Robotic wireless network connection of civilians for emergency response operations

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***Abstract*—Mobile robots equipped with wireless devices can prove very useful during emergency response operations. We envision such robots that locate trapped civilians and initiate an ad hoc network connection between them and the rescuers, so that the latter can better assess the situation and plan the rescue operation accordingly. We present a centralised formulation for the novel problem of optimally allocating robots so that they connect as many civilians as possible, while maintaining their multi-hop connection with a static wireless sink. This formulation stems from a combination of characteristics typically found in assignment and network flow optimisation problems. We have also developed a distributed heuristic with which the robots start from the location of the sink and move autonomously trying to connect the civilians while maintaining connectivity. We evaluate our distributed heuristic using a building evacuation simulator and compare it with the centralised approach.**

I. INTRODUCTION

In recent years, mobile robots have been routinely used in emergency response operations to reach areas that are inaccessible to humans. Usually, they are designed to search for victims, inspect structural integrity, or detect hazardous materials, but with recent advances in small-size robotics and wireless networking, emergency response robots can also be designed to form ad hoc networks. For example, the first priority during a disaster may be to establish network communication with immobilised civilians, so that the rescuers better assess their condition and plan their course of action accordingly. Our aim is to provide mobility mechanisms and strategies with which emergency response robots will establish two-way network connection between the rescuers and as many civilians as possible. We assume that the civilians carry some wireless device and the goal of the mobile robots is to get in range of these devices. At the same time, the robots also need to stay in connection with the group of rescuers, which we represent as a static wireless sink. In the general case, this connection will be multi-hop. Examples of robots, where this ad hoc networking paradigm applies include the Soryu III [11], which provides live video streaming and two-way voice connection with trapped civilians, and the Packbot that is designed for military operations [13].

The remaining of the paper is structured as follows. We briefly present the related literature in Section II and continue with our assumptions in Section III. A centralised and a distributed solution to our problem are presented in Sections IV and V respectively. We conclude with a summary of our contributions and suggestions for future work.

II. RELATED WORK

Ad hoc networking for the collaboration of search and rescue robotic operations was first suggested in [4] and further investigated in [6], [7], but their authors assumed star topology with a control station in the centre of the search area, which is usually impractical during a disaster. A more general system was proposed in [5], [8], where networked robots collaborated to detect a single injured civilian and maintained their connection while moving. In this paper, we tackle the fundamental problem of the optimal allocation of such robots that need to form an ad hoc network with all or as many static civilians as possible while at the same time being connected to a wireless sink over multiple hops. Related problems can be found in the field of network design, but they usually refer to wired networks and their goal is to select or add links to achieve some network objectives [2], [12]. In the mobile wireless case that we deal with, the addition of links is done implicitly with the location selection of the robots. A popular related problem found in the field of sensor networks is the positioning or scheduling of sensors to maximise area coverage while maintaining connectivity, which has produced a few interesting heuristics, such as [9], [10]. In our case, we deal with the connection of civilians instead of area coverage, and we provide both an exact centralised formulation and a distributed heuristic. Finally, mobility-assisted relocation has also been explored in sensor networks, but the focus in such networks is either the area coverage or the degree of connectivity, and not the connection of specific targets [14].

III. ASSUMPTIONS

Our focus is on the constrained environments. Thus, instead of a continuous or grid representation of the area, we choose a graph $G = (V, E)$ representation, which is preferable for environments where there are limited movement options for the robots. We assume that the civilians carry a wireless device of range R_{civ}, which is used to connect with the robots. The wireless device of each robot has range R_{rob}. Several wireless coverage models have been proposed in the literature, but for the sake of simplicity we will use the euclidian distance as the connectivity criterion. A civilian c is considered to be in two-way connection with a robot r if their euclidian distance is smaller than the minimum of their respective ranges: $d(c, r) < \min\{R_{rob}, R_{civ}\}$. The robots need to maintain multi-hop connectivity with a static wireless sink s. A civilian is successfully connected to the network if it is connected to a robot that is in turn connected to the sink. Also, we assume that the locations of the civilians and the movement graph G are known to the robots. Finally, we assume that the locomotion energy consumed by the robots while moving is linear with the distance travelled.

