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Location Aware Relay Node Placement for Energy Constrained Wireless Sensor Networks

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ABSTRACT

In this paper we consider the problem of the Relay Node Placement for sustainable data forwarding in Wireless Sensor Networks where an energy aware relay node deployment model is proposed. The proposed model considers the constrained placement. Hop Constraint and Distance Constraint are the two main constraints considered in this paper for the determination of energy based feasible path for any Sensor Nodes to reach the destination. The main objective of this paper is to reduce the maximum possible number of extra Relay Nodes to be deployed by which the deployment cost will be reduced. Further to preserve the energy of energy constrained Sensor Node; the distance constraint is put forward during the evaluation. Simulations are conducted over the proposed model with varying network characteristics demonstrate the effectiveness in the reduction of deployment cost and energy consumption.

Key words: Wireless Sensor Network, Relay node Placement, Hop constraint, Distance Constraint, Number of deployed relay nodes, Average Energy Consumption.

1. INTRODUCTION

In recent years, Wireless Sensor Networks (WSNs) has gained a lot of research interest due to its widespread deployment in various applications both in civilian and defense related applications. The applications which includes but not limited to are industrial monitoring, biomedical observation, environmental monitoring, as battlefield surveillance, and some other fields [1], [2]. Generally, WSNs composed of low-power and low-cost sensor nodes (SNs), which can sense, performs simple computations, and communicates with short range distances. The main problem in the WSN is limited energy resource availability and accessibility of SNs, which has a direct impact over the lifetime of network. Recently a new architecture, known as two-tire network architecture was evolved in which some extra nodes, called as Relay Nodes (RNs) are deployed in the network through which the network lifetime can be extended. These relay nodes have some ample power and having suitable wireless communication radius. The main responsibility of the RNs is to collect information from SNs and to forward to the Base Station (BS) or sink node [3]. This is an energy efficient approach through which the energy consumption of every SN was reduced. Though the accomplishment of RNs has obtained significant results in the reduction of energy consumption, the main challenge in the RNs deployment is finding the optimal locations at which the RNs can be placed. It also has to consider that as much as possible minimum number of RNs has to deploy considering that every SN in the network needs to be covered by at least one RN.

Based on the earlier studies, there are two models for RNs placement, constrained placement and unconstrained placement. In the unconstrained placement, the RNs can be placed at anywhere in the network's area, which is not a feasible solution due to the many scenarios where the placement faces physical problems and in the constrained placement, only some regions are considered for RNs placement [4], [5].

This paper focused over the constrained placement and develops a new model for location detection to deploy a RN. Based on the two constraints namely, the hop constraint and distance constraint, the proposed model establishes an energy based feasible path for every SN to reach the sink node through minimum number of RN. Simulation parameters considered are namely, the total number of deployed RNs, Delay, Average Energy Consumption, and Evaluation time. Simulation experiments are conducted by varying the total number of SNs and at every stage, the performance is compared with conventional approaches.

Rest of the paper is organized as follows; Section II illustrates the details of literature survey. Section III illustrates the details of materials and methods accomplished for node placement. Section IV illustrates the performance evaluation details and finally the conclusions are provided in section V.

2. LITERATURE SURVEY

In literature, various approaches are developed with an objective of optimal RNs placement such that the network meets the required objectives more efficiently. The existing approaches are categorized as one-tire models and two-tire models. In the former model, any SN can be used as RN to forward the data and in the latter one; the SNs can be used only to sense and to forward only their data and they cannot be utilized as RNs. The constrained RN placement is considered in [4], [6].

Misra et.al., [4] considered the problem of constrained RN placement to address the connectivity and survivability problem is solved through an approximation algorithm and proved that the time complexity follows a polynomial incremental nature.

The main aim of J. Bredin et.al., [6] is to determine the possible minimum number of RNs such that every SN should be connected to the BS through various node-disjoint paths, through which the fault tolerance can be achieved in the case of node failure. Most of the works are on one-tiered model, including [4],[6-9] considered the unconstrained deployment where RNs can be deployed anywhere which is unrealistic in major cases. The main challenge with the one-tired models is the fast energy exhaustion due to the utilization of any possible SN as a relay. In the case of SN with lower energy levels, if it is used as RN, then it will die immediately which effects the network lifetime. Hence the Two-tiered model has gained a significant importance and several approaches are developed in earlier [10-14].

