Maximizing the Robustness of Wireless Sensor Networks with Optimal Sink Designation

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Abstract

One of the fundamental design challenges in designing a Wireless Sensor Network (WSN) is to maximize the network lifetime, as each sensor node of the network is equipped with a limited power battery. To overcome this challenge, different methods were developed in the last few years using such techniques as network protocols, data fusion algorithms using low power, energy efficient routing, and locating optimal sink position. This paper focuses on measuring robustness of a net work and we show how selecting sink nodes in network is important to achieving high robustness level of the network. First we argue how positions of sink nodes, affect networks robustness and how our proposed method works to solve this problem. We present sets of metrics to measuring the suitability of nodes to be selected as sink node. With having suitability degree for each node the risky nodes have low chance to be selected. And also after ranking the nodes we present a simple method for selecting suitable nodes as sink nodes. Our simulation results show that the presented method leads to better results and high robust network and performance of network improved remarkably.

Key words: Network attacks, Robustness, Sink selection, Wireless Sensor network

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1. Introduction

WSNs have recently been the focus of researchers due to their wide range of applications such as disaster management, battlefield surveillance, medical diagnostics, and environmental and habitat monitoring. However, WSNs, as ad hoc networks, face several technical challenges in their design and implementation. Sensor nodes are battery limited and with geographical distribution and numerousness of sensor nodes recharging or changing their energy resources is difficult or impossible. Efficient use of energy resources in sensor nodes leads to several network operation management techniques. Sensor nodes are implemented in a way that can communicate with each other and also they transfer their sensory data that they sense from physical phenomena and finally route them to the sink nodes.

Commonly in sensor networks a sink node is a node among network nodes that, selected as a sink node, undertakes the responsibility of coordination and gathering sensory data from other nodes. As a matter of fact all sensor nodes send their sensory data to the nearest sink node. With considering sinks tasks it may be better to reduce their usual sensing task because compared to other nodes sink nodes have more communication tasks with other nodes. Also that is clear that sensor nodes consume more energy when they are communicating with other nodes.

Recent researches show that location of sensor nodes. especially sink nodes or base stations, have great impact on network output, energy consumption and network delay. In this area of research different techniques for selecting or locating network elements are proposed, that each techniques leads to better energy consumption and network total output. Majority of proposed researches aims are finding best location for locating or selecting sink nodes or base stations. They examine different metrics such as network topology, nodes distribution, distance, remaining energy of nodes, and capacity of sensor nodes to find a suitable location for a special node.

Generally wireless sensor networks are deployed in a hazardous area and it’s somehow costly or sometimes impossible to locate a node in a special geographical location. In most cases sensor nodes distributed randomly and set of sink nodes are selected across those sensors. The topology from a static or dynamic distribution of sensor nodes consider as a graph. Robustness of a network of sensor nodes is almost similar to robustness problems in graph theory.

Robustness of a network has direct impact on network persistence and network potency. Past researches show that in wireless sensor networks, vertex- and edge-connectivity are the most frequently used metrics for measuring the robustness of network topologies. These metrics take the topology graph as input and return the minimum number of vertices or edges, respectively that have to be removed in order to disconnect the graph. More precisely, a graph is said to be k-vertex-connected, if it remains connected whenever fewer than k vertices are removed, and the vertex-connectivity of a graph is the largest k for which it is k-vertex-connected.

However the problem of selecting a set of optimum nodes as a sink node is a kind of problem that is hard to compute but with a simple greedy method with new metrics will compute more optimally. The problem that we will focus on in this paper is maximizing the network robustness with better selection of sink nodes. As a matter of fact we describe how a sink node selection with prior method affected network robustness. Then we propose our method of measuring network robustness to select a sink node and finally we show how our method prevents network partitioning and results in a more robust network.

Firstly to get rid of high computational overhead of computing network robustness with considering set of metric that neglected in other methods, with a distributed computing in every node and set a value as a node suitability for each node we select the sink nodes. With this value we prevent selecting a sink node that is a risky node. We show how this scenario leads to more robust networks.

2. Related Works

In the literature on wireless sensor networks, vertex- and edge-connectivity are the most frequently used metrics for measuring the robustness of network topologies (Li et al., 2009), (Younis et al., 2008), (Misra et al., 2008), (Kashyap et al., 2006), (Zhang et al., 2007), (Han et al., 2007). Unfortunately connectivity degree as a metric for measuring network topology robustness has some weak points and its most important weak point is that it only values the graph remaining connected.