IV. A CENTRALISED APPROACH

A. A centralised formulation

Let us assume that all robots have the same range R_{rob}. Then all the robots have the same characteristics and do not have to be explicitly distinguished. Our goal is to maximise the number of connected civilians by selecting appropriate positions for the robots and also maintaining connectivity. In order to check connectivity of a robot to another robot or to a civilian, we use the binary matrices A and B respectively. Specifically, A is a $|V| \times |V|$ matrix with its $A_{u,v}$ element representing whether vertex $v \in V$ is in range R_{rob} of vertex $u \in V$. The $M \times |V|$ matrix B has elements $B_{c,u}$ equal to 1 if a robot at vertex u would be connected with civilian c.

To formulate the problem, we introduce the vector of binary decision variables $\mathbf{x} = \{x_u : u \in V\}$, where x_u represents whether a robot is at vertex u. The variables $y_c, c = 1, ..., M$ show whether civilian c has been connected by at least one robot. The problem can be initially formulated as follows:

$$\text{maximize} \sum_c y_c \tag{1a}$$

$$\sum_u x_u <= N, \tag{1b}$$

$$y_c = \min\{1, \sum_u x_u B_{c,u}\}, \forall c \tag{1c}$$

$$c_{u,v} = \max\{0, A_{u,v}x_u + A_{v,u}x_v - 1\}, \forall u < v \tag{1d}$$

$$c_{v,u} = c_{u,v}, \forall u < v \tag{1e}$$

$$c_{u,u} = 0, \forall u \tag{1f}$$

$$-\frac{1}{N}x_u + \sum_v f_{v,u} = \sum_v f_{u,v}, u \neq s \tag{1g}$$

$$\frac{1}{N}\sum_{u \neq s} x_u + \sum_v f_{v,u} = \sum_v f_{u,v}, u = s \tag{1h}$$

$$0 \leq f_{u,v} \leq c_{u,v}, \forall u, v \tag{1i}$$

$$x_u \in \{0, 1\}, \forall u \tag{1j}$$

where N is the number of robots, $f_{u,v}$ are continuous variables that denote the amount of traffic flow of the link (u, v), and the variables $c_{u,v}$ indicate the capacity of the link (u, v). A link capacity is nonzero if there are robots at vertices u and v and they are in range of each other. The auxiliary variables $f_{u,v}$ and $c_{u,v}$ have been employed to deal with the multi-hop connectivity constraint.

In the above formulation, Eq. (1b) indicates that less than N robots may be needed, while Eq. (1c) shows whether for given robot locations $\mathbf{x}$, civilian c is connected. To formulate the connectivity matrix of the robots for a given $\mathbf{x}$, we have employed a network flow formulation. In the approach we take we use the capacity of a given link $c_{u,v}$ to express whether link (u, v) is part of the robot network. According to Eq. (1d) - (1f), if link (u, v) is part of the formed graph then the capacities $c_{u,v}$ and $c_{v,u}$ are equal to 1 and 0 otherwise. Hence, the links of the undirected graph formed for a specific $\mathbf{x}$ are given by the nonzero capacities of the network.

The formed robot network is connected if there is a path from any robot to any other robot. In general, for an undirected graph, connectivity can be ensured if a path exists from one node to all other nodes. Connectivity is ensured if small flows from the wireless sink s can reach all robot nodes. Specifically, in the above formulation Eq. (1g)-(1i) are the flow conservation equations which show that the total incoming traffic to a vertex must be equal to the total outgoing traffic under the capacity constraints of the network. The first term of Eq. (1g),(1h) represents the supply b_u of vertex u which accounts for the amount of flow that enters the network from the outside. Note that a source vertex has positive supply $b_u > 0$, a sink vertex negative supply $b_u < 0$ while transshipment vertices have $b_u = 0$ [1]. In our case we guarantee connectivity by sending flows equal to $1/N$ from the sink vertex to each robot, and the maximum amount of traffic that can pass from one link is 1, so that the capacity constraint (1i) is never violated. Consequently, the set of Eq. (1g),(1h) is feasible only if all robots are connected to the sink. Note that in order for the formulation to be feasible, the sink's supply must be equal to the robots' total demand, $\sum_u b_u = 0$.