Zheng et al. [11] considered the RN placement jointly with sub-carrier allocation. This problem is modeled with the help of ‘mixed integer non-linear programming (MINLP)’ and to solve it based on the heuristics. Next, a new solution is proposed for RN placement for industrial sensor networks by Zhang et al., [12] modeled in two phases. In the first phase, the total number of topologies those meets the requirements of energy consumption and fault tolerance are measured and in the second phase, among the obtained topologies, one beset topology is selected. However the computational complexity of this method is observed to be very high.

Further based on the Steiner trees, a new method for RN placement is proposed by Gao et al., [13] which considered the minimum RNs addition and Steiner tree based heuristics jointly to connect the SNs and BSs. However the additionally added RNs are assumed to be communicating with each other directly irrespective of the physical environment and distance, which is not possible in real time.

Combined focusing over the security and power, Pooja and Nasib[18] proposed a secure and power aware routing protocol based on the weighted clustering [19] mechanism. Further the security provision is accomplished through Elliptical Curve Cryptography (ECC).

Further, Chelli et al. [14] considered constrained node placement in two-tiered model and proposed a one-step relay placement (OSRP) to construct a connected Steiner-tree topology. Some more approaches are proposed based on the minimum spanning tree (MST) for an efficient path establishment for every SN in the network based on tree heuristics [15-17]. They tried to establish a strong minimum energy topology (SMET) through which the energy consumption will be less. But just considering the tree heuristics have a significant effect on the resources of SNs.

3. MATERIALS AND METHODS

This section illustrates the details of proposed new method for relay node placement in the WSN. Let’s consider X as the set of Sensor Nodes (SNs), L is the set of locations at which the Relay Nodes (RNs) can be placed and B is the Base Station or Sink Node. Further, ‘p’ is the communication radius of a SN and ‘P’ is the communication radius of RN. Further ‘Q’ is the communication radius of sink node and it is greater than the communication radius of SN and also the communication radius of RN also. One more assumption is that $P \gg p$. Without loss of generality, here the objective is to deploy the RN at particular location, $l \in L$ and also a SN can also consider as a RN it is placed at an optimal position through which the objectives of proposed model can be achieved. The RN placed at particular location or the SN selected as RN must meet the main criterion such that it has to cover maximum set of SNs. Further it is also need to obtain that the number of RNs to cover all the set of SNs must be less in number. Finally our objective is to establish an energy efficient path for every SN to sink node which have minimum number of RNs.

Initially, for every SN in the network, a set of neighbor nodes are evaluated based on the Euclidean distance. Let’s consider m and n be the two SNs in the network, $\|m-n\|$ denotes h Euclidean distance between nodes m and n,

$$ED(m,n) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad (1)$$

Where $(x_1, y_1)$the location is coordinates of node m and (x_2, y_2) is the location coordinates of node n. If $ED(m,n) \leq r$, then the two nodes m and n are said to be neighbor nodes and we can also say that they can co-operate to each other. Let the path between two nodes m and n is denoted as $p(m,n)$, the hop count for that path can be denoted as $H(p(m,n))$. The shortest path is denoted as $S(m,n)$. To preserve the energy resource of every SN of the network, a hop constraint is employed in this paper and it is denoted as Δ_H, for a SN *m*, the hop constraint is represented as $\Delta_H(m)$. A path established between the SN *m* and the sink node B, $p(m, B)$ said to be a feasible path if the hop count is less than or equal to the hop constraint of node *m*.

In the proposed model, initially consider the union of both SNs and location points as a union matrix U, $U \leftarrow X \cup L$. Next, initially the total number of SNs to be covered is buffered into a new variable I_k, $I_k \leftarrow X$. For every component of U which measure the hop count by applying the shortest path tree algorithm. For this purpose, initially find the total number of possible paths towards the sink node for a given component $u \in U$. There are so many possible paths and among the available paths, one shortest path is selected which meets the hop constraint of node *u*, $\Delta_H(u)$. After the evaluation of shortest path, for every node in the I_k, check whether it is a neighbor of sink node or not. If it found as a neighbor of sink node, then remove it from I_k. Iterate the process until the complete set of SNs will be covered by component $u \in U$. For every component in the U, find the SNs in the $I_k$that can be effectively covered by *u*, i.e., *C(u)*. An important point to be noticed here that the component u has to cover the some other nodes without violating the hop-constraints. To address this feasibility problem, the following definitions and lemmas are proposed here.

