ORCID: Opportunistic Re-Connectivity for Network Management in the Presence of Dumb Nodes in Wireless Sensor Networks

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***Abstract*—In this work, we propose a scheme named *Opportunistic Re-Connectivity in the Presence of Dumb Nodes* (*ORCID*), which is adaptive and can be used for the formation of a network, opportunistically, while managing network connectivity, in a Wireless Sensor Network (WSN). A "dumb" node can sense its surroundings but is unable to transmit data to other nodes at a particular time instant due to its shrinkage in communication range in the presence of adverse environmental effects such as temperature, rainfall, and fog. The nature of connectivity re-establishment problem witnessed in these scenarios differs from the normal ones, thereby making this problem interesting and distinctive. In ORCID, we use a *Single-Leader-Multiple-Followers Stackelberg game*, where a dumb node acts as the *leader* and the other nodes within the adjusted communication range of the dumb node act as *followers*. The leaders try to establish connectivity with any of the activated nodes in the network by optimally adjusting their power levels using the proposed network management scheme so that the communication range is also adjusted. On the other hand, the followers try to be connected with the leaders by maximizing their utility.**

***Index Terms*—Dumb Node, Dynamic Shrinkage, Connectivity, Game Theory, Sensor Network.**

I. Introduction

With the technological advancement, the use of WSN has increased in various fields of applications such as wildlife monitoring, target tracking, health care, and surveillance [1], [2]. A WSN consists of sensor nodes that sense some physical phenomena from the environment, and transmit the sensed data to a centralized unit or sink through single or multi-hop connectivity [3]. Thus, for network management, each of the sensor nodes needs to participate actively to forward the data received from the other sensor nodes. The sensor nodes have limited battery power and are, thus, resource-constrained. Consequently, WSNs are prone to attacks, misbehaviors, and faults. To handle such problems in these networks, different approaches are proposed in the existing literature [4]. In this work, we consider a newly explored concept of misbehavior in adaptive WSNs – the "dumb" behavior [5], [6]. Such behavior of a node occurs in the presence of adverse environmental conditions such as an increase/decrease in temperature, rainfall, and fog. Eventually, the communication range of a node reduces and it is unable to communicate with any other node temporarily. However, such a node continues to sense its surroundings.

"Dumb" behavior is temporary in nature — in the presence of adverse environmental conditions, the sensor nodes, which behave as "dumb", are unable to transmit data packets to any of the other nodes in the network, whereas with the resumption of favorable conditions, the same nodes can resume transmission. The occurrence of dumb behavior in a node causes disconnectivity in the network. To maintain connectivity in an energy-constrained WSN, activating all the sensor nodes in the network continuously is not a desirable solution for efficient network management. In such a scenario, data gathering from a dumb node can be achieved with the help of mobile robots, called data mules [7]. When the intensity of environmental effects is high, then there may be a huge number of nodes that get isolated from the network. Consequently, gathering data from each of the isolated nodes with the help of a data mule may not be suitable for an energy-constrained WSN. Another possible solution to re-establish connectivity among the nodes (where the sensor nodes can adjust their communication ranges) for network management in a WSN is by increasing their communication ranges. However, increasing the communication range may cause rapid depletion of energy levels of sensor nodes, which leads to a reduction in network lifetime. Therefore, increasing the power levels of all the sensor nodes at the same time is not a feasible solution. Consequently, it is challenging to maintain connectivity in the adaptive network with an optimum number of nodes. This forms the main *motivation* for this work.

It is pertinent to clarify at this juncture that the existence of dumb behavior has already been studied in the existing literature [8], [9]. This work contributes to finding a Stackelberg game-theoretic solution to the graph abstracted phantom of the connectivity problem due to the existence of dumb nodes.

In this paper, we propose a game-theoretic scheme for the formation of a connected WSN for network management in the presence of dumb nodes. The proposed scheme, ORCID, opportunistically activates the sleep sensor nodes for re-establishing connectivity between the dumb and the other nodes in the network, for maintaining the network connectivity. In the ORCID, we use the *Single-Leader-Multiple-*

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Followers Stackelberg game. The overall *contributions* of the paper are summarized below:

1) We formulate a Single-Leader-Multiple-Followers game to re-establish connectivity between the dumb and the other nodes in a network. In this game, the dumb nodes are leaders and the sleep nodes within the adjusted communication range of a dumb node are followers.

2) The proposed scheme, *ORCID*, adopts an on-demand node activation approach to form a connected network. In this scheme, a dumb node adjusts its power level to increase the communication range, opportunistically, for efficient network management.

3) The proposed scheme is theoretically characterized and its proof of equilibrium is discussed.

It is congruous to highlight that the contributions of this work are positioning the existence of dumb nodes, which is already established in the literature [9], [10]. This specific contribution focuses on re-establishing connectivity between nodes in the presence of dumb nodes in a WSN. The nature of the connectivity problem occurring in this scenario differs from the similar problem studied in literature [11], [12]. Therefore, a fine articulated solution is built for this problem.

