Topology Control for Self-Adaptation in Wireless Sensor Networks with Temporary Connection Impairment

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In this work, the problem of topology control for self-adaptation in stationary Wireless Sensor Networks (WSNs) is revisited, specifically for the case of networks with a subset of nodes having temporary connection impairment between them. This study focuses on misbehaviors arising due to the presence of\enskip "dumb" nodes [Misra et al. 2014; Roy et al. 2014a, 2014b, 2014c; Kar and Misra 2015], which can sense its surroundings but cannot communicate with its neighbors due to shrinkage in its communication range by the environmental effects attributed to change in temperature, rainfall, and fog. However, a dumb node is expected to behave normally on the onset of favorable environmental conditions. Therefore, the presence of such dumb nodes in the network gives rise to impaired connectivity between a subset of nodes and, consequently, results in change in topology. Such phenomena are dynamic in nature and are thus distinct from the phenomena attributed to traditional isolation problems considered in stationary WSNs. Activation of all the sensor nodes simultaneously is not necessarily energy efficient and cost-effective. In order to maintain self-adaptivity of the network, two algorithms, named *Connectivity Re-establishment in the presence of Dumb nodes* (*CoRD*) and *Connectivity Re-establishment in the presence of Dumb nodes Without Applying Constraints* (*CoRDWAC*), are designed. The performance of these algorithms is evaluated through simulation-based experiments. Further, it is also observed that the performance of CoRD is better than the existing topology control protocols—LETC and A1—with respect to the number of nodes activated, overhead, and energy consumption.

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

General Terms: Connectivity Re-establishment, Performance, Data Gathering

Additional Key Words and Phrases: Dumb node, self-adaptivity, connectivity, dynamic shrinkage, wireless sensor network

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1. INTRODUCTION

Due to the rapid advancement of Micro Electro-Mechanical Systems (MEMSs), Wireless Sensor Networks (WSNs) have attained prominence in application domains that require monitoring physical phenomena and objects [Chandrasekar et al. 2008; Bhattacharjee et al. 2012; Fok et al. 2009]. A WSN consists of a set of low-power sensor

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nodes, with each having limited transmission range. Consequently, the intermediate nodes act as relays to forward the sensed information to the sink [Akyildiz et al. 2002a, 2002b]. Irrespective of the issue of self-adaptation and the type of deployment, sensor nodes work in a collaborative manner to measure their surrounding physical parameters such as light, pressure, temperature, humidity, and vibration. Consequently, active participation and collaboration of an optimum set of nodes is crucial to maintain Quality of Service (QoS) in the network. Maintaining connectivity among the nodes is essential for achieving this [Fan and Jin 2010; Zhang et al. 2009].

Various environmental conditions such as temperature, fog, and rainfall impact the communication between sensor nodes and, consequently, decrease the communication range [Anastasi et al. 2004; Paradis and Han 2007; Bannister et al. 2008; Boano et al. 2010]. Due to environmental factors, when the transmission range of a sensor node decreases below a threshold value, the node becomes incapable of continuing to communicate with its neighbor nodes, which were, otherwise, previously within the communication range of that particular node. In such a scenario, connectivity is lost between the sensor nodes, and thus, one or more nodes get isolated from the network. Such nodes can sense their surroundings but cannot transmit the sensed data to the other nodes. These nodes are characterized as *dumb* [Misra et al. 2014; Roy et al. 2014a, 2014b, 2014c; Kar and Misra 2015]. It may be noted that dumb behavior is a unique type of misbehavior and its difference from other misbehaviors or channel fading is elaborately discussed in Misra et al. [2014]. As the environmental conditions are temporal in nature, the dumb behavior in a sensor node is also temporal. Therefore, a dumb node can behave as a normal node when such adverse environmental conditions disappear. Considering the loss in connectivity in the network in the presence of dumb behavior of sensor nodes, we propose a scheme in order to re-establish connectivity. We emphasize that the problem we address and the solution we propose are specifically targeted to address this unique type of misbehavior. Additionally, many price-based and currency-based approaches were explored [Liu and Krishnamachari 2006; Edalat et al. 2009; Buttyan and Hubaux 2001] for studying the cooperation and routing of data packets between a pair of nodes in wireless networks. To address the issue of disconnection among nodes due to dumb behavior and to maintain self-adaptivity, we use a *price-based* scheme to choose the most reliable path.

1.1. Motivation

WSNs are, typically, resource constrained, unattended, and autonomous. So, they are prone to denial-of-service (DoS) attacks, wormhole attacks (specifically in IP-based WSNs) [Sarigiannidis et al. 2015a], sybil attacks [Sarigiannidis et al. 2015b], faults, bad environmental effects, and misbehavior [Krishnamachari and Iyengar 2004]. In this work, we focus on the *dumb* behavior [Misra et al. 2014] of nodes, which is caused by the shrinkage in communication range due to environmental factors such as fog, temperature, and rainfall. Therefore, connectivity may be lost between nodes in a network, and the sensed information by these nodes cannot be transmitted further. In a WSN, it is important to ensure that every sensor node can communicate with the sink directly or over a multihop path [Lloyd 2007]. Due to the temporal nature of the environmental effects, a sensor node exhibiting dumb behavior at a particular time instant may not exhibit this at a later instant. When dumb behavior arises in the sensor nodes, the intermediate nodes need to be activated for maintaining adequate connectivity. As sensor nodes have limited energy, the cost involved in the activation of intermediate nodes throughout the network lifetime is high [Chatterjee and Sengupta 2010; Wang et al. 2009]. Therefore, a subset of intermediate nodes should be activated to maintain connectivity between nodes in a network, instead of all of them. With the restoration of favorable environmental conditions, the sensor nodes start operating as normal, and these newly activated intermediate nodes should be progressively deactivated in a self-adaptive manner to avoid redundant connectivity [Misra et al. 2011] for reducing the overall energy consumption of the network. It is indeed true that the connectivity re-establishment problem is well known and is extensively researched, as stated earlier. But there is no literature that addressed connectivity re-establishment in the presence of dumb nodes. This work is the first to address the problem. Moreover, the concept of dumb node is newly explored by Misra et al. [2014]. Further, the existing schemes for re-establishing connectivity among sensor nodes assume stationarity in behavior, which makes them unsuitable for use in the case of dumb nodes.

1.2. Contribution

A WSN is a multihop communication network, in which connectivity between nodes is an important factor to send the sensed information to the sink. In this article, we consider the decrease in communication range due to environmental conditions such as temperature, rainfall, and fog. Consequently, there is loss in connectivity between the activated nodes, isolation of node(s) from the network, and network partitioning. The problem is interesting, as the effect is not permanent. It is transient, because with the restoration of favorable environmental conditions, the nodes can perform their normal operations. The specific *contributions* in this article are summarized as follows:

—Proposing a price-based scheme for establishing a path between different nodes, which is disconnected due to the shrinkage in communication range, and thus, ensuring that the selected path is the most reliable among all the existing ones
—The proposed solution is theoretically characterized from different perspectives
—Simulation-based performance evolution of the proposed scheme

The rest of the article is organized as follows. Section 2 describes the related work done in this area. Section 3.1 defines a dumb node and gives the characteristics of it. Section 3.2 describes different cases of connectivity loss and their respective topology changes. The system is modeled and the solution is proposed in Sections 4 and 5. We design the simulation and describe the simulation settings in Section 6. The analysis and discussion of results are given in Section 7. We conclude the work in Section 8.

2. RELATED WORK

In WSNs, cooperation among sensor nodes is a very important factor for maintaining successful operation of the network. Due to disruption (breakage) of links, existing cooperation among nodes is lost. This results in the degradation in the performance of the network. Misra and Jain [2011] proposed a Markov Decision Process (MDP)-based self-configuring and self-healing algorithm for activating an optimal number of neighbor nodes, which form the backbone of the entire network. However, dumb behavior impedes the neighbor nodes from communicating and getting an activation message. Fanimokun and Frolik [2003] discussed various issues of connectivity with a low-cost environmental sensing network. They have experimentally evaluated the propagation effects for three environments: open, wooded, and hilly. Bonvoisin et al. [2011] addressed the issues related to environmental impacts of WSNs and proposed an assessment model for them. This assessment model is based on a two-part analysis: life cycle assessment and network energy. They designed the environmental impacts as a sum of different stages, namely, deployment, replacement, energy consumption, and dismantling. The authors compared the result for two scenarios: (1) exploitation and (2) deployment dismantling. Rajagopalan and Varshney [2009] considered the variation in connectivity in WSNs with time. Environmental effects such as rainfall and growing plants reduces the signal strength for communication between sensor nodes.

Fog, rainfall, and snowfall have detrimental effects on the signal propagation and link quality of WSNs. These environmental effects reduce the signal strength, as they severely affect the communication range of a sensor node [Nadeem et al. 2009; Anastasi et al. 2004; Bannister et al. 2008; Markham et al. 2011]. Consequently, the communication range of sensor nodes may shrink, which may lead to some of the nodes getting isolated from the network, resulting in partitioning of the network into many parts. Anastasi et al. [2004] showed the change in performance of a sensor node due to the presence of environmental effects. Paradis and Han [2007] reported that permanent or temporary wireless link failures can happen due to the change in environmental conditions. Again, Bannister et al. [2008], Nadeem et al. [2009], and Boano et al. [2010] reported that temperature is also one of the influencing facts affecting signal strength. Consequently, the transmission power and communication links among the sensor nodes get affected. Jiang et al. [2007] presented a method that covers holes for reconnectivity and coverage in the network using a localized control technique. H. M. Ammari and S. K. Das [2008] discussed the issue of coverage and connectivity. In this work, the authors consider two problems: Sensing Coverage Phase Transition (SCPT) and Network Connectivity Phase Transition (NCPT). They developed the correlated disk model for addressing these issues, considering the nonorthogonal nature of sensing coverage and network connectivity.

There is saliency in the difference between the dumb behavior and behaviors arising due to other impairments such as fading, about which a lot of literature already exists. Some of the existing literature is discussed here. Banavar et al. [2010] estimated correlative information with different channel conditions over multiple access channels. They evaluated the asymptotic variation of multiple access fading channels. However, they have not proposed any solution to overcome environmental effects. Mousavi et al. [2016] studied time-varying fading channels and proposed a two-phase transmission scheme in order to select a subset of sensors to transmit the sensed observation to the Fusion Center (FC). D. E. Quevedo and Johansson [2013] estimated sufficient conditions for using the Kalman filter in the presence of channel fading in wireless sensor networks, while the underlying network is described as a (semi-) Markov chain. However, they have not proposed a solution to overcome any environmental effects.

On the other hand, Biswas et al. [2013] presented a work that studied the effects on energy efficiency due to the placement of a relay in a Wireless Sensor Network in the presence of a fading channel. They concluded that relay placement depends on constellation size (M), path loss exponent (n), and fading parameters (η and μ). Mostofi and Murray [2004] discussed the effects of time-varying communication links on the control performance of a mobile sensor network. Further, they provided the analytical and simulation results, which show that fading is one of the major reasons for poor performance of the network. However, they have not considered environmental effects other than fading. Liu [2006] discussed the effects on the MAC protocol of Wireless Sensor Networks in the presence of fading and shadowing. The author concluded that fading and shadowing have a significant impact on the performance of a WSN. However, the author did not propose a solution to overcome any environmental effects. Primarily, the work of Dong et al. [2007] focuses on the fading channel, in which they calculated the probability of a node being isolated from the network. Thereafter, the probability of forming a connected network was calculated. The authors in this work show the degradation of the network performance with the help of numerical results. Further, the authors determine the minimum density required in order to form a connected network. Fang and Li [2008] primarily focused on fading and noise in a channel. Further, the authors present a scheme designing the compression matrices. This work does not give any solution on the temporal behavior of a node, which can be taken into account in order to increase network performance.

