

CHOOSING OPTIMAL NODE ROLES IN A MULTI-GATEWAY WIRELESS AD HOC NETWORK

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Received: July 2020 / Accepted: October 2020

Abstract: This article considers a problem to choose parameters of a procedure for changing node roles in a multi-gateway wireless ad hoc network used in aerospace systems. Mathematical formulation of a mixed-integer programming (MIP) model to optimize the changing-node-role-procedure parameters is proposed, where the attention is focused on appropriate parameterization in order to make it possible to include additional constraints, if necessary. A practical two-stage technique used by the authors to solve the considered problem is briefly discussed. On the first stage, the branch-and-bound algorithm, provided with cutting plane constraints of some classes, is applied to choose optimal roles of the network nodes. On the second stage, the network simulator developed by the authors is used to estimate main characteristics of the resulting network. Workability of the proposed approach is demonstrated by results of computational experiments.

Keywords: Multi-Gateway Wireless Ad Hoc Network, Node Role Change, Self-Organization, Mixed-Integer Programming, Network Optimization, Network Simulation.

MSC: 68U99, 90B99.

1. INTRODUCTION

Wireless networks are widely used in many areas, among others, in the aerospace industry, to solve various problems related to monitoring parameters, e.g., load-

ness in the launch pad elements, the state of ground infrastructure objects, the psychophysiological state of cosmonauts, etc.

In this article we consider a problem of the optimal choice of node roles in a multi-gateway wireless ad hoc network used to measure necessary parameters by a set of sensors that are part of low-power computers interacting with each other over a radio channel. These computers form a self-organizing network intended to eventually deliver the obtained measurement results to some consumer for further processing. Possible advantages of using such networks in the aerospace industry are shown in [2], and [4].

We limit our consideration to wireless self-organizing networks, whose nodes are provided with energy from autonomous non-renewable power supply, and whose mission is to perform measurements and transmit the results for further processing. Many well-known works in this area are devoted to improving the network durability by reducing the energy consumption by the network nodes. To achieve this goal, it is proposed to use “duty-cycle” networks, see [12], and [13]. The durability issue is closely connected with another problem to increase the reliability of the network, where the reliability is understood as the ratio of successfully delivered measurement results to the total number of measurements to be performed. One of possible ways to increase the reliability, which we consider in the sequel, is to simultaneously use several gateways that provide communication between the network and an external consumer as proposed in [7], and [14].

Among of basic principles used on designing networks of the considered class is self-organization [9]. However, self-organizing network systems have some disadvantages; for example, searching for an appropriate network configuration may take a long time [3] that is not compatible with short duty cycles. A possible way to avoid this issue is to use so called *guided self-organization*, see [1], and [10]. In this article we investigate the possibility of using guided self-organization to optimize the choice of the node roles for a multi-gateway wireless ad hoc network.

2. PROBLEM DESCRIPTION

We assume that the considered self-organizing network has nodes which may play different roles. The nodes that perform measurements are called *sensors*. The nodes used to relay messages provided by the sensors to other nodes are called *routers*. Transmitting messages provided either directly by some sensors or indirectly by some routers to an external consumer (external network) is performed by the nodes called *gateways*. It is important to note that, in principle, a particular node may play any role; moreover, the node roles may change over the time.

Usually the node roles are assigned in advance, so on deploying the network its nodes are placed in predefined points according to their roles. Sometimes, however, this is impossible due to some factors. For example, if monitored objects change their positions (e.g., on moving masts of the launch pad, on moving cosmonauts within the spacecraft, etc.), the network topology also changes. Due to that, the network may become disconnected, and some sensor nodes will be unable to send the measurement results. The only way to avoid it is to change roles of some nodes,

for example, a node has to become a gateway to guarantee that the measurement results will not be lost.

