Simultaneous Optimization of Transmission Range and Actor Movement in WSANs

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***Abstract*—Wireless sensor and actor networks (WSANs) are composed of static sensor nodes and movable actors. We assume actors have a random initial location in the field. The objective is to move each actor to a location such that every sensor node is within one transmission hop from some actor. Because sensor nodes have limited energy, finding actor locations that minimize the transmission range required from the sensor nodes may significantly increase network lifetime. However, actors also have a limited (although larger) power supply, and their movement depletes their resources. It follows that an optimal pairing of actors with the chosen new locations may also provide energy savings for the actors. In this paper, we address the problem that simultaneously minimizes sensor transmission radius and total actor movement. Due to its complexity, we present a heuristic and compare it against an optimial ILP solution. More importantly, we consider two approaches for both the heuristic and the ILP. First, actor locations that minimize transmission range are found, and then the assignment of actors to locations is performed (double-step approach). Second, a joint-optimization (single-step) approach is proposed in which transmission range and actor movement are considered simultaneously. We show that the single-step approach outperforms the double-step approach.**

I. Introduction

Recent improved hardware technology allows wireless sensor and actor networks (WSANs), which have attracted much interest. WSANs are composed of wireless sensor nodes and movable *actors* (e.g., unmanned vehicles, mobile robots), which have the ability to change their location; although more powerful than sensor nodes, the energy of actors is still limited. When a sensor node gathers data for a specific event, it sends the sensing information to an actor. Actors make decisions for various issues and execute necessary actions based on the received information from sensor nodes and from other actors [1]. Furthermore, multiple mobile actors improve network performance by increasing network lifetime and reducing data latency. WSANs can be used in numerous applications, such as battlefield surveillance, urban search and rescue, environmental monitoring, etc..

In WSANs, one major challenge is choosing the location of actors to achieve various network goals, such as maximizing coverage of sensors, minimizing data collection delay, etc.. Though all sensor nodes have the same resources, some nodes can consume more energy because an amount of communication is different among nodes, due to their proximity to a point of interest. Because the resources at sensor nodes are limited and a longer transmission range implies more energy consumption, we determine the smallest transmission radius, r_{min}, such that each sensor node can communicate directly with at least one actor. Therefore, k locations must be determined, where k is the number of actors, such that, all sensor nodes are within r_{min} from at least one of these locations.

Although the actors are equipped with more powerful resources when compared to sensor nodes, they still have a constrained battery. Movement of actors consumes significant energy from their batteries in comparison to computation and collection of messages [2]. Because actors cannot be easily recharged after their deployment, minimizing the movement of actors is an important issue [3].

Motivated by the above observations, our goal is to find optimal actor positions in a network topology where both n sensor nodes and k actors are randomly located; sensor nodes have a fixed location, while actor nodes can relocate by their own power to optimize the network. Our objective is the joint optimization of two values. The first one is minimizing the transmission radius such that each sensor can communicate with at least one actor. The second one is minimizing total actor movement from their initial locations to the newly chosen locations. In this paper, we define this problem as MRAMS (Minimizing Range and Actor Movement Simultaneously). Due to the complexity of the problem, we present a heuristic, and compare it against an optimal ILP solution.

More importantly, we consider two approaches for both the heuristic and the ILP. First, actor locations that minimize transmission range are found, and then the assignment of actors to locations is accomplished (double-step approach). Second, a joint-optimization (single-step approach) is proposed in which transmission range and actor movement are considered simultaneously. We show that the single-step approach outperforms the double-step approach.

II. Minimizing Transmission Range

First, we discuss existing work on minimizing node transmission range. Consider finding the minimum radius r_{min} such that all sensor nodes are within a distance r_{min} from at least one of k actors. This problem is equivalent to the

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euclidean p-center problem [4][5][6]. They defined euclidean p-center problem which find p positions such that the furthest distance between given n demand points and their closest supply points is as close as possible. Their solutions may be obtained as follows [7].

Note that the problem is non-trivial because there are an infinite number of locations where actors may be placed (any point on the plane), and there are an infinite number of radii r to consider, since we do not assume r is discrete. At first glance, it appears to be a daunting task. However, although NP-hard, the problem is NP-complete, and a solution can be found by carefully selecting a finite set of possible actor locations and a finite set of radii. It can be shown [5][8] that the optimum radius r_{min} must belong to a finite set $R(S)$, where $|R(S)| \in \mathrm{O}(n^3)$. Also, for any r, if all sensor nodes can be covered by the actors using radius r, then the same can be accomplished if actor locations are chosen from some finite set $P(S, r)$, where $|P(S, r)| \in \mathrm{O}(n^2)$. I.e., if there is a solution with radius r, then there is also a solution with actor locations chosen from $P(S, r)$.