Another known topology robustness metric, with several theoretical results, is graph toughness (Bauer et al., 2006). Toughness measures the minimum ratio of vertices removed to the number of components in the resulting graph. Unfortunately, the toughness of a graph is NP-hard to compute, and thus, it is not well-suited for general practical use, especially when one is concerned with large graphs

Another similar metric is graph strength, which measures number of components in a graph (Li et al., 2009). The advantage of the minimum ratio of edges removed to the increase in the graph strength as a robustness metric is that it considers various attack strengths by default due to the fact that the minimum is taken over all possible edge removal attacks**.** However, unlike toughness, it can be computed efficiently**.**

In (Laszka et al., 2011) new metrics for measuring robustness of network with a weight for vertices and edges are defined, and by using them the algorithm starts with the set of selected sinks R as the empty set. In each step, a new vertex v is added to R; v is chosen in a simple but sensible way: such that the ratio of the gain in persistence by adding v to R to the selection cost c(v) is maximum. The algorithm stops when the persistence $\pi(G)$ of the network with set of sinks R is at least the required persistence π_0.

With their distributed nature and redundant operation capability, wireless sensor networks are very suitable for border surveillance scenarios that track intruders trying to breach to a safe side. In such scenarios, keeping the operation going on for as long as possible is the important aspect of the network. (kosar et al. 2012) propose that by placing sink at a carefully selected coordinate will result in a longer living network. (kosar et al. 2012) Also place restrictions on the candidate locations so that the sensing quality of the network is above a useful predetermined value and the sink is placed in a relatively safe location to avoid destruction. In order to find the suitable coordinates we propose a modified lifetime metric which takes quality and safety measures into account. (kosar et al. 2012) Also we propose a genetic algorithm which uses a discrete event simulator-in-the-loop over a three dimensional terrain to find locations for the sink that fit the given quality and safety restrictions. Using a three dimensional underlying terrain makes the proposed approach more realistic**.**

An ability to detect connectivity disruptions, also known as cut detection, allows WSN to conserve power and memory while reducing network congestion. (Won et al., 2012) Proposes ER**-** CD and LR-CD, protocols that detect cuts while providing energy efficiency and robustness to attack. Using distributed, cluster-based algorithms, ER-CD recognizes and determines the scope of disrupted connectivity while examining available data for evidence of an attack. For more resource-constrained networks, LR-CD enhances security through the use of a robust outlier detection algorithm.

(Isik et al., 2012) Proposes a cross layer geographic forwarding scheme MLBRF (Multi-Sink Load Balanced Reliable Forwarding) which aims to provide reliable and energy efficient video delivery in a multi-sink sensor network for target tracking. In order to provide load balancing among the sinks, MLBRF proposes a sink selection mechanism based on fuzzy logic for the frame forwarding which evaluates the traffic density in the direction of each sink by combining two dynamic criteria which are the number of contenders and the buffer occupancy levels in the neighborhood with the static distance criterion**.**

(HosseinZadeh et al., 2012) solved the problem of BS positioning in nonlinear environments. It proposes a weighted linear or nonlinear least squares optimization depending on the value of the path loss exponent. It also proposes a distributed algorithm that effectively handles the required computation by exploiting node cooperation. The goal is to minimize the total energy consumption and to prolong lifetime of the WSNs.

(Rahman et al., 2011) proposes a method for locating sink nodes in WSNs and it results in life time and energy improving in network. In this work there are some rely nodes in network to reduce the communication overhead from the nodes near the sink nodes. The nodes that are near the sink node because of high data forwarding tasks deplete their energy soon. And having relay node prevent this energy depletion from nodes near the sink nodes. In this paper for locating sinks nodes particle swarm optimization (PSO) is used.

3. Robustness of WSNs

As mentioned in prior sections, connectivity as a scale for measuring the robustness of sensor networks topology has some weak points that lead to having some restrictions in implementations of WSNs in hostile environments. Also toughness of a graph has its own problems besides this toughness of a graph is a NP-complete problem and it's computational overhead is remarkably high. And with considering limited sensor nodes energy this method cannot be used in implementation of WSNs.