There also exist literature on split networks. Some of the existing literature is discussed here. Ammari and Das [2006] developed the Augmented Equilateral Triangle (AET) model, which guarantees sensing k-coverage, and proved that the network connectivity of homogeneous and heterogeneous k-covered WSNs (kCWSNs) is higher than the degree of sensing coverage. Tseng et al. [2010] considered isolated WSNs that are disconnected from the outside world for an extended duration of time. It depends on mobile mules to visit the isolated node and carries its non-real-time sensed data to the outside world, which is collected once over several months. They also addressed the issue of a storage requirement arising due to infrequent collection of data from the isolated network. Dini et al. [2008] proposed a method for repairing a split network. They used mobile nodes by finding the proper position in the network, so that connectivity between the sensor nodes can be re-established. However, this method may not be useful when the WSN deployed area is not planer. In the presence of any obstacle, there is disruption in the movement of mobile nodes. Yang et al. [2013] proposed a Dynamic Local Stitching (DLS) algorithm that ensures repair of the broken path in a WSN. In DLS, the minimum energy consumption relay model is used to repair the broken path. Senel et al. [2011] proposed a spider-web-based approach with the help of a minimum spanning tree to reconnect the partitioned network. Senel et al. [2011] considered partitioning occurring due to the damage of sensor nodes. They deployed relay nodes to reconnect the partitioned network, which is permanently deployed. However, there may arise the condition that the network is partitioned due to the dumb nature of sensor nodes, resulting from some environmental conditions such as fog and rainfall. In such a scenario, permanent deployment of relay nodes may not be suitable, as the nodes resume their normal operation with the onset of favorable environmental conditions. In another work, Okorafor and Kundur [2009] studied the problem of node isolation in a wireless optical sensor network (WOSN). Specifically, the authors try to determine the node isolation property in a WOSN. Khelifa et al. [2009] studied the problem of loss in connectivity in a mobile wireless sensor network. They propose a scheme that enables one to monitor, maintain, and repair network connectivity. Therefore, the proposed scheme is useful to increase the degree of connectivity in the network. Yet, the increasing degree of a node does not ensure connectivity in the presence of environmental effects, as the communication range of each node reduces due to the presence of adverse environmental effects. However, this literature does not consider the dynamic loss in connectivity in WSNs. We consider a WSN where nodes get disconnected dynamically from the network in the presence of environmental conditions.

None of these existing literature works studies the problem of link re-establishment in dumb nodes, which is characteristically *dynamic* and *temporal* in nature. At this juncture, it is pertinent to emphasize that both “dynamic” and “temporal” behaviors in connectivity due to the presence of environmental conditions make this problem *unique* and, consequently, interesting in the case of dumb nodes. Additionally, the existing works do not provide any scheme for re-establishing connectivity in the presence of such environmental conditions. Thus, the problem discussed in this article is unique and is not addressed in any literature. A review of the existing literature reveals that different types of topology maintenance and connectivity re-establishment mechanisms are used between the isolated nodes and the partitioned network. However, all these mechanisms may not be suitable for establishing connectivity between isolated nodes due to shrinkage in the communication range in the presence of bad environmental conditions. The temporal nature of bad environmental conditions leads to variable shrinkage of the communication range, which changes the neighbor list of a node at

Table I. Notation Table

Notation	Description
Ψ_n	Normal behavior of a node
Ψ_d	Dumb behavior of a node
r_c^{ne}	Required communication range of a node to activated neighbor node *ne*
d_{min}	Distance to the nearest active neighbor node
R	Maximum specified fixed communication range of sensor node
$r_c(t)$	Communication range at time instant t
ne	List of activated neighbor node
E_f	Intensity of bad environmental effect
P_r	Receiving power
P_d	Power density
P_t	Transmission power
G_t	Transmission gain
RE_i	Residual energy of node n_i
RSS_i	Received signal strength of node n_i
HC_i	Hop count of a node n_i stating from START node
d_i	Distance of node n_i from straight line between START node and END node
de_i	Distance between any node n_i and END node
L	Distance between START node and END node
RE_{min}	Minimum residual energy
RE_{max}	Maximum residual energy
RSS_{min}	Minimum receive signal strength
RSS_{max}	Maximum receive signal strength
HC_{max}	Maximum hop count of a path
C_i	Cost of node n_i to precipitate in connectivity re-establishment
t_{reply}	Expected time to reply from END node
t_{repeat}	Expected time to repeat the algorithm
b_i	Benefit of node n_i
B_i^C	Cumulative benefit of node n_i

different times. The change in neighbor list makes the topology of a network vary with time. Consequently, the existing solutions are of limited use in such scenarios.

3. PROBLEM DESCRIPTION

3.1. Dumb Nodes

Our work is based on the concept of dumb nodes. As mentioned in Section 1, dumb behavior arises due to the occurrence of increased environmental phenomena such as fog, rainfall, and temperature. If the transmission range gets affected, then a node can sense the physical phenomena in its surroundings but cannot communicate with the other nodes.

We have considered two types of nodes in the network: (1) normal behaved node and (2) dumb node. Further, all the sensor nodes are considered to be homogeneous, which implies that each node has the same capabilities of sensing, transmitting, and receiving. Table I lists all the notations used in this work.

Definition 1. Normal Behavior: A sensor node that can sense the physical phenomena in its surroundings and transmit the sensed data during its entire lifetime is termed a normal behaved node. Such behavior is denoted as Ψ_n:

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

Definition 2. Dumb Behavior: A sensor node that can sense the physical phenomena in its surroundings and cannot transmit the sensed data at a certain instant of time

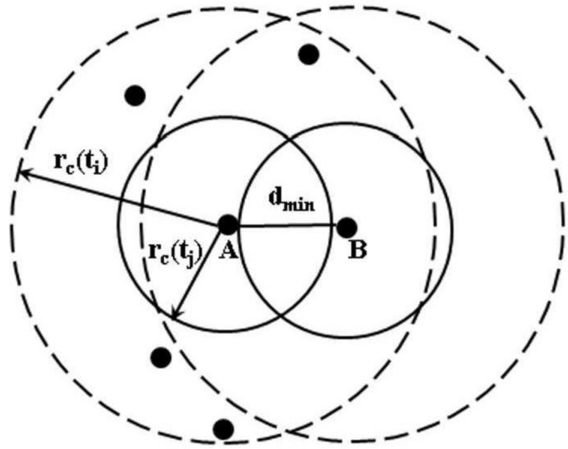


Fig. 1. Shrinkage in communication range of a sensor node.

due to the presence of adverse environmental conditions but can transmit at a later instant with the resumption of favorable environmental conditions is termed a dumb node. Such behavior is denoted by Ψ_d. Mathematically,

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

In Figure 1, we focus on a part of the deployed WSN. Here, node A represents any node in the network. At time instant t_i, the communication range of node is $r_c(t_i)$. All other nodes present in the communication range ($r_c(t_i)$) of node A are its neighbors. Among all the neighbor nodes of A, node B is the nearest neighbor node. Thus, we define the distance between nodes A and B as d_{min}. At time instant t_j, due to the presence of adverse environmental conditions, the communication range of node A shrinks below d_{min} and it becomes $r_c(t_j)$. At the time instant t_j, all the neighbor nodes of node A are outside its communication range, $r_c(t_j)$. Consequently, node A is unable to communicate with any of its neighbor nodes.

d_{min} is the distance from node A to its nearest neighbor node B, which is mathematically represented as

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

where $min(r_c^{ne})$ is the minimum communication range for the nearest activated neighbor node ne. Let, at time instant t_i, the communication range be $r_c(t_i)$. For proper connectivity in the network, each node should maintain the property $R \geq r_c(t_i) \geq d_{min}$. Due to environmental effects, at time t_j, a node becomes isolated when its communication range shrinks below d_{min}, that is, $r_c(t_j) < d_{min}$.

3.2. Change of Topology Due to Dumb Nodes

The intensity of bad environmental effects may vary both spatially and temporally. Consequently, the shrinkage in communication range of a sensor node also varies. In the existing literature [Boano et al. 2010; Markham et al. 2011], it has been established that with the increasing value of temperature and rainfall, the effects on signal strength also increase.

PROPOSITION 1. *If the effect of environmental intensity increases, the communication range of a node decreases.*

Proof. The intensity of environmental effects is denoted by E_f. We know that the receiving power, P_r, decreases with the increase of intensity of these environmental effects. So,

$$\frac{1}{E_f} \propto P_r. \tag{2}$$

Power Density, $P_d = \frac{P_t G_t}{4\pi R^2}$, where P_t is the transmission power, G_t is the transmission gain, and R is the transmission range of a sensor node, respectively. For computing the minimum power density $(P_d)_{min}$, there is maximum range R_{max}:

$$(P_d)_{min} = \frac{P_t G_t}{4\pi R_{max}^2}$$

$$G_t = \frac{(P_d)_{min} 4\pi R_{max}^2}{P_t}. \tag{3}$$

If the maximum transmission range R_{max} increases to R'_{max}, the transmission gain G_t also increases. We have

$$G'_t = \frac{(P_d)_{min} 4\pi {R'}_{max}^2}{P_t}. \tag{4}$$

From Equations (3) and (4), we get

$$\frac{G_t}{G'_t} = \frac{R_{max}^2}{{R'}_{max}^2}. \tag{5}$$

From Equation (5), we have

$$G_t \propto R_{max}^2. \tag{6}$$

Again, from Friis's equation [Levis 2005], we have

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2, \tag{7}$$

where P_r and P_t are the receiving and transmitting power, respectively; G_r and G_t are the receiver and transmitter gain, respectively; λ is the wavelength; and d is the distance between the two antennas. When the gain changes to G'_t, the new receiving power is expressed as:

$$P'_r = P_t G'_t G_r \left(\frac{\lambda}{4\pi d}\right)^2. \tag{8}$$

From Equations (7) and (8), we have

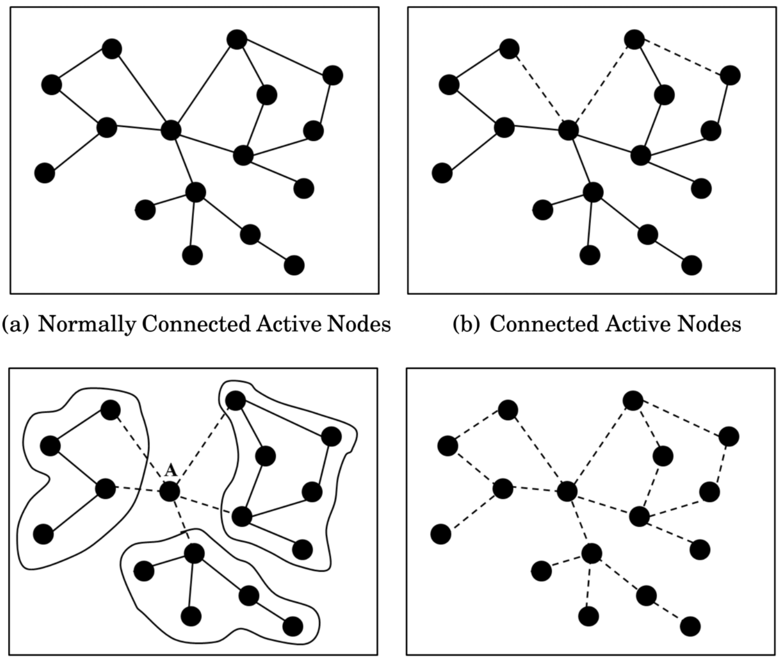
$$P_r \propto G_t. \tag{9}$$

From Equations (6) and (9), we have

$$P_r \propto R_{max}^2. \tag{10}$$

From Equation (2), put the value of P_r in Equation (10):

$$\frac{1}{E_f} \propto R_{max}^2. \tag{11}$$



(a) Normally Connected Active Nodes (b) Connected Active Nodes

(c) Disconnected Group of Active Nodes (d) Fully Disconnected Active Nodes

Fig. 2. Change in topology due to shrinkage of communication range [Misra et al. 2014].

From Equation (11), it is found that an increase in the intensity of these environmental effects determines the impact in the range of communication of a sensor node. □

We consider a network as shown in Figure 2(a). Consequently, a network can be considered as a graph $G = (V, E)$, where the set of nodes is represented by V, and the set of links between nodes is represented by E. The number of nodes $|V| = n$. The sink node is denoted as $\mathrm{s} \in V$. Depending on the shrinkage of communication range of sensor nodes, the effects due to environmental factors are classified into the following cases:

Case 1: If the intensity of the bad environmental effects is very little, there may be shrinkage in the communication range. This minimum shrinkage does not affect all existing connectivity in the network, and it disconnects few existing connectivities. Due to the low intensity of bad environmental effects, the received signal strength may decrease but remain above the communication threshold for a few links. In this case, every active node remains connected with every other node in the network via single-hop or multihop connectivity, as shown in Figure 2(b). This can be defined mathematically as $\forall v \in V$ there exists a path sv.

