is denoted by Ψ_d. Mathematically [Misra et al. 2014],*

$$\Psi_d = \begin{cases} 1, & \{(0 < d_{min} \leq r_c(t_i) \leq R)\} \wedge \{0 \leq r_c(t_j) < d_{min} < R)\} \quad \forall t_i, t_j \quad t_i \neq t_j \\ 0, & otherwise \end{cases} \tag{3}$$



(a) Normal-behaved node (b) Dumb node

Fig. 1. Change in communication range of a sensor node

***Change of Topology due to Dumb Nodes*: The communication range of a sensor node shrinks due to the presence of adverse environmental effects. Due to this shrinkage, a sensor node may get isolated from the network. As the adverse environmental effects are temporal and varying in nature, the shrinkage in communication range can also vary from time to time. Consequently, based on the shrinkage in communication range, there may be link breakage, network partitioning, and node isolation in a WSN.**

A WSN working under normal conditions is depicted in Fig. 2(a). It can be represented as a graph $G = (N, L)$, where N represents the set of nodes, and L the set of links between the nodes. $|N| = \kappa$ is the number of nodes in the network. The sink node is denoted as $s \in N$. Depending on the shrinkage in communication range of sensor nodes, the effects of adverse environmental factors can be divided into the following cases:

Case 1: In the presence of moderated adverse environmental effects, the shrinkage in communication range not much high. Hence, few links of the network break but leaving the whole network still connected as shown in Fig. 2(b). The scenario can be mathematically defined as $\forall n \in N$ there exists path sn.

In this case, as the network is connected, the proposed scheme *CoRAD* need not to execute on any node. But, Quality of Services (QoS) may degrade due breakage of links. However, we consider only re-establishment of connectivity of isolated nodes instead of degradation of QoS.

Case 2: The occurrence of dumb node in a stationary WSN is not only dependent on the shrinkage in communication range, but also the position of the active neighbor(s) of a node. In Fig. 2(c), when the communication range of node A shrinks in the presence of adverse environmental effects, all the links with node A breaks (as shown by dotted line. Consequently, node A becomes isolated from the network. Thus, the original network shown in Fig. 2(a), splits into three parts (as shown in Fig. 2(c)). Mathematically, the scenario can be defined as – For all positive integers $\kappa_1, \kappa_2, \cdots, \kappa_p$, such that $\sum_{i=1}^{p} \kappa_i = \kappa$, there exists a partition of $N(G)$ into p parts $N_1, N_2, \cdots, N_p$ such that $|N_i| = \kappa_i$, and N_i induces a connected sub-graph of G for $1 \leq i \leq p$ and N_s is a specific sub-graph having sink node s, where $1 \leq s \leq p$. Therefore, $\forall n \in (N_i \setminus N_s)$, where $(i \neq s)$ there is no path sn.

We consider the connectivity of temporarily isolated nodes with the network using *CoRAD*. The *CoRAD* initiates only when a node gets isolated from the network, and thus, the connectivity re-establishment among the network partitioned is not possible. However, the isolated nodes in such a scenario get connected to the network using

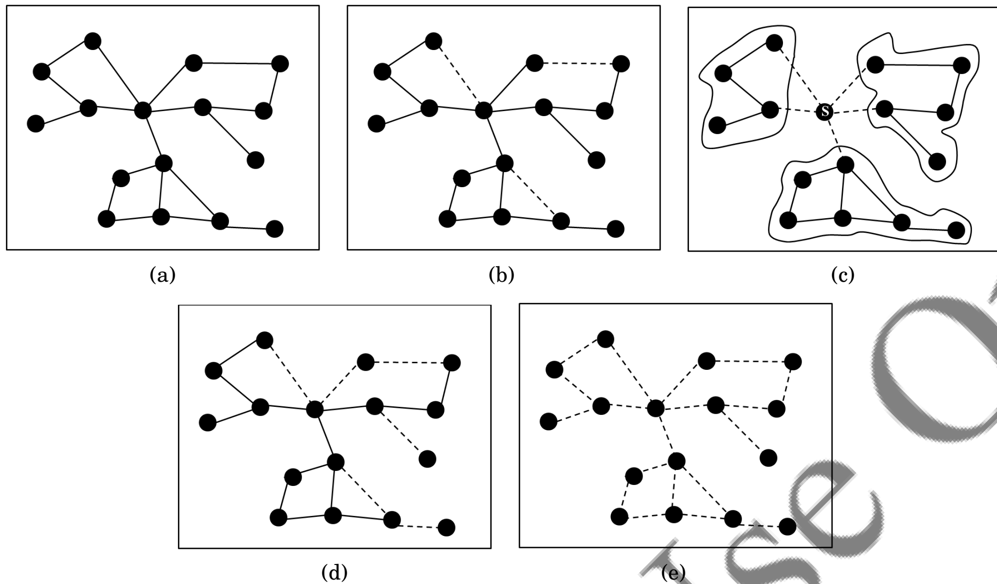


Fig. 2. Change in Topology due to Shrinkage of Communication Range

CoRAD.

Case 3: Some of the sensor nodes become isolated from the network due to the presence of adverse environmental effects. In such a situation, there is no path from isolated nodes to the sink. In Fig. 2(d), it is shown that there is isolation of some of the nodes due to the shrinkage in communication range. Mathematically, $\exists n \in N$, such that there is no path sn.

In this case, the isolated nodes can re-establish the connectivity with the network using the proposed scheme, *CoRAD*

Case 4: All the sensor nodes become isolated from one another due to the presence of extreme adverse environmental conditions. In such a situation, there is no path from any node to the sink. In Fig. 2(e), it is shown that all the nodes disconnected from each other due to the shrinkage in communication range. Mathematically, $\forall n, w \in N$ there is no path nw, when $n \neq w$.

In this case, as all the nodes become isolated from one another, every node needs to initiate the connectivity re-establishment process.

4. SYSTEM MODEL

This work is based on the problem of node isolation occurring due to the presence of dumb behavior of sensor nodes. As dumb behavior is temporary in nature, node isolation also occurs temporarily. In this work, our goal is to re-establish connectivity between the isolated nodes and the network. We propose a scheme, *CoRAD*, in order to achieve the mentioned goals, using adjustable sensor nodes. We assume that WSN is deployed in an obstruction free area, and thus, log-distance path loss channel model is suitable in such a scenario. In this path loss model relationship between transmitted power, received power and distance between transmitter and receiver [Levis 2005] as follows:

$$P_R = P_T G_R G_T \left(\frac{\lambda}{4\pi d}\right)^{\eta} \tag{4}$$

Where,
P_T and P_R is transmitted power and the received power,
G_T and G_R is the transmission and the receiving antenna gain,
λ is the wavelength and d is the distance between a pair of nodes.
η is path loss exponent and depends on attenuating effect of the medium. In free-space the value of η is 2, but it varies upto 8 in the presence of adverse environmental conditions. With the increase in the value of η the received power decreases. So, the transmitted signal from a sensor node reaches its receiving threshold in a lesser distance compared to the ideal situation. Therefore, communication range is directly proportional to received power of the signal and decreases in the presence of adverse environmental conditions.

Definition 3. *BEGIN Node: A BEGIN node, U, is an isolated node, which initiates CoRAD to connect with a STOP node.*

The communication range of a sensor node reduces in the presence of adverse environmental effects. Thereafter, a *BEGIN* node can activate sleep neighbor nodes within its current (reduced) communication range. In the absence of any sleep neighbor nodes within the current (reduced) communication range, a *BEGIN* node is able to adjust its communication range in order to find any neighbor node.

Definition 4. *STOP Node: A STOP node, V is connecting node of a particular BEGIN node U, with which the latter was connected, but it has ceased to be connected at present. The* CoRAD *scheme terminates its own execution on this node and selects a reliable and optimum path from this node to U.*

Each of the *STOP* node has its corresponding *BEGIN* node, which is an isolated node. A *BEGIN* node tries to re-establish connectivity between itself and the *STOP* node. The *CORAD* scheme starts on a *BEGIN* node and ends on a *STOP* node.

Definition 5. *FORWARD Node: A Forward node calculates its own regular benefit and cumulative benefit values. Further, it forwards the connectivity re-establishment process towards the STOP node. Finally, it selects a downstream FORWARD node based on the highest cumulative benefit value.*

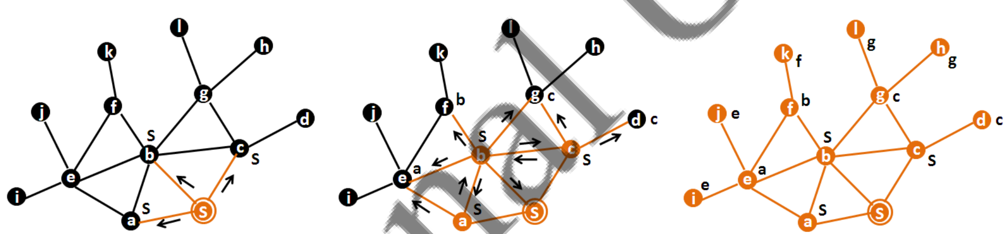
A *FORWARD* node is an intermediate entity between a pair of *BEGIN* and *STOP* nodes. It proceed the connectivity re-establishment process to the upstream neighbor nodes after calculating its own regular benefit and cumulative benefit. If a *FORWARD* node is unable to find any neighbor node within its current (reduced) communication range, it adjusts its communication range.