II. Related Work

In this section, we discuss the relevant existing literature as they relate to our work. Berman *et al.* [11] proposed work for placing sensor nodes within a WSN to maintain connectivity. The authors considered such type of sensor nodes that have the provision to adjust the communication range. The authors introduced a strong k-connectedness property that reduces transmission power. Younis *et al.* [12] proposed a localized algorithm, named RIM, for restoring inter-node connectivity for mobile WSNs. In RIM, due to the mobility of nodes, there is a loss in connectivity among nodes. Senel *et al.* [13] proposed a technique for the placement of relay nodes to join two disjoint segments of a network. The authors used a bio-inspired approach named, Spider Web, hin order to maintain connectivity. eIn order to replace the failed node in WSNs, a node placement algorithm is proposed by Misra *et al.* [14]. The authors used the *Markov Decision Process* (MDP) for measuring the long-run cost of the network, which helps to place the nodes in the network optimally. Barooah *et al.* [15] proposed a cut detection algorithm when node failures in the network occur. Node failure and mobility are permanent phenomena in WSNs. However, in the case of a dumb node, it works normally in the presence of favorable environmental conditions. Thus, the permanent placement of a relay node, to establish connectivity between a dumb node and other nodes in the network, results in redundant power consumption.

Misra *et al.* identified a new type of misbehavior, termed as "dumb behavior" [6]. The dumb nodes can sense their surroundings but are unable to communicate with any other node temporarily in the presence of adverse environmental conditions such as temperature, rainfall, and fog. Roy *et al.* [16] proposed a scheme for the detection of dumb nodes in WSNs. A pricing-based connectivity algorithm, CoRD, is proposed by Roy *et al.* [9]. CoRD is specially designed for WSNs, in which the communication range of sensor nodes are static. On the other hand, Cacciapuoti *et al.* [17] explored opportunistic routing algorithms for ad-hoc networks in the presence of opportunistic candidates with static transmission power, by considering the varying channel parameters. Here, the opportunistic candidates can be considered as dumb nodes.

Synthesis We, thus, infer that there exist numerous pieces of literature on misbehaviors and their detection in WSN. The study by Misra *et al.* [8] revealed that the existence of dumb nodes in a network degrades the network performance substantially. Thus, connectivity in the network in the presence of dumb nodes is an essential network management task to maintain normal operations of the network. On the other hand, many connectivity related works exist in the WSN literature. However, specifically, the problem of connectivity establishment in WSNs in the presence of dumb nodes is unexplored. Moreover, the communication range of sensor nodes considered in the existing literature is static. However, in the realistic scenario, the communication range of a sensor node may be adjustable for efficient network management.

III. System Model

Dumb Behavior of a node: As studied in the existing literature on dumb nodes (e.g., [9], [10]), when a node behaves as dumb, it can sense its surroundings, but is unable to communicate with any other node at a certain time instant, in the presence of adverse environmental condition such as temperature, rainfall, and fog. At a later instant of time, however, with the resumption of favorable environmental conditions, the node resumes its normal operation, i.e., it can sense and communicate with other nodes [5], [6], [8]. As the environmental condition is temporal, the dumb behavior of a node is not permanent. The mathematical definition of dumb behavior, Ψ_x, is as follows:

$$\Psi_x = \begin{cases} 1, & \{(0 \leq r_{xc}(t_j) < d_{min} \leq r_{xc}(t_i) \leq R)\}, \quad t_i \neq t_j \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where d_{min} is the minimum distance between a node x, and its nearest active neighbor. The communication ranges of x at two time instants is represented as $r_{xc}(t_i)$ and $r_{xc}(t_j)$, respectively. R represents the specified maximum possible communication range of sensor node x.

The assumptions for ORCID are listed as follows:

1) The sensor nodes are heterogeneous, i.e., each node has provision to adjust its power level[1] to increase or decrease the communication range.

2) We consider a random uniform distribution of stationary sensor nodes over a 2-dimensional terrain in order to ensure generality in topology.

3) Each sensor node has a unique id and is GPS-enabled.

Problem Scenario: Let us assume that a set of sensor nodes $\mathcal{N}$ is deployed on a terrain. Among these nodes, few are activated in such a way that the terrain is completely covered. The set of activated nodes is denoted by N_A, where $N_A \subseteq \mathcal{N}$.

[1]Practically, the adjustment power level is feasible with the help of micro-controller programming. Thereby, the power level of a node can be increased/decreased step-wise.