In this case, as there is no loss of connectivity, there is no need to activate any intermediate node(s). However, in respect of quality of service, there may be packet drops due to shrinkage of communication range, and as a remedy, the intermediate node(s) need to be activated. Our work concerns connectivity only, as we do not consider the issues related to quality of service.

Case 2: If the intensity of the bad environmental effect is nonuniform, there may be splitting of the network into many parts. In Figure 2(c), node A is affected by bad environmental effects and there is shrinkage of the communication range (shown by dotted line). Consequently, the original network is split into three parts. Mathematically, this can be defined as follows: for all positive integers $n_1, n_2, \ldots, n_k$, such that $\sum_{i=1}^{k} n_i = n$, there exists a partition of $V(G)$ into k parts $V_1, V_2, \ldots, V_k$ such that $|V_i| = n_i$, and V_i induces a connected subgraph of G for $1 \le i \le k$ and $\forall v \in V_i$ and there is no path sv.

In this case, as there is loss of connectivity between node(s), it is necessary to activate intermediate sleep node(s) to re-establish connectivity between the isolated node(s).

Case 3: If the intensity of the bad environmental effect is extreme, all the nodes in the network may become isolated from one another. There will be no path from a node to the sink node. In Figure 2(d), it is shown that there is isolation between nodes due to shrinkage of the communication range. Mathematically, $\forall v, \forall w \in V$ and there is no path vw when $v \neq w$.

Here, as all the node(s) become isolated from one another, every node needs to participate to re-establish connectivity between them by activating the intermediate sleep node(s).

4. SYSTEM MODEL

In this work, we have specifically considered network partitioning and isolation of nodes due to dumb behavior. A sensor node becomes isolated at a particular time instant but remains connected at different time instants due to the dynamic (changing) nature of the dumb behavior. Our goal is to re-establish the most reliable path between these disconnected nodes by activating the intermediate sleep nodes. For re-establishing reliable connectivity, the proposed scheme activates a reduced number of intermediate sleep nodes between the START and the END nodes. One of the two disconnected nodes starts the connectivity procedure by using a price-based scheme. The price-based scheme is formulated as $\Gamma = <P, B>$, where P is the set of participants, that is, $P = \{p_1, p_2, p_3, \ldots, p_n\}$, and $B = \{b_p \mid p \in P\}$ is the set of benefit functions. In our proposed algorithm, we use three types of nodes as follows:

START Node: A node S is said to be the *START* node if it satisfies the following conditions:
i. S is a dumb node.
ii. S initiates *CoRD* to connect with an *END* node.

END Node: A node E is said to be an *END* node, which is responsible for the following:
i. Being a parent node
ii. Choosing one of the paths from itself to S

MASTER Node: A node which is responsible for the following:
i. Calculating its own benefit, final benefit, and cumulative
ii. Forwarding the process by activating neighbor nodes within its reduced communication range

A collection of GPS-enabled sensor nodes are deployed over a terrain. After deployment, every node chooses its parent from the neighbor nodes that are within its communication range. Through the parent node, a node can communicate with the sink node; that is, if a node is connected to its parent node, then it is able to connect with the sink. After finding the parent node, each node holds its respective parent ids. Due to the existence of adverse environmental effects, there is shrinkage in the communication range in one or more node(s), and, consequently, the connectivity between a node and the parent node is lost, which in turn results in loss of connectivity with the sink node. In such a situation, a node having lost connectivity with the parent initiates the proposed scheme *Connectivity Re-establishment in the presence of Dumb Nodes* (*CoRD*) to re-establish connectivity. In *CoRD*, the isolated node activates the intermediate sleep nodes to re-establish connectivity with its parent node. In energy-constrained WSNs, it is important to find a node for activation that is optimized with respect to certain specified parameters. Energy is an essential resource for communication in WSNs. So it needs to choose such a node to be activated, which has substantial residual energy. The residual energy of a node n_i is represented by RE_i. We activate fewer intermediate nodes between the START and END nodes to choose reliable connectivity with less energy consumption. For activating fewer nodes, another parameter, effective distance D_i, is considered, which is the summation of d_i and de_i. In wireless communication, the receive signal strength (RSS) plays an important role for maintaining quality of service (QoS) of a link; that is, the increase of RSS yields better link quality. Additionally, in this network, RSS is given extra attention because a node can become dumb due to environmental conditions, which results in a decrease in RSS. So it is intended to choose a node having more RSS value. In this work, the RSS value of a node i is represented by RSS_i. The parameter D_i is characterized further in Lemma 4.1. As WSNs are energy constrained, it is better to choose a path between the START and the END nodes with less hop-count. Therefore, a parameter for hop-count HC is considered.

LEMMA 4.1. *To select the optimal neighbor node to re-establish connectivity between the START and END nodes, the distances d and de must be considered, with fixed RSS and RE.*

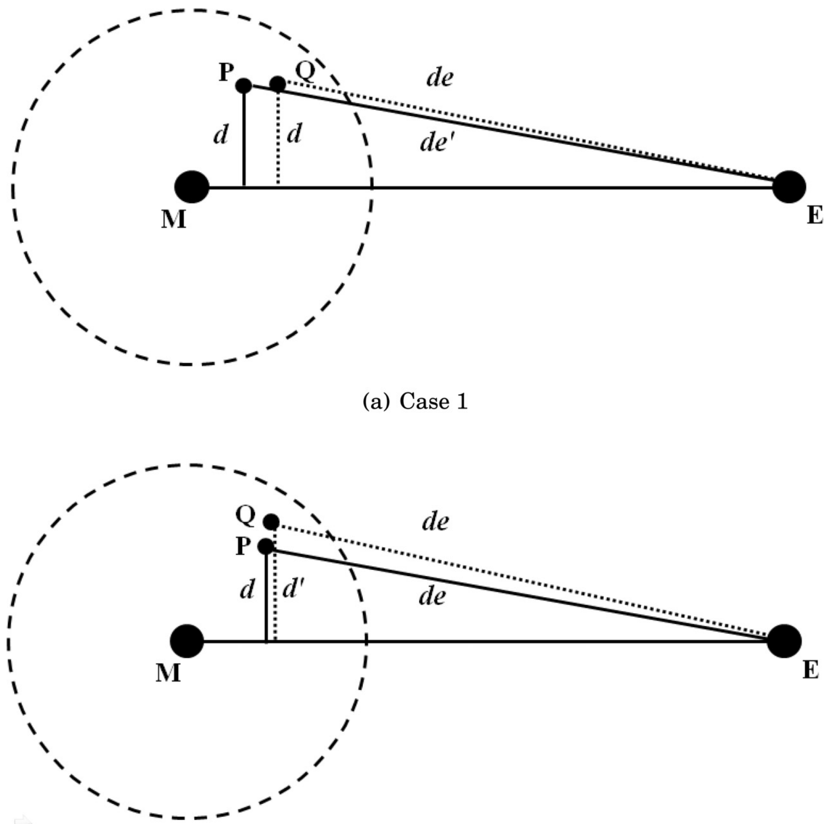
PROOF. To prove this, we have considered two cases:

Case 1: The perpendicular distances (d') from two neighbor nodes P and Q to the straight line joining the START and the END nodes are equal, but the distances (de and de') from P and Q to the END node are unequal, as shown in Figure 3(a).

Case 2: The perpendicular distances (d and d') from two neighbor nodes P and Q to the straight line joining the START and the END node are unequal, but the distances (de) from P and Q to the END node are equal, as shown in Figure 3(b).

If we draw a straight line between two disconnected nodes, it represents the minimum distance between them. So it is imperative to choose a node located the least distance from the straight line between two disconnected nodes. The perpendicular distance from a neighbor node and the straight line is represented by d. Again, the distance de between a neighbor node and the END node is also an important parameter, because if a node with the least de is chosen, then it will result in faster progress toward the END node. In Case 1, $de' > de$, so node Q should be chosen. In Case 2, $d' > d$, so node P should be chosen. From these it can be inferred that both the parameters d and de are important. For giving equal importance to both the parameters, we choose a neighbor node with the least D, where $D = d + de$. Therefore, it is prudent to assign higher preference to select a neighbor node with minimum D to re-establish connectivity between the START and the END nodes. □

Each node has an unique ID. Figure 4 represents the overall connectivity re-establishment process performed in a WSN with the help of *CoRD*. In this figure, nodes 1 and 13 (START and END nodes) denote the activated nodes. The rest of the nodes are in sleep mode. Node 1 establishes connectivity with node 13, which were connected earlier but ceased to be connected due to the onset of adverse environmental conditions. The connectivity re-establishment process is initiated by node 1, which activates the intermediate sleep nodes in order to re-establish reliable connectivity with node 13. A node that activates the neighbor nodes and brings them to participate in the connectivity re-establishment process is referred to as the MASTER node. Initially,



(a) Case 1

(b) Case 2

Fig. 3. Two cases for node selection based on distances.

the START node acts as the MASTER node. A MASTER node broadcasts an ACT (activation) message to activate the sleep nodes, which are in its reduced communication range. The packet format of an ACT message is shown in Figure 5(c). When the communication range of node 1 decreases below d_{min}, it fails to communicate with any of its neighbor nodes and becomes isolated from the network. Nodes 4, 5, and 9 are the sleep nodes within the reduced communication range r_c of the MASTER node, that is, node 1. It acts as a MASTER node and starts to broadcast an ACT message, which activates nodes 4, 5, and 9. After activation of these nodes, node 1 starts to broadcast REQ (request) packets to these nodes. A REQ packet contains seven fields, namely, SRT_ID, SRT_POS, MST_ADDR, END_ID, END_POS, BNF_VAL, and HC. These fields are the start node id, start position, master address, end node id, position of end node, cumulative benefit value, and hop-count, respectively. The request packet format is shown in Figure 6(a). A neighbor node calculates the distance from the line between the START and the END nodes to itself, by using a simple geometric method, as explained later.

Let the positions of the START and the END nodes be denoted by (x_s, y_s), and (x_e, y_e), respectively. Let the position of the i^{th} neighbor node be (α_i, β_i). The equation of the straight line connecting the START and the END nodes is

$$(y_e - y_s)x + (x_s - x_e)y + (x_e y_s - x_s y_e) = 0. \tag{12}$$

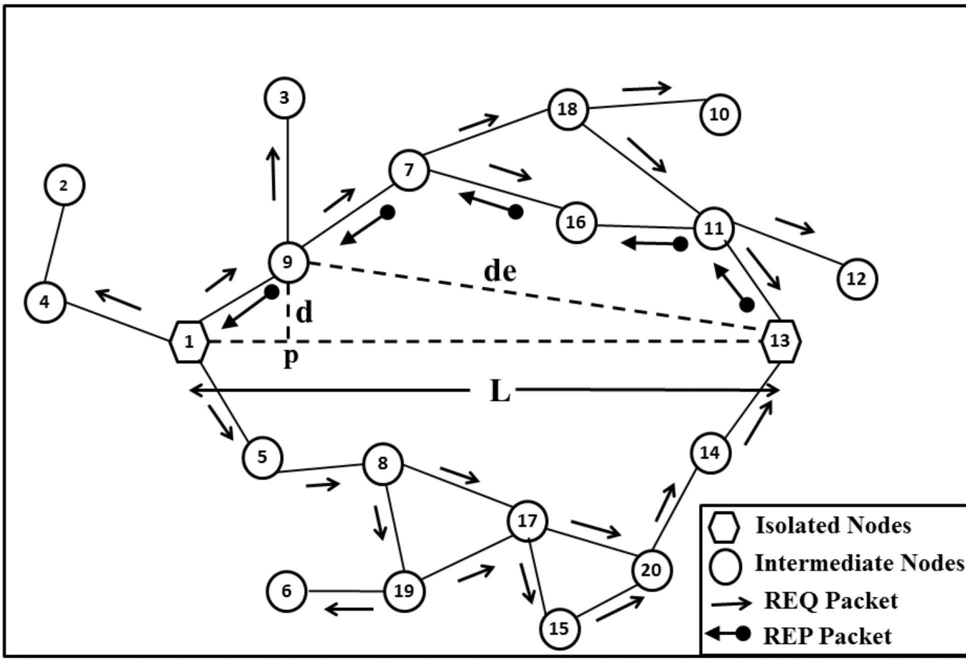


Fig. 4. Example scenario.