However, transmitting measurements to an external consumer leads to the increase of power consumption by the corresponding gateway nodes and, in turn, to premature exhaustion of the reserve of the autonomous power supply of the nodes. The nodes whose power supply is exhausted are no more workable: these are unable to relay/transmit messages from other nodes, neither to perform their own measurements. Thus, the reliability of the network (defined as the ratio of the number of measurement results delivered to the consumer to the number of measurements to be performed) is decreased. As the nodes fail, the reliability may fall below the minimum acceptable level. The moment when the minimum level of reliability has been reached determines the durability of the network. Reliability and durability are crucial indicators of the network operation and depend on the assigned roles to the well-founded nodes at some point in time.

If the network logic allows changing node roles, then the nodes should be able to play any role in the monitoring system: sensor, routers, and gateways. At the hardware level this means that the nodes need to be equipped with a sufficient set of sensors, so that such nodes can play the corresponding role, and a wireless interface (this can be IEEE 802.11, IEEE 802.16, or UMTS modem) that provides interaction with the external network, so that such nodes can play the role of gateways. Obviously, the node's software should provide not only possibility to perform the main function according to the node role but also to provide a procedure for changing roles.

3. MIXED-INTEGER PROGRAMMING MODEL

In this section the considered problem is formulated in a formal mathematical way as a mixed-integer programming (MIP) model. This allows solving the problem, which obviously has a combinatorial nature, with the well-known branch-and-bound algorithm [15]. The model described here is basic in the sense that it includes only essential constraints, however, the attention is focused on the appropriate parameterization in order to make possible if necessary including some additional constraints.

Since the node roles are not defined in advance and can change over time, they are unknown quantities to be determined. Formally, defining the node roles can be considered as finding the following finite mapping:

$$F : V \rightarrow H, \quad (1)$$

where V is a set of network nodes, $H = \{s, r, t\}$ is the set of node roles (s — sensor, r — router, t — gateway).

The mapping (1) can be modeled in a natural way by introducing characteristic binary variables y_{ih} , where

$$y_{ih} = \begin{cases} 1, & \text{if node } i \in V \text{ is assigned role } h \in H, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Obviously, in this case the variables y_{ih} should satisfy the following “mapping” constraints:

$$\sum_{h \in H} y_{ih} = 1 \quad \text{for all } i \in V. \tag{3}$$

To model conditions that reflect the possibility of sending messages from sensor nodes to gateway nodes, consider the digraph $N = (V, E)$, where V is the set of nodes, $E \subseteq V \times V$ is the set of arcs, and $(i, j) \in E$ means that node i is able to send a message to node j . Then the necessary condition that determines the functioning of the network is the condition that the gateway nodes are reachable from the sensor nodes either directly or indirectly through other gateway nodes, taking into account that the node roles are unknown quantities.

From the standpoint of the network analysis [8], reachability can be considered as the existence of valid solutions to the corresponding flow problem that includes the following constraints:

$$\begin{aligned} Ax &= b, \\ 0 &\leq x \leq 1, \end{aligned} \tag{4}$$

where A is the incident matrix of the digraph (network), b is a right-hand side vector, whose components define the flow divergence in every node ($b_i > 0$ for sources, $b_i < 0$ for sinks, and $b_i = 0$ for transshipment nodes where the flow is conserved). Note that for reachability of node j from node i , it is sufficient that an unity flow from i to j exists, so capacities of all the arcs can be taken equal to one. Then, since the node roles are determined by the binary variables y_{ih} (2), the equality constraint of the system (4) for a particular node $i \in V$ can be written as follows:

$$\sum_{(i,j) \in E} x_{ij} - \sum_{(j,i) \in E} x_{ji} = +y_{is} - y_{it}, \tag{5}$$

where the right-hand side (divergence) reflects the role of node i in the network.

Though the topology of the network is assumed to be arbitrary, in order to physically transmit messages, the distance between appropriate nodes should not be greater than the specified maximum. From the standpoint of the model, this restriction means that the digraph is incomplete, and the presence or absence of some arcs is determined by geometric positions of the nodes.