The connected network is formed using the set of links L_A among the activated nodes. The network is represented as a graph $G(N_A, L_A)$. P is the set of available power levels of a node, where $\rho_j \in P$. The minimum and maximum power levels of a node are denoted by ρ_m and ρ_M, respectively. We have, $\rho_m = min(P)$, and $\rho_M = max(P)$. We consider that at time t, node i has an adjusted communication range $r_{iw}(t) \in R_i(t)$, where $R_i(t)$ is the set of available communication ranges of node i and $1 \leq w \leq |R_i(t)|$. Each power level of a node yields the corresponding communication range value. In other words, the topology of the network changes with the change in power levels of the nodes. Initially, we consider that the communication range of node i is not affected at time t_x. However, in the presence of adverse environmental effects, the communication range decreases at time t_y. Additionally, we consider that the every $r_{ij}(t_y) \in R_i(t_y)$ must at least have a pre-image of power level in set P. Therefore, we argue that $R_i(t_y) \subset R_i(t_x)$. The neighbor list of node i is represented by a set $(nbr_i^{\rho_m})$. Any node k is said to be neighbor of node i if $D_{ik} < r_{ij}(\cdot)$, where D_{ik} is the distance between the nodes i and k and r_{ij} is the communication range of node i.

We consider that in the presence of adverse environmental effects, few of the activated nodes become dumb. Therefore, these nodes are unable to communicate with the other nodes. These dumb nodes try to reconnect with one of the activated nodes by adjusting their power levels or by activating the intermediate nodes, which are in the sleep state, between any activated node and itself.

IV. Opportunistic Re-connectivity in the Presence of Dumb Nodes (ORCID)

A. *Single-Leader-Multiple-Followers Stackelberg Game*

In a Stackelberg game, which is primarily studied in Micro-Economics, the players are of two types – *leaders* and *followers*. In this game, each of the leaders as well as the followers uses some strategy. In this work, we use a Single-Leader-Multiple-Followers Stackelberg game in order to re-establish connectivity among nodes by adjusting the power levels of the dumb nodes present in the network, opportunistically.

The Justification for Use: In the presence of adverse environmental conditions, the communication range of a sensor node reduces, which renders it as dumb. In such a scenario, the sink (a centralized unit) or any other node is unable to communicate with dumb nodes. Each dumb node adjusts its power level to get connected with any activated node. In an energy-constrained WSN, it is inconvenient to increase power up to the maximum level. However, it is not certain that with such an increase, a node can reach its maximum communication range. Thus, this problem invokes an issue of optimization between the increase in the power level of a dumb node and the number of activated nodes connected with the increase in the power level. Therefore, initially, a dumb node acts as a *Leader* and the neighbor nodes present in the communication range (that is achieved by adjusting the power level) of a dumb node, act as *Followers*. The leader has an intention to re-establish connectivity with an already activated node, by activating the nodes which are in the current communication range. If there is an absence of a sleep node within the current communication range of the leader, then it increases its power level for increasing its communication range, to reconnect with the previously activated node. On the other hand, the follower follows the leader in such a way that it tries to maximize the total residual energy of the nodes to which it is connected.

B. *Single-Leader-Multiple-Followers Stackelberg Game Formation for Opportunistic Re-connectivity*

We model the problem of forming a connected network as a Single-Leader-Multiple-Followers Stackelberg game. In this game, initially, a dumb node acts as a leader and it uses the strategy to re-connect with an activated node by adjusting its transmission power level. Similarly, all the nodes which are neighbors of the dumb node for a particular communication range act as followers.

The strategy of the follower is to maximize the total residual energy of the connected neighbor nodes. This scenario is referred to as an oligopolistic market, where a leader is the *Stackelberg* firm, and the followers are the *Cournot* firms.

Algorithm 1 ORCID: For each Leader

Inputs: $|\mathcal{N}|, \rho_M, \rho_i, \delta, \delta_1$, and $\zeta \in \mathbb{Z}^+$
Outputs: ρ^i_{adj}, n
Begin
  At $t = 0$,
  - $\rho^i_{adj}(t = 0) = \rho_i$
  - $\mathcal{N}^L_{adj}(t = 0) = \{\emptyset\}$
  - $\delta = \rho_M - \rho_i$

  Calculate $\mathcal{U}_L(t = 0)$ using Equation (4)
  $t \leftarrow t + 1$
  $\rho^i_{adj}(t) = \rho^i_{adj}(t - 1) + \delta$
  Do
    Broadcast a `Hello` Message
    Calculate $\mathcal{N}^L_{adj}(t)$ based on the reply messages
    If $\mathcal{N}^L_{adj}(t = 1) = \{\emptyset\}$
      Goes into sleep mode and remains dumb
      Exit
    EndIf
    Calculate $\mathcal{U}_L(t)$ using Equation (4)
    $\delta_1 = \zeta\Delta_i(t)$ ▷ $\Delta_i(t)$[2] `depends on the network topology`
    $\rho^i_{adj}(t) = \rho^i_{adj}(t - 1) - \delta_1$ ▷ δ_1 `is step size factor`
    $t \leftarrow t + 1$
  While ($\mathcal{U}_L(t) > \mathcal{U}_L(t - 1)$ and $\rho^i_{adj}(t) > \rho_i$)
  If $\mathcal{N}^L_{adj}(t) \neq \{\emptyset\}$
    Compare the utility value of the follower nodes
    Activate a follower node n having highest utility value
  EndIf
End