Having discussed the problem from that point of view we can look at it from another perspective as well. In all aforementioned methods task of nodes as a sink node or a common node is not considered. Indeed all metrics for measuring robustness of WSNs considers the present network robustness and they didn't consider this point that if we lose some connection or some nodes affected by an attack or energy depletion, what will be the robustness of network. Losing a sink node or edges that are a link between a sink and common node that have great impact on network robustness.

In our proposed method in selecting the sink nodes we select sink nodes in a way that, with having energy depletion in nodes or losing edges during attacks network graph remain connected with maximum robustness. Also in selected sink nodes, remaining energy and amount of sensing task are considered and prevent selecting nodes that with their deletion network graph will be partitioned.

4. Describe the problem

As it described in past sections the robustness of network is a challenging problem in wireless sensor networks implementation. Robustness of wireless sensor networks before and after attacks or node death has great impact in network efficiency. Designating some nodes as sink nodes leads to have different levels of robustness. Our aim is to employ some scenarios in selection of sink nodes in a way that in case of attack or nodes die or losing edges, the robustness of network is maximum. On the other hand minimize the cost of recovering network to the acceptable connectivity level.

Indeed we want to do selection of sink node in a way that the node with best suitability is selected as a sink node. Firstly we define types of nodes that are risky to select as sink node and will have negative impact on network robustness. After defining those nodes we propose a metric with the name of suitability of node for every node in the network. And then we use this metric to recognize which node is more suitable to be selected as a sink node.

A. Risky nodes

In this section we define three types of unsuitable nodes for being a sink node. If they are selected as sink nodes, they will have bad impact in our network robustness during attacks and node or edge losing. Also we consider different precedence level for each one. The first group of improper nodes is the nodes that despite their high neighbor connectivity are a bad choice of sink nodes because with losing some edges or nodes the robustness of network falls dramatically. The second group of node is the nodes that with their losing or death the network will be partitioned and the possibility of sending sensory report from a group of nodes missed. The last group is the nodes that have minimum overlapping degree with other nodes. Considering the sink task it's better to have less sensing task in sink nodes to prevent early energy depletion in sinks nodes.

1) *High edge-connected sink with low robustness*

Number of edges connected to the sink that selected as a sink node, form viewpoint of graph theory is a good metric for assessing robustness of network graph and at first glance it seems that the nodes that will be selected as a sink node should have high edge connectivity but there is an hidden fact that will be visible if we consider the attacks or sensors death or losing edges. As it is clearly portrayed in (fig. 1), where two graphs are shown. Each graph represents a sensor network, in which the objective is to transfer measurement data from the nodes to the sink, represented by the A and B vertex. Both of these graphs have an edge-connectivity of 2, and therefore, they are supposed to be equally robust. Obviously, this is not true, because if the dashed edges are removed from the graphs, a single vertex is separated from the sink in right hand graph, while all of the vertices are separated from the sink in left hand graph. So we can conclude that the graph on the right is more robust than the other.

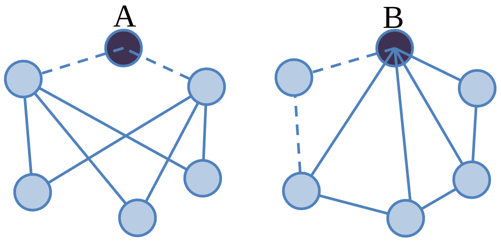

Fig 1: Illustration why edge connectivity is not a good metric for measuring network graph robustness

2) *Cut vertex's*

In consideration of network graph some nodes have a good position from the viewpoint of gathering the dada that come from other nodes and it seems that if they were selected as a sink node could have good results but with considering the failure of that node, may introduce a hole in the network coverage. In addition, the multi-hop inter-node communication paths can elevate the importance of so me nodes. Basically ,some nodes may act as cut-vertices in the network topology and thus the failure of any of these nodes would partition the network into multiple disjoint blocks so we should not select a cut vertex as a sink node e.g., Node A in (Fig. 2).

