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Energy Optimization in Mobile Wireless Sensor Networks with Mobile Targets Achieving Efficient Coverage for Critical Applications

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Abstract:

The Mobile Wireless Sensor Networks (MWSN), classified within MANETS, have multiple applications for critical situations management such as target monitoring and tracking in conflict zones, supporting urban security, critical infrastructure monitoring, remote locations exploration (i.e. aerospace exploration), and patients monitoring and care in health facilities, among others. All of these applications have requirements of certain intelligence in the network that can be used for network's self-configuration in order to find targets, guarantee connectivity and information availability until its reception.

This paper proposes a MWSN architecture with an initial random distribution in a specific work area, and a centralized management to perform autonomous decision making about the movement and connectivity of the sensors. The work area presents mobile targets with interesting events which must be covered by the mobile sensors, and thus, send the collected information through the network to any base station available. Our work shows a dynamic mathematical model used to maximize targets' coverage and send its sensed information to the base stations available, while minimizing system's power consumption and maximizing operation time. The heuristic algorithm we used to construct and find a feasible solution is also shown.

Keywords: MWSN, multiobjective optimization, shortest path, coverage, location, energy efficiency.

1 Introduction

Mobile Wireless Sensor Networks (MWSN) are systems with a large amount of limitations and restrictions inherited from WSN systems but with the additional degree of liberty to move the sensor nodes which make them complex systems. Nodes' mobility within the network enhance the applications of these kind of systems but makes decision making more difficult, since it introduces a new dynamic feature in the network that changes all other parameters in every step of the movement (connectivity, bandwidth, noise and energy). However, these kind of problems can be solved to be used in a series of critical applications with mobile scenarios like warfare situations, where targets will be moving in time and sensors can be deployed randomly to track these targets and send the information back to the base; disaster recovery situations, where robots with a central information management can move around the disaster area looking for targets like people trapped inside structures and send this information through a direct link or using other robots to convey the information to the base; and space exploration, where robotic rovers must move around to look for targets and communicate with satellites to send the information back to earth.

The model presented in this work assumes that every node is mobile and can act as a router, sending their own information and forwarding information from other nodes to base stations (BS). It is also assumed that the BSs don't have sensors embedded and can't move. Given mobile targets, it is necessary to adjust mobile sensors positions in order to maintain connectivity and minimize energy consumption. In other words, it is possible that certain sensors must move to cover a specific target, maintaining connectivity with their neighbours to send properly collected data to a base station. Since all network elements can move, it is necessary to use a dynamic mathematical model that takes into account each network state in order to guarantee connectivity and minimum energy consumption.

The remainder of the paper is organized as follows: Section II states the problem and some related work. Section III presents the solutions' mathematical model and computational algorithm, showing the methodology to implement it, and additionally, explaining several criteria to design the heuristic according to the MWSN constraints. Section IV shows some results for several instances with different parameters. Finally, in Section V, conclusions and future work are presented.

2 Problem statement and related work

This paper presents a difficult problem of Mobile Wireless Sensor Networks with Mobile Targets (MWSN-MT), which consists of an area of interest with mobile targets, mobile sensors and one or more base stations available inside, which can't move and its position is known. The targets position is unknown and the sensors positions can be changed with an order from a centralized management system. The problem consists in finding all the targets inside the area and create communication paths from them to the base stations while at the same time minimizing the energetic cost associated to the mobile sensors sensing, movement, transmission and reception of data. The problem can be seen as the iterative solution of multiple shortest path (SP) problems from the targets found to any base station available, multiple coverage problems where the mobile sensors will try to maximize the area covered looking for all the targets, in topologies where the paths may not exist or could change in future iterations.

Some related work used as basis for our research can be found in the book by Ahuja et al. [1] where the authors explain optimization for network problems and several algorithms used to solve them. Church and ReVelle [2] state the maximal covering location problem and set the basis for further research on the subject. Chvátal [3] states the set covering problem and solves it through a greedy heuristic. Baldacci et al [4] combine routing and covering problems and solve them with exact and heuristic algorithms. Powell [5] in his book states the basis of approximate dynamic programming (ADP) and gives models, examples and applications for its use. Chabini [6] presents solutions for all to one shortest path problems in discrete dynamic networks. Also, works on mobile robotics by Chakraborty and Sycara [7] present a dynamic approach for a mobile robotic network where the decisions can be taken centralized or distributed while maintaining connectivity in the network. Zavlanos et al. [8] use a distributed hybrid approach to control mobility of the robotic network while maintaining connectivity at desired rates. Works on mobile wireless sensor networks by Miao et al. [9] explore the problem of deployment and distribution of mobile sensor networks through swarm intelligence. Wang et al. [10] review mobile sensor networks challenges and applications. Finally, Cortes et al. [11] present control and coordination algorithms for mobile sensors. While the previous works serve as the basis for our research, this paper introduces the system energy consumption consideration in a distributed target searching application, a research that can lead to mobile, autonomous and efficient networks for disaster inspection and remote site exploration among other applications.