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1) Utility Function for Leader: In our scenario, the leader adjusts its transmission power to get connected with an already activated node. A leader finally adjusts the transmission power by applying the strategy (using the utility function of the leader, $\mathcal{U}_L$). Thereafter, the leader broadcasts an *activation* message `ACT`. The sleep nodes within the communication range (achieved by the current transmission power) receives an `ACT`. A follower may receive multiple `ACT`s from multiple dumb nodes. The utility function of the leader consists of two components – *revenue* and *cost*. The algorithm for the utility of a leader is depicted in Algorithm 1. To decide the optimal transmission power, each dumb node follows the game theory-based scheme, ORCID, while executing Algorithm 1. The time

[2] Refer to supplementary file.

complexity of Algorithm 1 is $O(|\mathcal{N}|)$. On the other hand, the messages transmitted by each node in Algorithm 1 is $O(|P|)$. We consider revenue function, $\mathcal{R}_L(\cdot)$, of the leader to follow the following constraints:

(i) With the increase in the number of available nodes within the communication range, $\mathcal{R}_L(\cdot)$ increases, where $\mathcal{R}_L(\cdot) > 0$.

(ii) $\mathcal{R}_L(\cdot)$ reaches its optimal point by maximizing its communication range. We consider that each node can cover a maximum $|\mathcal{N}|$ number of nodes, i.e., total available nodes.

The revenue $((\mathcal{R}_L(\cdot)))$ function is defined as the ratio between the number of nodes available within the communication range that is achieved after adjusting the transmission power level, $|\mathcal{N}^L_{adj}|$, and the total number of nodes that are available in the network, $|\mathcal{N}|$. Mathematically,

$$\mathcal{R}_L(\cdot) = \left(|\mathcal{N}^L_{adj}|/|\mathcal{N}|\right) \tag{2}$$

Similarly, we consider cost function of leader to follow the following constraints:

(i) With the increase in the transmission level, cost, $(\mathcal{C}(\cdot))$ increases.

(ii) The cost function achieves its maximum value when the transmission power level becomes maximum.

The cost function $(\mathcal{C}(\cdot))$ of the game is defined as the ratio between the adjusted power level, ρ_{adj}, and the maximum power level, ρ_M, of a node. Mathematically,

$$\mathcal{C}_L(\cdot) = \left(\frac{\rho^L_{adj}}{\rho_M}\right) \tag{3}$$

***Definition* 1.** *The utility function$(\mathcal{U}_L(\cdot))$ of the leader is defined as the difference between the revenue $\mathcal{R}(\cdot)$, and the cost $\mathcal{C}(\cdot)$. Mathematically,*

$$\mathcal{U}_L(\cdot) = \mathcal{R}_L(\cdot) - \mathcal{C}_L(\cdot) \tag{4}$$

Algorithm 2 ORCID: For each Follower

Inputs: $RE_x, \rho_j, \delta, \delta_2, \rho_M$, and $\zeta \in \mathbb{Z}^+$
Outputs: $\mathcal{U}_F(t), \rho^j_{adj}(\cdot)$
Begin
  $\delta = \rho_M - \rho_j$
  At $t = 0$, $\rho^j_{adj}(t = 0) = \rho_j$
    Receive `Hello` message from a leader
    Calculate number of neighbor nodes $f_N(t = 0)$
    Calculate $\mathcal{U}_F(t = 0)$ using Equation (5)
    $t \leftarrow t + 1$
    $\rho^j_{adj}(t) = \rho^j_{adj}(t-1) + \delta$
  Do
    Broadcast a `Hello` Message
    Calculate $f_N(t)$ based on the reply messages
    Calculate $\mathcal{U}_F(t)$ using Equation (5)
    $\delta_2 = \zeta\Delta_j(t)$ ▷ $\Delta_j(t)$[3] depends on the network topology
    $\rho^j_{adj}(t) = \rho^j_{adj}(t-1) - \delta_2$ ▷ δ_2 is step size factor
    $t \leftarrow t + 1$
  While$(\mathcal{U}_F(t) > \mathcal{U}_F(t-1)$ and $\rho^j_{adj}(t) > \rho_j)$
    Send a reply packet to the leader with its utility value, $\mathcal{U}_F(t)$
End

2) *Utility Function for Follower:* In the proposed scheme, the leader adjusts its transmission power in order to increase its communication range. The leader broadcasts an activation message `ACT` to activate the sleep nodes within the communication range. On receiving an `ACT`, all the sleep nodes within the current communication range of the leader are activated and act as followers. Each follower again broadcasts a `HELLO` message to learn the residual energy from its neighbor nodes. Each follower calculates the utility using Equation (5). The algorithm of a follower is depicted in Algorithm 2. The time complexity of Algorithm 2 is $O(|\mathcal{N}|)$. On the other hand, the messages transmitted by each node in Algorithm 2 is $O(|P|)$. Therefore, we have:

$$\mathcal{U}_F(\cdot) = \sum_{v=1}^{f_N} RE_v \tag{5}$$

where f_N is the number of neighbor nodes of a follower F and RE_v is the residual energy of neighbor node v. Finally, based on the payoff value of the follower, the leader chooses one of the followers to remain activated in order to ensure the connectivity of the network.