The proposed price-based distributed scheme activates an optimum subset of intermediate sleep nodes between the *BEGIN* and *STOP* nodes. In few cases, the scheme also readjusts the communication range of intermediate nodes, or *BEGIN* node, to re-establish connectivity, while there is insufficient number of intermediate nodes between the *BEGIN* and *STOP* nodes.

Let $\mathcal{P}$ represents the set of participants, i.e., $\mathcal{P} = \{\rho_1, \rho_2, \rho_3, \cdots, \rho_n\}$. The set of benefit functions are denoted by $\mathcal{B}$, where $\mathcal{B} = \{b_\rho \mid \rho \in \mathcal{P}\}$. Thus, we define the price-based scheme as $\xi = \langle \mathcal{P}, \mathcal{B} \rangle$

Some GPS-enabled adjustable communication range sensor nodes are deployed over an area of interest randomly. Initially, all the sensor nodes are activated. The activation of all the sensor nodes for the remaining time is undesirable for energyconstrained WSNs, because the sensor nodes unnecessarily consume energy, while resulting in redundant coverage. So, a minimum subset of sensor nodes are to be activated for covering the entire area optimally. Due to the occurrence of adverse environmental effects, the communication ranges of sensor nodes shrink. If the communication range of a node shrinks below the range of its nearest active neighbor node, the node becomes isolated from the network. This isolation is temporary, because on the resumption of favorable environmental conditions, a node starts behaving normally and become connected with the network. When a sensor node detects itself as isolated from the network, it initiates the proposed scheme, *CoRAD*, to re-establish connectivity between the *BEGIN* and the *STOP* nodes.

After initial deployment all the activated sensor nodes find their connecting node. If all the sensor nodes remain connected with their connecting node that ensures fully connected network. To be more specific, connectivity of all the sensor nodes with their connecting node ensures at least a path from each node to the sink node. At the beginning the sink node broadcast a HELLO message. After receiving HELLO message single-hop neighbor nodes select sink node as their connecting node. Thereafter, these neighbor nodes broadcast HELLO message. After receiving HELLO message if a single-hop neighbor node does not selected any connecting node yet or it is not the sink node, selects a node as connecting node from which it receives HELLO message. This process gradually proceeds among the other nodes in the network until all the nodes have selected their connecting node. The process of connecting node selection is shown in Fig. 3.



(a) (b) (c)

Fig. 3. Connecting node finding of all the nodes in a network. (a) Sink node **S** broadcast HELLO message. Node **a**, **b**, and **c** receive HELLO message and select S as connecting node. (b) Node **a** broadcast HELLO message which is received by the neighbor nodes **S**, **e**, and **b**. Among these nodes, **S** is sink node and **b** already finds its connecting node. So, node **e** selects node **a** as its connecting node, Similarly, node **b**, and **c** also follow the same process. Node **f** selects node **b** and node **g** and **d** select node **c** as connecting node. (c) All nodes in the network find their respective connecting nodes and connecting node finding process terminates

The objective of the proposed scheme is to re-establish reliable connectivity between the *BEGIN* and the *STOP* nodes. In order to re-establish the connectivity, the proposed scheme, *CoRAD*, activates an optimum number of intermediate sleep nodes. In case of absence of sleep neighbor node within the reduced communication range a node, it requires to adjustment of the communication range of that particular node. Similarly, if the *BEGIN* node has no neighbor node(s) within its reduced communication range, it adjusts its communication range. Residual energy $\mathcal{E}_i^r$ is an important parameter for affecting reliability of a node n_i in a sensor network. The quality of links is an important parameter influencing inter-node connectivity in a network. Specifically, Received Signal Strength (RSS) is an important link quality metric. Higher RSS indicates improved link quality. RSS of a node n_i is represented as $\mathcal{R}_i^l$. It is also required to activate less number of nodes to re-establish connectivity between the *BEGIN* and the *STOP* nodes for reducing overall energy consumption of a network. To activate less number of nodes, we take another parameter, the effective distance $\mathcal{D}_i^e$, as follows.

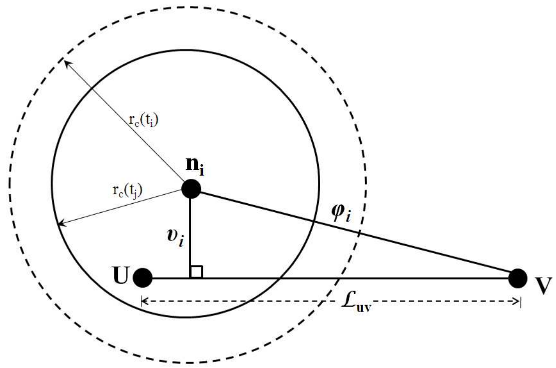


Fig. 4. Effective distance of a node

$$\mathcal{D}_i^e = \varphi_i + \upsilon_i \tag{5}$$

In Equation (5), φ_i is the distance between a node n_i and the *STOP* node V, υ_i is the distance between node n_i and the line joining the *BEGIN* and *STOP* nodes, as shown in Fig. 4. The summation between these two parameters is used to derive the effective distance $\mathcal{D}_i^e$, because the activation of less number of nodes requires the selection of a node which is nearest to the *STOP* node and closest to the line joining the *BEGIN* and *STOP* nodes. Hence, the effective distance $\mathcal{D}_i^e$ is minimum when both φ_i and υ_i are minimum. The hop-count of a node from the *BEGIN* node is considered as another parameter. A reliable path, which has lesser hop-count, is chosen, as doing so results in reduced node activation. We denote the hop-count of a node n_i as $\mathcal{H}_i^c$. For re-adjusting the communication range of a sensor node, there are different energy levels of a transmitter. Normally, the sensor nodes function in the minimum energy level. When it requires the increment of its communication range, the node switches from the lower energy level to the higher one at the cost of additional energy consumption. The aim of the proposed scheme is to keep the energy level Γ_i^e of a sensor node n_i at a reduced level.

BGN_ID (2 bytes)	BGN_POS (4 bytes)	FWD_ADDR (4 bytes)	STP_ID (2 bytes)	STP_POS (4 bytes)	BNF_VAL (2 bytes)	HC (2bytes)

(a) REQUEST Packet

STP_ID (2 bytes)	STP_ADDR (4 bytes)	BGN_ID (2 bytes)	BGN_ADDR (4 bytes)

(b) REPLY Packet

FWD_ID (2 bytes)	BROADCAST_ADDR (4 bytes)

(c) ACTIVATION Packet

NBR_ID (2 bytes)	NBR_ADDR (4 bytes)

(d) ACK Packet

Fig. 5. REQ, REPLY, ACTIVATION, and ACK packets

Let us consider κ number of sensor nodes deployed after assigning each node an unique ID such that $id = \{1 \ldots \kappa\}$. Due to the occurrence of adverse environmental conditions, if a sensor node gets isolated from the network, it starts to behave as the *BEGIN* node, and initiates connectivity re-establishment. A *BEGIN* node re-establishes connectivity with a *STOP* node, which is the nearest activated neighbor node of the *BEGIN* node, if it was connected before with the *BEGIN* node, but has ceased to be connected. Fig. 6 shows how the *BEGIN* node, U, re-establishes connectivity with the *STOP* node, V. Initially, the *BEGIN* node functions as the *FORWARD* node, which activates its neighbor node and coalesces them to participate in the connectivity re-establishment process. Gradually, the activated neighbor nodes takes turn to act as the *FORWARD* node and progressed with the connectivity re-establishment process until the *STOP* node becomes a *FORWARD* node. The *FORWARD* node broadcasts the node ACTIVATION message within its single hop neighbor to activate the neighbor nodes in the sleep state. On receiving the ACTIVATION message, the neighbor nodes, which did not participate initially as a *FORWARD* node for the connectivity re-establishment process corresponding to this particular *BEGIN* node, satisfies the selection constraint, and replies back with an ACK packet. If the *FORWARD* node does not receive any ACK, it switches from the lower energy level to the higher one to increase its communication range and perform the same process until it receives any ACK. If it does not receive any ACK at its maximum energy level, it cannot participate in the connectivity re-establishment process. The ACTIVATION message contains the *FORWARD* node id, *FWD_ID*, and the Broadcast address, *BROADCAT_ADDR*. The ACK message contains the neighbor id, *NBR_ID*, and neighbor address, *NBR_ADDR*. The packet format for ACTIVATION and ACK packets are shown in Figs. 5(c) and 5(d), respectively. Node U initiates the connectivity re-establishment process and acts as the *FORWARD* node. It broadcasts the ACTIVATION message to Nodes 2, 3, 4, and 12 within its reduced communication range. On receiving ACK from the neighbor nodes, Node U sends REQUEST packets to Nodes 2, 3, 4, and 12. The REQUEST packet contains *BEGIN* node id, *BGN_ID*, *BEGIN* node position, *BGN_POS*, *FORWARD* node address, *FWD_ADDR*, *STOP* node id, *STP_ID*, *STOP* node position, *STP_POS*, cumulative benefit value, *BNF_VAL*, and hop-count, *HC*, as shown in Fig. 5(a). Nodes receiving REQUEST packet remain active for the next t_{rep} time and calculate their own benefit and the cumulative benefit values. The parameter t_{rep} is the estimated time for receiving REPLY packet from the *STOP* node. Thereafter, each of the nodes receiving a REQUEST packet functions as the *FORWARD* node and proceeds the same process until the *STOP* node is reached. Based on the highest cumulative benefit value, the nodes receiving REQUEST packets from multiple *FORWARD* nodes, select one of the *FORWARD* node as the downstream node to the *BEGIN* node. In Fig. 6, it is shown that Node 8 sends a REQUEST packet to the upstream Node 9 after increasing its communication range (indicated as a dotted line), because there is no node to reach the *STOP* node within its reduced communication range. Similarly, Nodes 16 and 18 also increase their communication range to get neighbor node. On receiving REQUEST messages from multiple *FORWARD* nodes, the *STOP* node selects one of them as the downstream node to the *BEGIN* node and sends a REPLY packet to it. The REPLY packet contains the *STOP* node id, *STP_ID*, *STOP* node address, *STP_ADDR*, *BEGIN* node id, *BGN_ID*, and *BEGIN* node address, *BGN_ADDR*, as shown in Fig. 5(b).