3 Problem solution

3.1 Mathematical Formulation

The network begins with an initial graph $G = (S, B, T, E, A)$, where S is the node set composed of mobile sensors, B is the set of Base Stations (nodes without mobility nor sensing capabilities but with connectivity outside the network) and T is the targets set; E is the edges set, which are the feasible connections between mobile sensors and between sensors and Base Stations, and A is the arcs set, which are the feasible links from targets to sensors. The graph G is converted in a new graph $G' = (S', B', T', E', A')$ after each run of the algorithm. This process is performed iteratively to reach the targets and guarantee connectivity between mobile sensors and base stations as the network elements move.

The sensors have transmitting and sensing features which follow the well known disk coverage model where each sensor is assumed to cover a disk centered at itself with fixed sensing and transmitting ranges as disk radii. If a sensor cannot reach any target, it can move seeking it or serving as a relay node for communications. However, the use of these capabilities affects the energy consumption of the network and reduces its lifetime; therefore, in the initial state, sensors have an energy level which is reduced by movement, data transmission and reception. In each following state it is necessary to minimize the energy consumption in order to extend the lifetime of the network and increase the probability to find targets. The system also has to maximize coverage trying to find all targets. In figure 1, the basic structure of the optimization model is shown.

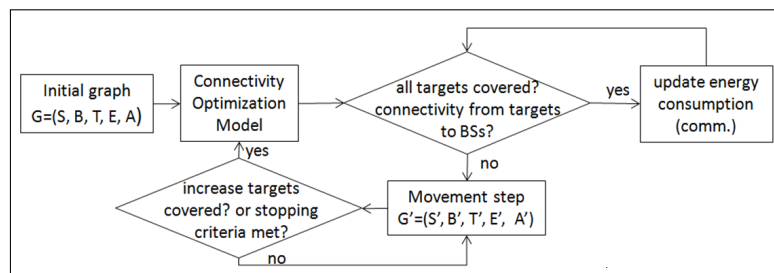


Figure 1: Optimization model structure

The mathematical model notation is shown in Table 1. A is the arcs set, representing sensors to targets connections. E is the edges set, representing sensors to sensors or to Base Stations connections. rc is the maximum distance for wireless links between sensors and sensors to Base Stations and rs is the maximum distance for sensing (sensor to target). Parameters rc and rs are assumed to be constants for all nodes.

T	Targets set t	bat_{ik}	Battery level available at edge $(i, k) \in E$
S	Mobile sensors set i, j	Cap_{ik}	Capacity of edge $(i, k) \in E$
B	Base stations set b	$dist_{ik}$	Length of edge $(i, k) \in E$
E	Edges set $(i, k), i \in S, k \in S \cup B$	f_t	Data flow demand (in bps) from target $t \in T$
A	Arcs set $(i, t), i \in S, t \in T$	c_{ik}	Energetic cost of edge $(i, k) \in E$
d_{it}	Cost of arc $(i, t) \in A$	rc	Communication radius between nodes in $S \cup B$
rs	Sensing radius between (S) and (T)		

Table 1: Mathematical model notation

Decision variables: x_{ik}^t is "1" if edge (i, k) is in the path for target t to any Base Station and

"0" otherwise; and z_{it} is "1" if target t is covered by sensor i , "0" otherwise.

$$\min w_1 \sum_{t \in T} \sum_{e \in E} c_{ik} x_{ik}^t + w_2 \sum_{(i,t) \in A} d_{it} z_{it} \quad (1)$$

subject to:

$$w_1 + w_2 = 1 \quad (2)$$

Construction constraints

$$\sum_{t \in T} dist_{ik} x_{ik}^t \leq rc \quad \forall (i, k) \in E \quad (3)$$

$$dist_{it} z_{it} \leq rs \quad \forall i \in S, t \in T \quad (4)$$

Energy consumption constraints

$$\sum_{t \in T} c_{ik} x_{ik}^t \leq bat_{ik} \quad \forall (i, k) \in E \quad (5)$$

$$\sum_{i \in S} z_{it} = 1 \quad \forall t \in T \quad (6)$$

$$\sum_{t \in T} z_{it} = 1 \quad \forall i \in S \quad (7)$$

Data flow and connectivity constraints

$$\sum_{t \in T} f_t x_{ik}^t \leq Cap_{ik} \quad \forall (i, k) \in E \quad (8)$$

$$\sum_{(i,t) \in A} f_t z_{it} = \sum_{(j,b) \in E} f_t x_{jb}^t \quad (9)$$

$$\sum_{j \in S} \sum_{t \in T} x_{ij}^t - \sum_{j \in S} \sum_{t \in T} x_{ji}^t = 0 \quad \forall i \in S \quad (10)$$