V. Theoretical Analysis

In this section, we evaluate the existence of Stackelberg equilibrium for ORCID in Theorem 1. Additionally, we prove the uniqueness of the equilibrium in Proposition 1.

Theorem 1. *Given the behavior of the followers, there exists a Stackelberg equilibrium for the proposed scheme, ORCID, such that-*

$$\mathcal{U}(\rho^{L^*}_{adj}, |\mathcal{N}^{L*}_{adj}|) \geq \mathcal{U}(\rho^L_{adj}, |{\mathcal{N}^L_{adj}}^*|) \tag{6}$$

where ρ_{adj} is the adjusted transmission power level of leader, ρ^*_{adj} is the optimum value of ρ_{adj}, and $(\rho_{adj}, \rho^*_{adj}) \leq \rho_M$. Moreover, $|{\mathcal{N}^L_{adj}}^*|$ denotes the optimal number of neighbor nodes of the leader.

Proof. In order to find the Stackelberg equilibrium of the proposed scheme, ORCID, we assume that the leader knows the behavior of the follower – *selfish* and *rational*.

The selfish behavior of the followers signifies that the transmission power level of the followers, i.e., $P^{follower}$ will be lower than that of the maximum transmission power level of a node, i.e., ρ_M. Mathematically:

$$0 \leq P^{follower} < \rho_M \tag{7}$$

Hence, the leader chooses the transmission range of zero, to increase its lifetime. In this case, the leader chooses to behave *selfishly*, as the followers are selfish. On the other hand, if the follower behaves rationally, it contributes its maximum transmission power level, ρ_M, in order to have a connected network. Mathematically:

$$P^{follower} = \rho_M \tag{8}$$

Therefore, in order to have the proof of existence of Stackelberg equilibrium, we prove that there exists a variational inequality (VI) solution. By using the Lagrangian multiplier, we have the Karush-Kuhn-Tucker (KKT) conditions as follows:

[3]Refer to supplementary file

$$\nabla \mathcal{U}(\cdot) - \nabla \lambda(\rho_M - \rho_{adj}^L) = 0 \tag{9}$$
$$\lambda(\rho_M - \rho_{adj}^L) = 0 \tag{10}$$
$$\lambda \geq 0 \tag{11}$$

where λ is the Lagrangian multiplier. Now, if $\lambda > 0$, we have:

$$\rho_{adj}^L = \rho_M \tag{12}$$

On the other hand, if we have $\lambda = 0$,

$$\rho_M - \rho_{adj}^L \neq 0 \tag{13}$$

Therefore, $\rho_M \neq \rho_{adj}^L$. We know, $\rho_M \geq \rho_{adj}^L$.

We observe that there are Stackelberg solutions in both cases. Hence, we conclude that there exists a Stackelberg solution for the proposed scheme, ORCID. □

***Proposition* 1.** *The Stackelberg equilibrium of the proposed scheme, ORCID, is unique. Additionally, if the nodes are deployed, while following the polynomial distribution $|\mathcal{N}_{adj}^L| = \Phi {\rho_{adj}^L}^x$, where Φ and x are constants, the optimum transmission power chosen by the leader, ρ_{adj}^L, is as follows:*

$$\rho_{adj}^L = \sqrt[x-1]{\frac{|\mathcal{N}|}{2\Phi\rho_M}} \tag{14}$$

Theorem 2. *Given the nodes are distributed in a uniform random fashion $f(x, y)$, each leader activates $|\mathcal{N}^L|$ number of nodes using ORCID, where $|\mathcal{N}^L| = \frac{N}{K_1}[K_2 + \sum_{n=1}^{N\frac{K_2}{K_1}} K_3]$, $K_1 = \oiint_{A^2} f(x, y)dxdy$, $K_2 = \oiint_{R^2} f(x_L, y_L)dxdy$, and $K_3 = \oiint f(x_n, y_n)dxdy$.*

Proof. Suppose L activates $|\mathcal{N}_{adj}^L|$ number of nodes. Considering that each follower node sets its transmission power at maximum, i.e., ρ_M.

Considering that the nodes are uniformly distributed over the terrain, we get the probability density function K_2

Hence, we get: $R^2, \widetilde{R}^2 \subseteq A^2$. Therefore,

$$N_{adj}^L = \frac{K_2}{K_1} N \tag{15}$$

where $R^2 = \int_{\theta=0}^{2\pi} \int_{r=0}^{\rho_{adj}^L} r dr d\theta$ and $\widetilde{R}^2 = \int_{\theta=0}^{2\pi} \int_{r=0}^{\rho^M} r dr d\theta$.