To solve the problem, let us consider given a set S of n sensors, $s_1, \ldots s_n$, which are randomly deployed in a two-dimensional plane. A total of k actors, $t_1, \ldots t_n$ are to be placed on the field. Then, assume there exists a procedure, $solve(S, k, r)$, to determine if, for a given radius r, it is possible to cover all sensor nodes with k actors. Obviously, if $r \geq r'$ and $solve(S, k, r')$ is successful, then so will $solve(S, k, r)$. Hence, a binary search is performed over the elements of $R(S)$ to find the smallest r satisfying $solve(S, k, r)$. This yields the optimum radius r_{min}.

The complexity of the problem arises not from the binary search ($O(\log n)$ steps), but from performing procedure $solve(S, k, r)$. As mentioned above, for a given radius r, a solution must exist by selecting actor positions from set $P(S, r)$, which is finite. Thus, $solve(S, k, r)$ may be implemented by testing all subsets of $P(S, r)$ of cardinality k, which has exponential complexity.

Due to space restrictions, we do not discuss why $P(S, r) \in \mathrm{O}(n^2)$ (See [4][9][10] for details). Briefly, however, we discuss why $R(S) \in \mathrm{O}(n^3)$.

Consider a subset S' of sensor nodes, and deliberate on the *smallest* circle that covers each node in S'. In Fig. 1, we describe all possible cases. Fig. 1. (a) shows when the edge of the circle touches three or more sensors (drawn larger for clarity). Note that any three points in the plane define a unique circle that touches these three points. Fig.1. (b) depicts when the smallest circle touches two nodes at opposite ends of its diameter. Fig. 1. (c) shows the degenerate case where $|S'| = 1$ and the radius is zero. Let $R(S)$ be the circles defined by all triples, doubles, and singletons that can be obtained from the set S of sensor nodes. Note that $|R(S)| \in \mathrm{O}(n^3)$. Thus, there are $\mathrm{O}(n^3)$ minimum circles (and their corresponding radii) that cover subsets of S. Also, note that any solution (i.e., with radius r_{min}) must contain at least one actor whose sensors are at the edge of its range, otherwise, the transmission range could be diminished. Hence, $r_{min} \in R(S)$.

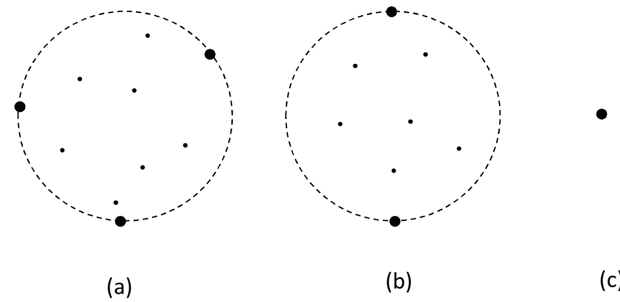

Fig. 1. Minimum circles covering a set of points.

III. Minimizing Actor Movement

There has been few works in the area of minimizing actor movements. Most works address only the selection of locations where actors (or other significant nodes) are to be placed. Some of these works are the following. In [9], the k-sink placement problem is defined whose goal is to minimize the maximum hop-distance between a node and its nearest sink. In [12], the placement of actors for load balancing is addressed. Their objective is to find clusters such that the size of each cluster is at most k and all sensor nodes in a cluster are within d-hops from a cluster head. In [13], the location for k sinks are chosen such that the average hop and euclidean distance between all sensor nodes and their nearest sink are minimized.

Once locations are chosen for actors, pairing actors with their new location poses an optimization problem if the distance traveled by actors is to be minimized. In [14] and [15], the authors proposed a pairing of actors and cluster heads using heuristic whose goal is to minimize total actor movement or total matching distance between actors and cluster head.

We distinguish ourselves from the above works in two ways. First, all the works above consider a constant transmission radius while in our approach the transmission radius is a parameter to be optimized. Second, we consider a joint optimization of the transmission radius and the actor movement, as discussed below.

IV. Simultaneous Approach for MRAMS

Minimizing sensor transmission range and actor movement are conflicting goals. E.g., actor movement is minimized to zero by simply extending the transmission range. We thus choose to optimize one of these two values, transmission range in particular, and then optimize actor movement given the minimum transmission range.