Let the geometric space F of all possible positions of the nodes (the monitoring area) be splitted onto non-intersectable cells:

$$F = \bigcup_{k=1}^N F_k. \tag{6}$$

Then the geometric position of a particular node $i \in V$ can be modeled with a binary vector $z_{ik} \in \{0, 1\}$, where $z_{ik} = 1$ means that the node i belongs to the cell F_k . Since all the cells are not intersected, each node can belong to only one cell, that is, the vectors $z_i = (z_{ik})$ should satisfy the following constraint:

$$\sum_{k=1}^n z_{ik} = 1 \quad \text{for all } i \in V. \tag{7}$$

This allows defining the distance between cells F_k and F_l as follows:

$$\rho_{kl} = \max_{u \in F_k, v \in F_l} \|u - v\|, \quad (8)$$

where $\|\cdot\|$ is an appropriate vector norm. Note that the partition (6) is assumed to be given, so all the distances ρ_{kl} can be previously computed.

It is understood that node i belongs to cell F_k and node j belongs to cell F_l simultaneously if and only if

$$(z_{ik} = 1) \ \& \ (z_{jl} = 1). \quad (9)$$

The logical condition (9) can be modeled in many ways. In this work it is modeled with the following equivalent double-sided linear constraint:

$$0 \leq z_{ik} + z_{jl} - 2t_{ijkl} \leq 1, \quad (10)$$

where t_{ijkl} are auxiliary binary variables.

Formulae (8) and (10) allow estimating the distance between corresponding cells F_i and F_j as follows:

$$r_{ij} = \sum_{k=1}^N \sum_{l=1}^N t_{ijkl}. \quad (11)$$

Let r_{\max} be the maximal distance between nodes, on which transmitting messages is still possible. Then arc (i, j) of the underlying digraph exists if and only if $r_{ij} \leq r_{\max}$. Note that the absence of some arc is equivalent to the condition where that arc has zero capacity. This allows replacing inequality constraints of the system (4) by the following constraints that take into account distances between nodes:

$$r_{\max} - Mx_{ij} \leq r_{ij} \leq r_{\max} + M(1 - x_{ij}), \quad (12)$$

where M is so called ‘‘big M’’ (that can be set to the total number of the nodes in the network).

Though a set of the constraints described above determines solutions that satisfy the condition of node reachability, this set is still incomplete. In fact, the system (5) may have zero solutions (because this system is homogenous), and a zero solution appears when there are no source nodes (sensors). Since the considered network is intended to monitor environment parameters in some area, we need to take into account additional requirements that the monitored area is covered by a sufficient number of sensor nodes. This is equivalent to the requirement where near every part of the monitored area there exists at least one sensor node. Using variables z_{ik} that define node locations in the cells of the monitored area, this requirement can be written as follows:

$$\sum_{i \in S} z_{ik} \geq 1 \quad \text{for all } k = 1, \dots, N \quad (13)$$

meaning that each cell should contain at least one sensor node.

Now consider the objective function. As was noted in the previous section, such important characteristics of the network as its reliability and durability eventually depend on the capabilities of the autonomous power supply of individual nodes. Thus, increasing reliability and durability can be achieved by minimizing the total energy consumption of all nodes in the network. Here we make an assumption that the power consumption of an individual node depends on its current role as well as on the length of the transmission route of individual messages, and message delays at each step of the route. The delay is affected by the algorithm of competitive access to the channel and the number of nodes competing for the channel. This value is random since a change in the node roles changes the number of nodes competing for the channel in a certain area of the network. For this reason in the considered case, we use the average value of the message delivery duration at each step of the route.

Thus, the objective function to be minimized can be written as follows:

$$W = \sum_{i \in V, h \in H} c_{ih} y_{ih} + \sum_{(i,j) \in E} \tilde{c}_{ij} x_{ij}, \quad (14)$$

where c_{ih} is the power consumption of node i , if it is assigned role h , \tilde{c}_{ij} is the average power consumption on sending a message from node i to node j .