Each node $n \in |\mathcal{N}_{adj}^L|$ explores its neighbor. Hence, f_N for each node n is calculated as follows:

$$f_N = N\frac{K_2}{K_1} \tag{16}$$

Therefore, $\mathcal{U}_F(\cdot)$ is rewritten as — $\sum_{v=1}^{N\frac{K_2}{K_1}} RE_v$. Therefore, total number of nodes are activated by above process is shown in Equation (17). □

Lemma 1. *The maximum and minimum theoretical utility value of the leader is (δ_{max}-δ_{min}) and -1, respectively, where δ_{max} and δ_{min} are the maximum value of the revenue function and minimum value of the cost function, respectively.*

***Proposition* 2.** *The worst-case asymptotic time complexity to activate an intermediate node for establishing connectivity through ORCID is $O(|\mathcal{N}|^2)$.*

TABLE I: Simulation Parameters for ORCID

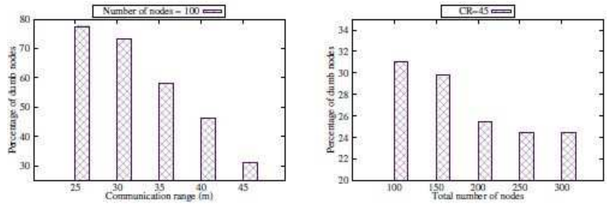
Parameter	**Value**
Number of nodes ($\|\mathcal{N}\|$)	100-300
Simulation area	$1000 \times 1000\ m^2$
Sensing range	25 m
Maximum communication range	25-45 m
Data rate	250 kbps
Constant value (ξ)	0.0005
Power consumption of transmitting circuitry (P_{T0})	15.9 mW
Power consumption of receiving circuity (P_{R0})	22.2 mW
Drain efficiency (η)	15.7 %
Packet Size	127 octets
Path loss exponent (α)	2.5

VI. Performance Evaluation

A. Simulation Design

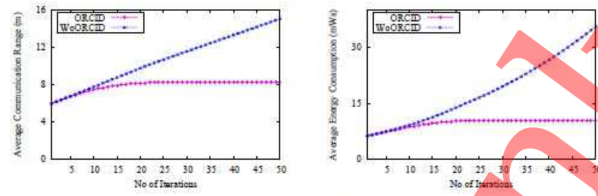
In this section, we evaluate the simulation-based performance of the proposed scheme, ORCID. We have simulated the proposed scheme in the MATLAB simulation platform. MATLAB is used, as our focus is on the mathematical modeling of ORCID while considering the networking aspects. In simulation we consider the work of Kasirajan *et al.* [18] for data aggregation in the context of WSN. To simulate the scheme, we consider that the sensor nodes communicate using the IEEE 802.11 protocol, and are heterogeneous having different power levels. Due to the effects of the adverse environment, the communication range of sensor nodes shrinks, and consequently, few nodes in the network become dumb. Each of the dumb nodes tries to establish connectivity with the other active nodes, using ORCID. To evaluate ORCID, we consider the total number of nodes in the network to be between $100 - 350$. We varied the maximum communication range of nodes from 25 to 45 m, and observe the modified optimal communication range of the nodes. We execute 100 iterations of the simulation for analyzing the performance of the proposed scheme, ORCID. We also depict the performance, considering 98% of confidence interval. The simulation parameters are depicted in Table I. We present the results for ORCID considering the following parameters:

$$N_{adj}^L + \sum_{n=1}^{|\mathcal{N}_{adj}^L|} f_n = \frac{N}{K_1}\left[\oiint_{\widetilde{R}^2} f(x_L, y_L)dxdy + \sum_{n=1}^{\frac{K_2}{K_1}} N\frac{K_2}{K_1}\right] \quad \text{where } R^2, \widetilde{R}^2 \subseteq A^2 \tag{17}$$



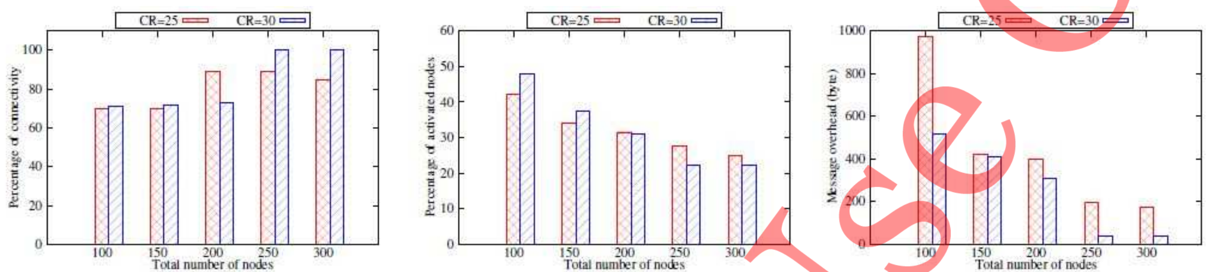
(a) Varying communication range (b) Varying number of nodes

Fig. 1: Percentage of dumb nodes



(a) Average communicarion range (b) Average energy consumption

Fig. 2: Percentage of dumb nodes



(a) Percentage of connected dumb nodes (b) Percentage of activated nodes (c) Message overhead

Fig. 3: Same deployment. The positions of the previously deployed nodes remain same.