SRT_ID (2 bytes)	SRT_POS (4 bytes)	MST_ADDR (4 bytes)	END_ID (2 bytes)	END_POS (4 bytes)	BNF_VAL (2 bytes)	HC (2bytes)

(a) Request Packet

END_ID (2 bytes)	END_ADDR (4 bytes)	SRT_ID (2 bytes)	SRT_ADDR (4 bytes)

(b) Reply Packet

MST_ID (2 bytes)	BROADCAST_ADDR (4 bytes)

(c) Activation Packet

Fig. 5. Request, reply, and activation packets.

From Equation (12), the distance d_i from the neighbor node (α, β) to the line between the START and the END nodes is

$$d_i = \frac{|(y_e - y_s)\alpha - (x_e - x_s)\beta + (x_e y_s - x_s y_e)|}{\sqrt{(y_e - y_s)^2 + (x_s - x_e)^2}}. \tag{13}$$

Likewise, the neighbor node calculates the Euclidean distance from the END node to itself, using the following equation:

$$de_i = \sqrt{(x_e - \alpha_i)^2 + (y_e - \beta_i)^2}. \tag{14}$$

5. PROPOSED SOLUTION

5.1. Path Exploration

A WSN can be modeled as a graph $G(V, E)$. Here, every node $n_i \in V$ and link between nodes is $l_{ij} \in E$, where l_{ij} is the link between nodes n_i and n_j. Each node n_i has a benefit b_i, which depends on RE, RSS, D, and HC for participation in establishing connectivity between the START and the END nodes. These parameters are used in our solution to choose a node for participating in the connectivity procedure. In the network, there are three different types of nodes: START node n_s, END node n_e, and intermediate sleep nodes ($n_i \in V \mid \{n_s, n_e\}$) that can participate to establish the connectivity between the START and the END nodes. Each node n_i calculates its benefit b_i as follows:

$$b_i = (w_i - C_i), \tag{15}$$

where b_i, w_i, and C_i represent the benefit, worth, and cost functions, respectively, which are defined in Equations (27), (19), and (24), respectively.

A Price-Based Scheme

The network is modeled as a price-based system in order to give importance to residual energy and received signal strength of a sensor node. We choose the price-based approach over game-theoretic approach for the perceived simplicity of execution. However, game-theoretic approaches may also be used alternatively. Additionally, we emphasize the hop-count required for re-establishing connectivity among the sensor nodes. Using a price-based approach, we quantify the profit of each dumb node based on these parameters. Therefore, in our proposed algorithm, profit is calculated by subtracting loss from gain. Here, the benefit (profit) of selecting a node for path re-establishment is calculated by subtracting the cost from the worth of selecting the node. Here, worth is the quantized value of the advantage (gain) of selecting the node and cost is the quantized value of the disadvantage (loss) of selecting the node. Each activated node participates in the reconnectivity procedure between two disconnected nodes.

We have modeled worth w_i for each node n_i considering the parameters RE_i and RSS_i such that

$$w_i = f_1(RE_i) + f_2(RSS_i) \tag{16}$$

$$f_1(RE_i) = \left(\frac{RE_i}{RE_{max}}\right) \tag{17}$$

$$f_2(RSS_i) = \left(\frac{RSS_i}{RSS_{max}}\right). \tag{18}$$

Replacing Equation (16) by the values of Equations (17) and (18), we get

$$w_i = \left(\frac{RE_i}{RE_{max}}\right) + \left(\frac{RSS_i}{RSS_{max}}\right). \tag{19}$$

D_i is calculated as follows:

$$D_i = de_i + d_i. \tag{20}$$

Considering the parameters D_i and HC_i, the cost function C_i of each node n_i is as follows:

$$C_i = g(D_i) + h(HC_i) \tag{21}$$

$$g(D_i) = \left(\frac{D_i}{L}\right) \tag{22}$$

$$h(HC_i) = \left(\frac{HC_i}{HC_{max}}\right), \tag{23}$$

where HC_{max} is the maximum hop-count between the START and the END nodes.

$$C_i = \left(\frac{D_i}{L}\right) + \left(\frac{HC_i}{HC_{max}}\right) \tag{24}$$

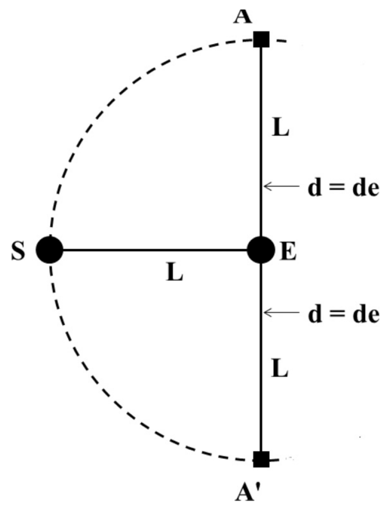


Fig. 6. Maximum value of cost function.

By placing the values of Equations (19) and (24) into Equation (15), the benefit b_i of a node n_i is computed as

$$b_i = \left[\left(\frac{RE_i}{RE_{max}} + \frac{RSS_i}{RSS_{max}}\right) - \left(\frac{D_i}{L} + \frac{HC_i}{HC_{max}}\right)\right]. \tag{25}$$

A node n_i is chosen depending on another selection parameter η_i, as follows:

$$\eta_i = \begin{cases} 1, & RE_{th} \le RE_i \le RE_{max} \wedge RSS_{th} \le RSS_i \le \\ & RSS_{max} \wedge 0 \le de_i \le L \\ 0, & \text{otherwise,} \end{cases} \tag{26}$$

where RE_{th} is the minimum threshold of RE above which a node n_i can communicate with other nodes, and RSS_{th} is the minimum threshold of RSS for the same. The resulting benefit function is as follows:

$$b_i = \eta_i \left[\left(\frac{RE_i}{RE_{max}} + \frac{RSS_i}{RSS_{max}}\right) - \left(\frac{D_i}{L} + \frac{HC_i}{HC_{max}}\right)\right]. \tag{27}$$

LEMMA 5.1. *Let the distance between the START and the END nodes be L. Then, the maximum effective distance D_{max} is $2L$.*

PROOF. Let S be the MASTER node, which chooses a neighbor node. The neighbor node gives the maximum value of D, when both d and de are maximum. This condition arises when a node is located at A or A', as shown in Figure 6. At this position, $de = d = L$. Therefore, $D_{max} = d + de = 2L$. □

THEOREM 5.2. *The maximum and minimum values of the benefit function with total N number of nodes in the network in Equation (27) are*

$$b_i^{max} = 2 - \frac{1}{N-2}$$
$$b_i^{min} = \frac{RE_{th}}{RE_{max}} + \frac{RSS_{th}}{RSS_{max}} - 3,$$

when $RE_{th} \le RE_i \le RE_{max}$, $RSS_{th} \le RSS_i \le RSS_{max}$, and $0 \le de_i \le L$.

Proof. The benefit function b_i is a linear function of four variables RE_i, RSS_i, D_i, and HC, and η is a constant for choosing a node as mentioned in Equation (26). The function is derived by subtracting the cost function from the worth function shown in Equations (19) and (24). The benefit function in Equation (27) gives the maximum value, when worth is maximum and the cost is minimum. The benefit is maximum when $RE_i = RES_{max}$ and $RSS_i = RSS_{max}$. So the maximum worth value is

$$w_i^{max} = \frac{RE_{max}}{RE_{max}} + \frac{RSS_{max}}{RSS_{max}} = 2. \tag{28}$$

The cost function is minimum when the values of $g(D_i)$ and $h(HC_i)$ are minimum.

The minimum value of D_i is 0, and it is possible only when the END node acts as the MASTER node. When the END node acts as the MASTER node, d_i and de_i result in the value 0. So the minimum value of $g(D_i)$ is 0.

The minimum value of HC_i is 1. When the START node forwards the process of re-establishment of connectivity, the value of HC becomes 1. So the minimum value of $h(HC_i)$ is $\frac{1}{N-2}$ So the minimum cost becomes

$$C_i^{max} = 0 + \frac{1}{(N-2)}. \tag{29}$$

From Equations (28) and (29), the maximum benefit value of function in Equation (27) is

$$b_i{}^{max} = 2 - \frac{1}{(N-2)}.$$

Again, for the minimum value of the benefit function, worth is minimum and cost is maximum. Worth is minimum when $RE_i = RE_{th}$, $RSS_i = RSS_{th}$. The minimum worth value is

$$w_i^{min} = \frac{RE_{th}}{RE_{max}} + \frac{RSS_{th}}{RSS_{max}}. \tag{30}$$

The value of the cost function becomes maximum when $g(D)$ and $h(HC)$ both are maximum.

From Lemma 5.1, we have the maximum value of $g(D)$ and $h(HC)$ when the value of HC is HC_{max}, that is, $h(HC) = 1$. So the maximum cost value is

$$C_i^{max} = 3. \tag{31}$$

From Equations (30) and (31), the minimum value of the benefit function is

$$b_i{}^{min} = \left(\frac{RE_{th}}{RE_{max}} + \frac{RSS_{th}}{RSS_{max}}\right) - 3. \quad \square$$

Lemma 5.3. *The benefit function in Equation (27) is continuous in the intervals* $RE_{th} \le RE_i \le RE_{max}$, $RSS_{th} \le RSS_i \le RSS_{max}$, $0 \le D \le 2L$, *and* $0 \le HC \le (N-2)$.

Proof. The given benefit function in Equation (27) is

$$b_i = \eta_i \left[\left(\frac{RE_i}{RE_{max}} + \frac{RSS_i}{RSS_{max}}\right) - \left(\frac{D_i}{L} + \frac{HC_i}{HC_{max}}\right)\right], \tag{32}$$

where η_i is a constant.

Let $y = f(x, y)$ be a multivariable function that is continuous at point (x_0, y_0), if the following condition satisfies:

$$\forall \epsilon > 0 \; \exists \delta(\epsilon) > 0 \text{ such that} |x - x_0| < \delta, |y - y_0| < \delta \Rightarrow |f(x, y) - f(x_0, y_0)| < \epsilon. \quad (33)$$

Therefore, the benefit function is continuous at any point (RE_0, RSS_0, D_0, HC_0). Whenever $|RE_i - RE_0| < \delta$, $|RSS_i - RSS_0| < \delta$, $|D_i - D_0| < \delta$, and $|HC_i - HC_0| < \delta$, then $|f(RE_i, RSS_i, D_i, HC_i) - f(RE_0, RSS_0, D_0, HC_0)| < \epsilon$, where δ and ϵ are positive constants. Also, η_i is a positive constant in the interval of $RE_{th} \leq RE_0 \leq RE_{max}$, $RSS_{th} \leq RSS_0 \leq RSS_{max}$, $0 \leq D_0 \leq 2L$, $1 \leq HC_0 \leq HC_{max}$.

Therefore,

$$\begin{aligned}
|b_i - b_0| &= \left| \left\{ \left(\frac{RE_i}{RE_{max}} + \frac{RSS_i}{RSS_{max}} \right) - \left(\frac{D_i}{2L} + \frac{HC_i}{HC_{max}} \right) \right\} \right. \\
&\qquad \left. - \left\{ \left(\frac{RE_0}{RE_{max}} + \frac{RSS_0}{RSS_{max}} \right) - \left(\frac{D_0}{2L} + \frac{HC_0}{HC_{max}} \right) \right\} \right| \\
&\leq \left| \frac{1}{RE_{max}} \right| |RE_i - RE_0| + \left| \frac{1}{RSS_{max}} \right| |RSS_i - RSS_0| - \left| \frac{1}{L} \right| |D_i - D_0| \\
&= \left(\frac{\delta}{RE_{max}} + \frac{\delta}{RSS_{max}} \right) - \left(\frac{\delta}{2L} + \frac{\delta}{HC_{max}} \right) \\
&= \epsilon.
\end{aligned}$$

Therefore,

$$\delta = \frac{\epsilon}{\kappa}, \quad (34)$$

where

$$\kappa = \left(\frac{1}{RE_{max}} + \frac{1}{RSS_{max}} \right) - \left(\frac{1}{2L} + \frac{1}{HC_{max}} \right). \quad (35)$$

In Equation (35), η_i, RES_{max}, RSS_{max}, L, and HC_{max} are positive constants and $(\frac{1}{RE_{max}} + \frac{1}{RSS_{max}}) \geq (\frac{1}{2L} + \frac{1}{HC_{max}})$. Hence, κ is a positive constant, such that $\kappa \neq 0$. Equation (34) signifies that for every $\epsilon \geq 0$ there is a $\delta \geq 0$. So the given benefit function in Equation (27) is continuous. □

At the beginning of the process, the START node acts as the MASTER node. The cumulative benefit B_i^C is initialized as 0, and hop-count HC is initialized with 1. The MASTER node activates all its neighbor nodes and sends the request packet REQ to them. The activated neighbor nodes (with $\eta_i = 1$) calculate their own benefit values b_i and add with them the B_i^C values received from the MASTER node, whereas the neighbor nodes $\eta_i = 0$ go to the sleep state.