Integrality constraints

$$x_{ik}^t \in \{0, 1\} \quad \forall (i, k) \in E, t \in T \quad (11)$$

$$z_{it} \in \{0, 1\} \quad \forall (i, t) \in A \quad (12)$$

Constraints (3) and (4) state that the links between nodes can only exist if the distance between them is less than the communications coverage radius parameter (rc) and a sensor can only cover a target if the distance from the node to the target is less than the sensing coverage radius parameter (rs). Constraint (5) states that energy consumption on a link between two nodes can't be greater than the energy available at that link. Constraint (6) assures that a target must be covered by at least one sensor while (7) assures that at most one sensor covers a target actively. Constraint (8) states that data flow through a link must be less or equal than the links capacity. Constraint (9) states that the data flow generated from the targets covered must arrive at the base stations. Constraint (10) is the balance constraint, stating that all the flow entering a sensor node must be equal to the flow leaving that sensor node.

3.2 Computational implementation

Figure 2 presents the solution algorithm pseudo-code. In this table the algorithms functional characteristics are shown. The solution seeks to cover all targets one at a time by looking for a communications path from a sensor covering the target to any base station in the grid. If a target isn't covered by a sensor, the algorithm will move the n most energetic sensors spreading them around unexplored areas, maximizing the area coverage while looking for the target(s) missing for a predefined number m of steps or until the target(s) is covered.

Our solution uses a greedy heuristic procedure based in minimum cost (cost is defined as a combination of distance and energy consumption). Some relaxations from the mathematical model discussed before are implemented in the algorithm, those relaxations are as follows:

- Constraints (6) and (7). Each target must be covered by at most one mobile sensor. Whether there is more than one mobile sensor covering the target, it is necessary to select the sensor with minimum cost and greater energy. If there is no sensor covering the target, the algorithm will try to find it through sensors movement.
- Constraints (9) and (10). For a given target, it is required to find a path form the target to any base station. Therefore, a base station is able to receive information from different targets, and it is possible that a base station will not be selected to receive information. Also, if the target can't send its information to a base station, the algorithm will try to create a path to a base station through sensor movement.

```

read positions and energy status for Mobile Sensors and Base Stations
while (counter < |T|)
  while ((tcounter is not covered) || (steps <= m))
    move 1 step the n most energetic sensors not belonging to any Path nor covering other t
    steps ++2
    update energy
  end
  if (tcounter is covered by at least 1 sensor)
    get minimum cost sensor i covering tcounter at minimum cost to any BS
    add sensor i to Path
    search = sensor i
    while (search doesn't have connectivity to any BS)
      get minimum cost sensor j covering search at minimum cost to any BS and
      sensor j doesn't belong to Path
      search = sensor j
      add sensor j to Path
    end
  end
  counter++
end

```

Figure 2: Solution algorithm pseudo-code

4 Results

This section presents computational results for the heuristic algorithm described in the previous section. The algorithm was coded in MATLAB[®] from MathWorks. The experiments were performed on a CORE 2 DUO personal computer equipped with 4 GB of RAM and running under Microsoft Windows 7. We considered 5 random instances with parameters stated in Table 2. The instances present variations in the numbers of mobile sensors, targets and base stations and nodes and targets initial positions. Parameters like communications coverage radius (rc), sensing coverage radius (rs), initial energy level ($einit$), energy consumption by communications ($ecomm$), sensing ($esens$) and movement actions ($emove$), number of maximum steps to move looking for a target (m) and number of mobile sensors to move in each step (n) are kept constant