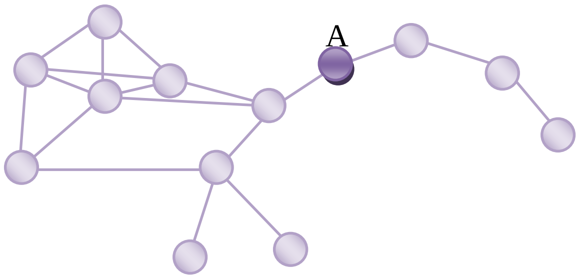

Fig 2: The failure of sink node A will partition this network into 2 disjoint blocks

3) *Nodes with minimum overlapping degree*

Sink nodes are usually selected from sensor nodes. Each sensor node has its own sensory task in its coverage area and it senses the physical phenomena and reports them, so if a node selected as a sink node besides its sensory task, task of being a sink such as coordinating and receiving other nodes sensory data and directing queries to other nodes are added to its task too. So it's clear that sink nodes consume more energy compared to other nodes that have only sensory tasks. But if the sink nodes have overlapping in their covered area they can relegate their sensory tasks to the other nodes that have overlapping with the sensing area. So it can save more energy and with this quick energy depletion in sink nodes is prevented efficiently. (Fig. 3) between A and B selecting of A is more suitable than b because it's sensing area is completely covered by other nodes and we can eliminate its sensory task and limit just to the sink tasks.

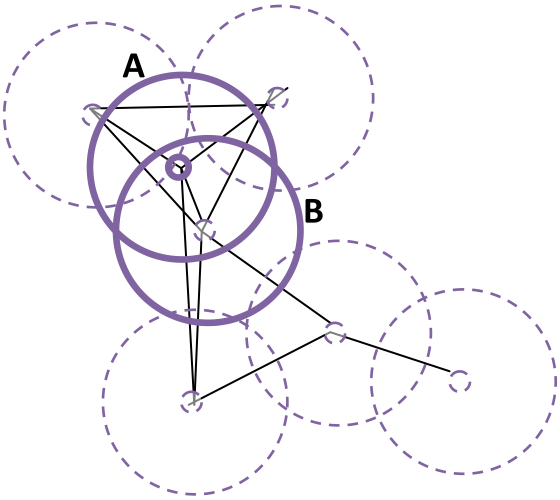

Fig 3: sink sensing area that fully covered by other nodes

B. *Suitability of node*

To prevent election of improper nodes that have been illustrated in previous sections we propose an evaluation function with the name of suitability function. The suitability is calculated for every node in the network and according to this parameter we decide whether a node is suitable for selecting as sink node or not. Suitability function has three parts such that each part comes with a priority coefficient α. It means that with considering the prospect of network and practical results the priority coefficients are adjusted.

Each node maintains a table of its direct (neighbor 1-hope) and 2 hope (neighbor 2 –hope). Such table will be used to calculate the suitability of node. By applying distributed algorithm like one proposed in (Liu et al., 2006) the suitability function can be calculated for each node. With this function the nodes that are risky give less suitability, in first part of this formula we tried to select a node that have more edges with others but for this purpose we calculate the ratio of node degree to average degree of neighbors and with this calculation we force the function to have better suitability amount for the nodes that have proper connections with other nodes.

Second most important section of the formula is the part that we prevent selecting of the nodes that have less energy and health. The health of a node is influenced by its remaining energy because, if the node with less energy selected as a sink node considering the sink communication task it depletes energy soon and it imposes the reselection cost or network repair cost so in this part of formula we add the ratio of node health to overall health of the network. In last part of the formula we tried, with a minimal priority coefficient, consider the overlapping for the sinks. To select nodes that have higher overlapping degree, we calculate the ratio of overlapped degree to sensing area (πR_s^2)

The suitability function will be as follows (Eq. 1):

$$\text{Suitability} = \alpha_1 \frac{\text{Node Degree}}{\text{Average Degree Of Neighbors}} + \alpha_2 \frac{\text{Node Health Status}}{\text{Overal Network Health Status}} + \alpha_3 \frac{\text{Overlapped Degree}}{\Pi R_s^2} \quad (1)$$

The coefficients α_1, α_2 and α_3 used to prioritize the scales and according to the network prospects will be defined. Clearly for achieving high connectivity and robustness in network α_1 should be greater than others and also α_3 will be less than the others; to have more robust networks the coefficients will be as follows: $\alpha_1 > \alpha_2 > \alpha_3$

5. Sink selection problem and solution

According to the definition of suitability for nodes and their impact on network graph robustness, in this section we address the sink selection problem and we show how our methods of selection with using suitability to a given topology works well.

Also in this section we show that how prior methods that employ node distance and edge connectivity as a metric for sink selection to prevent more messages passing through the network. Then we present our method of sink selection and we show how our method works more beneficially and with an acceptable estimation select the sinks and leads to more robust network and optimal energy consumption.