4. A TECHNIQUE USED TO SOLVE THE PROBLEM

Practical solution and analysis of the considered problem include two stages. On the first stage the MIP problem described in the previous section is solved so that allows determining optimal roles of all nodes of the network. Note that in real conditions this stage is assumed to be performed by an external computer and is based on the current network configuration, in particular, on the current geometric positions and statuses of the network nodes, which can be obtained in the same way as the measurement results. The second stage is used to simulate the network for obtaining its main characteristics (e.g., the total power consumption, etc.).

Choosing optimal node roles with the MIP model. The model to choose optimal node roles is of mixed-integer programming (MIP) class. To solve the corresponding optimization problem, we used the package ILOG CPLEX 7.5 [5], though any modern high-performance software implementing the branch-and-bound algorithm could be used.

Since the considered problem has a combinatorial nature, its LP relaxation is known to be quite weak, which in the standard case essentially increases the solution time, especially on solving the instances of a real size, where the number of binary variables may be tens of thousands. To make the solution process more efficient, we used some standard features provided by the CPLEX package as well as specific ones developed by the authors.

Before passing the model to the solver, it is automatically reformulated to obtain much stronger LP relaxations for “mapping” constraints (3) and (7); details

of this technique can be found in our article [6]. During the branch-and-bound search, LP relaxation of each subproblem is made stronger by adding cutting plane constraints. Preliminary experiments had shown that the most appropriate classes of generic cutting planes are mixed-integer rounding (MIR) and Gomory mixed integer cuts. Also we used some specific cutting planes derived from the conservation constraints (5). All the used cut generators were implemented by the authors.

Simulation of the network. To numerically estimate main characteristics of the optimized network, i.e., when the roles of all the network nodes have been established, we developed a special computer program to simulate the network. Since the nodes function in parallel and use a radio channel to interact with each other in a non-deterministic manner, it is impossible to describe functioning of the network by closed analytical formulae even when characteristics of all the nodes are known. This is the main reason why we decided to use the simulator.

The simulator is based on the principles of discrete event and agent modeling. For developing the simulator, we used the NS3 network simulator, a free research software distributed under the GNU GPLv2 [11]. NS3 was chosen for two reasons: ready-made model libraries and the fact that in NS3 models are executed as C++ programs. The library of models, including, in particular, the LrWpan module, allowed building models of our network according to the IEEE 802.15.4 standard and reducing the efforts to develop the simulator. C++ allowed using the program code developed for node models for programming a real network with minimal modifications.

The architecture of the simulator includes: a simulation core provided with an event queue; models of the radio channels, sensors and gateways; an input data subsystem; and a diagnostics and statistics subsystem. The input data subsystem checks the given data for correctness, creates objects needed for the simulation, attaches auxiliary models to them, sets up the specified attributes of the objects. The core of the simulator provides the simulation process, maintains a queue of events, provides models to access necessary information, etc. The sensor model determines actions when various events occur (receiving a message on the radio, expiration of a time interval). The gateway model, in addition to the actions performed by the sensor model, controls constructing of the spatio-temporal structure for node interactions. The radio channel model simulates transmitting messages and provides interactions between the sensor and gateway models. On simulating message transmissions the radio channel model takes into account the influence of interference and obstacles. During the work the models of nodes and the radio channel generate data about their state and current events. These data are saved by the diagnostics and statistics subsystem for subsequent analysis.

5. RESULTS OF COMPUTATIONAL EXPERIMENTS

To test workability of the proposed approach, the authors used the developed simulator to simulate a network, where the node roles were chosen randomly, and a network with optimized parameters of the procedure for changing the node roles.

(Need to note that in the first case some features of the simulator, namely, collecting initial data about nodes for solving the optimization problem, transmitting the collected data to an external computer, solution of the optimization problem on an external computer, and transmitting the selected parameter values back to the network nodes, were not used.)

The network to be simulated in both cases had 50 nodes randomly distributed over an area of 250×250 m. It is assumed that each node has autonomous power supply with the available energy reserve of 10 J (small energy reserve was used to reduce the simulation time), and that on exhausting the power supply, the corresponding node fails and stops functioning.