Because of the *min* and *max* terms in Eq. (1c) and (1d) respectively the above formulation is not linear. However, we can transform it into the following equivalent linear mixed integer programming formulation:

$$\text{maximize} \sum_c y_c \tag{2a}$$

$$\sum_u x_u <= N, \tag{2b}$$

$$\sum_u x_u B_{c,u} \geq y_c, \forall c \tag{2c}$$

$$0 \leq y_c \leq 1, \forall c \tag{2d}$$

$$A_{u,v}x_u + A_{v,u}x_v - 1 \leq c_{u,v}, \forall u < v \tag{2e}$$

$$A_{u,v}x_u \geq c_{u,v}, \forall u < v \tag{2f}$$

$$A_{v,u}x_v \geq c_{u,v}, \forall u < v \tag{2g}$$

$$0 \leq c_{u,v} \leq 1, \forall u, v \tag{2h}$$

$$c_{v,u} = c_{u,v}, \forall u < v \tag{2i}$$

$$c_{u,u} = 0, \forall u \tag{2j}$$

$$-\frac{1}{N}x_u + \sum_v f_{v,u} = \sum_v f_{u,v}, u \neq s \tag{2k}$$

$$\frac{1}{N}\sum_{u \neq s} x_u + \sum_v f_{v,u} = \sum_v f_{u,v}, u = s \tag{2l}$$

$$0 \leq f_{u,v} \leq c_{u,v}, \forall u, v \tag{2m}$$

$$x_u \in \{0, 1\}, \forall u \tag{2n}$$

Constraint (1d) is equivalent to constraints (2e)-(2h). Eq. (2f) and (2g) force $c_{u,v}$ to zero when not both terms $A_{u,v}x_u$ and $A_{v,u}x_v$ are equal to 1. In addition, when both terms are equal to 1 then from Eq. (2e) $c_{u,v} \geq 1$ and from Eq. (2f) and (2g) $c_{u,v} \leq 1$, implying that $c_{u,v} = 1$.

In our case, constraint (1c) is equivalent to the combination of Eq. (2c), (2d) and the goal function (2a). That is because Eq. (2c) forces y_c to zero when $\sum_u x_u B_{c,u}$ is equal to zero. When $\sum_u x_u B_{c,u} \geq 1$, then $0 \leq y_c \leq 1$ and expression (2a) ensures that y_c will take the maximum value in that interval, i.e. $y_c = 1$.

B. Numerical results using the general centralised approach

We have performed numerical evaluation of our approach for varying robot and civilian ranges as well as number of robots. In all cases with constant number of robots and civilians we have used $N = 20$ and $M = 20$ respectively. For the solution of problem (2) a standard mixed integer programming solver was employed.

Fig. 1 shows three instances of optimally allocated robots for combinations of robot and civilian ranges. When the range of the wireless devices carried by the civilians is too small, then in practice there must be one robot per each civilian in order to connect them, but for larger ranges the robots move to areas of higher civilian density. Fig. 2 illustrates the maximum number of connected civilians for different R_{rob} and R_{civ} values. It can be observed that in all cases the maximum possible number of connected civilians is achieved for $R_{civ} = 8m$. On the contrary, Fig. 3 shows that there is a threshold for R_{rob} in the range [6m,8m); below this threshold no civilian is connected, while above it the number of connected civilians increases substantially and reaches a maximum. In Fig. 4 the effect of the number of robots was examined for different combinations of civilian and robot ranges. Interestingly, the civilian connectivity increases linearly with the number of robots.

C. Minimise the number of robots and the energy consumption

Although our primary goal is to maximise the number of connected civilians, it is also important to minimise the number of required robots or the locomotion energy used by the robots to achieve maximum connectivity. By locomotion energy we refer to the energy consumed by the robots to travel to their destinations. For this, we include these goals in the objective function and compare the results for the cases that emphasis is given in minimising a) the number of robots and b) the average locomotion energy consumed by the robots. We denote $E_{u,v}$ the normalised energy consumed by a robot to travel from vertex u to vertex v so that $0 \leq E_{u,v} \leq 1, \forall u, v$.

Concerning the robot minimisation, the new objective function is the following:

$$\text{maximize } M_y \sum_c y_c - \sum_u x_u \tag{3}$$

where M_y is sufficiently large so that any increase of the civilian maximisation term is larger than the maximum possible value of the robot minimisation term. In this way, the optimal solution corresponds to the lexicographically greatest of the feasible ordered sets $(\sum_c y_c, -\sum_u x_u)$.