5. PROPOSED SOLUTION

We propose a price-based [Edalat et al. 2009], [Liu and Krishnamachari 2006] scheme to re-establish connectivity of an isolated node with the network. The proposed scheme re-establishes reliably, the connectivity of an isolated node with the network by activating an optimum subset of intermediate sleep nodes or by increasing the communication range of sensor nodes, when there are no neighbor nodes within the reduced communication range. The price-based solution is designed based on the residual energy, $\mathcal{E}^r$, received signal strength, $\mathcal{R}^l$, effective distance, $\mathcal{D}^e$, hop-count, $\mathcal{H}^c$, and energy level, Γ^e.

A WSN is modeled as a graph $G(N, L)$, in which every node $n_i \in N$ and $\forall l_{ij} \in L$, where l_{ij} is the link between any node n_i and n_j, $i \neq j$. For the re-establishment of

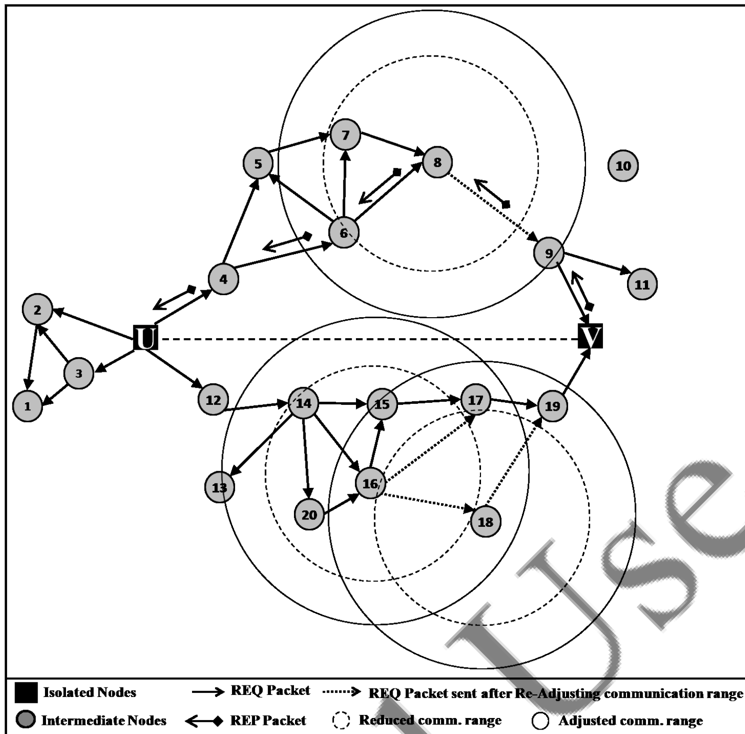


Fig. 6. Example Scenario

connectivity between each pair of nodes, a *BEGIN* node tries to establish connectivity with a *STOP* node, while the rest of the nodes act as the intermediate nodes. According to the price-based approach, each node n_i satisfies a constraint (discussed later), and calculates its own benefit value as follows:

$$b_i = (\omega_i - \varsigma_i) \tag{6}$$

where, b_i, ω_i, and ς_i are the benefit, worth, and cost functions respectively of each node n_i, $i \in \kappa$.

The worth function, ω_i, quantizes the advantage of selecting a node n_i for connectivity re-establishment. This worth function takes the parameters as E^r and R^l, because a node having more residual energy and received signal strength, respectively, is a better choice for connectivity re-establishment than others. Therefore, the worth function, ω_i, is designed as follows:

$$\omega_i = \left(\frac{\mathcal{E}_i^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_i^l}{\mathcal{R}_m^l} \right) \tag{7}$$

where, E_m^r and R_m^l are the maximum residual energy, i.e., initial energy and maximum received signal strength, respectively.

The cost function ς_i quantizes the disadvantage of selecting the corresponding node n_i. This cost function takes the parameters D^e, H^c, and Γ^e, because a node having more effective distance, hop-count, and higher energy level, respectively, is inferior choice for connectivity re-establishment than others. Before designing the cost function, it is necessary to formulate the effective distance of a node n_i.

Let the positions of *BEGIN*, *STOP*, and any intermediate node n_i be (x_u, y_u), (x_v, y_v), and (α_i, β_i), respectively. The equation of the straight line connecting the *BEGIN* and *STOP* nodes is:

$$(y_v - y_u)x + (x_u - x_v)y + (x_v y_u - x_u y_v) = 0 \tag{8}$$

From Equation (8), the distance υ_i from the node n_i to the straight line connecting the *BEGIN* and *STOP* nodes is:

$$\upsilon_i = \frac{|(y_v - y_u)\alpha_i - (x_v - x_u)\beta_i + (x_v y_u - x_u y_v)|}{\sqrt{(y_v - y_u)^2 + (x_u - x_v)^2}} \tag{9}$$

The distance, φ_i, from the *STOP* node to a node n_i is:

$$\varphi_i = \sqrt{(x_v - \alpha_i)^2 + (y_v - \beta_i)^2} \tag{10}$$

The distance, $\mathcal{L}_{uv}$, between the *BEGIN* and *STOP* nodes is calculated as:

$$\mathcal{L}_{uv} = \sqrt{(x_v - x_u)^2 + (y_v - y_u)^2} \tag{11}$$

Therefore, from Equations (5), (9), and (10), we have, the effective distance, $\mathcal{D}_i^e$, of a node n_i is:

$$\mathcal{D}_i^e = \frac{|(y_v - y_u)\alpha_i - (x_v - x_u)\beta_i + (x_v y_u - x_u y_v)|}{\sqrt{(y_v - y_u)^2 + (x_u - x_v)^2}} + \sqrt{(x_v - \alpha_i)^2 + (y_v - \beta_i)^2} \tag{12}$$

The cost function, ς_i, is designed as follows:

$$\varsigma_i = \left(\frac{\mathcal{D}_i^e}{\mathcal{L}_{uv}} + \frac{\mathcal{H}_i^c}{\mathcal{H}_m^c} + \frac{\Gamma_i^e}{\Gamma_m^e} \right) \tag{13}$$

The parameters $\mathcal{H}_m^c$, Γ_m^e are the maximum hop-count and the maximum number of energy levels of a node n_i, respectively.

Therefore, the benefit function, b_i, quantizes the effective advantage of selecting a node n_i for connectivity re-establishment. From Equations (6), (7), and (13), we get the benefit function, b_i, as follows:

$$b_i = \sigma_i \left[\rho + \left(\frac{\mathcal{E}_i^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_i^l}{\mathcal{R}_m^l} \right) - \left(\frac{\mathcal{D}_i^e}{\mathcal{L}_{uv}} + \frac{\mathcal{H}_i^c}{\mathcal{H}_m^c} + \frac{\Gamma_i^e}{\Gamma_m^e} \right) \right] \tag{14}$$

where, σ_i is the selection constraint of a node n_i. This selection constraint is defined as follows:

$$\sigma_i = \begin{cases} 1, \ (\mathcal{E}_{th}^r \le \mathcal{E}_i^r \le \mathcal{E}_m^i) \wedge (\mathcal{R}_{th}^l \le \mathcal{R}_i^l \le \mathcal{R}_m^l) \wedge (0 \le \varphi_i \le \mathcal{L}_{uv}) \\ 0, \ \text{otherwise} \end{cases} \tag{15}$$

where, $\mathcal{E}_{th}^r$ and $\mathcal{R}_{th}^l$ are the minimum communication threshold for residual energy and received signal strength. As the benefit value has to be non-negative, a constant ρ is added with the benefit function in Equation (14). The value of ρ is derived in Lemma 5.3.

Each node n_i calculates its cumulative benefit value (b_i^c) by adding up its own benefit value with the total benefit value of all the downstream nodes from itself to the *BEGIN* node, as follows:

$$b_i^c = b_i + \sum_{j=1}^{i-1} b_j \tag{16}$$

LEMMA 5.1. *The maximum effective distance $\mathcal{D}^e$ for a pair of* BEGIN *and* STOP *node is* $2\mathcal{L}_{uv}$.