These activated neighbor nodes hold the address of the previous MASTER node whose B_i^C value is maximum, increases the HC by 1, and acts as the MASTER node in order to process the same in the next hops. A MASTER node remains activated for t_{reply} time, where t_{reply} is the expected time for receiving the REP packet from the END node. If a neighbor node receives REQ packets from multiple MASTER nodes, it chooses one based on the highest value of B_i^C. Each intermediate node n_i calculates its B_i^C value as follows:

$$B_i^C = b_i + \sum_{j=1}^{i-1} b_j. \quad (36)$$

5.2. Path Selection

Algorithm 1 presents the procedure for exploring the path from the START to the END nodes. In the path exploration procedure, if an intermediate node between the

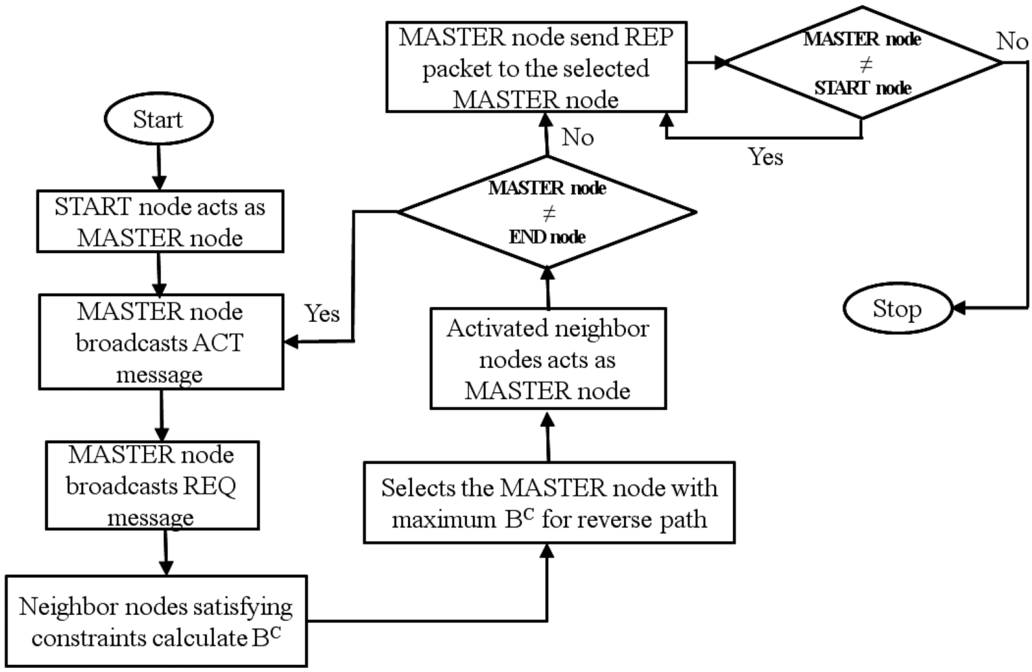


Fig. 7. Path exploration and selection.

START and the END nodes satisfies the condition of η, it selects a downstream node toward the START node, based on the highest cumulative benefit value B_i^C. Thereafter, this intermediate node acts as a MASTER node, and the scheme, *CoRD*, continues its execution in the upstream nodes (nodes toward END node).

The scheme continues until it reaches the END node. Finally, the END node acts as the MASTER node and chooses a downstream node with the highest benefit value B_i^C. The END node sends the *REP* packet to the START node through the selected downstream node. The flow diagram of the connectivity re-establishment procedure is shown in Figure 7.

PROPOSITION 2. *The best-case computational complexity of CoRD is O(n), when n is the given set of intermediate nodes between the START and the END.*

PROOF. *CoRD* is divided into two parts, namely, *path exploration* and *path selection*. For *path exploration*, the best possible path to reach the END node is chosen so that each intermediate node participating in *CoRD* has at most one neighbor node toward the END node. The total number of intermediate nodes between the START and the END nodes is n. The time taken to explore the intermediate next node is constant C. Thus, the recurrence can be modeled as $T(n) = T(n-1) + \Theta(C) \simeq O(n)$.

Similarly, for *path selection*, the return path consists of the same set of nodes in the opposite direction. Thus, the computational complexity for path selection is $O(n)$.

Hence, the complexity of *CoRD* is $O(n) + O(n) \simeq O(n)$. □

PROPOSITION 3. *The worst-case asymptotic time complexity of CoRD in a d-ary tree topological network is* $O(d^p + \mathcal{L}(END))$, *where* $\mathcal{L}$ *indicates the level of a node and p the path length.*

ALGORITHM 1: Path Exploration

Require:

—SRT_ID: id of START node
—END_ID: id of END node
—(x_s, y_s): position of START node
—(x_e, y_e): position of END node
—t_{reply}: expected reply time from END node
—t_{repeat}: repeat time

if $(ID = SRT\_ID)$ **then**
  $(x_m, y_m) \leftarrow (x_s, y_s)$
  $B^C \leftarrow 0$
  $HC \leftarrow 0$
end if
if $(ID \neq END\_ID)$&&(received REQ) **then**
  $(\alpha, \beta) \leftarrow$ node position
  $L \leftarrow \sqrt{(x_e - x_s)^2 + (y_e - y_s)^2}$
  $D \leftarrow d + de$
  $RE \leftarrow$ Residual Energy of node
  $RSS \leftarrow$ Received Signal Strength of node
  if $((RE_{th} \leq RE_i \leq RE_{max})$ && $(RSS_{th} \leq RSS_i \leq RSS_{max})$
    && $(0 < de \leq L))$ **then**
    $b \leftarrow \left[\left(\frac{RE}{RE_{max}} + \frac{RSS_i}{RSS_{max}}\right) - \left(\frac{D}{L} + \frac{HC}{HC_{max}}\right)\right]$
    if $(ID \neq SRT\_ID)$ **then**
      $B^C \leftarrow BNF\_VAL + b$
      if (Number of REQ received with same SRT_ID > 1) **then**
        $node\_buffer \leftarrow MST\_ADDR$ with $max(B^C)$
        $BNF\_VAL \leftarrow max(B^F)$
      end if
      if (Number of REQ received with same $SRT\_ID = 1$) **then**
        $node\_buffer \leftarrow MST\_ADDR$
      end if
      $HC \leftarrow HC + 1$
    end if
    $(x_m, y_m) \leftarrow (\alpha, \beta)$
    Activate node for next t_{reply} time
    node broadcast ACT message followed by REQ message
  end if
end if
if (!timeout(t_{reply}) && (received REP)
  && $(MST\_ID \neq SRT\_ID)$) **then**
  $MST\_ADDR \leftarrow$ MST_ADDR from the $node\_buffer$
  forward REP to MST_ADDR
  Activate node for next t_{repeat} time
end if

PROOF. The worst-case complexity occurs when every possible path, involving every node of the network, is explored. In such a case, the START node becomes the root of the topology, and the END node turns out to be one of the leaves. For a d-ary tree topology of the network, the path exploration procedure of the tree essentially implies

ALGORITHM 2: Path Selection

Require:

—*master_add*[ ]: list of addresses of master nodes
—*bnf_val*[ ]: list of utility values
—*hc*[ ]: list of hop-count

```
if ((MST_ID = END_ID) && (received REQ)) then
    bnf_val[ ] ← BNF_VAL from REQ packets
    for i do = 1 to bnf_length
        master_add[i] ← MST_ADDR
    end for
    if Number of REQ received > 1 then
        MST_ADDR ← master_add with max(bnf_val)
    else
        MST_ADDR ← master_add
    end if
    send REP to MST_ADDR
end if
```

a Breadth-First Search (BFS) from the START node to the END node. Therefore, the longest path p from the START to the END node is $\mathcal{L}(END)$. Hence, the asymptotic worst-case computational complexity for path exploration is $O(d^p)$, where d can be also viewed as the branching factor of the tree.

For the path selection procedure, the REQ packet backtracks from the END node through the previous MASTER node of every level, down to the START node. In such a scenario, the worst-case computational complexity becomes $O(\mathcal{L}(END))$.

Hence, we infer that the total computational complexity of *CoRD*, in the worst case, is $O(d^p + \mathcal{L}(END))$. This completes the proof. □

THEOREM 5.4. *The minimum number of iterations required for establishing connectivity between a pair of disconnected nodes increases (decreases) with the increase (decrease) in intensity of environmental effects.*

PROOF. Let the communication range of any node X be r_c, and let the distance between another node Y and itself be l. A minimum number of nodes N_{min} needs to be activated between these two nodes X and Y for establishing connection. The number of activated nodes is minimum if and only if each activated node lies on the straight line connecting these two nodes and on the circumference of one another, as shown in Figure 8. When the communication range is r_c, the minimum number of nodes required to be activated is

$$N_{min} = \left\lceil \frac{l}{r_c} \right\rceil - 1. \tag{37}$$

Due to environmental effects, at time t_i, the communication range is reduced by $\Delta r_c(t_i)$, and the new communication range is $r_c(t_i) = r_c - \Delta r_c(t_i)$. To establish connectivity between X and Y, nodes 1, 2, and 3 are required to be activated. Now the minimum number of nodes required to activate at time t_i is

$$N_{min}(t_i) = \left\lceil \frac{l}{r_c(t_i)} \right\rceil - 1. \tag{38}$$

Therefore, at time t_i, the minimum $N_{min}(t_i)$ number of iterations is required for establishing connectivity between the nodes X and Y.

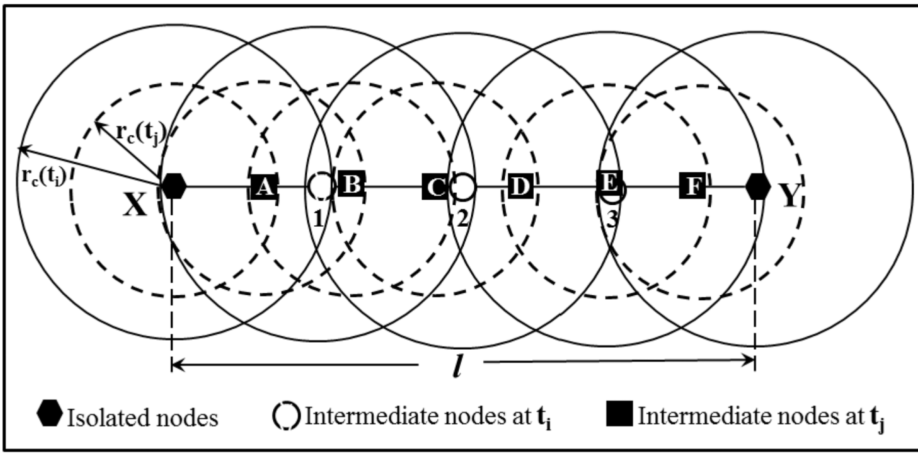


Fig. 8. Nodes require activation during two different intensities of environmental effect.

