Emergency broadcasting strategies for distributed robotic groups under limited communication

Maksim Kenzin, Igor Bychkov and Nikolai Maksimkin
Matrosov Institute for System Dynamics and Control Theory of the Siberian Branch of the Russian Academy of Sciences, 134 Lermontov str., 664033 Irkutsk, Russia
E-mail: gorthauers@gmail.com, bychkov@icc.ru, mnn@icc.ru

Abstract. Execution of large-scale search and survey operations by groups of autonomous mobile robots requires the ability to respond to unforeseen events of different nature in a quick and efficient manner. In order to achieve this requirement, the available information about recent changes should be spread among all active group members as soon as possible. Informing a non-stationary group of mobile robots distributed across different regions of the operational area is a nontrivial task for large groups with limited communication capabilities. The paper addresses the problem of agent-based information distribution throughout a network in a new original formulation. In essence, the problem is to define an effective order of transferring data between single robots in order to achieve the fastest way of sharing it among the whole group. A number of heuristic strategies are proposed for building initial solutions alongside with the local search scheme for their further optimization. The comparison between the suggested approaches is made regarding both the solution quality and the speed of algorithm operation. Some issues related to the test instances generation are also considered.

1. Introduction
At the present moment, the use of coordinated groups of autonomous mobile robots is one of the most advanced technologies for answering a variety of operational search and survey challenges in different natural environments. The reliability of such multi-component robotic systems depends largely on the ability to adjust their behaviour in dynamically changing conditions efficiently. This ability is ensured by maintaining a high level of situational awareness when information about any emerging events and environmental changes is immediately broadcasted among the group [1]. The whole group awareness of the updated mission conditions allows consistent cooperative decision-making (replanning) to manage the changes properly [2]. While this work is solely focused on the broadcasting process, we have addressed the replanning problem for dynamic missions of the robotic groups in our previous works [3].

In this paper, we present the emergency broadcasting problem for an autonomous group of mobile robots. The task is to distribute a message from a single robot to all other members of the non-stationary robotic group under limited communication. The main feature of the proposed problem statement is the fact that each robot that receives the message immediately joins the broadcasting task. The problem combines the key elements of multi-agent discrete models and vehicle group routing formulations.

The paper is organized as follows. The mathematical problem statement is proposed in the next section. Section 2 also includes some notes on the problem classification. Section 3
provides a description of both the solution decoding scheme and the suggested heuristics to solve the problem. The results of computational experiments are presented and discussed in Section 4. The last section concludes the paper.

2. Problem statement

In general, robotic multi-vehicle search and survey operations involve a group of mobile agents travelling within the operational area to perform some exploration activities in the given set of locations. As the robots spread across the area to explore the locations, the current group strategy (group route) may lose its relevance or even become disadvantaging. For instance, one of the group members may find the sought object or become aware of some information of vital importance [4]. Within the shortest possible time, this agent should decide if it is time/resource-worthy to warn the rest of the group, or it is more reasonable to let other robots finish their prescribed routes. In this situation, communication constraints become a significant limitation as for many multi-vehicle robotic systems inner-vehicle communication channel could be established only for close-enough agents [5]. Thus, the agent, who has observed the changes in the first place, has to travel consequently from one mobile agent to another in order to share the obtained information. If the shared information is crucial enough, other already informed agents should also discontinue their current work to join the broadcasting task.

Summarizing the above, the broadcasting problem is to find a route for the starting agent, commonly referred as originator, and all other future informed agents to achieve the fastest message distribution among the group [6]. As unaware group members are non-stationary and time-dependent (even though their future positions are prescribed and known), it still lays an additional layer of complexity to the group routing problem. In this work, we propose a relatively abstract mathematical model in order to obtain the first fundamental results.