PROOF. From the constraint given in Equation (15), we see that the proposed scheme *CoRAD* is bounded by a distance constraint, $0 \leq \varphi_i \leq \mathcal{L}_{uv}$, which forces only those nodes to participate, which are within the semi-circle $X - U - X'$ centered on the *STOP* node V, as shown in Fig. 7. The effective distance $\mathcal{D}^e$ is maximum, when both φ and υ are maximum. This is possible for the nodes situated in X and X' where $\varphi = \upsilon = \mathcal{L}_{uv}$. In such a situation, $\mathcal{D}^e$ gets the maximum value, which is:

$$\begin{aligned} \mathcal{D}^e &= \varphi + \upsilon \\ &= \mathcal{L}_{uv} + \mathcal{L}_{uv} \\ &= 2\mathcal{L}_{uv}. \end{aligned} \tag{17}$$

□

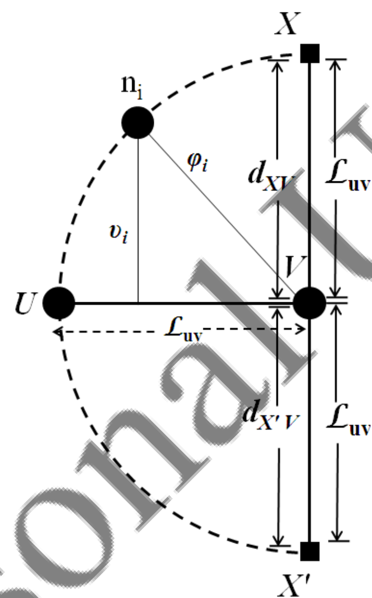


Fig. 7. Maximum value of cost function

THEOREM 5.2. *The benefit function in Equation (14) has the maximum and minimum value as:*

$$b_i^{max} = \rho + 2 - \frac{1}{N-2}.$$

$$b_i^{min} = \rho + \frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m} - 4.$$

when, $\mathcal{E}^r_{th} \leq \mathcal{E}^r_i \leq \mathcal{E}^r_m$, $\mathcal{R}^l_{th} \leq \mathcal{R}^l_i \leq \mathcal{R}^l_m$, $0 \leq \varphi_i \leq \mathcal{L}_{uv}$, *and* $\sigma_i = 1$.

PROOF. The benefit function, b_i, in Equation (14) is a linear combination of $\mathcal{E}^r_i$, $\mathcal{R}^l_i$, $\mathcal{D}^e_i$, $\mathcal{H}^c_i$, and Γ^e_i, when $\sigma_i = 1$. This function is designed by subtracting the cost function, ς_i, from the worth function, ω_i. When the worth function yields maximum value and the cost function yields minimum value, the benefit function yields the maximum value.

The worth function gives maximum value, when $\mathcal{E}_i^r = \mathcal{E}_m^r$ and $\mathcal{R}_i^l = \mathcal{R}_m^l$. Therefore, the maximum value of the worth function is:

$$\omega_i^{max} = \left(\frac{\mathcal{E}_m^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_m^l}{\mathcal{R}_m^l} \right) \\ = 2. \tag{18}$$

The value of the cost function is minimum, when node n_i is the *STOP* node, there is no intermediate node, and the power level shifting of the sensor nodes are not required. i.e., $D_i^e = 0$, $H_i^c = 1$, and $\Gamma_i^e = 0$. Therefore, the minimum value of the cost function is:

$$\varsigma_i^{min} = \left(\frac{0}{\mathcal{L}_{uv}} + \frac{1}{N-2} + \frac{0}{\Gamma_m^e} \right) \\ = \frac{1}{N-2}. \tag{19}$$

So, the maximum value of benefit function is:

$$b_i^{max} = \rho + \omega_i^{max} - \varsigma_i^{min} \\ = \rho + 2 - \frac{1}{N-2}. \tag{20}$$

When the worth function yields a minimum value and the cost function yields maximum value, the benefit function yields minimum value. The worth function gives minimum value, when $\mathcal{E}_i^r = \mathcal{E}_{th}^r$ and $\mathcal{R}_i^l = \mathcal{R}_{th}^l$. Therefore, the minimum value of the worth function is:

$$\omega_i^{min} = \left(\frac{\mathcal{E}_{th}^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_{th}^l}{\mathcal{R}_m^l} \right) \tag{21}$$

The value of the cost function is maximum, when $\mathcal{D}_i^e = 2\mathcal{L}_{uv}$, $\mathcal{H}_i^c = \mathcal{H}_m^c$, and $\Gamma_i^e = \Gamma_m^e$. Therefore, the maximum value of cost function is:

$$\varsigma_i^{max} = \left(\frac{2\mathcal{L}_{uv}}{\mathcal{L}_{uv}} + \frac{\mathcal{H}_m^c}{\mathcal{H}_m^c} + \frac{\Gamma_m^e}{\Gamma_m^e} \right) \\ = (2 + 1 + 1) \\ = 4. \tag{22}$$

So, the minimum value of the benefit function is:

$$b_i^{min} = \rho + \omega_i^{max} - \varsigma_i^{min} \\ = \rho + \left(\frac{\mathcal{E}_{th}^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_{th}^l}{\mathcal{R}_m^l} \right) - 4. \tag{23}$$

□

LEMMA 5.3. *The value of ρ in Equation (14) is* $\left[4 - \left(\frac{\mathcal{E}_{th}^r}{\mathcal{E}_m^r} + \frac{\mathcal{R}_{th}^l}{\mathcal{R}_m^l} \right) \right]$

PROOF. To get a positive benefit value, it is necessary to add a constant to shift the minimum benefit value to 0. Then, all the benefit values derived from Equation (14) are positive. Equation (23) gives the minimum benefit value. In this equation, if we put $\rho = \left[4 - \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right)\right]$, the minimum benefit value becomes 0.

$$\begin{aligned} b_i^{min} &= \rho + \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right) - 4 \\ &= 4 - \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right) + \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right) - 4 \\ &= 0. \end{aligned}$$

As $\mathcal{E}^r_{th}$, $\mathcal{E}^r_m$, $\mathcal{R}^l_{th}$, and $\mathcal{R}^l_m$ are constants, ρ is also a constant.
Hence, $\rho = \left[4 - \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right)\right]$. □

LEMMA 5.4. *The benefit function in Equation (14) is continuous over the interval* $\mathcal{E}^r_{th} \le \mathcal{E}^r_i \le \mathcal{E}^r_m$, $\mathcal{R}^l_{th} \le \mathcal{R}^l_i \le \mathcal{R}^l_m$, $0 \le \mathcal{D}^e_i \le 2\mathcal{L}_{uv}$, $0 \le \mathcal{H}^c_i \le \mathcal{H}^c_m$, *and* $0 \le \Gamma^e_i \le \Gamma^e_m$.

PROOF. A multi-variable function $y = f(x, y)$ is continuous at any point (x_0, y_0) if

$$\forall \epsilon > 0\ \exists \delta(\epsilon) > 0 \text{ such that } |x - x_0| < \delta, |y - y_0| < \delta \implies |f(x, y) - f(x_0, y_0)| < \epsilon$$

The given benefit function in Equation (14) is:

$$b_i = \sigma_i \left[\rho + \left(\frac{\mathcal{E}^r_i}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_i}{\mathcal{R}^l_m}\right) - \left(\frac{\mathcal{D}^e_i}{\mathcal{L}_{uv}} + \frac{\mathcal{H}^c_i}{\mathcal{H}^c_m} + \frac{\Gamma^e_i}{\Gamma^e_m}\right)\right]$$

where σ_i is a constant. The function is continuous at any point $(\mathcal{E}^r_0, \mathcal{R}^l_0, \mathcal{D}^e_0, \mathcal{H}^c_0, \Gamma^e_0)$ whenever $|\mathcal{E}^r_i - \mathcal{E}^r_0| < \delta$, $|\mathcal{R}^l_i - \mathcal{R}^l_0| < \delta$, $|\mathcal{D}^e_i - \mathcal{D}^e_0| < \delta$, $|\mathcal{H}^c_i - \mathcal{H}^c_0| < \delta$, and $|\Gamma^e_i - \Gamma^e_0| < \delta$, then $|f(\mathcal{E}^r_i, \mathcal{R}^l_i, \mathcal{D}^e_i, \mathcal{H}^c_i, \Gamma^e_i) - f(\mathcal{E}^r_0, \mathcal{R}^l_0, \mathcal{D}^e_0, \mathcal{H}^c_0, \Gamma^e_i)| < \epsilon$, where δ and ϵ are positive constants. Also, σ_i is a positive constant in the interval of $\mathcal{E}^r_{th} \le \mathcal{E}^r_i \le \mathcal{E}^r_m$, $\mathcal{R}^l_{th} \le \mathcal{R}^l_i \le \mathcal{R}^l_m$, $0 \le \mathcal{D}^e_i \le 2\mathcal{L}_{uv}$, $0 \le \mathcal{H}^c_i \le \mathcal{H}^c_m$, and $0 \le \Gamma^e_i \le \Gamma^e_m$. Therefore,

$$\begin{aligned} |b_i - b_0| &= \left|\sigma_i \left\{\rho + \left(\frac{\mathcal{E}^r_i}{\mathcal{E}^e_m} + \frac{\mathcal{R}^l_i}{\mathcal{R}^l_m}\right) - \left(\frac{\mathcal{D}^e_i}{2\mathcal{L}} + \frac{\mathcal{H}^c_i}{\mathcal{H}^c_m} + \frac{\Gamma^e_i}{\Gamma^e_m}\right)\right\}\right. \\ &\quad \left. - \sigma_i \left\{\rho + \left(\frac{\mathcal{E}^r_0}{\mathcal{E}^e_m} + \frac{\mathcal{R}^l_0}{\mathcal{R}^l_m}\right) - \left(\frac{\mathcal{D}^e_0}{2\mathcal{L}} + \frac{\mathcal{H}^c_0}{\mathcal{H}^c_m} + \frac{\Gamma^e_0}{\Gamma^e_m}\right)\right\}\right| \\ &\le \left|\frac{\sigma_i}{\mathcal{E}^r_m}\right| |\mathcal{E}^r_i - \mathcal{E}^e_0| + \left|\frac{\sigma_i}{\mathcal{R}^l_m}\right| |\mathcal{R}^l_i - \mathcal{R}^l_0| \\ &\quad - \left|\frac{\sigma_i}{2\mathcal{L}}\right| |\mathcal{D}^e_i - \mathcal{D}^e_0| - \left|\frac{\sigma_i}{\mathcal{H}^c_m}\right| |\mathcal{H}^c_i - \mathcal{H}^c_0| - \left|\frac{\sigma_i}{\Gamma^e_m}\right| |\Gamma^e_1 - \Gamma^e_0| \\ &\le \left(\frac{\delta\sigma_i}{\mathcal{E}^r_m} + \frac{\delta\sigma_i}{\mathcal{R}^l_m}\right) - \left(\frac{\delta\sigma_i}{2\mathcal{L}} + \frac{\delta\sigma_i}{\mathcal{H}^c_m} + \frac{\delta\sigma_i}{\Gamma^e_m}\right) \\ &= \delta \left(\frac{\sigma_i}{\mathcal{E}^r_m} + \frac{\sigma_i}{\mathcal{R}^l_m} - \frac{\sigma_i}{2\mathcal{L}} - \frac{\sigma_i}{\mathcal{H}^c_m} - \frac{\sigma_i}{\Gamma^e_m}\right) = \epsilon \end{aligned} \tag{24}$$