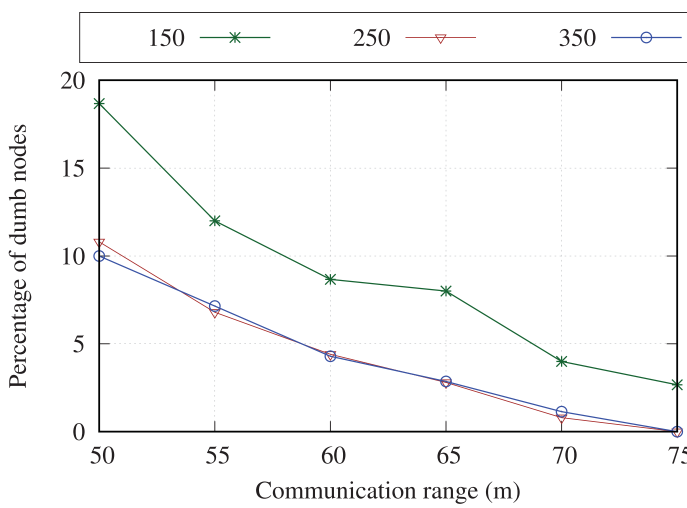
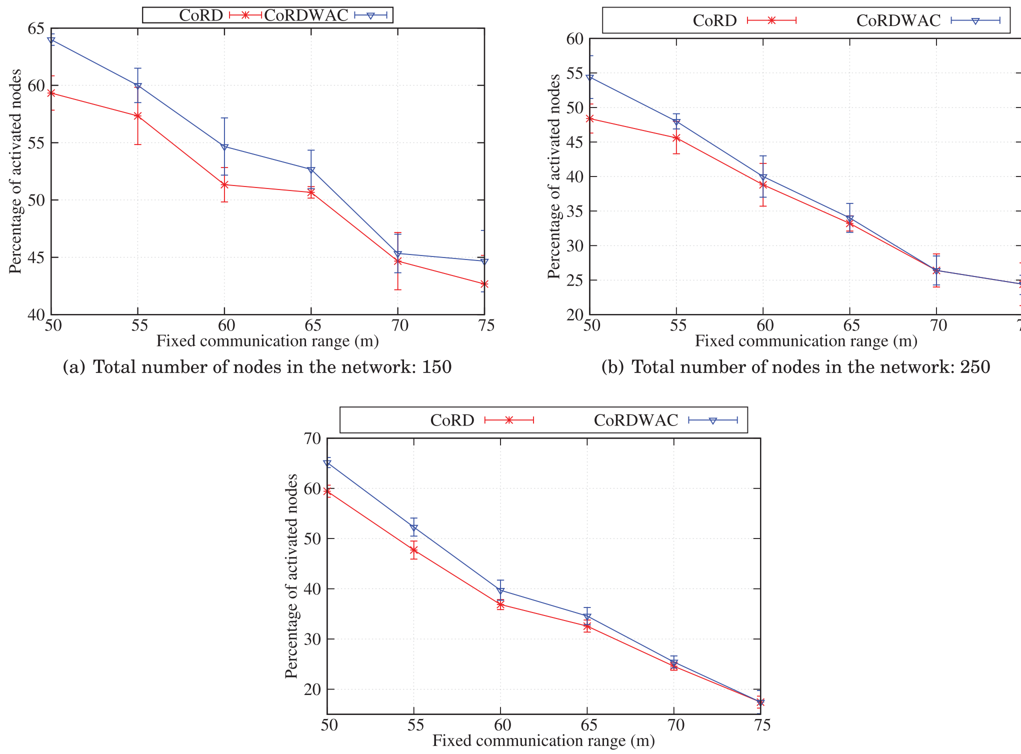


Fig. 9. Percentage of dumb nodes with fixed communication range.

At time instant t_j, due to the increased intensity of environmental effects, let the decrease in communication range be $\Delta r_c(t_j)$, such that $\Delta r_c(t_j) > \Delta r_c(t_i)$. The reduced communication radius of each node is $r_c(t_j) = r_c - \Delta r_c(t_j)$, and the minimum number of nodes $N_{min}(t_j)$ required to be activated between two nodes for re-establishment of connectivity is

$$N_{min}(t_j) = \left\lceil \frac{l}{r_c(t_j)} \right\rceil - 1. \tag{39}$$

So, at time t_j, minimum $N_{min}(t_j)$ iterations are required for establishing connectivity between X and Y nodes. From Equations (38) and (39), $N_{min}(t_j) > N_{min}(t_i)$, as $\Delta r_c(t_j) > \Delta r_c(t_i)$. Hence, it is proved that the minimum number of iterations required for re-establishing connectivity between two nodes increases (decreases) with the increase (decrease) in the intensity of environmental effects.



(a) Total number of nodes in the network: 150

(b) Total number of nodes in the network: 250

(c) Total number of nodes in the network: 350

Fig. 10. Percentage of activated nodes with fixed communication range.

THEOREM 5.5. *Connectivity between two isolated nodes cannot be re-established when the communication range of nodes becomes less than the minimum distance between any pair of nodes in the network.*

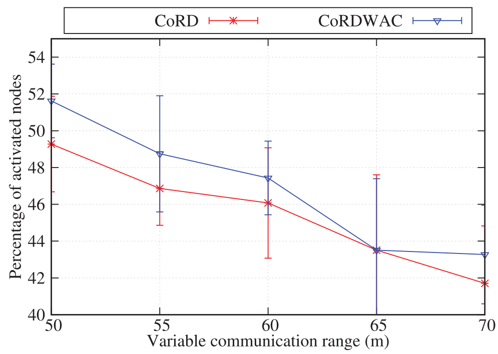
PROOF. A sensor node in a WSN behaves as dumb when its communication range decreases below its nearest active neighbor node due to the change in various environmental phenomena such as fog, rainfall, and high temperature. Node n_i has distance with its nearest neighbor node d^i_{min} as

$$d^i_{min} = min\left(r_c^{ne_i}\right) \quad \forall ne_i.$$

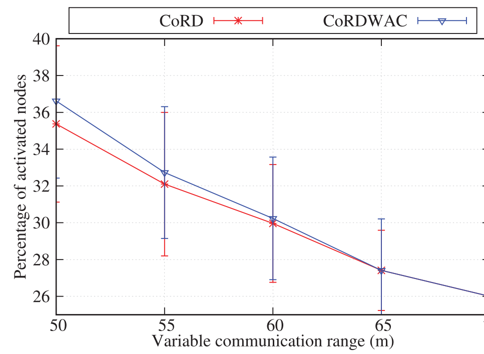
A node n_i starts to behave as dumb when its communication range $r^i_c < d^i_{min}$, whereas the minimum distance among all pairs of nodes (including the sleep and active nodes) d^{all}_{min} is as follows:

$$d^{all}_{min} = min(d^i_{min}) \quad i \in N, \text{where} N \text{ is the set of all nodes in the network.}$$

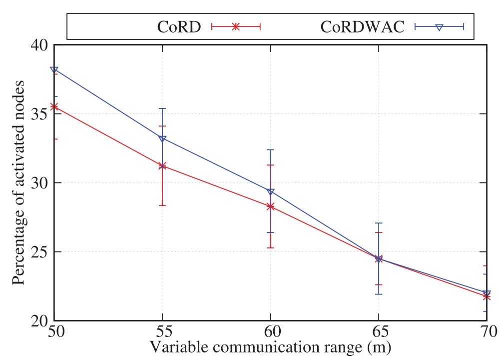
So $d^{all}_{min} \leq d^i_{min}$. When the communication range r_c decreases below d^{all}_{min}, all the nodes in the network start to behave as dumb nodes. *CoRD* re-establishes multihop connectivity between two isolated nodes by activating the intermediate sleep nodes. If the communication range of all the nodes decreases below the distance to their nearest neighbor (active and sleep) nodes, then these nodes are unable to find any neighbor node. Hence, there is no scope of activation of neighbor nodes for establishing multihop connectivity between two disconnected nodes. Therefore, connectivity re-establishment between isolated nodes is not possible. □



(a) Total number of nodes in the network: 150



(b) Total number of nodes in the network: 250



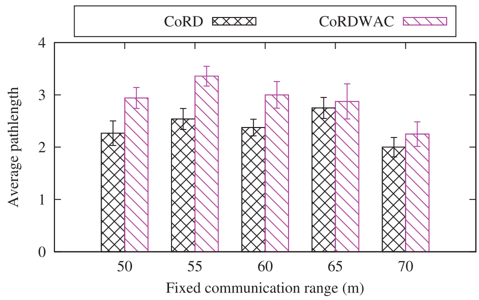
(c) Total number of nodes in the network: 350

Fig. 11. Percentage of activated nodes with variable communication range.

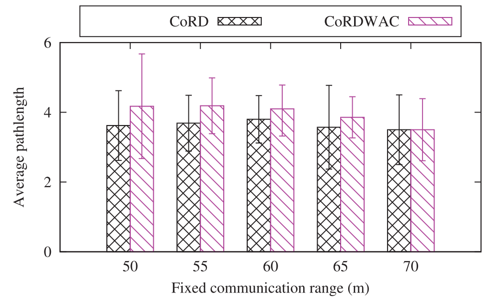
6. SIMULATION DESIGN

In this section, we evaluate the performance of the proposed algorithm, *CoRD*, which is designed to re-establish the connectivity between the START and the END node in a WSN. The concept of dumb node is new, and due to the change in network topology in their presence, the problem of re-establishing connectivity is distinct from the existing works (e.g., Dini et al. [2008] and Senel et al. [2011]). Therefore, it is difficult to compare with any existing topology control algorithm.

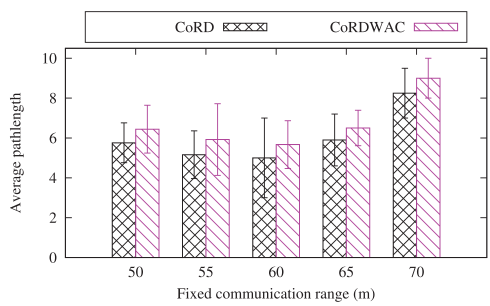
In regard to *CoRD*, by applying the constraint η on the parameter *de*, we reduce the number of nodes to be activated in the network by considering the limited energy of WSNs, as well as the network congestion. Another scheme, *Connectivity Re-establishment in the Presence of Dumb node Without Applying Constraint (CoRDWAC)*, which is similar to *CoRD*, was designed for re-establishing connectivity. The fundamental difference between *CoRD* and *CoRDWAC* is that in *CoRDWAC*, there is no constraint on the parameter *de*, as in *CoRD*, to choose its neighbor nodes. Therefore, in *CoRDWAC*, each node chooses and activates any of the neighbor nodes available within its communication range, without considering any constraint such as the constraint of distance, (*de*). So we have compared the results of *CoRD* with *CoRDWAC* and other topology management protocols, called *Learning automata-based Energy-efcient Topology Control (LECT)* [Torkestani 2013] and *Distributed Topology Control Algorithm (A1)* [Rizvi et al. 2012], with respect to the following performance parameters:



(a) Total number of nodes in the network: 150



(b) Total number of nodes in the network: 250



(c) Total number of nodes in the network: 350

Fig. 12. Average path length with fixed communication range.

—*Percentage of activated nodes*: Total number of nodes to be activated in the network per 100 nodes required. It is represented by $\mathcal{P}_A$. Mathematically,

$$\mathcal{P}_A = \frac{a}{N} \times 100, \tag{40}$$

where a is the number of activated nodes in the network and N is the total number of nodes in the network.

—*Success rate*: Ratio between the number of START nodes that can successfully establish connection with the END nodes and the total number of dumb nodes present in the network. Success rate is represented by $\mathcal{S}$. Mathematically,

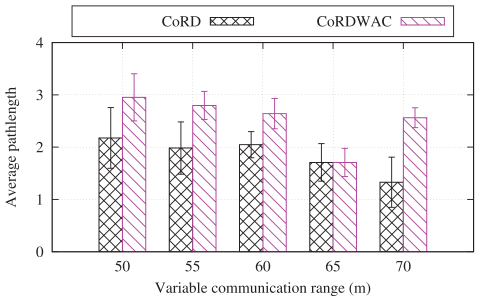
$$\mathcal{S} = \frac{N_C}{I_N}, \tag{41}$$

where N_C is the number of isolated nodes successfully established in the connectivity in the network and I_N is the total number of isolated nodes in the network.

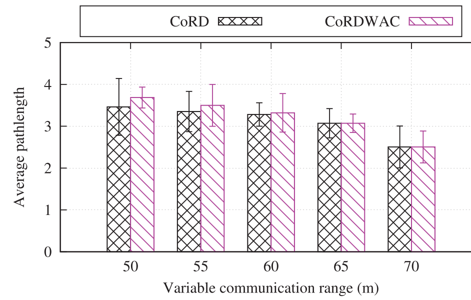
—*Average path length*: The ratio between the total number of links for establishing successful connectivity and the number of successfully connected pairs of START and END nodes. Average path length is represented by $\mathcal{A}$. Mathematically,

$$\mathcal{A} = \frac{n_a}{N_C} + 1, \tag{42}$$

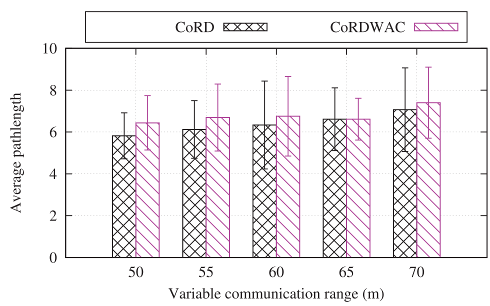
where n_a is the number of nodes activated to re-establish the connectivity of the isolated nodes with the network.