Let the graph \( G = (V, E) \) represent the operational area of the mission. The area is partitioned into a set of \( m \) locations represented by the graph vertices \( v_i, i = 1, ..., m \). Each edge \( e_{ij} \) represents here a path segment between two adjacent locations \( v_i \) and \( v_j \). Let the graph \( G \) be connected, unweighted, and undirected.

Let the search and survey operation be implemented in the operational area by the group \( A \) of \( n \) entirely identical robots (agents) denoted by \( a_1, a_2, ..., a_n \). Each agent \( i \) travels through the graph \( G \) on a discrete-time \( T = \{T_0, T_1, T_2, ...\} \) according to its preplanned route \( R_i \). Route \( R_i = (r_{i0}, r_{i1}, ..., r_{iq}) \) is a path with cycles as agents may stay on the same vertex \( r_{ik} = r_{ik-1} \) doing some time-consuming research activities or even return on the previously explored locations with time. We assume that each robot in the group knows preplanned routes \( R_i \) of other robots. We also assume that all robots should gather in a common location at the end of their routes to conduct a communication session \( r_{iq} = r_{jq}, a_i, a_j \in A \). It should be noted that any number of agents can be located within the same vertex \( v \) at any point in time.

We denote the state of the \( i \)-th agent at time moment \( T_j \) as a combination of its current location and current status \( s_i(T_j) = (v_{ij}, s_{ij}) \). The agent status \( s_{ij} \in \{0, 1\} \) displays if the agent is already aware at the particular time moment or it is not yet informed about any essential mission condition changes. All agents are unaware at the beginning of the mission \( s_{i0} = 0, i = 1, ..., n \).

At some instant time moment, random agent \( x \) (the originator) became aware of information that is crucial for the mission success. Without loss of generality, let this time moment be \( T_1 \), \( s_{x1} = 1 \). Since becoming aware, any agent receives two abilities:

(i) To drop its preplanned routes and become a subject of control;
(ii) To share the critical information with other agents within the same vertex (making them aware)

\[
s_{kj} = \max_{i=1,...,n} \{s_{ij}|v_{ij} = v_{kj}\}. \tag{1}
\]
Knowing the initial routes \( R_1, R_2, ..., R_n \) of the whole group, the originator \( a_x \) has to determine if it is possible to distribute the message among the group by the time of \( T_h \), \( h < q \) (\( h \) here is an evaluation of the time/resource-worthy period). In order to do this, the originator should solve the broadcasting problem by finding the solution in the matrix form \( F = \{ a_i(T_j) \}, i = 1, ..., n, j = 1, ..., h \) such that:

- Each agent is unaware when the mission starts \( a_i(T_0) = \langle v_{i0}, 0 \rangle, i = 1, ..., n \);
- Unaware agents travel strictly according to their preplanned routes \( \{ v_{ij} = r_{ij} | s_{ij} = 0 \} \);
- The random agent \( x \) became aware at \( T_1, a_x(T_1) = \langle v_{x1}, 1 \rangle \);
- Aware agents make other unaware and neighbouring agents aware (1);
- All agents should become aware not later than \( T_h, s_{if} = 1, i = 1, ..., n, f \leq h < q \).

As there could be various ways to build a feasible matrix \( F \), those with lesser \( f \) would be preferable, \( \min_f(A) \).

A schematic representation of the proposed problem is given in figure 1. One of the robots (boldly outlined circle in the center) has detected a potentially hazardous object and now has to warn the remaining team of travelling agents by catching them on their routes (figure 1a). Each warned agent also changes its current task to join the broadcasting. After a short period, half of the group is already warned (figure 1b).

![Figure 1](image)

**Figure 1.** Schematic representation of the information broadcasting problem.

### 2.1. Problem classification

The proposed formulation combines principles of group routing problems (like mTSP or VRP variations) with the special aspects of different discrete-time multi-agent network models. Such network models with several static or mobile agents affecting each other under a specific set of rules are commonly used to represent the information distribution process in communication and social networks [7, 8, 9] or even the infection disease transmission [10, 11]. Standard features of these models are the lack of the direct control object and predominantly probabilistic nature. By the former, we refer to numerous problem statements when it is required to find the optimal network topology or to examine the current network for particular properties, for example, burning speed [12].