Therefore,

$$\delta = \frac{\epsilon}{\lambda} \tag{25}$$

where,

$$\lambda = \left(\frac{\sigma_i}{\mathcal{E}^r_m} + \frac{\sigma_i}{\mathcal{R}^l_m} - \frac{\sigma_i}{2\mathcal{L}} - \frac{\sigma_i}{\mathcal{H}^c_m} - \frac{\sigma_i}{\Gamma^e_m}\right) \tag{26}$$

In Equation (26) σ_i, $\mathcal{E}^r_m$, $\mathcal{R}^l_m$, $\mathcal{L}$, $\mathcal{H}^c_m$, and Γ^e_m are positive constants and $\left(\frac{1}{\mathcal{E}^r_m} + \frac{1}{\mathcal{R}^l_m}\right) > \left(\frac{1}{2\mathcal{L}} + \frac{1}{\mathcal{H}^c_m} + \frac{1}{\Gamma^e_m}\right)$. Hence, λ is a non-zero positive constant. From Equation (25), it is found that for every $\epsilon > 0$ there is a $\delta > 0$. So, benefit function in Equation (14) is continuous. □

5.1. Connectivity exploration

The proposed scheme re-establishes connectivity between a *BEGIN* node and the corresponding *STOP* node, while they are isolated due to the shrinkage in communication range attributed to the occurrence of adverse environmental effects. The initiation for connectivity re-establishment is taken by the *BEGIN* node, when it detects itself as isolated from the network. Initially, during the connectivity re-establishment process, the *BEGIN* node acts as the *FORWARD* node, and it broadcasts an ACTIVATION message to its single hop neighbors. The neighbor nodes, on receiving the ACTIVATION message become activated. Among these activated neighbor nodes, the ones that have not participated in the connectivity re-establishment process for this particular *BEGIN* node, but satisfy the constraint defined in Equation (15) with $\sigma_i = 1$, reply back with an ACK to the *BEGIN* node. When a *FORWARD* node does not receive an ACK from its neighbor node, it switches from a lower level to higher one. Further, it sends an ACTIVATION message and waits for an ACK. The *FORWARD* node continues the same until it receives any ACK from its neighbor node. If a *FORWARD* node reaches its maximum energy level, but does not receive any ACK packet, it is debarred from participating in the connectivity re-establishment process. The neighbor nodes, which satisfy the constraint, remain activated for the next t_{rep} time, and the rest of the neighbor nodes go to the sleep state. The parameter t_{rep} is the estimated time for receiving a reply packet from a *STOP* node. The *BEGIN* node then sends a REQUEST packet to its neighbor nodes. Each activated neighbor node calculates its own benefit value, and the cumulative benefit value(b^c_i) using Equations (14) and (16). The process continues for the active neighbor nodes. The active neighbor nodes start to function as the *FORWARD* nodes and they send an ACTIVATION message to all their neighbors. Those neighbor nodes, which have not functioned as a *FORWARD* node for this particular pair of *BEGIN* and *STOP* nodes, but satisfy the constraint given in Equation (15), send back an ACK to the corresponding *FORWARD* node and remain activated for the next t_{rep} time. They also calculate their own regular benefit and cumulative benefit values upon receiving a REQUEST packet from the *FORWARD* node. If a neighbor node receives a REQUEST packet from multiple *FORWARD* nodes, it selects one of them as the downstream node on the path to the *BEGIN* node, based on the highest cumulative benefit value. This process iterates in the neighbor nodes and progress through the neighbor nodes until the *STOP* node is reached. Algorithm 1 presents the connectivity exploration procedure from a *BEGIN* node to the corresponding *STOP* node.

5.2. Path selection

After receiving REQUEST packets from multiple *FORWARD* nodes, the *STOP* node selects one of the *FORWARD* nodes as the downstream node to the *BEGIN* node, based on the highest cumulative benefit value. Thereafter, the *STOP* node sends a REPLY packet to its immediate downstream *FORWARD* nodes. An intermediate node, on receiving a REPLY packet, forwards it to such an immediate downstream, which was selected in the connectivity exploration process based on highest cumulative benefit value. This process continues until the REPLY packet reaches the corresponding *BEGIN* node. The nodes receiving the REPLY packet establish connectivity from the *BE-*

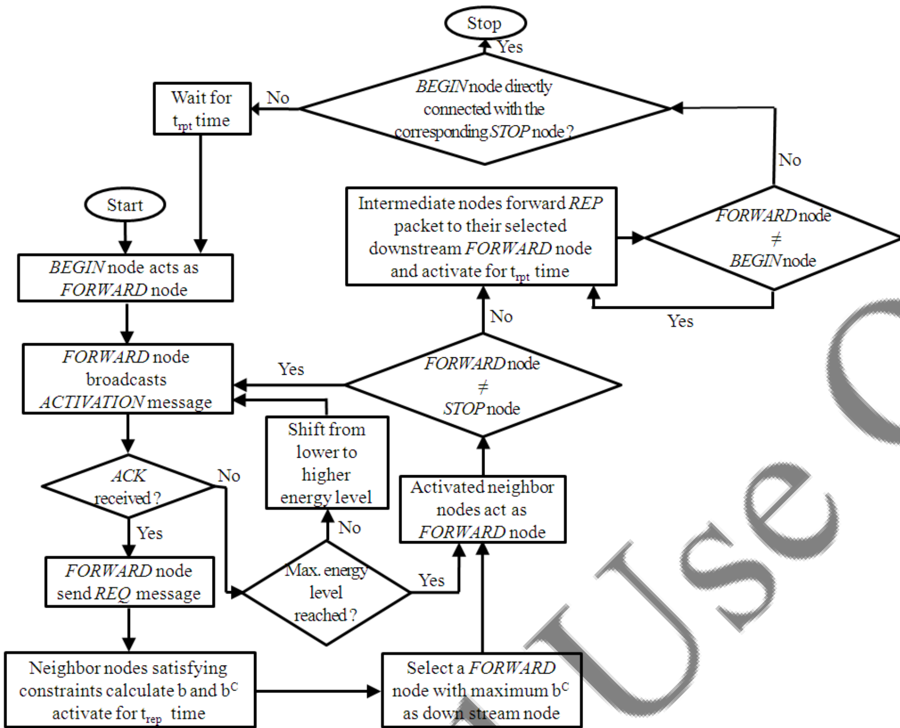


Fig. 8. Connectivity exploration and path selection

GIN node to the corresponding *STOP* node. The intermediate nodes receiving the REPLY packet remain activated for next the t_{rpt} time, where t_{rpt} is the estimated time for repeating the execution of the proposed connectivity re-establishment process. Algorithm 2 presents the process of path selection from a *STOP* node to the corresponding *BEGIN* node. The overall flow of operation is shown in Fig. 8

Proposition 1. *The best case and the worst case time complexities of* CoRAD *are* $O(1)$ *and* $O(N)$*, respectively, when there are* N *number of nodes in the network*

PROOF. *CoRAD* is divided into two parts, namely *connectivity exploration* and *path selection*. In the *connectivity exploration* process, the best case is, in the absence of any sleep neighbor nodes within the reduced communication range, the *BEGIN* node adjusts its communication range. Following this adjustment, the *BEGIN* node is connected to the *STOP* node. Therefore, in such a situation, the time complexity of the *path selection* process is also $O(1)$, because the *STOP* node can directly send REPLY packet to the *BEGIN* node. So, the best case time complexity for *CoRAD* is $O(1) + O(1) = O(1)$

On the other hand, the worst case situation arises, when the *connectivity exploration* process needs to traverse through all the nodes in the network, before it reaches the *STOP* node. In such a situation, the *connectivity exploration* process takes $O(N)$ time. In this case, the selected path should be an average length path of $O(N)$. So, REPLY packet takes $O(N)$ time to traverse from the *STOP* to the *BEGIN* nodes. Therefore, the time complexity of the *path selection* process is $O(N)$. Hence, the worst case time complexity for *CoRAD* is $O(N) + O(N) = O(N)$. □

THEOREM 5.5. *The final connectivity establish by* CoRAD *is an equilibrium.*

Algorithm 1 Connectivity Exploration

Require:

— BGN_ID: id of *BEGIN* node
— STP_ID: id of *STOP* node
— (x_u, y_u): position of *BEGIN* node
— (x_v, y_v): position of *STOP* node
— t_{rep}: expected reply time from *STOP* node
— t_{rpt}: repeat time

if $(ID = BGN\_ID)$ **then**
  $(x_f, y_f) \leftarrow (x_u, y_u)$
  $b^c \leftarrow 0$
  $H^c \leftarrow 0$
end if
Broadcast ACTIVATION message
if ACK received **then**
  Send REQUEST packet
else
  while ACK not received **do**
    Shift from low to high energy level
    if at max energy level **then**
      Break
    end if
  end while
end if
if $(ID \neq STP\_ID)$&&(received REQUEST) **then**
  $(\alpha, \beta) \leftarrow$ node position
  Calculate $\mathcal{L}_{uv}$, φ, υ_i, and $\mathcal{D}^e$
  $\mathcal{E}^r \leftarrow$ Residual Energy of node
  $\mathcal{R}^l \leftarrow$ Received Signal Strength of node
  if $((\mathcal{E}^r_{th} \leq \mathcal{E}^r \leq \mathcal{E}^r_m)$ && $(\mathcal{R}^l_{th} \leq \mathcal{R}^l_i \leq \mathcal{R}^l_m)$ && $(0 < \varphi \leq \mathcal{L}_{uv}))$ **then**
    $\rho = 4 - \left(\frac{\mathcal{E}^r_{th}}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l_{th}}{\mathcal{R}^l_m}\right)$ ▷ Shifting parameter
    $b \leftarrow \left[\rho + \left(\frac{\mathcal{E}^r}{\mathcal{E}^r_m} + \frac{\mathcal{R}^l}{\mathcal{R}^l_m}\right) - \left(\frac{\mathcal{D}^e}{\mathcal{L}_{uv}} + \frac{\mathcal{H}^c}{\mathcal{H}^c_m} + \frac{\Gamma^e}{\Gamma_m}\right)\right]$
    if $(ID \neq BGN\_ID)$ **then**
      $b^c \leftarrow BNF\_VAL + b$
      if (Number of REQUEST received with same BGN_ID > 1) **then**
        $node\_buffer \leftarrow FWD\_ADDR$ with $max(b^c)$
        $BNF\_VAL \leftarrow max(b^c)$
      end if
      if (Number of REQUEST received with same $BGN\_ID = 1$) **then**
        $node\_buffer \leftarrow FWD\_ADDR$
      end if
      $\mathcal{H}^c \leftarrow \mathcal{H}^c + 1$
    end if
    $(x_f, y_f) \leftarrow (\alpha, \beta)$
    Activate node for next t_{rep} time
    node broadcast ACTIVATION message followed by REQUEST message
  end if
end if

PROOF. We assume that *CoRAD* has found the connectivity $C = (n_u, n_1, n_2, \cdots n_i, n_j, \cdots, n_k, \cdots, n_p, n_v)$ from a *BEGIN* node U to a *STOP* node V. So, the cumulative benefit value of this path is:

$$b^c_v = b_v + b_u + \sum_{j=1}^{p} b_j \tag{27}$$

By the proof of contradiction, we assume that this path is not in equilibrium. The other nodes not located on this path may also satisfy the constraint. Hence, *CoRAD* finds another path $C' = (n_u, n_1, n_2, \cdots n_i, n_l, \cdots, n_m, \cdots, n_q, n_v)$ from a *BEGIN* node U

Algorithm 2 Path Selection

Require:

— $forward\_addr[\ ]$: list of addresses of master nodes
— $bnf\_val[\ ]$: list of utility values

```
if ((FWD_ID = STP_ID) && (received REQUEST)) then
    bnf_val[ ] ← BNF_VAL from REQUEST packets
    for i do = 1 to bnf_val.length
        forward_addr[i] ← FWD_ADDR

    end for
    if Number of REQUEST received > 1 then
        FWD_ADDR ← forward_addr with max(bnf_val)
    else
        FWD_ADDR ← forward_addr
    end if
    send REPLY to FWD_ADDR
end if
if ((FWD_ID ≠ BGN_ID) && (received REQUEST)) then
    if (!timeout(t_rep) then
        FWD_ADDR ← FWD_ADDR from the node_buffer
        forward REPLY to FWD_ADDR
        Activate node for next t_rpt time
    end if
end if
```

to a *STOP* node V, such that $q \leq p$. The cumulative benefit value of this path is:

$$b_v^{c'} = b_v + b_u + \sum_{j=1}^{q} b_j \tag{28}$$

CoRAD explores all possible connectivities between the *BEGIN* and *STOP* nodes, and selects one of them, based on the highest cumulative benefit value. Therefore, $b_v^c \nless b_v^{c'}$, though $q < p$. Otherwise, *CoRAD* chooses C' as the connectivity between the *BEGIN* and *STOP* nodes. Hence, the connectivity established by *CoRAD* is an equilibrium. □

6. SIMULATION RESULTS

6.1. Simulation Design

In this section, we evaluate the performance of the proposed algorithm *CoRAD*. We consider the temporary isolation of sensor nodes due to the presence of dumb behavior of a node. The proposed scheme *CoRAD* only re-establishes connectivity during the period of node isolation. For simulating the proposed algorithm, we deployed 150-350 inhomogeneous sensor nodes on an area of 500m × 500m. Initially, all the nodes are active. After deployment, a subset of sensor nodes remain activated to cover the entire area optimally and the rest of the sensors transit to the sleep state. The packet formats used for the simulation, (ACTIVATION, ACK, REQUEST, and REPLY) are depicted in shown in Fig. 5. We also consider that the transmission and reception of packets consume 50 nJ/bit. The sensing range of nodes is 50m and the communication range is 110m for normal scenario. To simulate the shrinkage of communication range due to adverse environmental effects, we vary the communication range from 85-30m with an interval of 5m. The list of simulation parameters is shown in Table II. We evaluated the proposed algorithm *CoRAD* based on the following parameters.

— *Percentage of isolated nodes*: Total number of isolated nodes present per 100 nodes in the network. The percentage of isolated nodes calculated as $\frac{I}{N} \times 100$, where I is the number of isolated nodes and N is the total number of nodes in the network.

— *Percentage of activated nodes*: Total number of activated nodes per 100 nodes in the network. The percentage of activated nodes calculated as $\frac{A}{N} \times 100$, where A is the number of activated nodes and N is the total number nodes in the network.
— *Success ratio*: Ratio between the number of isolated nodes that can successfully establish connection (C) with the network and the total number of isolated nodes (I) present in the network. The success ratio is calculated as $\frac{C}{I}$.
— *Average path length*: Average hop-count of the re-established connectivity between a *BEGIN* and the corresponding *STOP* node. The average path length is calculated as $\frac{\chi}{C} + 1$, where χ is the number of nodes activated for connectivity re-establishment in the network, and C is the number of isolated nodes that can successfully establish connectivity with the network.
— *Message overhead*: Total number of control messages required to be exchanged for the execution of the connectivity re-establishment process for all the isolated nodes in the network. The message overhead is calculated as $N_{act}S_{act}+N_{ack}S_{ack}+N_{req}S_{req}+N_{rep}S_{rep}$, where N_{act}, N_{ack}, N_{req}, N_{rep} are the number of ACTIVATION, ACK, REQ, and REP packets, respectively, and S_{act}, S_{ack}, S_{req}, and S_{rep} are the sizes of ACTIVATION, ACK, REQUEST, and REPLY packets, respectively.
— *Energy consumption*: Total amount of energy require for execution of the connectivity re-establishment process for all the isolated nodes with the network. Thus, energy consumption is the total energy spent for the transmission and reception of ACTIVATION, ACK, REQUEST, and REPLY packets.

We compared the proposed algorithm *CoRAD* with two recently proposed existing topology management schemes – *Learning automata-based Energy-efficient Topology Control (LECT)* [Torkestani 2013] and *Distributed Topology Control Algorithm (A1)* [Rizvi et al. 2012] – with respect to the number of nodes activated, overhead, and energy consumption. The results are plotted by taking an ensemble average over 30 runs with varying topologies. In all the plots, we vary the communication range along the x-axis and different simulation parameters along the y-axis.

Table II. Simulation Parameters

Parameter	Value
Number of nodes	150-350
Simulation area	500 × 500m
Sensing range	50m
Initial residual energy	1.5-2.0 J
Communication range in normal situation	110m
Change in communication range due to shrinkage	85-30m
Increase of communication range per energy level shifting	20m

6.2. Results Discussion

We analyze and discuss the results of the simulation of the proposed scheme *CoRAD*. In Fig. 9, it is shown that the change in percentage of isolated nodes with the variation in communication range due to the effect of adverse environmental conditions for different number of nodes in the network. The plot shows that with the gradual increase in communication range, the percentage of isolated nodes in the network decreases. If the communication range of a node increases, the chances of getting activated nodes in the reduced communication range of a node increases. Therefore, the number of isolated nodes decreases with the increase in communication range. It is also found that the decrease in the total number of nodes in the network increases the percentage of isolated nodes. The possible reason behind this is that, when the number of nodes reduce, the network becomes sparser, and the number of activated neighbor nodes also decreases. Consequently, more number of nodes do not find any active neighbor node within their communication range. Therefore, the number of isolated nodes increases with the decrease in the total number of nodes in the network.