3.1. Feasible Path

For example consider *(k-1)* iterations are completed and the *k*th iteration is about to start. The set of nodes obtained in the *k-1* iterations are denoted as I_{k-1}.

Definition 1: node *u* is said to be effectively covered by node *v*, $(u, v \in X \cup L)$ if they satisfies the following constraints;

$$H(S(v, B)) < \Delta_H(u) - 1 \quad (2)$$

$$u \in N(v) \quad (3)$$

Let's *C(v)* is the possible set of nodes covered by node *v*. Along with this we has to remember that every node can cover itself and it can be notified as the $v \in C(v)$. A node v is said to be a feasible node if it satisfies the constraint $|C(v)| > 1$. To mention that the node v can cover the possible set of remembering the hop constraints, it needs to follow the following formula and based on these constraints only the hop constraint of node *v* can be evaluated as;

$$\Delta_H(u) = \min\left(\min_{u \in c(v)}(\Delta_H(u) - 1,\ \Delta_H(v))\right) \quad (4)$$

Here the inner term $\min_{u \in c(v)}(\Delta_H(u) - 1,\ \Delta_H(v))$ obtains the nodes with minimum hop constraint in the subset cover $c(v)$ of main cover set $C(v)$. A simple explanation for the above constraint for understanding is to say that for a node *v*, if it is more nearer to the sink node and also if it is there in the neighbor list of node *u*, then only it can cover and absolutely the hop constraint of node *v*, $\Delta_H(v)$ must be less compared to the hop constraint of node u, $\Delta_H(u)$. In this manner the entire set *C(v)* is divided into the cover of subsets and in every subset, the hop constraint of node v is checked whether it can cover the entire set of nodes or not.

Lemma 1: for every node *u* in *C(v)* there must be at least one feasible path to the sink node which passes through the node *v*.

Proof: this lemma is proved by establishing a path between the sink node and SN *u*, which is in the cover set *C(v)* of node *v*. According to the discussion explained in the above paragraph (above lemma 1), the node *v* is assumed to be nearer to the sink node compared to the node *u*. If node *u* find a path $p(u, B)$ within its hop constraint limits, then the node *v* also becomes a one-hop neighbor to node *u*. then based on the definition 1 we can formulate that

$$H(p(u, B)) = H(p(v, B)) + 1 \leq \Delta_H(u) \quad (5)$$

If the path passing through node v is selected as a shortest path, then this proof straight forwarding proves the lemma 1.

Lemma 2: Let node *u* be in the node set obtained at k-1 iterations from node set X, i.e., $u \in I_{k-1}$. Further in the next iteration just there is a need to find one feasible node *v* which meets the following constraints;

$$u \in C(v) \quad (6)$$

$$\Delta_H(u) = \Delta_H(v) + 1 \quad (7)$$

Proof: This lemma is proved with the help of figure.1 shown below.

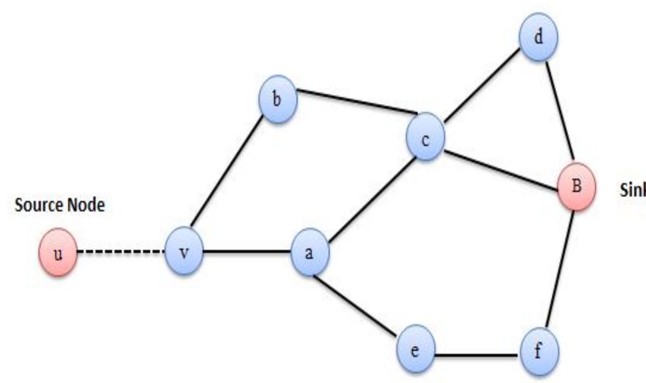

Figure 1: Example Illustration

According to figure.1, for a node u to reach the sink node, there are so many possible paths. The possible paths drawn from figure.1 are;

$$P_1 = u \rightarrow v \rightarrow a \rightarrow c \rightarrow B$$

$$P_2 = u \rightarrow v \rightarrow b \rightarrow c \rightarrow B$$

$$P_3 = u \rightarrow v \rightarrow b \rightarrow c \rightarrow d \rightarrow B$$

$$P_4 = u \rightarrow v \rightarrow a \rightarrow e \rightarrow f \rightarrow B$$