Unlike models mentioned above, the suggested broadcasting problem is both deterministic and involves a group of controllable (through their travelling routes) agents. These problem’s attributes lead us to the vehicle routing problem variations. The VRP objective is to find the optimal route for multiple agents visiting a set of locations (clients). In general, VRP
formulations are characterized by the interaction between agents and clients only. In other words, agents do not affect each other, which does not apply to the proposed statement. Moreover, in our case, each robot represents both vehicle (being already informed) and dynamic location (when still unaware). Besides, in terms of vehicle routing problems, dynamic conditions refer to either dynamism or stochasticity (or both) [13] while in our case mission conditions are dynamic but still deterministic.

Furthermore, the standard travelling salesman problem can be represented as a subproblem of the proposed broadcasting problem, in which unaware agents standstill on the same vertices for the whole mission and do not join the originator in its broadcasting task after becoming aware. It follows here-from that the proposed problem is also NP-hard. With the absence of the actual delivering process, it can be classified as some kind of time-dependent multiple travelling salesman problem.

3. Solving methods

In this section, we propose several strategies to build and improve group routes $F$ providing quick message distribution. It is beyond argument that the matrix representation of the solution $F = \{a_i(T_j)\}, i = 1, \ldots, n, j = 1, \ldots, h$ is inconvenient and unmanageable when it comes to the route generation. As the matrix $F$ contains a vast amount of excessive information like agents’ through-points, we suggest using the shortened form of the solution representation, which would include only the key information.

For this reason, we propose encoding the solution as the order $P$ of agents’ activation (the moments of becoming aware and, therefore, controllable). In general, for single-vehicle problems such representation is of the next form $P = \{p_1, p_2, \ldots, p_k\}, p_i \in \{1, \ldots, k\}, p_i \neq p_j, i \neq j$ ($k$ is a number of clients), while for group routing problems of $l$ agents $P$ becomes a matrix of $l$ rows. As the proposed problem is a combination of these two models, we have considered two different variations of the solution encoding.

First one is a 2-by-$n$ matrix representation, in which the top row encodes the order of activation, and the second row assigns the activator (agent delivering the message) to each agent above:

$$P = \begin{pmatrix} x & p_1 & \cdots & p_{n-1} \\ 0 & x & \cdots & p_k \end{pmatrix}, p_i \in \{1, \ldots, n\}, p_i \neq x \tag{2}$$

Two requirements should be met for the solution $P$ in the form (2) to be feasible:

(i) Each agent should be included in the top row once and only once, $P_{11} = x$;
(ii) No agent could appear in the bottom row earlier than in the top row, $P_{21} = 0, P_{22} = x$.

The second solution representation form is a list of agents’ action commands in their arising sequence (vector of size $2n$):

$$P = \{x, p_1, \ldots, p_{2n-1}\}, p_i \in \{0, 1, \ldots, n\}, p_i \neq x \tag{3}$$

The requirement for the next action command arises for an unaware agent when it becomes aware, and for an aware agent each time it activates an unaware one (usually, two events happen simultaneously for a pair of agent). The action command $p_i > 0$ refers to an index of the unaware agent to be activated next by the current one, while $p_i = 0$ means that the current agent has no one more to activate, and his broadcasting task is finished.

Two following requirements should be met for the vector $P$ (3) to be feasible:

(i) Each agent should be included in the top row once and only once, $P_1 = x$;
(ii) The number of 0-values ahead of any $z$-th element of $P$ should be less than the number of positive elements: $\prod\{p_i \mid p_i = 0 \forall i \leq z\} < \prod\{p_i \mid p_i > 0 \forall i \leq z\}, z = 1, \ldots, 2n.$


In this work, we have used vector representation of the solution (3) as it seems to be more easily handled in terms of neighbourhood search and local optimization. The matrix form $F$ can be restored from $P$ (3) by replacing agents’ sub-routes after their activation moment with the shortest paths to the unaware agents they are commanded to activate (algorithm 1). Using the representation form (3), we have suggested several different heuristics to construct centralized solutions (originator building the whole group route) for the emergency broadcasting problem.

