

An Effective Method for Ensuring the Reliability of a Critical Infrastructure Monitoring Network

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Abstract. One of the most valuable and compelling IoT applications are mission-critical infrastructure monitoring systems. Nowadays, research centers, commercial companies, and government agencies are actively researching and developing sensor-based long pipeline monitoring systems. In a wireless sensor network used to monitor pipelines, power grids, bridges, highways, all network nodes equipped with sensors form a special elongated topology. The harsh environment may cause wireless links to malfunction. Thus, maintaining network connectivity is a major issue. To improve network connectivity, i.e. to improve the reliability of monitoring, a number of approaches are used: networks are often supplemented with auxiliary relay nodes, the transmitter power is increased, resource-intensive protocols of error-correcting coding are used, etc. All this leads to unnecessary costs, which in many cases can be avoided. This paper proposes an effective method for assessing network connectivity that allows you to optimize and dose the costs of ensuring the reliability of a critical infrastructure monitoring systems.

Keywords: IoT · Wireless sensor network · Long pipeline monitoring

1 Introduction

The management and control of vital systems requires real-time monitoring, and the corresponding monitoring networks must be sufficiently reliable. Very often in the literature, network reliability is considered as the probability that any two nodes are connected (directly or through a set of intermediate nodes), taking into account unreliable links. A number of analytical approaches have been proposed to solve this problem. Researchers model the topology of a network using a random graph where any edge exists with some probability, and develop various

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techniques to calculate the probability of the connectedness of the graph. This probability is also known as the reliability polynomial. Calculating the reliability polynomial is a complex computational task. Brute-force and branch-and-bound methods are not suitable for huge networks. However, as we show in this work, the features of the topology of some networks, such as pipeline monitoring systems, make it possible to obtain efficient methods for calculating the reliability polynomial.

To utilize the specificity of long pipeline monitoring network topology we use properties of a two-vertex cut. It allows to perform the structural decomposition of a network. Also, for networks of an extensional spatial structure with many such cuts, arranged in series, we describe a method for identifying such cuts and a method for their subsequent traversal. As a result, it becomes possible to calculate the reliability of the network with a united calculation of the reliability of its components, as well as components merged by the cutting nodes. This way can be used to significantly improve the calculation of the reliability of the networks under consideration.

One of the most valuable and compelling IoT applications are mission-critical infrastructure monitoring systems. There are several projects on, and standardization initiatives for, sensor networks, which may eventually converge with the Internet of Things (IoT), for example European Union projects of Internet of Things Architecture (IoT-A) have been addressing the challenges of IoT solutions development from the wireless sensor networks (WSNs) perspective. Therefore, it is reasonable to apply WSNs for pipeline monitoring. Moreover, nowadays, research centers, commercial companies, and government agencies are actively researching and developing sensor-based long pipeline monitoring systems. According to an analytical report from GlobeNewswire published in 2020, even for such a particular task as monitoring water pipes to detect leaks, the solution market reaches a billion dollars and is growing at 5% per year.

A WSNs based monitoring system reduces the damage of natural and man-made disasters, the effects of infrastructure wear, and environmental and economic risks. However, radio channels in WSNs are usually quite unreliable. In order to fully utilize the potential of such systems, it needs to solve the problem of the system reliability.

In a wireless sensor network used to monitor pipelines, power grids, bridges, highways, all network nodes equipped with sensors form a special elongated topology. The harsh environment may cause wireless links to malfunction. Thus, maintaining network connectivity is a major issue. To improve network connectivity, i.e. to improve the reliability of monitoring, a number of approaches are used: networks are often supplemented with auxiliary relay nodes, the transmitter power is increased, resource-intensive protocols of error-correcting coding are used, etc. All this leads to unnecessary costs, which in many cases can be avoided. This paper proposes an effective method for assessing network connectivity that allows you to optimize and dose the costs of ensuring the reliability of a long pipeline monitoring systems.