(a) Total number of nodes in the network: 150



(b) Total number of nodes in the network: 250



(c) Total number of nodes in the network: 350

Fig. 13. Average path length with variable communication range.

Table II. Simulation Parameters

Parameter	**Value**
Number of nodes	150–350
Simulation area	500m × 500m
Sensing range	50m
Communication range	50–110m
Initial energy	1.5–2.0J

—*Percentage of dumb nodes*: Total number of dumb nodes present per 100 nodes in the network. Percentage of dumb nodes is represented by $\mathcal{P}_D$. Mathematically,

$$\mathcal{P}_D = \frac{N_D}{N}, \tag{43}$$

where N_D is the number of dumb nodes present in the network.

—Energy consumption: Required energy to re-establish connectivity between the START and the END nodes in the network.

—*Overhead*: Total amount of control messages required to re-establish connectivity between all the START and END nodes.

The list of simulation parameters used is shown in Table II.

We simulate the algorithm on stationary WSNs, with 150- to 350-sensor nodes, including a sink node deployed randomly over a simulation area of 500m × 500m. Initially, a minimum set of nodes is required to be activated to cover the entire simulation area while the remaining nodes are in the sleep state. We assume that all the sensor nodes are homogeneous. Hence, they have the same characteristics of sensing and communicating. The packet size for ACT, REQ, and REP are 6, 20, and 12 bytes,

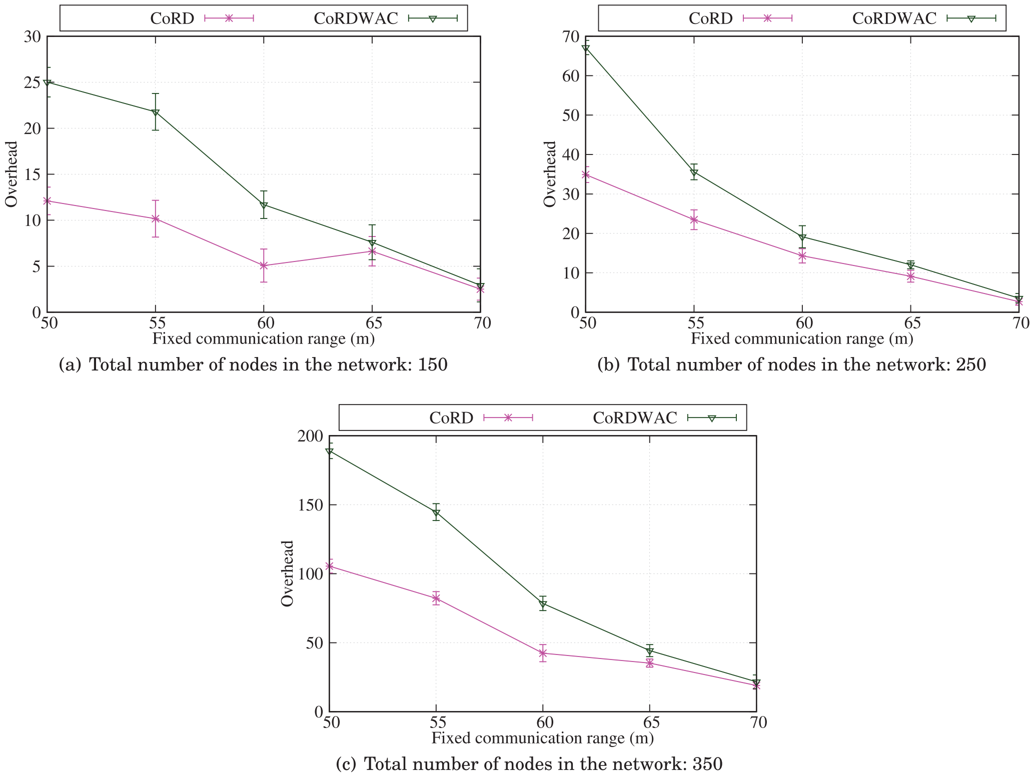


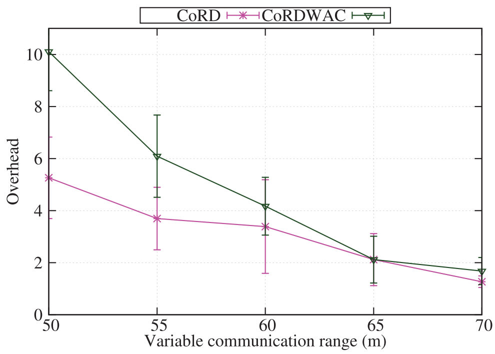
Fig. 14. Overhead with fixed communication range.

respectively, as shown in Figure 5. The transmission or reception of data takes place at 50nJ/bit. Initially, all the sensor nodes are assigned with energy level randomly drawn from a uniform distribution in the interval [1.5J, 2.0J]. Initially, we have taken the sensing range to be 50m and the communication range to be 110m. For simulating the environmental effect on sensor nodes, the communication range of these nodes was randomly varied between 50 and 110m.

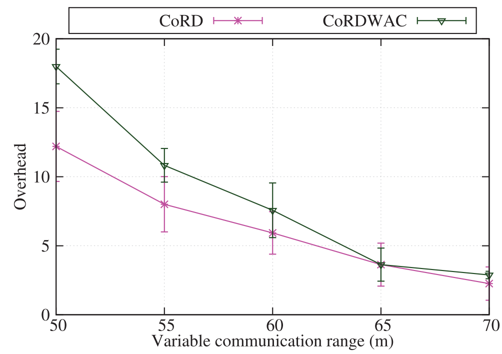
7. DISCUSSION OF RESULTS

Figure 9 depicts the percentage of dumb nodes versus the communication range. Three scenarios are shown corresponding to 150, 250, and 350 nodes in the network. The communication range of each node is increased from 50 to 70m in steps of 5m. In each of the three plots, the percentage of dumb nodes decreases with the increase in the communication range.

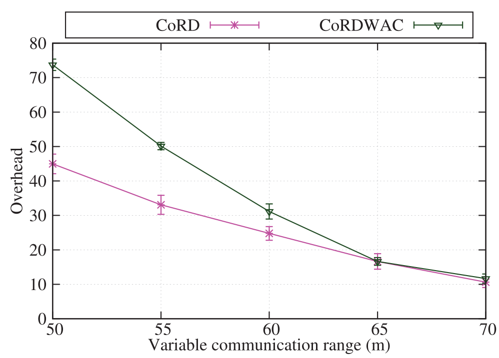
Figure 10 shows how the percentage of activated nodes using *CoRD* and *CoRDWAC* changes with the communication range in the presence of 150, 250, and 350 nodes in the network. When the communications range r_c is 50m, the percentage of activated nodes is maximum. The percentage of activated nodes decreases with the increase in communication range. The possible reason for degradation in the percentage of activated nodes is that with the increase in communication range, the percentage of dumb nodes decreases. So a smaller number of nodes are required to be activated in a higher communication range. There is a general decreasing trend of the plots for *CoRDWAC* when the communication range increases. This is similar to the plot of *CoRD*. However, the percentage of activated nodes in *CoRDWAC* is the same as



(a) Total number of nodes in the network: 150



(b) Total number of nodes in the network: 250



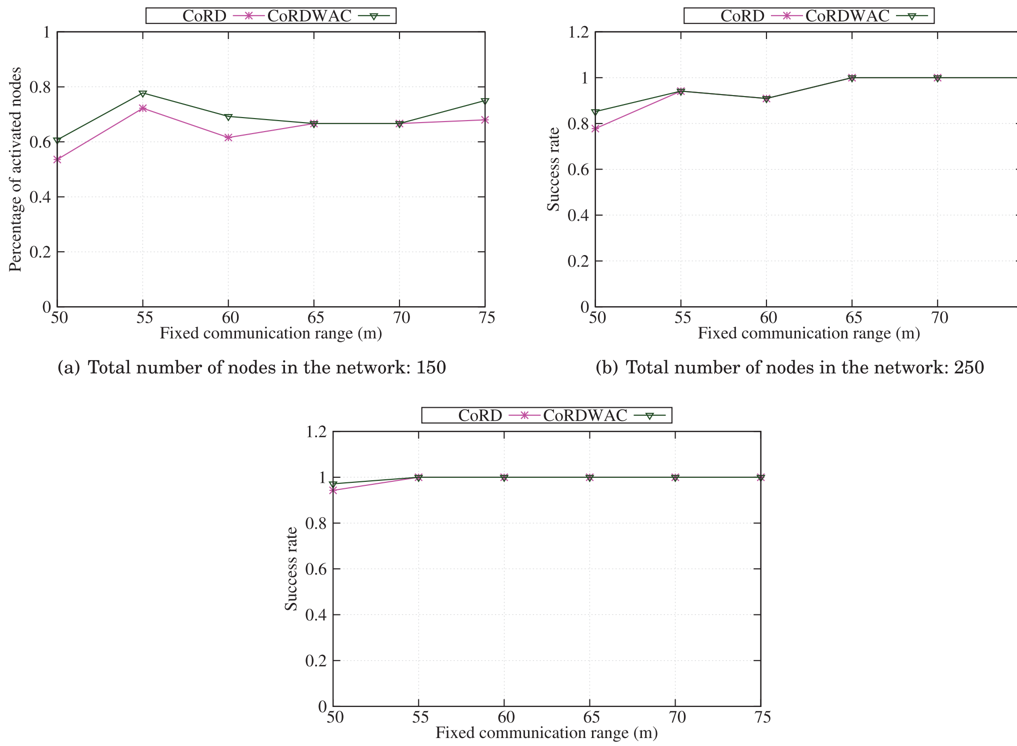
(c) Total number of nodes in the network: 350

Fig. 15. Overhead with variable communication range.

or higher than that in *CoRD* because *CoRDWAC* reconnects more dumb nodes with the network than *CoRD*. Figure 11 shows the percentage of activated nodes with varying communication range. The minimum communication range along the x-axis varies between 50 and 70m with an interval of 5m. The maximum range, however, is 110m (under ideal environmental condition) or less (in the presence of adverse environmental condition). Figures 11(a), 11(b), and 11(c) show the variations in the percentage of activated nodes by considering the total number of 150, 250, and 350 nodes, respectively. In each of the plots, we observe that there is a general decreasing trend in the plot of both *CoRD* and *CoRDWAC* with an increase in communication range. *CoRDWAC* activates more nodes as compared to *CoRD* as it re-establishes connectivity with more dumb nodes by exploring all possible paths in the network.

Figure 12 shows the variation in the average path length versus the fixed communication range along the x-axis when the range varies between 50 and 70m with an interval of 5m. We observe that there is random variation of the path length due to the random topology of the network. The required path length for re-establishing connectivity between a pair of isolated nodes is largely dependent on the deployment of the nodes in the network. So the variation in path length observed in each of the plots is random.

In Figure 13, the plots are shown for the average path length versus the variable communication range, which is considered to be the same as that mentioned for the experiments corresponding to Figure 11. In this case as well, we observe the random variation of path length for re-establishing the connectivity between a pair of disconnected nodes for reasons similar to the ones mentioned in Figure 12.