Simulation results for the non-optimized and optimized networks are shown, resp., on Fig. 1 and 2. It is seen that in the first case the network durability is 200 working cycles while in the second case, the durability is 415 cycles (in both cases the minimal allowable reliability was taken equals to 0.8). The difference, more than twice, in the network durability is explained by much higher power consumption by the nodes of the non-optimized network, in which case too many of its nodes are excessively used as gateways.

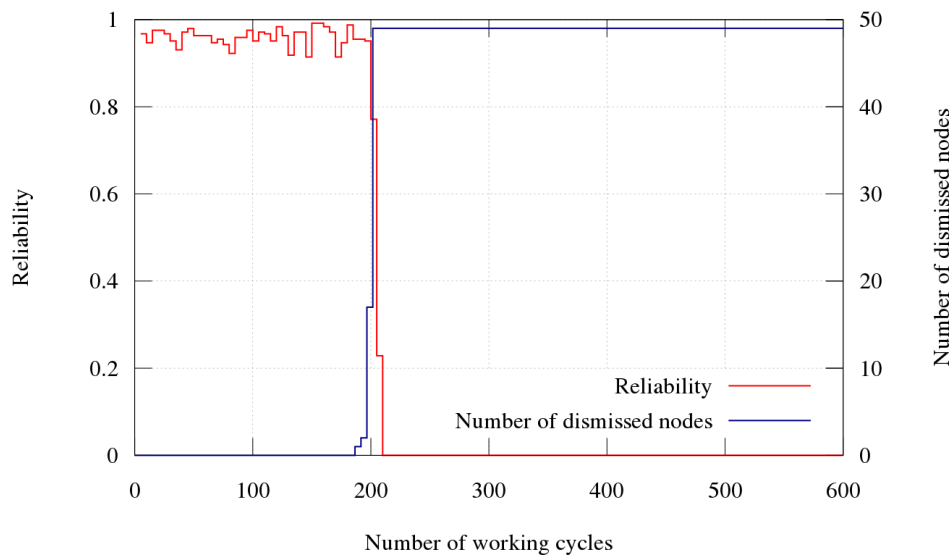


Fig. 1: Simulation results for the non-optimized network

The obtained results allow to conclude that optimization of the parameters of the procedure for changing roles of the network nodes reduces the energy consumed by the nodes, that, in turn, increases the durability of individual nodes as well as of the entire network.

Nonetheless, the ability to optimize the parameters of the procedure for changing the node roles is limited since not all networks are able to obtain source data