From the above possible paths, Path 3 (P_3) and Path 4 (P_4) are not valid due to the non-shortest paths even though they can cover the node v, which is a close neighbor of node u. Further the paths P_1 and P_2 are obtained as a shortest paths. Both the paths have same hop count, i.e., $H(P_1(u,B)) = 4$ and $H(P_2(u,B)) = 4$. In the both paths, if we consider the hop count then we can have two feasible paths in which both the paths have node v. For both paths, if we consider the path $P_1(v,B)$ and $P_2(v,B)$ the hop constraint $\Delta_H(v) = 3$, which can also be obtained through the constraint specified in the eq.7 after rewriting it as $\Delta_H(v) = \Delta_H(u) - 1$ and here the 1 denotes an extra hop joining the nodes u and v. Hence the lemma 2 is proved.

3.2. Energy Focused Feasible Path

If we focus over the energy preservation during the relay nod placement, we can deploy the RN at the specified locations obtained through above feasible paths with energy harvesting characteristics but it adds an additional cost due to the extra hardware requirement for harvesting capabilities. Instead of this, we can choose an energy based feasible path over the possible paths for a node u and sink node B. For instance in the example described to prove the lemma 2, if we consider the hop constraint along with distance constraint Δ_d, we can obtain an energy feasible path for every SN to reach the sink node. Since the energy consumption has a linear relation with distance, i.e., $E \propto d^{\alpha}$, where E is the energy required, d is the distance between two nodes, and α is an arbitrary constant and generally it is assumed to be 2. This linear relation strongly recommends considering the distance constraint also deriving a feasible path for a SN to reach the destination.

Once after obtaining the feasible paths which satisfies the hop constraints and also if they are more in number, then only the proposed distance constraint is imposed to find only one feasible and energy efficient path. To obtain an energy focused feasible path, it needs to satisfy the following distance constraint;

$$\Delta_d(u) = \min_{u \in C(v)} \Delta_d(v) + ED(u,v) \qquad (8)$$

Where $\Delta_d(v)$ is the distance constraint of node, v which is a final node cover selected by node, u to reach the sink node, B, $ED(u,v)$ is the Euclidean distance between node u and node v and it won't vary because in the k-1 iteration, node v is already selected as feasible node to cover the node u. For the two paths with same hop constraint, the final feasible path selection needs to satisfy the constraint as specified in Eq.(8). In general for any path to become feasible for a node u, it needs to satisfy the both constraints as specified in Eq.(2) and Eq.(8). Then only the network can achieve an extended lifetime.

4. PERFORMANCE EVALUATION

In the simulation experiments, the proposed model is accomplished to deploy over a randomly created network with N number of sensor nodes with a network size of 1000*1000 m^2. The simulation experiments are executed through the MATLAB software running in the personal computer with hardware specifications as 1TB hard disk and 8 GB RAM. The maximum simulation time consider here is 50sec.The SNs communication radius, p and RNs communication radius range, P are assigned during run time .Since the network created here is a randomly created one, every time, the SNs positions are varying in nature and thereby the radii also varying. Hence to realize this aspect, the radii of both SN and RN are evaluated during simulation only. Further the energies of SNs are also randomly created and assigned.

4.1. Parameters

To measure the performance of proposed model, here some performance metrics are considered and they are evaluated with varying network characteristics like number of sensor nodes.

Number of Deployed RNs: This parameter is defined as the total number of RNs deployed between the SN and sink node in the path established between those two nodes. The simulation considers the average value and this average is evaluated after multiple simulations over different SNs.

Evaluation Time: This parameter is defined as the total time taken by the proposed model to establish an energy efficient feasible path for a given source and sink pair. The simulation considers the average evaluation time and this average is evaluated after multiple simulations over different paths establishment between different SNs to sink node.

Energy Cost: This parameter is defined as the amount of energy consumed by both SNs and RNs to transfer the information from source node to sink node through the established energy based feasible path. This parameter is also considered as an average value and these averages are obtained after the multiple simulations with varying Source and sink node pairs.