The article is structured on 4 sections: after this introduction, Sect. 2 demonstrates state of the arts. Subsequently, Sect. 3 presents computational method for reliability of network topology. Finally, Sect. 4 summaries the paper and discloses future research.

2 Preliminaries

Research into the use of WSNs for pipeline monitoring was carried out as part of joint research projects between Stanford University, the University of Southern California and Chevron Corporation [1]. As an application, pipelines for steam heating and water supply were indicated, but the research results can be extended to other types of pipelines. The authors concluded that the SCADA system is a low-efficiency digital telemetry system for real-time data collection and analysis, on the basis of which Cisco offers commercial solutions for pipeline monitoring. The disadvantages of SCADA are the lack of flexibility, scalability, as well as the very high cost of its deployment and maintenance. Also, American researchers noted a general drawback of existing pipeline monitoring systems (including modifications and improvements to SCADA) compared to a system based on the low-power wide-area network: they do not use the advantages of a distributed system, are limited to data collection, or are specially designed to solve one narrow class of problems. At the same time, the results of the study noted the importance of the problem of ensuring the reliability of the system, the need to take into account the specifics of the topology, but there are no solutions for this. In addition, the monitoring system proposed by the authors is based on the outdated WSNs concept, which does not provide for the expansion of the functionality of critical network nodes due to mobility, the use of the ability to recharge sensors (energy harvesting), etc.

In the present literature a number of the following works, only individual problems of using WSNs for monitoring pipelines or problems of WSNs deployed on extended objects with similar properties (linear sensor networks) are considered. For example, an approach is proposed to increase the lifetime of a wireless connection between a pair of stationary transmitters and receivers using mobile relays, which are initially placed arbitrarily on the line between the transmitter and the receiver [2]. An analytical model has been developed to assess the impact of damaged nodes on linear sensor networks coverage [3].

The lack of reliable, low-cost pipeline monitoring solutions is reported by the US Federal Government Agency (Bureau of Reclamation), which organized a competition to find the specified solution on the INNOCENTIVE crowdsourcing platform.

When analyzing the reliability of networks for various purposes, including wireless sensor networks, the apparatus of random graphs is used, as a rule. The most common index of network reliability is the probability of connectivity of a subset of vertices of a random graph with unreliable edges [4], which describes the reliability of the network in terms of the possibility of establishing a connection between each pair of network nodes from the selected subset K of

the network nodes, which are called terminals. This index is called K-terminal network reliability. If this subset coincides with the set of all network nodes, we arrive to the network probabilistic connectivity (all-terminal network reliability).

This indicator is the major one, it allows us to describe the ability of proper functioning of networks for various purposes in conditions of independent failures of elements. We also note that various other reliability indices are considered and actively studied, including those for wireless sensor networks description [5–8].

However, the problem of calculating the reliability of the network is NP-hard [9], therefore, the exact calculation requires exponential complexity. In this regard, the probabilistic connectivity compares favorably with other reliability indices, since by now it has been developed an extensive mathematical and algorithmic apparatus for its calculation and estimation. So, for networks of a suitable structure of hundreds of elements, it is often possible to carry out an exact calculation of their probabilistic connectivity.

Thus, in next Section we focus on the problem of all-terminal connectivity and use the mentioned facility to offer an efficient method for the choice of optimal topology manning the required monitoring network reliability.

3 Computational Method for Reliability of Network Topology

Assume, a set of network architectures can be dynamically used to maintain a monitoring system: $A_1, A_2, \ldots A_k, \ldots$. These architectures are ordered by resource consumption (e.g. in terms of system cost). Each architecture A_i generates topology that is described by a graph G_i in which nodes correspond to sensors and edges to wireless channels. Due to harsh conditions channels are unreliable.

Let p be the channel reliability (the existence probability). Therefore, G_i is a random graph. Let $R(G_i)$ be the reliability polynomial of this graph (the probability of all-terminal connectivity). In fact, our task is as follows:

$$i^* = \arg\min\{R(G_i) \geq e\}$$

where e is the desired level of reliability. This approach was given further details in the paper [10].