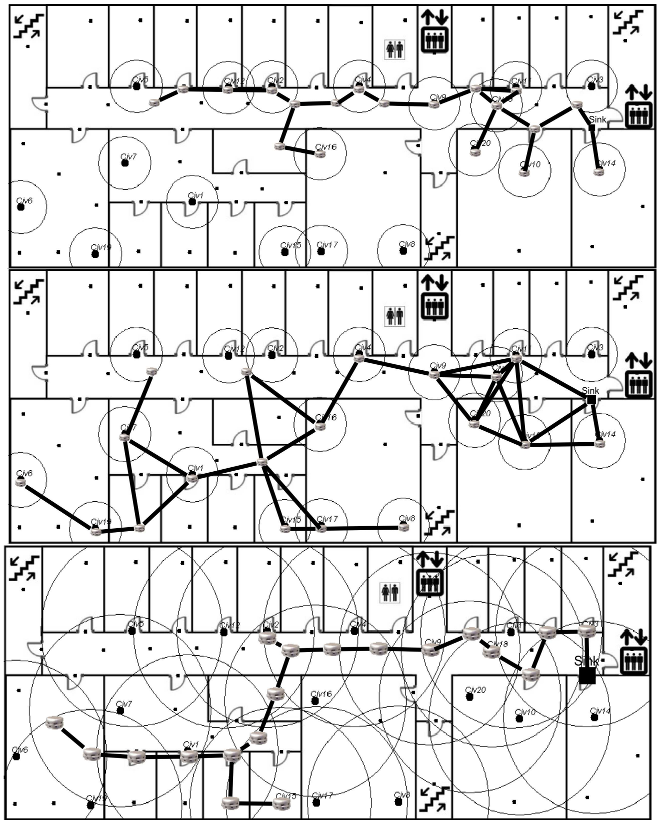

Fig. 1. Robot allocations according to the centralised solutions for (i)$R_{rob} = 8m$ and $R_{civ} = 4m$, (ii)$R_{rob} = 14m$ and $R_{civ} = 4m$, (iii)$R_{rob} = 8m$ and $R_{civ} = 14m$

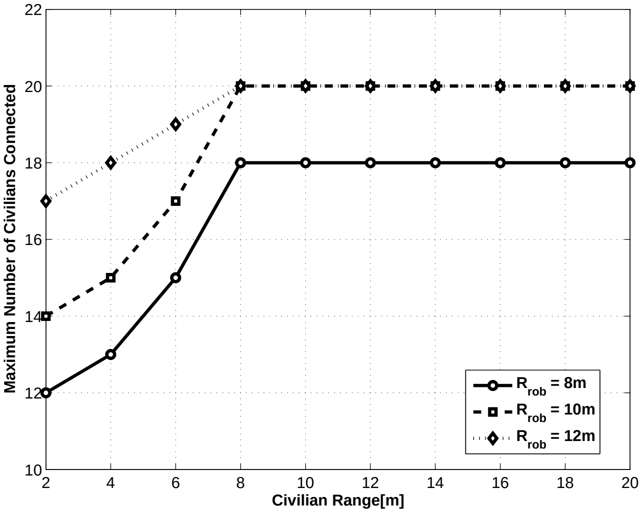

Fig. 2. Maximum number of connected civilians for varying R_{civ} and $R_{rob} = 8m, 10m, 12m$

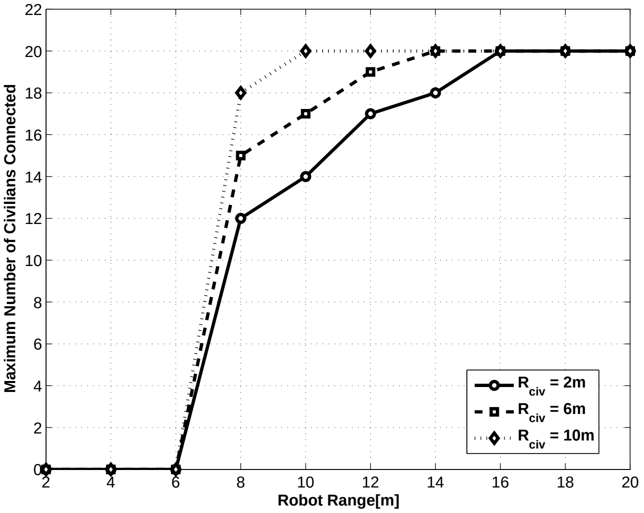

Fig. 3. Maximum number of connected civilians for varying R_{rob} and $R_{civ} = 2m, 6m, 10m$