4.2. Simulation Results

In the simulation results, the proposed approach is applied a randomly created network and the performance is evaluated through the performance metrics specified above. Here the performance is measured with varying number of SNs. For every SNs number, the total number of RNs needs to be deployed will vary which has a direct relation with the further performance metrics like end-to-end delay, energy consumption and evaluation time. The evaluated metrics are depicted in the following figures.

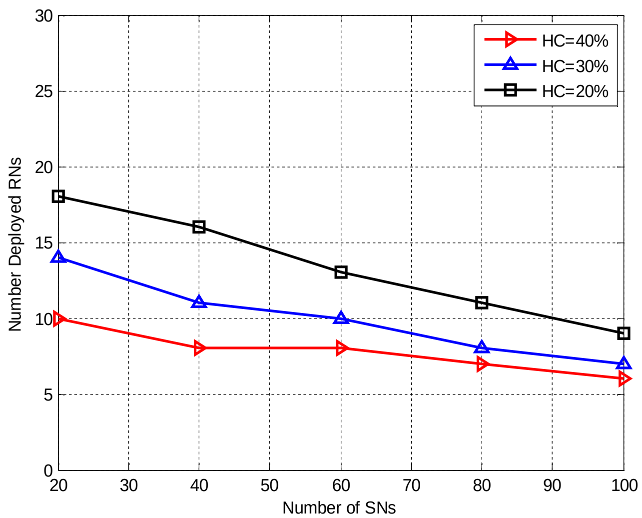

Figure 2: Number of deployed RNs for varying Hop-constraints

Figure.2 represents the details of total number of deployed RNs for varying number of SNs and also for varying Hop-constraints. As it can be seen from the above figure, the total number of deployed RNs is decreasing with the increasing number of SNs. According to the proposed methodology, the Relay node placement mechanism considers the union of SNs and Locations, there is a possibility to obtain the location at which the SN is already deployed and then it can acts as a RN. If there is no SN deployed at the location obtained through the proposed mechanism, then we can deploy a new RN which accumulates to the parameters called total number of deployed RNs. In the case increasing number of SNs in the network, there is a possibility to obtain the SN only as a RN by which the total number of RNs will reduce.
Further, the HC=40%, 30% and 20% represents the percentage of nodes considered as hop nodes from the total SNs deployed in the network. It can also be observed from the above figure, the total number of deployed RNs have inverse relation with hop-constraint. Here the hop constraint defines the maximum possible hops for a SN to reach to the sink node. For any SN, after crossing the hop-constraint, the extra RNs needs to deployed to reach to the Sink node by which for less hop-constraint the total number of deployed RNs should be more.

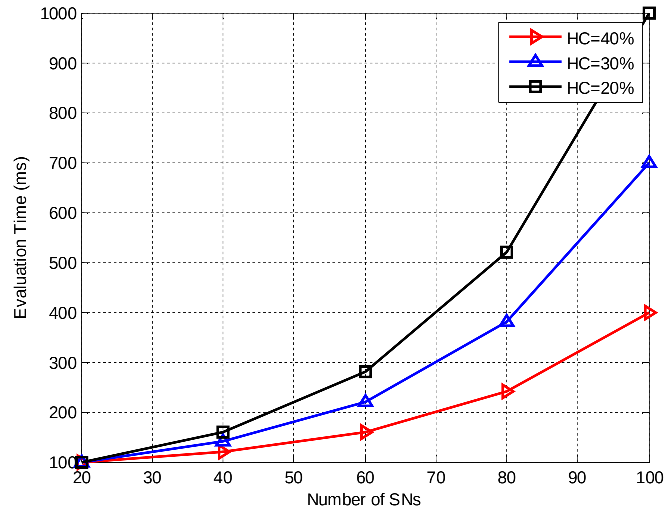

Figure 3: Evaluations time for varying hop constraints

Figure.3 represents the details of Average Evaluation time for varying number of SNs. As it can be seen the total evaluation increases exponentially with the number of SNs. It is because the proposed method needs to scan every deployed SN and the predefined locations to find which is more suitable for relay node replacement. And the scanning time is also increase as the number of SNs increases. Further, for a limited HC, it needs still more time to find the exact SN to use as RN or location to deploy a new RN and this makes the evaluation time more for less hop-constraint. For a high HC, the evaluation time is less and for low, it is high, as shown in figure.3.
The energy is an important for a static WSN, which needs to be preserved more efficiently. As the number of nodes participated in the process are more, the total energy consumed also more. The same is depicted in figure.4, the increasing nature of average energy consumption for increasing number of SNs. However, this has an inverse relation with hop-constraint. As the hop-constraint increases, the average energy consumption is observed as less due to the deployment of new RN or the utilization of already existed SN as RN.