A. Our method of sink selection

For selecting a set of sink nodes usually the nodes with minimum distance and more links are selected. Determination of distance and number of direct and indirect links can be done easily; however, the problem of finding the sets of nodes with minimum distance with other and more edges is one of the famous graph theory problems and is known as a np-hard problem. Our proposed method behaves based on suitability, so with suitability scale, not only help to have more robust networks, it helps to select sink nodes efficiently. Suitability of nodes is attached to the given topology. We just select the most proper (nodes with high suitability) nodes as sink nodes. It means that with a given topology of N sensor nodes, we select M nodes that have greater suitability.

The following table (Table 1) compares our proposed method features with optimal sink selection and it shows that in our proposed method the issues like overlapping and energy balancing are considered and also the chance of selecting nodes with less energy and cut vertexes is low.

Optimum	Our Method	
No	Yes	Overlapping
Yes	Yes	Message Transmission Distance
No	Yes	Energy Balancing
High	Low	Chance Of Selecting Energy Less Node
High	Low	Chance Of Selecting A Node With Low Overlapping
High	Low	Chance Of Selecting Cut Vertexes
Possible	Possible	Regional Selection Of Sink

Table 1. features of proposed method compared to optimal selection of sink nodes

6. System implementation

In this section we first introduce our simulation setup and then in next section we analyze how to achieve the optimal setting of robust network efficiently. The most prevalent model of a wireless sensor network is a unit disc graph, which models a wireless network where each node has the same transmission radius, and two nodes are considered to be neighbors if they are within each other’s transmission range. In our simulations, we generated graphs of this type in a probabilistic manner. More precisely, a given number of nodes topology with suitability of nodes were placed in a square of 500_m*500_m we select the sink nodes. The network consists of N nodes $n_0,\ldots,n_{N-1}$. The properties of the sensor network are as follows:

- Sensor nodes are static. Because we use the given topology and suitability values to elect sink nodes, if some nodes moving, the topology of sensor network have to reconstruct, our method will be invalidated.
- Nodes are localized by GPS or other methods because the topology of sensor network is position based.
- There are uniform nodes. All nodes have similar capabilities (processing/communication/memory). Because this paper studies homogeneous sensor network.
- Sinks can connect to the sensor network from every position.
- The density of the sensor network is high enough, which can guarantee that in the network have one or more sensors as sink nodes.

7. Performance evaluation

We place 100 static nodes uniformly in a square with 500_m*500_m, all nodes in the network have the same communication range R (R=50). Also we set the α_1, α_2 and α_3 respectively 0.7, 0.2 and 0.1.We employ elapsed duration for selecting sink nodes as metrics for the performance evaluation of our selection method.

In the first simulation number of nodes is constant number of 100 and number of sinks varies from 10 to 100. In the second simulation the number of sinks is constant number of 10 and number of nodes varies 10 to 100 (fig. 4).

In both settings the figures of simulation results show that our method works more efficiently. And it’s clear that in terms of energy consumption our method is more beneficial.

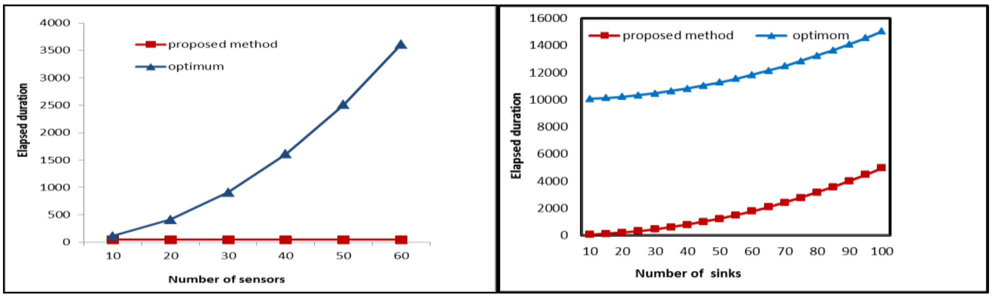

Fig 4: elapsed time for sink selection with different number of nodes and sinks

To survey our method in more detailed settings we employ different number of sensor nodes for different number of sink nodes and the results of simulation for both optimal method and our presented methods are portrayed in (figs. 5 ~ 6).