Formally, our problem can be defined as follows. We are given a sensor set S and a set of initial random locations I for actors. Our objective is to find a set A of new actor locations, where $|I| = |A|$, and a one-to-one function M, $M : I \rightarrow A$, such that, each sensor node can reach at least one actor within the minimum radius r_{min}, and the mapping M results in the least total actor movement among all functions from I to A.

Note that there could be multiple solutions for the actor locations that provide the same radius r_{min}. Not all solutions, however, provide actor locations that minimize actor movement. I.e., some solutions have the new actor locations close to the initial actor locations, while others do not.

From the above, if actor movement is to be minimized, choosing actor locations must be done such that the minimum transmission range is found, *and*, the minimum actor movement is obtained. We refer to this approach as the *single-step* approach. We refer to choosing first all the actor locations based on transmission range, followed then by pairing actors with the new locations, as the *double-step* approach.

V. Heuristics for MRAMS

In this section, we present our *single-step* heuristic for the MRAMS problem. Because an optimal positioning for actors is known to be NP-hard [16], a heuristic is necessary for practical reasons. An exact Integer-Linear Programming solution is presented in Section VI.

As discussed in Section II, the minimum radius must belong to the set $R(S)$, where $|R(S)| \in O(n^3)$. Thus, we perform binary search over the values in $R(S)$, as described before.

For a specific transmission radius r, we present a heuristic *joint-solve*(S, I, r) to find the actor locations A and the mapping M such that each sensor is within a distance r from some actor, and M minimizes the actor movement. The actor locations A are chosen from set $P(S, r)$ as described earlier.

Our heuristic is similar to the one we presented in [10]. It consists of a greedy approach, in which actor locations are iteratively chosen one by one. An actor location is chosen if it covers more sensors than any other actor location. Once the location is chosen, the sensors it covers are removed from the set of available sensors, and the process is repeated.

However, to incorporate actor movement, we need more flexibility in the choice of the next actor location. That is, at each iteration, we select a subset of actor locations that provide sensible, but not necessarily the largest, coverage of sensors. From this set, we chose the location with the smallest distance to any unassigned actor. This flexibility is governed by a user-defined parameter α, $0 \leq \alpha \leq 1$, as described below.

We thus perform the following steps for k iterations.

- Determine the maximum number of sensor nodes (*MaxSensors*), which are covered by any one potential position from $P(S, r)$.
- Find the potential positions from $P(S, r)$ that cover at least (*MaxSensors* $\times$ $(1 - \alpha)$) sensor nodes.
- Among these potential positions, select the pair (initial actor position i, potential position p) with the closest distance from i to p.

The pseudocode of the heuristic is presented in more detail in Algorithm 1.

Note that, because at each iteration we do not choose the location with the best coverage, we might end up with a larger radius than the heuristic in [10] (i.e. if we choose $\alpha = 0$). However, significant gains are made in movement (as shown in Section VII) without significant sacrifices in radius.

We have evaluated other heuristics, but the on in Algorithm 1 has shown the best performance. Please refer to [11] for more details.

Algorithm 1 *joint-solve*(S, I, r, α)

Set selected actor positions $A \leftarrow \emptyset$
Set mapping $M \leftarrow \emptyset$
Set unmapped initial positions $I' \leftarrow I$
Set uncovered sensor nodes $S' \leftarrow S$
while $|I'| > 0$ **do**
  Find the maximum number of sensor nodes, *MaxSensors*, from S', which are covered by a single potential position in $P(S, r)$.
  Let T be the set of potential positions in $P(S, r)$ such that each position in T covers at least (*MaxSensors* $\times$ $(1 - \alpha)$) sensor nodes in S'.
  Let (i, p), where $i \in I'$ and $p \in T$, be the pair with minimum distance from i to p.
  Set $A \leftarrow A \bigcup \{p\}$
  Set $M \leftarrow M \bigcup (i, p)$
  Set $I' \leftarrow I' - \{i\}$
  Set $S' \leftarrow S' - \{$neighbor sensor nodes of $p\}$
end while
Return *success* if $S' = \emptyset$, otherwise *failure*.

VI. ILP Formulation for MRAMS

Above, deciding if all sensors can be covered using a particular radius r and obtaining the mapping M were based on a heuristic; these may incorrectly result in values that are larger than the optimal.

To ensure that we obtain the true optimal values, we replace our heuristic *joint-solve*(S, I, r) by an ILP formulation. Because our ILP formulation is implemented as a single-step for MRAMS, we call it as *single-ILP*. The *single-ILP* uses the finite potential positions P, where $P = P(S, r)$. The objective function of *single-ILP* is to minimize total distance traveled by actors after their initial random deployment of actors. Moreover, we enforce that each sensor is within a distance r from some actor.