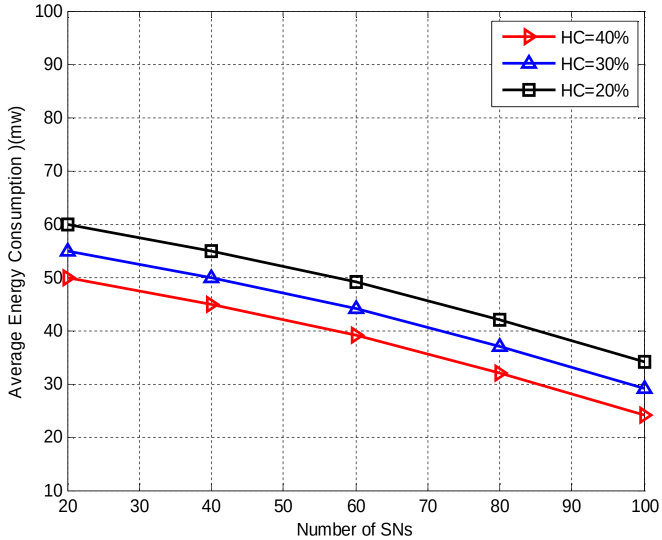

Figure 4: Average Energy consumed for varying hop constraints

Here the total energy consumption is measured with respect to the total number of RNs deployed in the network. According to the figure 2, the total number of deployed RNs is decreasing in nature, the energy also has same characteristics and depicted in figure.4.

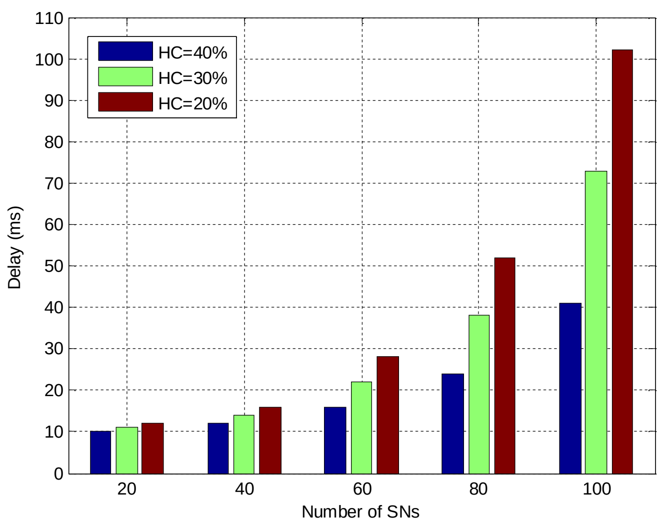

Figure 5: Average Delay for varying hop constraints

Figure 5 depicts the details of overall delay happened with varying number of SNs and varying HCs. As the number of SNs increases, the delay will be more because the information has to process through multiple nodes and at every node, there exists a minimum delay. This delay will increase as the number of nodes increases for every HC. Further, this delay has inversion relation with HC. As much as HC increases, the delay will decrease due to the additional RNs deployment. Since the Communication radius of RN is larger when compared to the communication radius of SN, the delay will be less.

4.3. Comparative Analysis

To alleviate the effectiveness of proposed approach, the performance evaluation obtained through the metrics namely total number of deployed RNs and Average energy consumption is compared with the conventional approaches. The details are described in the following figures.