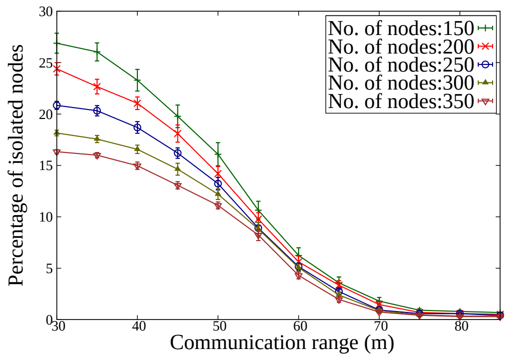


Fig. 9. Change in percentage of isolated nodes with the variation in communication range

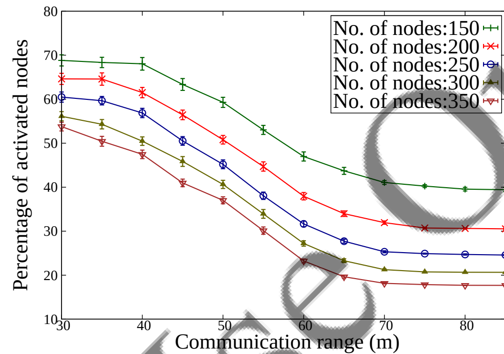


Fig. 10. Change in percentage of activated nodes with the variation in communication range

The change in the percentage of nodes required to be activated to maintain topology with the variation of communication range for different number of nodes is shown in Fig. 10. We observe the decrease in percentage of activated nodes with the increase in communication range. The increase in the communication range decreases the number of isolated nodes in the network, which results in more number of node activations to re-establish connectivity of isolated nodes in the network. The plot also depicts that the decrease in total number of nodes increases the number of activated nodes for the re-establishment of connectivity of isolated nodes in the network. The decrease in the total number of nodes leads to increase the number of isolated nodes in the network. Therefore, the decrease in total number of nodes increases the number of nodes that required to be activated for re-establishing connectivity of isolated nodes in the network.

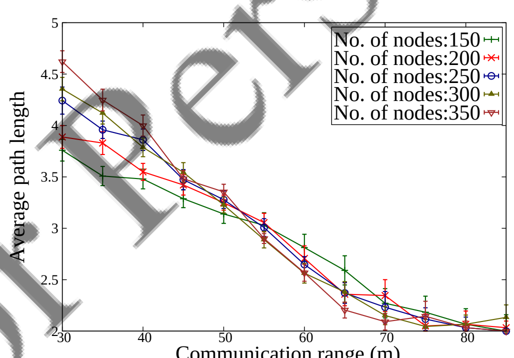


Fig. 11. Change in average path length of re-established connectivity with the variation in communication range

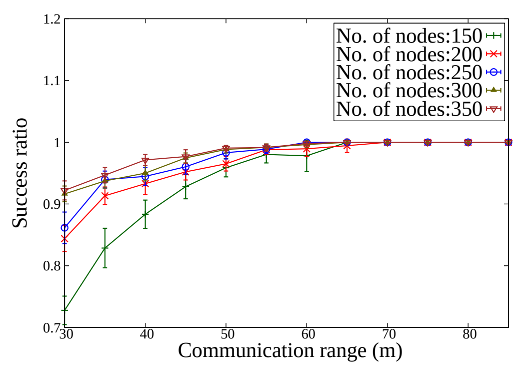


Fig. 12. Change in success ratio of connectivity re-establishment with the variation in communication range

Fig. 11 depicts the average path length of re-established connectivity between the *BEGIN* and the *STOP* nodes with varying number of nodes in the network. In this plot, we observe that the average path length decreases with the increase in communication range. The reason behind this is that the communication range of all the intermediate nodes also shrinks in a manner similar to the isolated nodes, due to the presence of adverse environmental effects. It is also found that the average path length varies randomly with the variation in the total number of nodes in the network, because of random deployment of sensor nodes in the network.

Fig. 12 presents the variation in success ratio with the communication range of sensor nodes for different number of nodes in the network. The plot depicts that the success ratio increases with the increase in the total number of nodes in the network. From this plot we also observe that the success ratio increases with the increase in the communication range. The increase in the total number of nodes and their respective communication range also increases the number of neighbor nodes. Therefore, the increase in number of neighbors increases the probability of getting a neighbor node of an isolated node to re-establish the connectivity in the network. The plot also shows that, for any number of nodes above 150 in the network, the success ratio attains the value of unity above the communication range of 65m or above. This is because all the isolated nodes become connected with the network with the communication range of 65m or above.

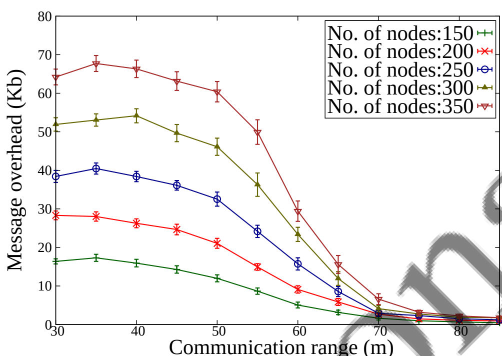


Fig. 13. Change in message overhead of connectivity re-establishment with the variation in communication range

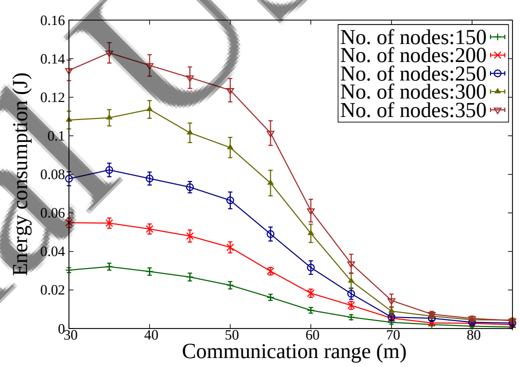


Fig. 14. Change in energy consumption for connectivity re-establishment with the variation in communication range

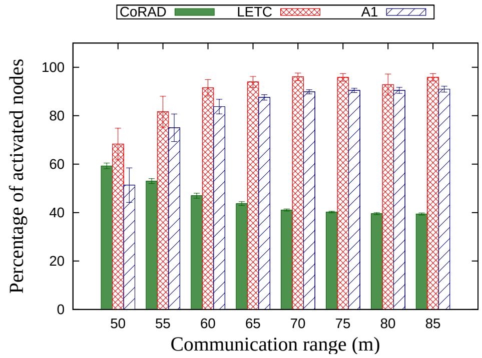
Variation in message overhead for re-establishment of connectivity versus communication range for varying number of nodes is shown in Fig. 13. This plot shows an increase in message overhead with the increase in the total number of nodes, as well as decrease in their respective communication range. The increase in the total number of nodes in the network increases the number of neighbors of a node, which, in turn, increases the number of ACTIVATION, ACK, and REQUEST packets in the network. On the contrary, the decrease in communication range increases the number of isolated nodes in the network. Therefore, it increases the required number of ACTIVATION, ACK, and REQUEST packets to re-establish connectivity of more number of isolated nodes in the network. Hence, the increase in the number of ACTIVATION, ACK, and REQUEST packets increases the message overhead in the network.

Energy consumption for re-establishment of connectivity with the variation in communication range for varying number of nodes is shown in Fig. 14. This plot shows an increase in energy consumption with the increase in the total number of nodes and decrease in their respective communication range. The increase in the total number of nodes in the network increases the number of neighbors of a node, which, in turn, increases the number of transmitted and received packets in the network. On the other hand, the decrease in communication range increases the number of isolated nodes in the network. So, it increases the required number of packets transmitted and received to re-establish connectivity of isolated nodes in the network. The increase in the number of packet transmission and reception increases the energy consumption in the whole network.

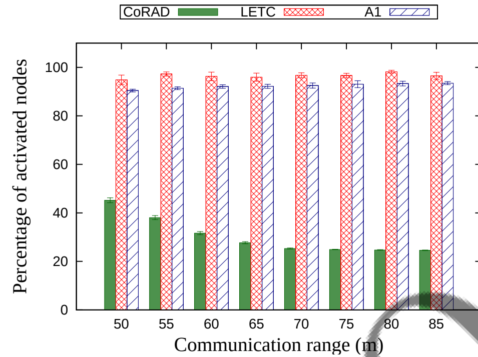
In Fig. 15, a comparison of the percentage of activated nodes of *CoRAD* with two recently proposed existing topology management schemes, *LETC* and *A1*, is shown. In Figs. 15(a), 15(b), and 17(c), the total number of nodes considered are 150, 250, and 350, respectively. In these plots, it is observed that, in case of *LETC* and *A1*, the percentage of activated nodes decreases with the decrease in the communication range of the nodes. However, using the proposed scheme *CoRAD*, the percentage of activated nodes increases with the decrease in the communication range of nodes. The possible reason behind this is that, due to the decrease in the communication range, gradually the sensor nodes become isolated. Hence, the existing topology management schemes fail to re-construct the topology of the entire network. However, the proposed scheme, *CoRAD*, re-constructs the topology of the entire network by activating additional nodes or by adjusting the communication range of nodes, while there is insufficient number of neighbor nodes within the reduced communication range. In these plots, it is also observed that, in case of *LETC* and *A1*, an increase in the total number of nodes in the network increases the percentage of activated nodes. However, in case of the proposed scheme, *CoRAD*, the percentage of activated nodes decreases. The possible reason is that, in case of *LETC* and *A1*, the increase in the total number of nodes increases the re-constructed part of the entire network. However, in case of *CoRAD*, an increase in the total number of nodes in the network decreases the number of isolated nodes in it, which, in turn, decreases the number of nodes activated for topology re-construction.