Note that a binary search over all values in $R(S)$ is still necessary, since *single-ILP* only determines if the specific radius r is sufficient to cover all sensors, but does not directly obtain r_{min}.

A. Notation

We define notations in the ILP formulation as follows.

P: set of potential locations for the actors.
n: total number of sensor nodes.
m: total number of potential locations for actors ($m = |P|$).
k: total number of deployed actors.
i: index for a sensor node ($1 \leq i \leq n$).
j: index for a deployed actor ($1 \leq j \leq k$).
p: index for a potential position in the set P ($1 \leq i \leq m$).
$\delta_{i,p}$: distance from sensor node i to potential position p.

$d_{j,p}$: distance from potential position p to initial location of actor j.

Also, we define the following integer variables.

$$X_{i,p} = \begin{cases} 1, & \text{if the sensor node is associated with potential position } p \\ 0, & \text{otherwise.} \end{cases}$$

$$Y_{j,p} = \begin{cases} 1, & \text{if an actor } j \text{ moves to potential position } p \\ 0, & \text{otherwise.} \end{cases}$$

$$Z_p = \begin{cases} 1, & \text{if potential position } p \text{ is chosen as one of the } K \text{ positions} \\ 0, & \text{otherwise.} \end{cases}$$

B. ILP formulation

Our objective function is to minimize the sum of the distances between the initial and the position for transmission range. So, the objective function is to

$$\textbf{Minimize} \sum_{j=1}^{k}\sum_{p=1}^{m} d_{j,p} \cdot Y_{j,p} \quad (1)$$

Subject to:

$$\delta_{i,p} \cdot X_{i,p} \leq r, (\forall i, \forall p) \quad (2)$$

$$\sum_{p=1}^{m} X_{i,p} = 1, (\forall i) \quad (3)$$

$$X_{i,p} \leq Z_p, (\forall i, \forall p) \quad (4)$$

$$\sum_{p=1}^{m} Y_{j,p} = 1, (\forall j) \quad (5)$$

$$Y_{j,p} \leq Z_p, (\forall j, \forall p) \quad (6)$$

$$\sum_{p=1}^{m} Z_p = k \quad (7)$$

C. Justification of the ILP equations

The objective function, given in (1), minimizes the total distance between initial actor positions and potential positions related to transmission radius, such that constraints (2) through (8) are satisfied.

Constraint (2) makes sure that the transmission range of each sensor node is at most r, which is the transmission range in use by Algorithm 1. To find the smallest transmission range, we check the smallest r which allows ILP formulation to be solvable. In constraint (3), we ensure that each node is connected with exactly one potential position. Constraint (4) forces a potential position to be one of the selected k positions, provided at least one sensor node is associated with this location. From Constraint (5), each actor j is allowed to move to exactly one potential position p. Constraint (6) requires that if an actor selects some potential position, it has to be one of the selected K positions. Constraint (7) forces the number of selected actor locations for MRAMS to be k.

VII. Experimental Evaluation

In this section, we analyze the performance of our heuristic and ILP formulation. To verify our performance, we define four approaches: *single-heuristic*, *double-heuristic*, *single-ILP* and *double-ILP*.

Our heuristic and ILP formulation in Sections V and VI are referred to as *single-heuristic* and *single-ILP*, respectively. On the other hand, *double-heuristic* and *double-ILP* operate in two steps. In the first step, they find a solution to $solve(S, k, r)$ by searching for the k actor locations irrespective of actor movement. *Double-heuristic* uses the heuristic we presented in [10] (similar to that of Section II) and *double-ILP* uses an ILP formulation also described in [10]. In the second step, actors are paired with their new locations. In *double-heuristic*, a greedy approach is accomplished that iteratively pairs each actor with its closest location, while in *double-ILP* a simple ILP formulation obtains the optimal matching.

We simulated our various experiments in a square-shaped sensor area of size 500 $\times$ 500 m^2. Furthermore, each experiment represents average result by different 10 graphs where sensor nodes and k actors are randomly deployed in a graph. We implemented our simulations with various numbers of sensor nodes ranging from 30 to 100. The number of actors ranges between 6 and 20. When we execute *single-heuristic* and *double-heuristic* for MRAMS, we used C^{++}, and the results for *single-ILP* and *double-ILP* are obtained using CPLEX [17].