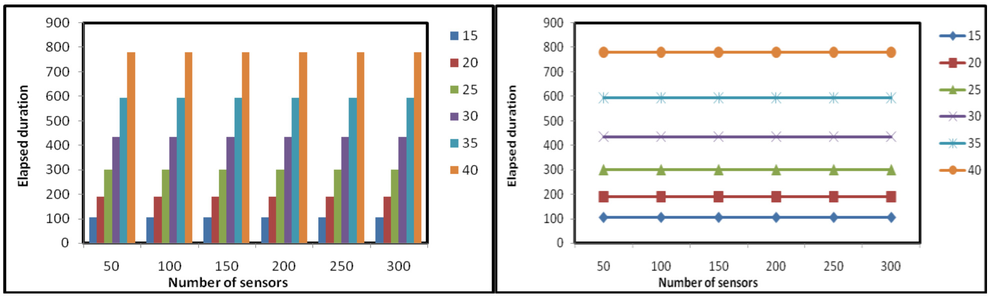

Fig 5: elapsed time for different number of sinks and network size in our method

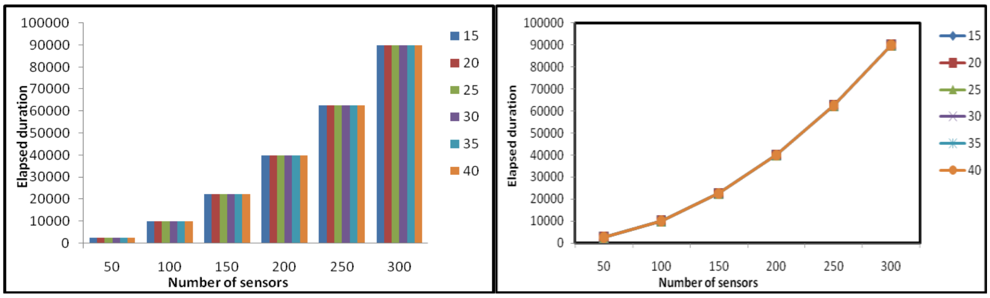

Fig 6: elapsed time for different number of sinks and network size in optimal method

(Fig. 5) shows that the duration of selection in our method didn't influenced by network size and have slight increase influenced by increase in sink numbers, also

(Fig. 6) of simulation results shows that in optimal method, the selection duration influenced by network size and with increasing in network size the duration of selection experience a dramatic increase.

In (fig. 7) we measure the connectivity and coverage's of sink nodes. We employ different network sizes and we select the 10% of them as sink nodes in (left fig. 7) we count the direct 1 hope neighbors of the all sink nodes an name it sinks total connectivity and in (right fig. 7) we calculate the sum of overlapping that sink nodes have with other nodes. In bother metrics clearly we can conclude that our method acts more efficient.

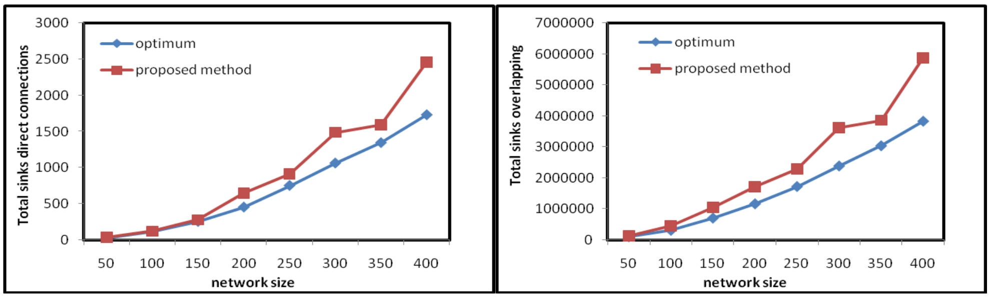

Fig 7: Selected sink nodes connectivity and overlapping

8. Conclusion And Future Work

In this paper, we study the optimization problem in selecting sink nodes with minimum cost in term of energy and time. For a given network topology with detection of risky nodes and prevention of selecting them as sink nodes we maximize the robustness of network. We proposed a measuring and suitability scale for network resisting approach. Considering this method of arraying for nodes we can efficiently select some node as sink nodes by their suitability. Our evaluations results showed that our approach is both efficient and practical.

This paper focuses on only part of general problem of designing robust wireless sensor networks, namely we assume that network topology is given, and our task was to finding best set of sink nodes such that satisfy our robustness needs and also selection cost minimized. In the future we intend to work on a more general setting. Also we want to answer this interesting question that, how we can maximize robustness of network with adding a new node or moving a node to certain location?

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