(a) Total number of nodes in the network: 150

(b) Total number of nodes in the network: 250

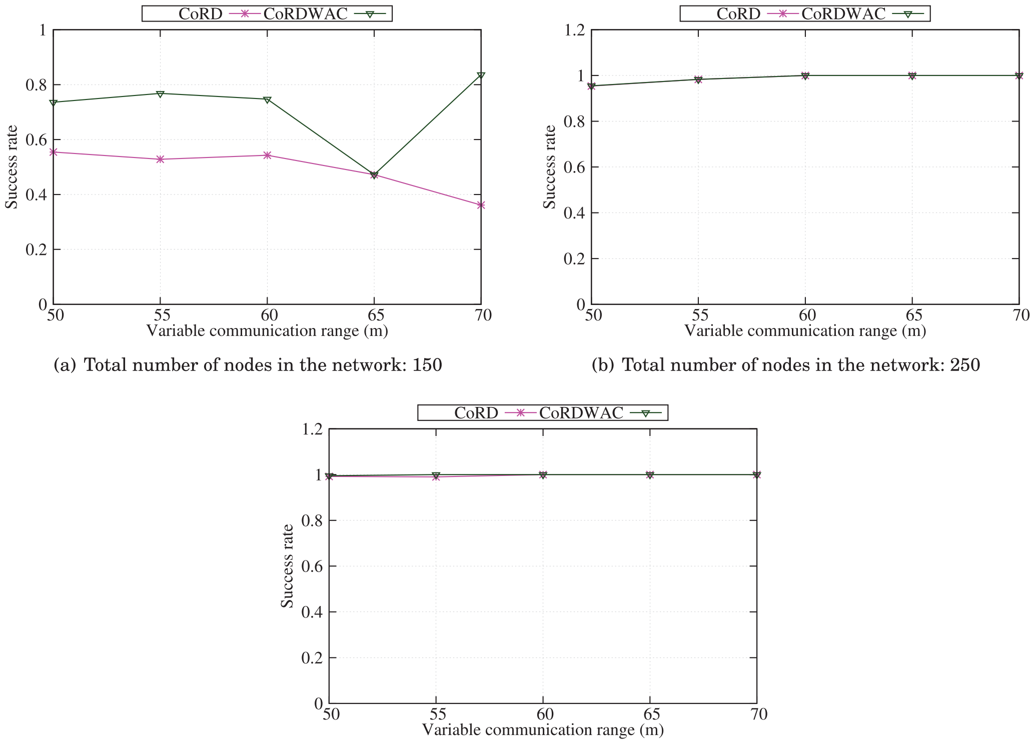
(c) Total number of nodes in the network: 350

Fig. 16. Success rate with fixed communication range.

The overhead of the network for both the schemes is shown in Figure 14. In the figure, three different scenarios for overhead are shown by considering 150, 250, and 350 nodes in the network. With the increasing total number of nodes in the network, the overhead increases. The possible reason for these observations is that with an increasing number of nodes in the network, the possibility of the presence of a higher number of intermediate nodes between a pair of source-destination nodes is more. As a result, these nodes transmit and receive the ACT, REQ, and REP messages. In each of the plots in Figures 14(a), 14(b), and 14(c), there is a gradual degradation in overhead with increasing communication range. The possibility of the presence of more nodes increases with an increase in the communication range. Therefore, the overhead decreases with the increase in the communication range.

In Figure 15, the variation of overhead versus variable communication range is shown. For the same reason as mentioned in the case of Figure 14, these plots have the similar decreasing trend with the increase in the communication range.

Figure 16 depicts the variations in success rate with increasing communication range from 50 to 75m in steps of 5m. In each of the plots in Figures 16(a), 16(b), and 16(c), there is a general increasing trend in the success rate with the increase in the communication range of nodes. When the total number of nodes in the network is 150, the success rate is below unity, because there does not exist a sufficient number of intermediate nodes to re-establish connectivity for all the dumb nodes. However, in the rest of the cases, the success rate attained is unity. The success rate with variable communication range is shown in Figure 17. In Figures 10 through 17, the performances of *CoRD* and *CoRDWAC* are shown. In *CoRD*, there is a constraint to choose neighbor nodes



(a) Total number of nodes in the network: 150

(b) Total number of nodes in the network: 250

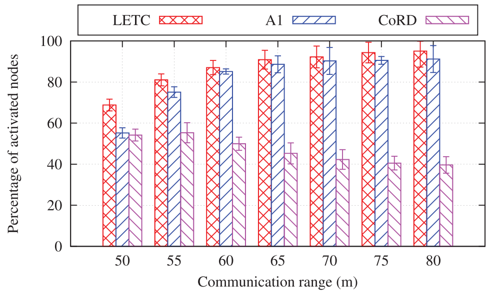
(c) Total number of nodes in the network: 350

Fig. 17. Success rate with variable communication range.

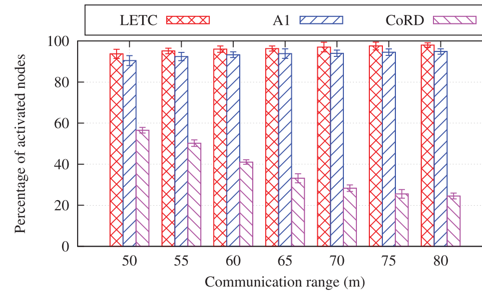
for re-establishing connectivity between the START and the END nodes, whereas in *CoRDWAC*, there is no such constraint. Therefore, in Figures 16 and 17, *CoRDWAC* exhibits better performance with respect to only the success rate, but there is inferior performance with respect to the percentage of activated nodes, average path length, and overhead.

In addition to the performance results for *CoRD* and *CoRDWAC*, we have shown the plots comparing another two topology control algorithms, *LETC* [Torkestani 2013] and *A*1 [Rizvi et al. 2012], in Figures 18 through 20. In *LETC* and *A*1, topology is maintained by forming *Connected Dominating Sets* (CDSs) and the nodes belong to this set. We have implemented *LETC* and *A*1 in our experimental setting along with *CoRD*. The percentage of activated nodes in *LETC*, *A*1, and *CoRD* is shown in Figure 18. The percentage of nodes activated increases with increasing communication range in case of *LETC* and *A*1, whereas in case of *CoRD*, it decreases. With the increase in communication range, the possibility of the presence of a higher number of nodes within the communication range also increases. Therefore, in *LETC* and *A*1, more nodes get included in CDS with the increase in communication range. However, in case of *CoRD*, initially, a minimum set of nodes is activated to maintain topology. After dumb nodes get created, a minimum subset of additional nodes is activated to re-establish connectivity. As the increase in communication range decreases the number of dumb nodes, the number of nodes activated also decreases in the communication range.

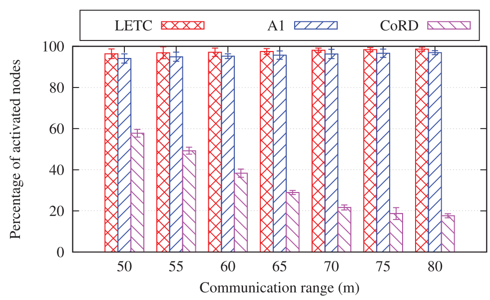
The overheads in *LETC*, *A*1, and *CoRD* are shown in Figure 19. As the number of nodes activated increases with increasing communication range, the number of control messages transferred in the network also increases. As the overhead is dependent on



(a) Total number of nodes in the network: 150

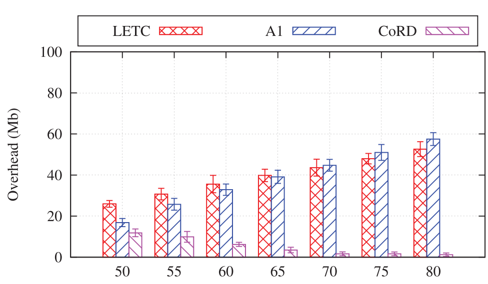


(b) Total number of nodes in the network: 250

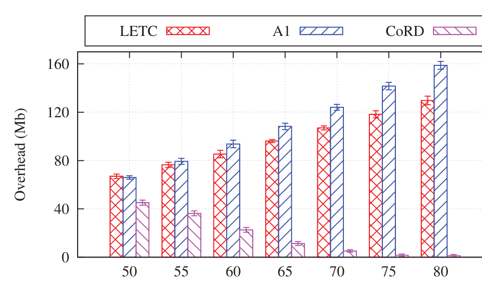


(c) Total number of nodes in the network: 350

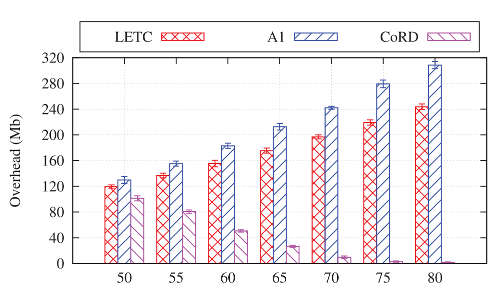
Fig. 18. Percentage of activated nodes in LETC, A1, and CoRD.



(a) Total number of nodes in the network: 150

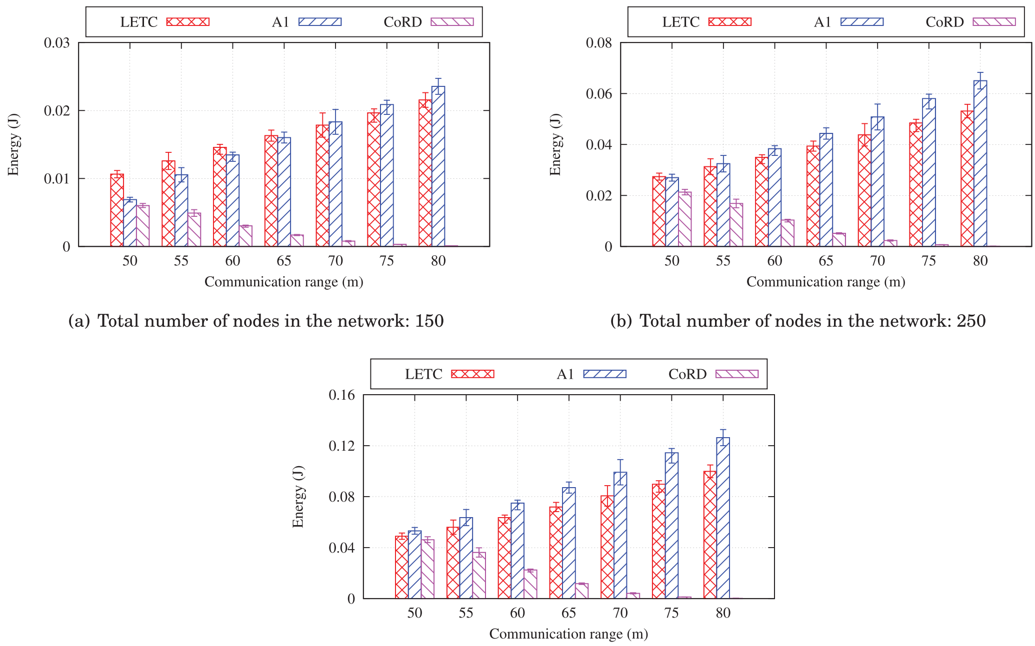


(b) Total number of nodes in the network: 250



(c) Total number of nodes in the network: 350

Fig. 19. Overhead of LETC, A1, and CoRD.



(a) Total number of nodes in the network: 150

(b) Total number of nodes in the network: 250

(c) Total number of nodes in the network: 350

Fig. 20. Energy consumption of LETC, A1, and CoRD.

the control message transfer in the network, it increases with the increase in communication range in case of *LETC* and *A*1. However, in case of *CoRD*, it is observed that there is less overhead with the increase in communication range due to the decrease in the number of activated nodes, with the increase in the communication range.

The energy consumption of the network is also an important parameter in WSNs. The number of nodes activated and the overhead increase with increasing communication range in case of *LETC* and *A*1, but in case of *CoRD*, it is the reverse. The energy consumption in the network is dependent upon both the overhead and the number of nodes activated in the network. Therefore, as seen in Figure 20, there is an increasing trend of energy consumption with the increase in communication range in case of *LETC* and *A*1 and a decreasing trend in the case of *CoRD*.

8. CONCLUSION

In this work, we have considered the problem of topology control in sensor networks with temporary connection impairments due to the occurrence of adverse environmental conditions. As the dumb nodes get isolated from the network, it is a challenge to get information sensed by these nodes to the rest of the network. The lack of connectivity among nodes due to the occurrence of dumb behavior in WSNs is distinct from the traditional existing problem of loss of connectivity arising due to the failure of nodes. To re-establish connectivity and maintain self-adaptivity of nodes in WSNs, we propose a price-based scheme for topology control. Simulation-based experiments show that the proposed scheme yields better performance with respect to the number of nodes activated, overhead, and energy consumption than the existing topology management protocols, LETC and A1.

In the future, we plan to extend our work with respect to re-establishment of connectivity in the presence of heterogeneous sensor nodes, detection of dumb nodes using a game-theoretic approach, and transfer of sensed information from a dumb node to a sink node by data mules. Game theory embeds the dynamic formulation and incorporation of strategies. As already discussed, dumb behavior is temporary and dynamic. Therefore, an approach using mathematical optimization is appropriate, as every time the network topology changes, it would be required to perform all the steps of the optimization algorithm at each iteration. Intuitively, this is computationally intensive and time consuming as well. Using the game-theoretic approach, we can avoid these limitations.

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