**Simple greedy heuristic.** The first method is a trivial but in many cases, reasonable approach. The action list $P$ is built here in such way that agents are always commanded to activate the temporally nearest (as quickest to reach) unaware agent if any.

Experimental results have shown that the simple greedy strategy has two observable drawbacks. Firstly, it works poorly in the situation, when several single agents travel diversely far away from the rest of the team. Secondly, it underperforms in areas with a vast amount of dead-ends. To answer these weaknesses, we propose two different modifications of the greedy heuristic, which we have called Soft greedy and Smart greedy heuristics, respectively.

**Algorithm 1:** Vector-solution encoding scheme

```
Input : Set of $n$ robots $a[i]$, index $x$ of originator, initial group route $R[i][]$ of size $n \times h$, vector-solution $P[]$ of size $2n$
Output : Group route $F[][]$ of size $n \times n$
Functions: MinTimeAgent($i$) finds the agent $j$ with minimal $a[j].$Time among those with $a[j].$Status = $i$, ShortestPath($a[i], a[j]$) builds the shortest path for agent $a[i]$ to reach $a[j]$ considering $a[i].$Time and $a[i].$Node, Replace($F[i][k], Path$) replaces the elements of the $i$-th agent’s route with the elements of the route Path starting from $F[i][k]
```