***Percentage of dumb-connectivity*:** The percentage of dumb-connectivity is defined as the percentage of dumb nodes which are able to connect with an activated node. Mathematically, Percentage of dumb-connectivity = $\frac{N_d^c}{N_d} \times 100$
where N_d^c is the total number of dumb nodes that can establish connectivity with an active node.
***Message overhead*:** Number of bytes required to transmit and receive to connect all possible dumb nodes with the active nodes.
***Energy consumption*:** The amount of energy required to connect all possible dumb nodes with an active node in the network. Additionally, we neglect the energy consumption for data aggregation. For evaluating the performance of ORCID, we follow the energy consumption model considered in the existing literature [19], [20], where the required energy for transmitting a packet of N bits, E_T, with data rate R is as follows:

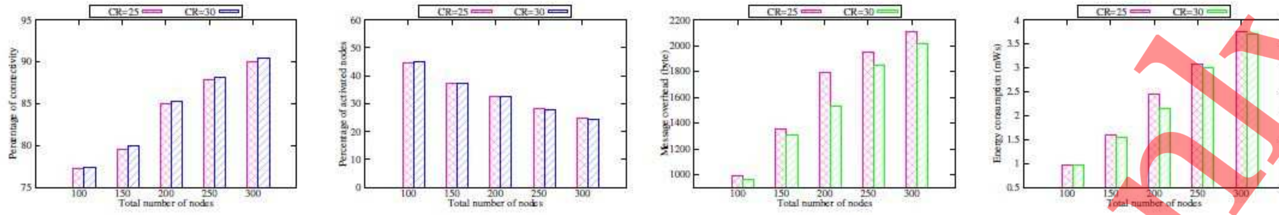
$$E_T = \frac{P_T \times N}{R} \text{ and } P_T = P_{T0} + \frac{\xi \times d^\alpha}{\eta} \quad (18)$$

B. Results

Fig. 1 depicts the occurrence of dumb nodes due to the decrease in communication range and the number of nodes present in the network. In Fig. 1(a), we considered that the total number of nodes present in the network is 100. We observed that with the increase in the maximum communication range, the percentage of dumb nodes in the network decreases. Fig. 1(b) depicts the variation in the percentage of dumb nodes with the variation in the total number of nodes in the network. In this figure, we considered that the maximum communication range CR for each of the sensor nodes is 45 m. We observed that the percentage of dumb nodes decreases with the increase in the number of nodes in the network. This is due to the fact that with the increase in the maximum communication range, a subset of nodes has a non-empty neighbor list, which in turn reduces the number of disconnected networks. Thus, we infer that the percentage of occurrence of dumb nodes present in the network not only depends on the decrease in the communication range but also on the number of nodes present in the network.

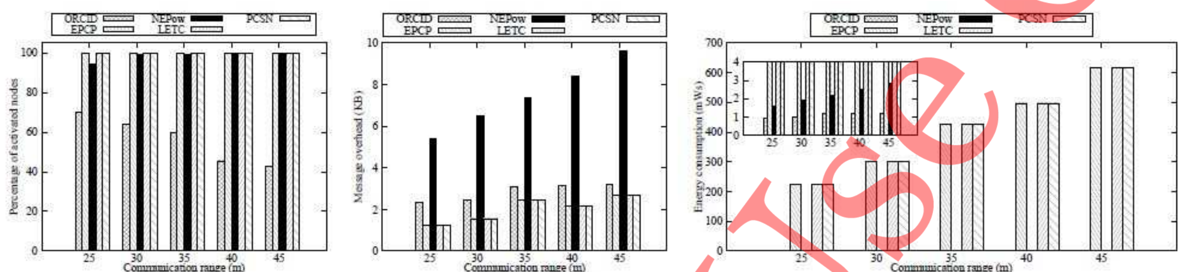
Fig. 2 shows the comparison of two different schemes – the proposed scheme, ORCID, and another named *WoORCID*, which is not game-theoretic. In WoORCID, we assume that each node increases its communication range until it reaches the maximum communication range, i.e., ≤ 45m, to explore the maximum possible connectivity of the network. As a result, we observed that with the increase in the number of iterations, the average communication range of the nodes available in the network reaches the Stackelberg equilibrium state (after 10-15 iterations), using ORCID. On the contrary, using WoORCID, the average communication increase linearly until the nodes reach their feasible communication range, i.e., there is no such equilibrium state, as shown in Fig. 2(a). Additionally, Fig. 2(b) depicts that the average energy consumption of each node in the network also reaches an equilibrium state after 10-15 iterations using the proposed scheme, ORCID. However, the average energy consumption per node increases in each iteration using WoORCID. Therefore, we conclude that using the proposed scheme, ORCID, we reach Stackelberg equilibrium within 10-15 iterations, while choosing an optimum communication range for each node. Hence, the energy consumption profile of the network is optimized.

Fig. 3 depicts the percentage of connected dumb nodes, the percentage of activated nodes, and the message overhead in the network, to re-establish connectivity between dumb and the activated nodes. In this figure, we consider that the total number of nodes varies between 100-300 with increments with



(a) Percentage of connected dumb nodes (b) Percentage of activated nodes (c) Message overhead (d) Energy consumption

Fig. 4: New deployment. The co-ordinates of all the nodes including the previously deployed nodes are changed.