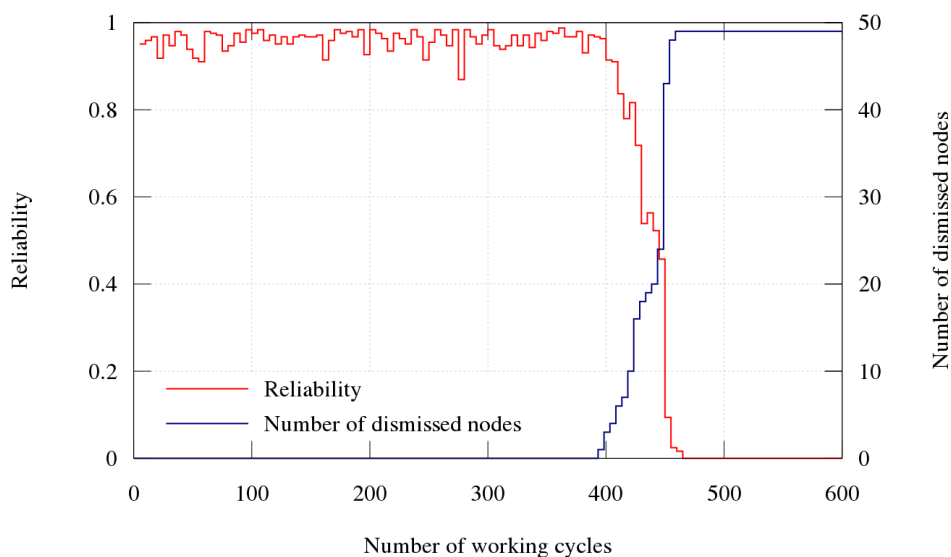


Fig. 2: Simulation results for the network with optimized node roles

needed for optimization, to transmit these data for processing to an external computer, and to receive back optimal parameter values. Thus, this approach is appropriate if there exists a non-energy-consuming way to detect positions of the network nodes.

6. CONCLUSIONS

As a result of the study carried out with the mixed-integer programming technique and the method of simulation modeling, it was shown that the use of guided self-organization in the procedure for changing the role of a network node allows to obtain higher values of its performance indicators. In the used scenario of the network operation, its higher durability is provided in comparison with the network with a random assignment of a role.

Acknowledgement: The work was supported by the Russian Foundation for Basic Research as part of the scientific project No. 17-06-01641a.

REFERENCES

- [1] Ay, N., Der, R., and Prokopenko, M., “Guided self-organization-perception-action loops of embodied systems”, *Theory in Biosciences*, 131 (3) (2012) 125–127.
- [2] Claudia, P., Martin, D., Christian, S., and Catherin, D., “Wireless compose—communication and positioning network in ISS and antarctic greenhouse”, *IEEE Wireless Communications and Networking Conference (WCNC)*, April 2019, Article number 88857802019.

- [3] Dressler, F., “A study of self-organization mechanisms in ad hoc and sensor networks”, *Computer Communications*, 31 (13) (2008) 3018–3029.
- [4] Gao, S., Dai, X., Hang, Y., Guo, Y., and Ji, Q., “Airborne wireless sensor networks for airplane monitoring system”, *Hindawi Wireless Communications and Mobile Computing*, 2018, Article ID 6025825, DOI: 10.1155/2018/6025825.
- [5] ILOG CPLEX 7.5 Reference Manual, ILOG S. A., France, 2005.
- [6] Makhorin, A.O., “Integer formulations of injections and bijections”, *Scientific and Technical Volga Region Bulletin*, 12 (2019) 75–79.
- [7] Padalko, S.N., and Terentiev, M.N., “Self-organization in the tree-like personal wireless networks with multiple gateways”, *Herald of the Bauman Moscow State Technical University. Series Instrument Engineering*, 1 (1) (2017) 75–85.
- [8] Phillips, D., and Garcia-Diaz, A., *Fundamentals of Network Analysis*, Prentice Hall, Englewood Cliffs, New York, 1981.
- [9] Prehofer, C., and Bettstetter, C., “Self-organization in communication networks—principles and design paradigms”, *IEEE Communications Magazine*, 43 (7) (2005) 78–85.
- [10] Prokopenko, M., (ed.) *Advances in Applied Self-Organizing Systems*, Springer-Verlag, London, 2013.
- [11] Riley, G., and Henderson, T., “The NS-3 Network Simulator”, *Modeling and Tools for Network Simulation*, Springer-Verlag, Berlin, 2010, 15–34.
- [12] Saraswat, J., and Bhattacharya, P., “Effect of duty cycle on energy consumption in wireless sensor networks”, *International Journal of Computer Networks & Communications (IJCNC)*, 5 (1) (2013) 125–140.
- [13] Suhonen, J., Hämäläinen, T., and Hännikäinen, M., “Availability and end-to-end reliability in low duty cycle multihop wireless sensor networks”, *Sensors*, 9 (3) (2009) 2088–2116.
- [14] Terentiev, M.N., “Review of publications on wireless sensor networks self-organization”, *Trudy MAI*, 94 (2017) <http://www.trudymai.ru/eng/published.php?ID=81149&eng=Y>
- [15] Wolsey, L.A. *Integer Programming*, John Wiley & Sons, 1998.