1 for $i \leftarrow 1$ to $n$ do 9 while Iterator $\leq 2n$ do
2 $a[i].$Status $\leftarrow 1$; 10 $y \leftarrow$ MinTimeAgent(0);
3 $a[i].$Time $\leftarrow 1$; 11 $z \leftarrow P[\text{Iterator}]$;
4 $a[i].$Node $\leftarrow R[i][1]$; if $z > 0$ then
5 end 13 Path $\leftarrow$ ShortestPath($a[y], a[z]$);
6 $a[x].$Status $\leftarrow 0$; 14 MeetTime $\leftarrow a[y].$Time + Path.Length;
7 Iterator $\leftarrow 2$; 15 if MeetTime $\leq h$ then
8 $F[][] \leftarrow R[][]$; 16 $\text{MeetNode} \leftarrow \text{Path[Path.Length]}$;
10 $y \leftarrow \text{MinTimeAgent}(0)$;
11 $z \leftarrow P[\text{Iterator}]$;
12 if $z > 0$ then
13 Path $\leftarrow$ ShortestPath($a[y], a[z]$);
14 MeetTime $\leftarrow a[y].$Time + Path.Length;
15 if MeetTime $\leq h$ then
16 $\text{MeetNode} \leftarrow \text{Path[Path.Length]}$;
17 $a[z].$Status $\leftarrow 0$;
18 Replace($F[y][a[y].$Time], Path$);
19 $a[y].$Time $\leftarrow$ MeetTime;
20 $a[z].$Time $\leftarrow$ MeetTime;
21 $a[y].$Node $\leftarrow$ MeetNode$;
22 $a[z].$Node $\leftarrow$ MeetNode$;
23 $\text{Iterator} \leftarrow$ Iterator + 1;
24 else
25 $a[y].$Status $\leftarrow 2$;
26 end
27 else
28 $a[y].$Status $\leftarrow 2$;
29 $\text{Iterator} \leftarrow$ Iterator + 1;
30 end
31 end
```

**Functions:**
- **MinTimeAgent**($i$) finds the agent $j$ with minimal $a[j].$Time among those with $a[j].$Status = $i$.
- **ShortestPath**($a[i], a[j]$) builds the shortest path for agent $a[i]$ to reach $a[j]$ considering $a[i].$Time and $a[i].$Node.
- **Replace**($F[i][k], Path$) replaces the elements of the $i$-th agent’s route with the elements of the route Path starting from $F[i][k]$. 

IOP Publishing Journal of Physics: Conference Series 1864 (2021) 012043 doi:10.1088/1742-6596/1864/1/012043
**Soft greedy heuristic.** This method is a probabilistic variant of the greedy approach: each time an action command is to be assigned to an agent, the probability of selecting each unaware agent is inversely proportional to the time distance between that agent and the current one (with the probability of "0"-command being the lowest). The difference between extreme probabilities is changing with time according to the ratio of already messaged agents.

**Smart greedy heuristic.** The Smart greedy heuristic is a variation with a stringent condition of the action selection: each time an action command is to be assigned to an agent, it picks the nearest one not among all unaware agents, but among only those of them, which he can reach quicker, than any other aware agent in the group. If there are no acceptable agents at all, the current agent receives action command "0".

**Local search.** We suggest using a specialized local search procedure as an improvement heuristic for solutions generated with the proposed construction heuristics. This step aims to reassign the last-messaged robots to those agents that have been stopped (received a "0"-command) earlier. In order to do this, the procedure performs a recursive search for more efficient solutions in the swap neighbourhood \( \text{swap}(a, b) \), where \( ab = 0 \) and \( a + b > 0 \).

### 4. Computational experiment

The proposed problem and the heuristics suggested above have been software-implemented in our simulation framework ”Multiobjective Mission Planner” to run a series of simulation studies. We have generated a set of test problem instances to conduct a computational experiment and collect statistical data. Each problem instance was produced in two steps.

The first step is to generate the mission graph \( G \). In order to do this, we create a set of random two-dimensional points (vertices) in the plane. Then we use one of two different methods (planar and non-planar) to generate edges based on this set. First is a standard Delaunay triangulation, in which we remove 10% of the longest edges both to create a more complex environment and to prevent fast travelling through the graph, especially by the graph borders. The second method connects each pair of vertices within the given distance \( S \). We define this distance as a neighbourhood size and evaluate it as a function of the relative location density. The final graph is then modified to provide its connectivity.

For the initial group route \( R \) construction, we propose using three route generating schemes. According to the first one, at each time-step an agent chooses either to travel on a random adjacent vertex or to loiter (standstills on the same location). For the second scheme, agents travel from one random location to another using the shortest path between them. In the third approach, agents in the group behave according to one randomly chosen scheme of the two described above. An in-detail description of the test instances generation schemes, including pseudo-codes and illustrated examples, can be found in our previous work [14].

Test instances \( XY - m(n) \) are divided into nine categories. The first letter stands for one of three graph generation options \( X = \{T, B, S\} \) for Delaunay Triangulation, Big- and Small-sized neighbourhoods, respectively. The second letter decodes the approach for the group route generation scheme \( Y = \{R, C, M\} \) (Random edge, Checkpoints, Mixed strategy). Then, for each combination of \( XY \) we have instances of \( n = \{25, 50, 100\} \) agents on the graph sizes of \( m = \{500, 2000, 5000, 10000\} \).