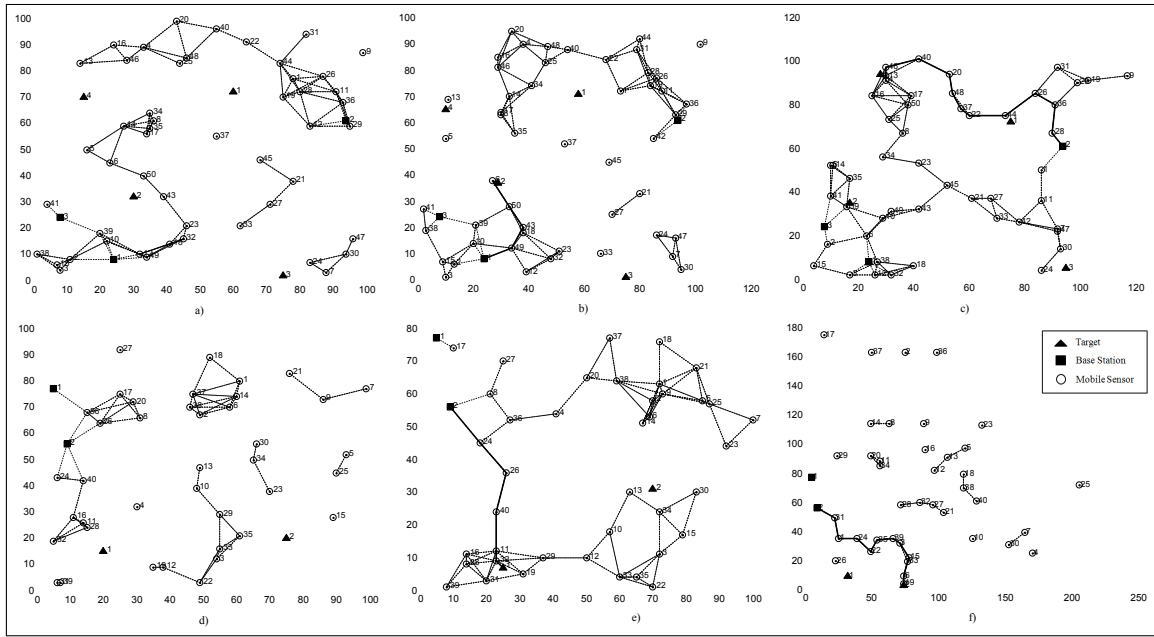


Figure 3: Graphical results for two different instances

Instance name	Mobile sensors	Targets	Base Stations
MWSN50.2.2	50	2	2
MWSN50.4.3	50	4	3
MWSN50.3.5	50	3	5
MWSN40.2.2	40	2	2
MWSN40.4.3	40	4	3

Table 2: Instances used

for all instances; these parameters values are shown in Table 3. The graphical results shown in Figure 3 are graphs representations for two different instances were a) and d) show the initial graph and c) and f) show a feasible solution found. Restriction compliant links are painted in the figures. Triangular nodes (\blacktriangle) represent the target to be covered. Circular nodes (\odot) represent the sensor nodes that can cover the targets and provide connectivity to base stations. Square nodes (\blacksquare) represent base stations nodes that can be reached to convey target information. The path(s) shown were found searching for the most efficient path in terms of jumps and energy saving from coverage node to base station node.

The numerical solution results for Figure 3 and the other instances in Table 2 are shown in Table 4. We performed 10 runs of the algorithm for each instance and the values for the number of iterations, energy consumption and CPU time were averaged over those 10 runs, however in the cases were the algorithm didn't find a path, the results weren't taken into account. The algorithm couldn't find a first path 5% of the runs and the last path (covering all targets) 20% of the runs.

5 Conclusions and Future Work

We have presented a novel dynamic multi objective optimization approach using a greedy heuristic and a two step optimization procedure where several objectives are searched at a time

Parameter	Value
<i>rc</i>	15[m]
<i>rs</i>	2[m]
<i>einit</i>	10000[mA/hr]
<i>ecomm</i>	10[m]
<i>emove</i>	40[m]
<i>esens</i>	5[m]
<i>m</i>	1[step]
<i>n</i>	20%[nodes]

Table 3: Parameters values used for all instances

instance	first path	first path	first path	last path	last path	last path
	iterations	energy	CPU time[s]	iterations	energy	CPU time[s]
MWSN50.2.2	120,4	18,5267	0,49452	313,2	46,4009	1,04676
MWSN50.4.3	31,5	9,672	0,3354	191,8	53,8483	1,15752
MWSN50.3.5	4,7	0,6747	0,21372	92,6	18,8868	0,546
MWSN40.2.2	57	10,78841	0,3354	209,5	37,16683	0,74256
MWSN40.4.3	52,8	20,52101	0,4368	162,8	59,17033	0,92508

Table 4: Numerical results for all instances

and where the network configuration can change at any time. The instances presented were constructed randomly and the algorithm was tested several times with each one of them achieving promising results. The system was able to find a path to at least a target 95% of the times before the energy consumption forbids it. Also a path from all targets was achieved 80% of the times in the instances tested, showing some baseline performance over further research can be contrasted and compared.

If the network has few mobile sensors, the movement action will waste most of the energy to find the targets, this action should be restricted and used wisely in order to enhance systems lifetime. The number of targets in the system related with the mobile sensors number will determine the emphasis of the algorithm, coverage or path finding. The results in this paper show that it is possible to automate the decision making in critical response time scenarios where information can flow in the system and a centralized management system can take actions to ensure coverage and information flow to support decision at a higher level.

Further research can be done using real life scenarios, taking into account propagation models for the communications links, realistic areas with obstacles for mobility and connectivity, target mobility models based on different applications, exact algorithms in conjunction with heuristics and distributed computing like swarm intelligence for problem solving.

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