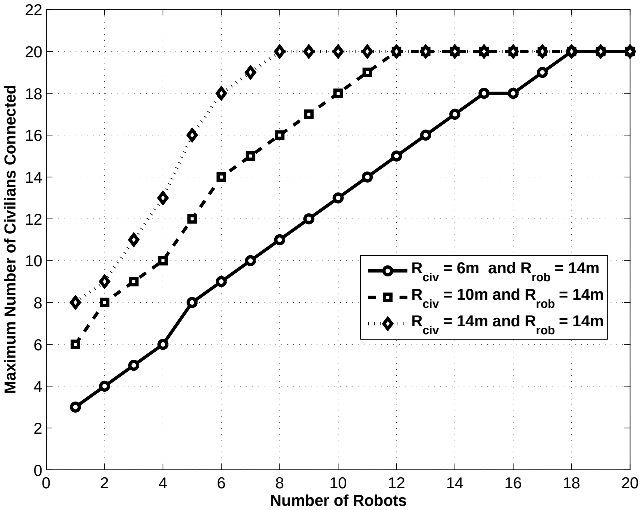

Fig. 4. Maximum number of connected civilians for varying number of robots and different combinations of ranges

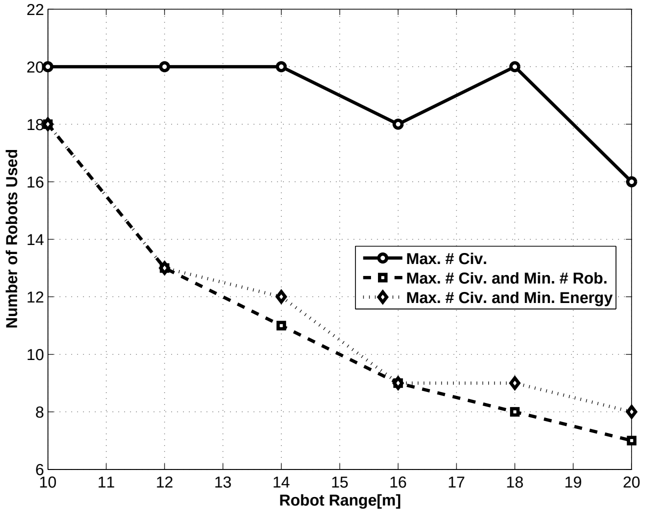

Fig. 5. Minimum number of robots required to connect all civilians when objectives (2a), (3) and (4) are utilised.

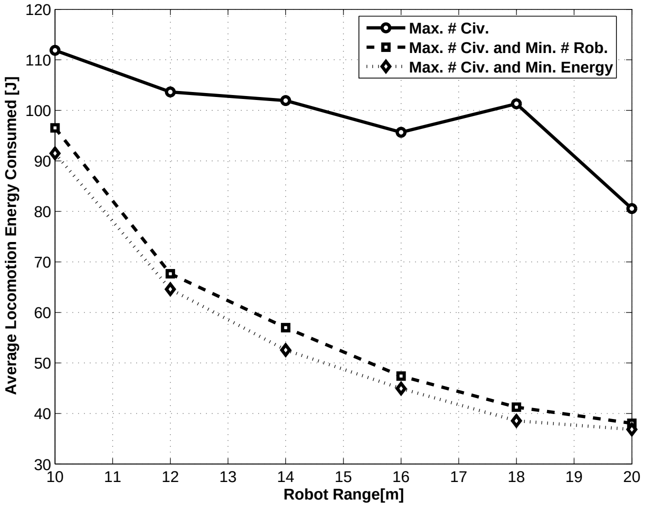

Fig. 6. Average locomotion energy consumed per robot when objectives (2a), (3) and (4) are utilised.

When we are interested in minimising the energy instead of the number of robots the objective function becomes:

$$\text{maximize } M_y \sum_c y_c - \sum_u E_{s,u} x_u \tag{4}$$

where again M_y must be sufficiently large and the solution is the best lexicographically ordered feasible set($\sum_c y_c, -\sum_u E_{s,u} x_u$).

We have solved the centralised problem for objectives (3) and (4) for R_{rob} ranging from $10m$ to $20m$ and $R_{civ} = 12m$, computing the minimum number of robots required and the total consumed energy. We have selected the particular robot and civilian ranges because they have feasible solutions for the connection of all civilians as already shown in Fig. 2 - 3.