Statistical results for the several executed problem instances are presented in table 1. Starred heuristics here include post-optimization with the proposed local search procedure. Solution time \( t \) is measured in milliseconds (ms). A note on computation time: all calculations are running on the single core of 2.667 GHz processor of an Intel Core 2 Duo E6750 Conroe.
It can be seen that the Soft greedy heuristic constructs on average better routes than a simple greedy approach. The Smart greedy heuristic, in its turn, produces much more effective solutions (which is especially noticeable on large-size instances), but at a higher computational cost. Nevertheless, sometimes Soft heuristic can outperform other approaches even on complex large-sized problems. The proposed local search operator allows reliable improvement of the previously generated routes: for weak solutions, it has high efficiency at high time costs, while for strong ones, it allows for quick but minor improvements.

5. Conclusion
In this paper, we have proposed a new emergency broadcasting problem for a distributed group of autonomous mobile robots with limited communication capabilities. The proposed problem is to find the temporary shortest route for the starting agent to distribute the message among the rest of the group and is formulated as a combination of discrete-time multi-agent network models and vehicle routing problems. The main feature of the problem is that yet unaware agents act as mobile clients to visit, but after becoming aware, they drop their preplanned routes to join the broadcasting task.

Several heuristic strategies were proposed to build a centralized solution for the broadcasting problem. We also presented the solution encoding scheme to treat the problem more efficiently. Computational testing on the generated set of benchmarks has shown that the addition of even simple problem-oriented rules allows standard greedy heuristic to perform effectively, in terms of both solution quality and computational efficiency. As the local search also showed itself to be a viable solution technique, it is an interesting issue to apply more sophisticated optimization approaches to operate group routes.

Among the other future developments, there is a more realistic environment with continuous time, complex weighted and directed graphs, heterogeneous (by speed and communication capabilities) agents and even some uncertainties. We also plan to develop and test several decentralized broadcasting strategies along with a number of new heuristics to deal with the alternative criteria of the fastest gathering of all aware group at the common location.

Acknowledgments
This work is supported by the RFBF, project no. 20-07-00397.
References

[1] Dunbabin M and Marques L 2012 Robots for environmental monitoring: significant advancements and applications IEEE Robotics & Automation Magazine 19(1) 24–39

[2] Gan S K, Xu Z and Sukkarieh S 2016 Distributed situational awareness and control (Encyclopedia of Aerospace Engineering) eds Blockley and W Shyy pp 1–11

[3] Kenzin M, Bychkov I and Maksimkin N 2019 Two-level evolutionary approach to persistent surveillance for multiple underwater vehicles with energy constraints SPIIRAS Proceedings 18(2) 267–301

[4] Papp Z 2012 Situational awareness in intelligent vehicles (Handbook of Intelligent Vehicles) ed A Eskandarian (London: Springer London) pp 61–80

[5] Arvin F, Murray J, Shi L, Zhang C and Yue S 2014 Development of an autonomous micro robot for swarm robotics 2014 IEEE International Conference on Mechatronics and Automation 635–640

[6] Grigoryan H 2013 Problems related to broadcasting in graphs A thesis in The Department of Computer Science and Software Engineering, Concordia University

[7] Elsasser R, Lorenz U and Sauerwald T 2004 Agent-based information handling in large networks (Mathematical Foundations of Computer Science 2004. Lecture Notes in Computer Science. Vol 3153) ed J Flára, V Koubek and J Kratochvíl (Berlin: Springer)

[8] Harutyunyan H A and Wang W 2010 Broadcasting Algorithm Via Shortest Paths 2010 IEEE 16th International Conference on Parallel and Distributed Systems, Shanghai 299–305

[9] Simon M, Huraj L, Shi L, Dirgova-Luptakova I and Pospichal J 2019 Heuristics for spreading alarm throughout a network Applied Sciences 9(16) 3269

[10] Pastor-Satorras R and Vespignani A 2001 Epidemic dynamics and endemic states in complex networks Physical Review E63.6

[11] Riley S 2007 Large-scale spatial-transmission models of infectious disease Science 316(5829) 1298–1301

[12] Farokh Z, Tahmasbi M, Tehrani Z and Buali Y 2020 New heuristics for burning graphs Preprint cs-dm/2003.09314

[13] Punnen A P 2007 The traveling salesman problem: applications, formulations and variations (The Traveling Salesman Problem and Its Variations) eds G Gutin and A P Punnen (Boston: Springer US) pp 1–28

[14] Kenzin M, Bychkov I and Maksimkin N 2020 Situational awareness for distributed mobile robot teams under limited communication Proceedings of 2nd International Workshop ICCS-DE-2020 146–155