A comparison in message overhead of the schemes is shown in Fig. 16. Figs. 16(a), 16(b), and 16(c) consider the total number of nodes in the network as 150, 250, and 350, respectively. In these plots, it is seen that, in case of *LETC* and *A1*, the message overhead for topology re-construction decreases with the decrease in the communication range of the nodes. However, in case of *CoRAD*, the message overhead increases with the decrease in the communication range of the nodes. The possible reason behind this is that, due to the decrease in communication range, gradually, the sensor nodes become isolated. Hence, in cases of the existing topology management schemes, all the nodes do not participate in the topology re-construction process. Therefore, the number of control messages reduces. However, the proposed scheme, *CoRAD*, increases the participation of additional nodes by activating them or by adjusting their communication range, while there is insufficient number of neighbor nodes within the reduced communication range. Hence, the number of control messages increases with the decrease in the communication range of the nodes. In these plots, it is also observed that, in case of *LETC* and *A1*, the increase in the total number of nodes in the network increases the message overhead. However, in case of *CoRAD*, the message overhead decreases. The possible reason is that, in case of *LETC* and *A1*, the increase in the total number of nodes increases the number of nodes that participate in the topology re-construction process. However, in case of *CoRAD*, the increase in the total number of nodes in the network decreases the number of isolated nodes in it, which, in turn, decreases the number of nodes that participate in the topology re-construction process.

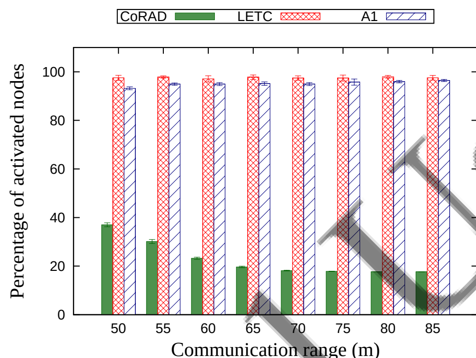
A comparison of energy consumption of the schemes is shown in Fig. 16. Figs. 16(a), 16(b), and 16(c) consider the total number of nodes in the network as 150, 250, and



(a) Number of nodes in the network is 150



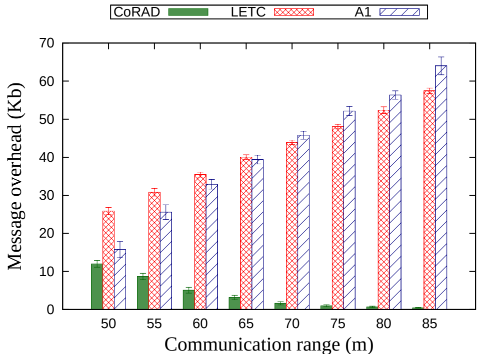
(b) Number of nodes in the network is 250



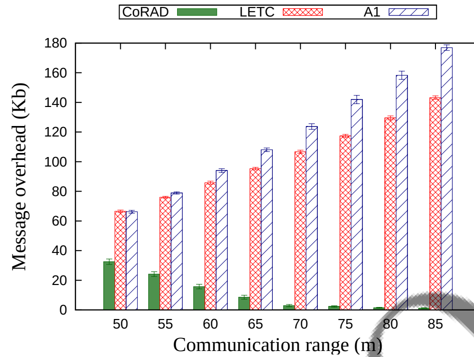
(c) Number of nodes in the network is 350

Fig. 15. Comparison in percentage of node activation of different schemes with varying communication range

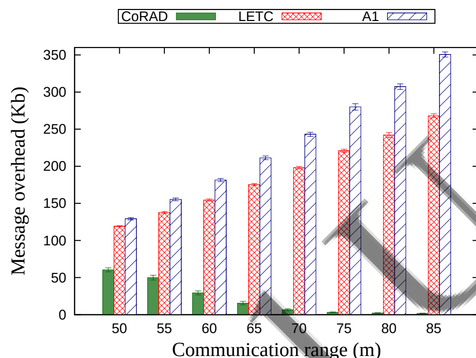
350, respectively. In these plots, it is observed that, in case of *LETC* and *A1*, the energy consumption for topology re-construction decreases with the decrease in the communication range of the nodes. However, in case of *CoRAD*, energy consumption increases with the decrease in the communication range. This observation is attributed to the decrease in communication range of nodes, gradually, due to which, the sensor nodes become isolated. Hence, in the cases of the existing benchmark topology management schemes, all the nodes do not participate in the topology re-construction process. Therefore, the number of control messages transmitted and received reduces. However, *CoRAD*, increases the participation of additional nodes by activating them or by adjusting communication ranges, when there is insufficient number of neighbor nodes within the reduced communication range. Hence, the number of control messages that are transmitted and received increases with the decrease in the communication range. In these plots, it is also observed that, in case of *LETC* and *A1*, the increase in the total number of nodes in the network increases the energy consumption. In case of *CoRAD*, however, it decreases. This is due to the fact that, in case of *LETC* and *A1*, the increase in the total number of nodes increases the number of nodes that participate in the topology re-construction process. However, in case of *CoRAD*, the increase in the total number of nodes in the network decreases the number of isolated nodes, which, in turn, decreases the number of nodes that participate in the topology re-construction process.



(a) Number of nodes in the network is 150



(b) Number of nodes in the network is 250



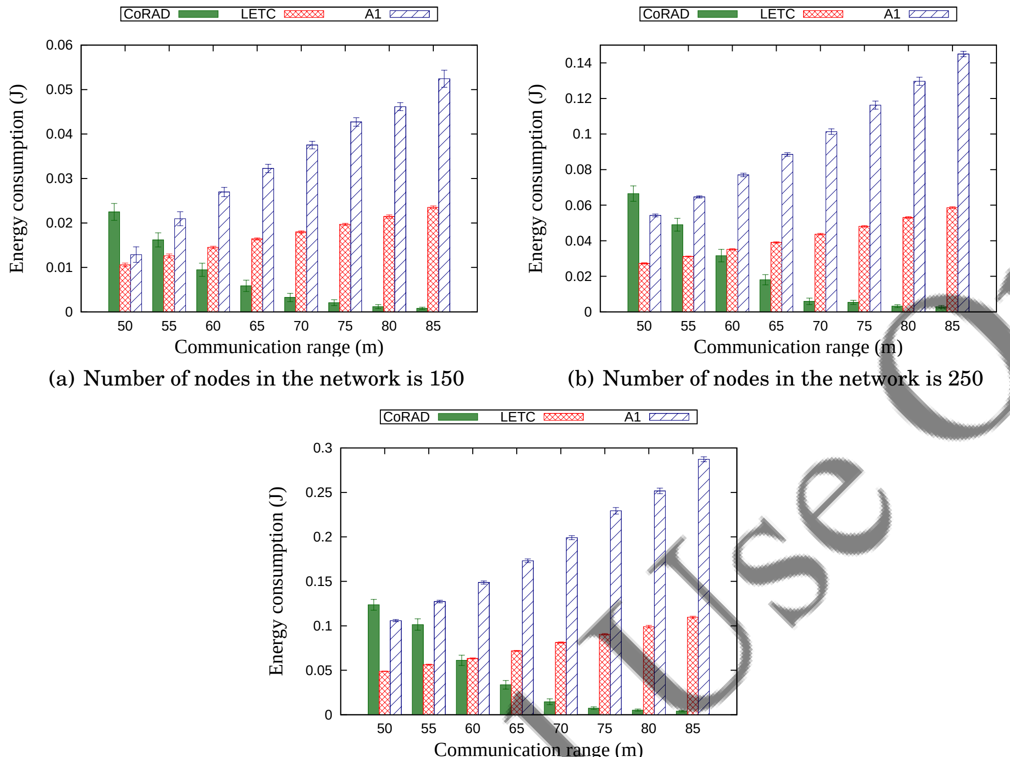
(c) Number of nodes in the network is 350

Fig. 16. Comparison in message overhead of different schemes with varying communication range

7. CONCLUSION

Due to attenuating effect by the presence of adverse environmental conditions communication range of sensor nodes shrinks. The shrinkage in communication range leads to behave a sensor node as a dumb node. The temporal behavior of the adverse environmental effects makes dumb behavior of a node temporary. Sensor nodes become temporarily isolated from the network, and thus, dumb behavior is considered to be a serious misbehavior due its detrimental effects on network performance, similar to the other misbehavior. Complete elimination of these nodes from the network operation for the remaining lifetime is not a good solution, because these nodes can provide resources and services to the network when they behave normally. Therefore, to utilize resources and services of dumb nodes during their period of isolation, we need to re-establish connectivity with the network. Here we proposed a price-based scheme to re-establish connectivity of a dumb node with the network during their period of isolation. The proposed scheme re-establishes the best possible connectivity by activating intermediate sleep nodes or by adjusting communication range of sensor nodes, when there is insufficient number of neighbor nodes within the reduced communication range.

In the future, we plan to extend our work to re-establish connectivity among temporary network partitions arise due to shrinkage in communication range attributed to adverse environmental effects. We also plan to incorporate the concept of learning into the proposed connectivity re-establishment algorithm. A sensor node may learn itself about the possibility of node isolation and node activation from its previous attempts



(a) Number of nodes in the network is 150

(b) Number of nodes in the network is 250

(c) Number of nodes in the network is 350

Fig. 17. Comparison in energy consumption of different schemes with varying communication range

of connectivity re-establishment. The sensor node takes decision about the next connectivity re-establishments based on its learned information. Additionally, we plan to perform this study in a real WSN testbed in the future.

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