A comparison of the efficiency of the objectives (2a), (3) and (4) in terms of the minimum number of robots used and the locomotion energy consumed, is illustrated on Fig. 5 and 6. In Fig. 5, it is clear that when using the objective function (2a) the results are significantly worse because no effort is put on minimising the number of robots. Interestingly, the results for the case of minimising the energy are very close to the optimum values which are obtained using objective (3).

The numerical results presented in Fig. 6 correspond to the locomotion energy consumption being linear with the distance, at $2.0J/m$, which is a typical value for small wireless-equipped robots, such as robomote [3]. Similar observations to the ones associated with Fig. 5 are valid for this case as well. Nonetheless, the energy consumed when utilising objective 3 is always more than the optimal in contrast to Fig. 5 where in some cases minimising the energy resulted in minimizing the number of robots required as well. Based on the above observations, we can argue that minimising the number of robots or the locomotion energy consumed are highly associated goals.

V. A DISTRIBUTED APPROACH

The centralised approach presented in Section IV provides an exact solution to the problem of allocating robots to locations, but may be considerably demanding in terms of processing. For this reason, a more practical approach is to use a distributed algorithm that can be run on each robot and make use of the ad hoc network that the robots are forming for their cooperation.

A. The distributed algorithm

The main challenge that one has to address for this problem is to maintain the connectivity of the robots at all times. For this we make the assumption that the civilians in a disaster area are clustered in groups, either because they were together when the disaster happened or because they grouped with others in their effort to survive. If we assume the maximum radius of each cluster to be smaller than the communication range R_{rob} of a robot and the graph G to be sufficiently dense, then when inside a cluster the connectivity constraint is always satisfied and the robots can simply be allocated according to the number of civilians they will connect. The wireless sink or one of the robots has to group the locations of the civilians into clusters according to the k-means clustering algorithm and inform all robots about this grouping. Connectivity between clusters is maintained by forming chains of robots with maximum distance R_{rob} between them. Essentially, the heuristic approach is composed of two stages:

- *Find the most attractive cluster*. The metric for the attractiveness of a cluster is the number of civilians that it contains divided by the distance to the cluster
- *Allocate robots inside this cluster and the rest move on to the next cluster*. When on a cluster centre, each robot moves to a location that maximises the number of connected civilians of this cluster, until all are connected.

This is presented in more detail in Algorithm 1.

B. Simulation results for the distributed algorithm

In order to evaluate our distributed algorithm, we implemented it as the movement decision model of robot agents in the Building Evacuation Simulator [15]. Figure 7 shows the final allocation of the robots for the given civilian clustering, where the larger circles represent the clusters and the smaller circles are the ranges of the civilians. The robots moved first to cluster 1, which was closer and had the most civilians, connected all its civilians, and the remaining robots moved to clusters 2, 3 and 4 according to the attractiveness metric. The distributed heuristic reached comparable results with the centralised solution (Fig. 8 and 9), but with an average increase in the locomotion energy consumption of approximately 40%. This was expected since with the centralised approach, the robots know their destination before they start moving and go there directly, while in the distributed case, the robots need to move inside the area and gradually identify their final positions.