(a) Percentage of activated nodes (b) Message overhead (c) Energy consumption

Fig. 5: Comparison of ORCID with LETC, NEPow, PCSN, and EPCP

a step-factor of 50. Each time the previous deployment is maintained while deploying an additional 50 nodes in the network. In each of the plots of Fig. 3, we examined the network parameters while varying the maximum communication range CR of nodes to 25 and 30 m. Fig. 3(a) shows the percentage of connected dumb nodes in the network using ORCID increases, due to the fact is that the possibility of getting activated nodes in the network increases with the increase in the total number of nodes. The possibility of getting an activated node increases when the total number of nodes in the network increases. Consequently, the total number of hop-counts needed to establish connectivity between the dumb and the other activated nodes decreases. Thus, the percentage of activated nodes decreases with the increase with a decrease in the number of nodes in the network, as shown in Fig. 3(b). When the hop-count, the number of messages transmitted in the network decreases, which results in a decreasing trend of the message overhead, as shown in Fig. 3(c).

Fig. 4 depicts the results for the proposed scheme, ORCID, in which we considered that the total number of the nodes in the network varies to vary between 100-300 with an interval of 50 nodes. In these plots, the deployment is re-initializes with the change in the number of nodes in the networks. The reduced communication range considered is the same as that considered in Fig. 3. Similar inferences are drawn from Figs. 4(a) and 4(b), as mentioned for Figs. 3(a) and 3(b), respectively. In Fig. 4(c), the message overhead increases with the increase in the percentage of the total number of nodes in the network. This is due to the fact that, with the increase in the number of nodes in the network, the number of messages transmitted for exploring neighbor nodes increases. We observed an increasing pattern of the plot for energy consumption, as depicted in Fig. 4(d), as energy consumption is dependent on the number of messages transmitted in the network (i.e., overhead).

Further, the results are compared with the existing topology control protocols — Learning automata-based Energy-efficient Topology Control (LETC) [21], Joint Topology Control and Power Scheduling (NEPow) [22], Power Control via Pricing (EPCP) [23], and Distributed Power Control (PCSN) [24]. In LETC, a degree-constrained minimum-weight version of the Connected Dominating Set (CDS) is considered by Torkestani. In PCSN, Sengupta and Chatterjee proposed a non-cooperative game with incomplete information while deciding an optimum power of the sensor nodes. Saraydar *et al.* [23] proposed a distributed power control protocol using a non-cooperative power control game while maximizing QoS of the network. Ren and Meng [22] proposed a game-theoretic approach to achieve high QoS while minimizing power consumption. Fig. 5 depicts the comparison of ORCID with the existing schemes.

For comparison, we considered that the total number of nodes in the network is 250. The percentage of activated nodes is shown in Fig. 5. We observe that the percentage of activated nodes using ORCID varies from 50-70%, whereas using other schemes, it is more than 95%. Similarly, the message overhead and energy consumption increases in LETC, NEPow, PCSN, and EPCP with an increase in the communication range of the nodes. However, using ORCID, the message overhead and energy consumption are negligible, as compared to the other schemes. This is due to the fact that ORCID establishes connectivity by adjusting the communication range of the nodes on-the-fly, as there is no requirement to construct the topology of the network from the beginning. On the contrary, LETC, NEPow, PCSN, and EPCP start executing from scratch, in order to form a connected network. Consequently, a high number of messages are transmitted.

VII. CONCLUSION

In this work, we studied the problem of forming a connected network in the presence of dumb nodes in WSN. In order to maintain the normal performance of the adaptive network, it is essential to re-establish connectivity between the dumb and the other activated nodes in the network. We proposed a solution to indemnify the challenge in connectivity establishment due to the occurrence of dumb nodes. This problem has a specific characteristic of temporariness, which renders the problem interesting. In the proposed scheme, ORCID, a dumb node establishes connectivity with an activated node, opportunistically, by adjusting its power level in an adaptive-way for efficient network management. We modeled the problem as a *Single-Leader-Multiple-Followers Stackelberg game*. Through simulation, we observed that using ORCID, the number of activated nodes reduces by 26.32–47.37% than using the existing approaches. Additionally, we yield that ORCID outperforms the existing schemes in terms of message overhead and energy consumption.

In the future, we plan to extend the work to enable a dumb node to detect and re-establish connectivity with an adaptive network using a learning-based scheme. It helps a dumb node to adapt a scheme while choosing one of the available neighbors to ensure the connectivity of the network without exploring all the possibilities. Therefore, the message overhead and energy consumption of the network may reduce. Here, the node automatically detects itself when it is dumb, and thereafter, it re-establishes connectivity in an adaptive-way. Moreover, we plan to evaluate the performance of the proposed scheme for different topology – sparse and dense deployment. The work can be further extended by considering the presence of a set of dumb nodes simultaneously in a network, and thereafter, proposing a solution for establishing connectivity between the set of dumb nodes with other nodes in the network.

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