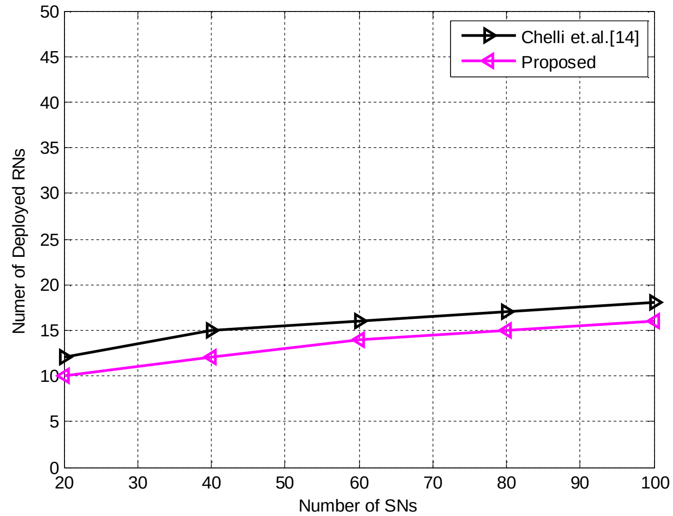

Figure 6: Comparison of Number of deployed RNs for varying number of SNs

Figure 6 shows the comparative analysis between the proposed and conventional approach, Chelli et.al [14] through the performance metric, total number of deployed RNs. We can observe that the proposed approach outperforms the conventional approach in the deployment of extra RNs. Compared to the RNs deployed through the conventional approach, the RNs deployed through the proposed approach are less in number and this less number reduces the deployment cost. Since the proposed model is based on the HC, the extra RNs which have more communication radius come into picture. Whereas in the conventional approach, there is no such constraint and due to this, there exists a conflict in the selection of SNs as relay or to deploy a new RNs. This conflict is cleared in the proposed method by which the total number of RNs has to deploy are obtained in less number for every set of SNs. Next, the RNs deployment has a direct effect on the energy characteristics of network and they are depicted in the figure.7.

Figure 7 shows the comparative analysis between the proposed and conventional approaches, Chelli et.al [14] and Panda et.al [16]. As it can be observed from the figure.7, the average energy cost occurred for the proposed approach is less compared to the energy cost of conventional approaches. Since the total number of deployed SNs and RNs for an established between any SN and sink node are less in the proposed model.

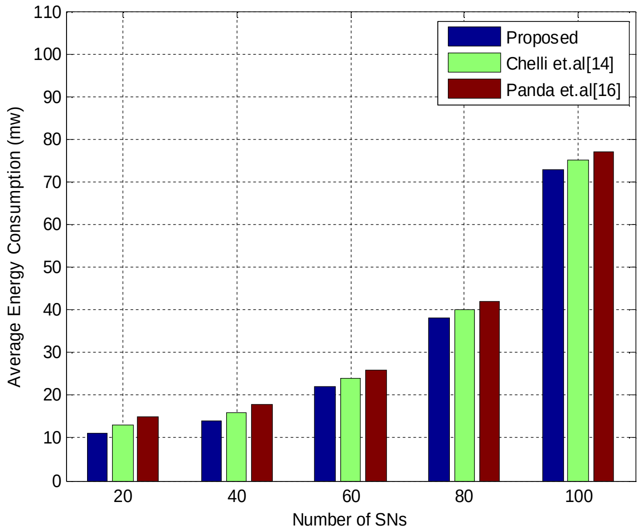

Figure 7: Comparison of Average Energy consumption for varying number of SNs

As the number of nodes participated in the process are less, the amount of energy consumption is also less. Though the Chelli et.al [14] focused over the relay node placement, the total number of deployed RNs is high in number by which the energy cost incurred is also more. Further the one more conventional approach, Panda et.al [16] didn't focused over the relay node placement and only tried to establish a path with less energy consumption.

5. CONCLUSION

In this paper, we had investigated the relay node placement problem in WSNs. Firstly, the relay node placement is formulated as the determining an optimal location to deploy the RN. If the optimal location is determined in such a way that a SN is already deployed, then that SN only act as a RN, otherwise a new RN is deployed at that location. Furthermore this model also focused over the energy constraints of SNs and established energy based feasible path for every SN to reach the sink node. An extensive simulation experiments accomplished over the proposed model has proved the performance efficiency of proposed approach in the view of energy preservation and also in the deployment cost. The performance is measured through the performance metrics, number of deployed RNs and Average energy consumption incurred. The comparative analysis demonstrates the performance improvement of the proposed model from the conventional approaches.

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