Algorithm 1 Heuristic distributed algorithm

```
Run on the sink or one of the robots before they start moving
Partition the vertices of the civilians into clusters of maximum distance $R_{rob}$ from the cluster's centre using the k-means algorithm, and inform all robots about the resulting partition.
Run on all robots before they start moving
Identify most attractive cluster centre, set it as objective and move towards it. The metric is the number of civilians that belong to the cluster divided by the distance to the cluster's centre.
Run on each robot every time they arrive at a vertex
if Current vertex is the objective then
  if Current vertex is a cluster's centre then
    if Some other robot already settled on this vertex then
      if There exists at least one civilian of this cluster that is not yet connected to the network then
        Find vertex from where the maximum number of unconnected civilians of this cluster are connected, set it as objective and move towards it
      else
        Identify next most attractive cluster centre, set it as objective and move towards it.
      end if
    else
      Stay on this vertex and inform other robots accordingly
    end if
  else
    Stay on this vertex to ensure connectivity and inform other robots accordingly
  end if
else
  if Connectivity will be lost if this robot continues towards its objective then
    Stay on this vertex to ensure connectivity and inform other robots accordingly
  else
    Continue towards objective.
  end if
end if
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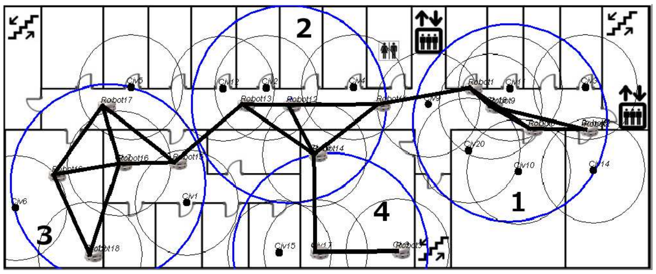

Fig. 7. Solution of the distributed algorithm for the given clustering of civilians

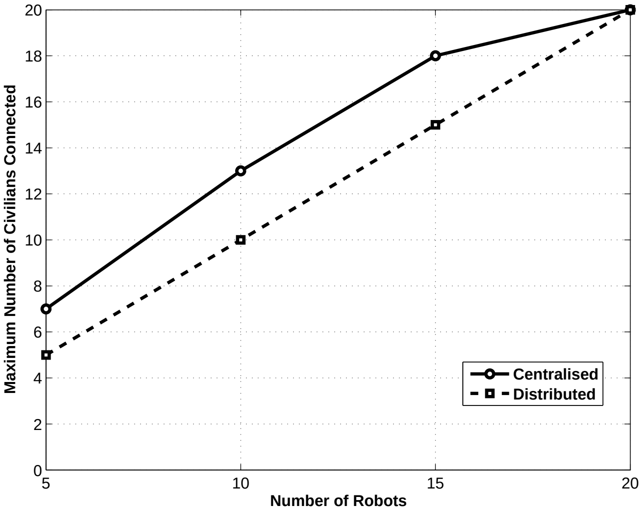

Fig. 8. Comparison between the distributed and centralised approach in terms of number of connected civilians against the number of robots

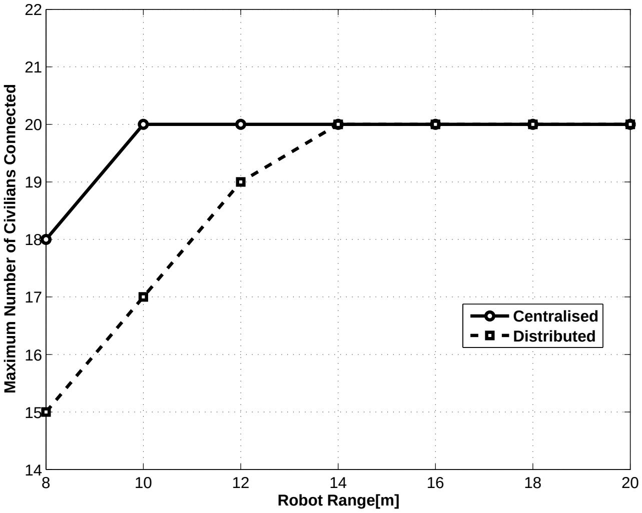

Fig. 9. Comparison between the distributed and centralised approach in terms of number of connected civilians against the wireless range of the robots

VI. CONCLUSIONS AND FUTURE WORK

We have addressed the problem of optimal allocation of robots in a disaster area with the goal of maximising the number of civilians that are connected to an ad hoc network formed by the mobile robots. The major challenge of this problem was to combine the assignment of robots to locations and simultaneously maintain multi-hop connectivity. For this, we developed a linear mixed integer programming formulation that maximises the number of connected civilians and can also minimise the necessary number of robots or the energy consumed to travel to the optimal locations. This centralised formulation allows us to examine the effect of the different parameters of the problem, as well as provide a comparison basis to evaluate any non-optimal approaches. We present such a non-optimal heuristic that can be run in a distributed fashion and with which the robots can achieve results comparable with the ones of the centralised approach, with only limited redundancy in terms of the number of robots.

In this work, we assumed that all civilian locations are known a priori. As future work, we will extend it for the case of partially known or completely unknown locations, by performing a probabilistic analysis of the civilian locations. Also, the current distributed heuristic can be improved with an additional level of optimisation in terms of the selection of clusters and the parallel choice of different clusters by groups of robots, so that the necessary number of robots and the average energy consumption are minimised.

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