In the first simulation, for sum of actor movement distance, we compared four approaches with the number of sensor node = 100 and α = 0.2; *single-heuristic*, *single-ILP*, *double-heuristic* and *double-ILP*. The number of actors ranges from 6 to 20. The comparison is shown in Fig. 2. As we expected it, *single-ILP* has the best result because it is optimal for total actor movement. In particular, our *single-heuristic* is sufficiently better result than *double-heuristic*.

In the second second scenario, we also compared four approaches for the smallest node transmission range with the number of sensor node = 100 and α = 0.2. Fig. 3. shows the result. Interestingly, as the number of actors in the network grows, the result by our *single-heuristic* becomes closer to the optimum using ILP. For example, when the number of actors is 20, the gap between the *single-ILP* and *single-heuristic* is very small.

Lastly, we verify the results by the third and fourth experiments. We implemented our *single-heuristic* with the number of sensor nodes = 100 by different α parameter as 0.1 and 0.2 and 0.3, respectively. We could check total actor movement by different α in Fig. 4. Furthermore, Fig. 5. shows the result by different α for transmission range. As the number of actors increases, the smallest transmission radius for three different α decreases. Moreover, as the number of actors grows, the results of transmission radius for three different α have a little gap.

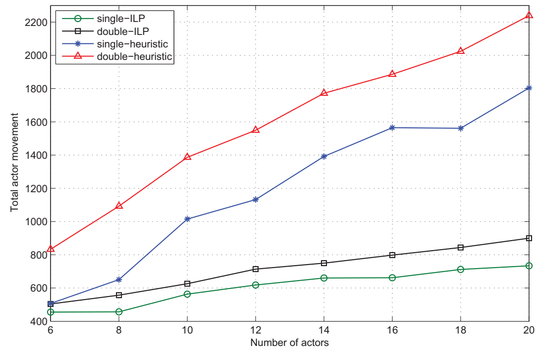

Fig. 2. Comparison of the total actor movement with the number of sensor nodes = 100 and α = 0.2 by different approaches

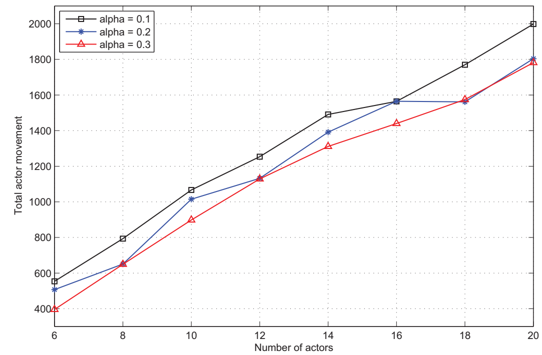

Fig. 4. Total actor movement by different α(alpha) with the number of sensor nodes = 100 using *single-heuristic*

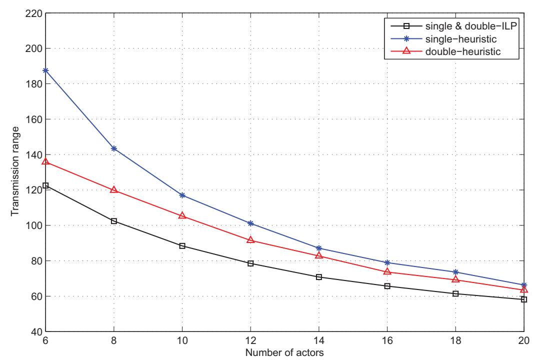

Fig. 3. Comparison of the smallest transmission range with the number of sensor nodes = 100 and α = 0.2 by different approaches

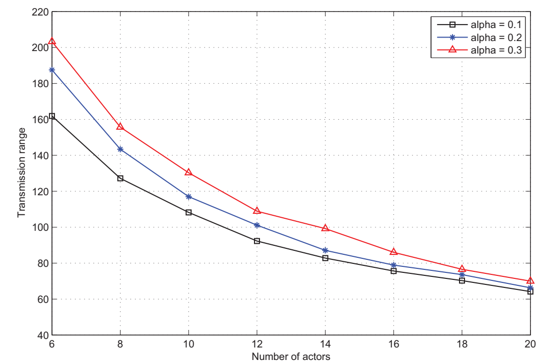

Fig. 5. Smallest transmission range by different α(alpha) with the number of sensor nodes = 100 using *single-heuristic*

VIII. Summary and Concluding Remarks

In this paper, we studied the problem for minimizing transmission range and actor movement simultaneously in WSANs. The simultaneous optimization problem depends on how to choose k actor locations not on existing sensor nodes but at any place in the field. We proposed a heuristic for the problem and compared the heuristic with the result by our ILP formulations. As future work, we extend MRAMS problem for multi-hop communication.

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