In general, the problem of calculation $R(G_i)$ is NP-hard. Thus, our problem statement boils down to finding an efficient way to calculate $R(G_i)$ using their specific properties.

The reduction and decomposition methods [11] have become universal methods for speeding up the calculation; a more detailed overview of the calculation methods is given in [12]. One of corresponding approaches is the decomposition of the network via a vertex cut and reduction to the calculation of reliability in smaller subgraphs. This approach was firstly proposed by R.K. Wood for two-vertex cuts (2-cuts) [13]. This approach was developed, including for cuts of an arbitrary size, in our papers [14–16] and, later, by J.M. Burgos [17]. So, for a

graph G with a 2-cut dividing it into G_1, G_2 (Fig. 1), we have got a formula that was presented in this form in [15,16] later, as well as by J.M. Burgos in 2016 [17]:

$$R(G) = R(G_1)\big(R(G_2') - R(G_2)\big) + R(G_2)\big(R(G_1') - R(G_1)\big) + R(G_1)R(G_2). \quad (1)$$

Here, G_i' denotes the graph obtained from G_i by merging vertices x and y, $i = 1, 2$.

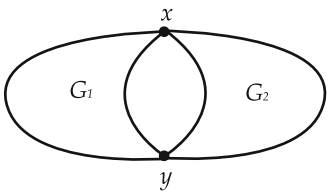

Fig. 1. Graph with two-vertex cut

Wireless sensor networks designed for monitoring the spatial extended objects, such as pipelines, themselves have an extensional structure. This class of networks is distinguished as linear wireless sensor networks. Despite their linear physical structure, a graph of such a network is not necessarily be linear topologically, since wireless communication channels are possible not only between the nearest neighboring nodes. The structure of such an extensional wireless sensor network is described by a graph with many cross-cuts. Let us consider the case when a network contains two-vertex cuts; the corresponding graph we call longitudinal (Fig. 2). The formal definition is given below.

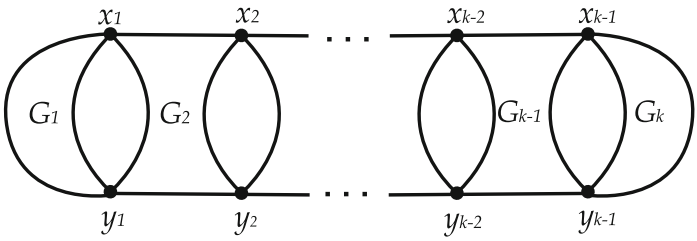

Fig. 2. Longitudinal graph

Note that if a network is decomposed into small-size biconnected components, then the calculation of its reliability is not a complicated task, since we may multiply the reliabilities of all biconnected components. It is also possible that a graph of such a longitudinal structure can be completely reduced by a serial-parallel transformation [11] within polynomial complexity. For example,

any lattice of width 2. These cases are trivial. Thus, we assume that the graph of a wireless sensor network is already decomposed into biconnected components and reduced, and the components reliability calculation problem arises.

Let us generalize the calculation method based on the application of formula (1) to longitudinal graphs. The recursive application of this formula to such a graph leads to repeated recalculation of reliability the graph components. To avoid this, we propose a method for finding all cross-cuts and a method for their subsequent traversal using (1) formula, which significantly speeds up the calculation of the reliability of extensional WSNs.

Below we introduce the necessary definitions and notations.

Let $G_1, \ldots, G_k$ $(k > 1)$ be a sequence of biconnected graphs such that:

1) G_i and G_{i+1} have exactly two common vertices x_i, y_i and do not have common edges;
2) G_i and G_j such that $|i - j| > 1$, have no common elements.

Then graph

$$G = \bigcup_{i=1}^{k} G_i$$

is called *longitudinal graph* (Fig. 2). Subgraphs G_i $(1 \leq i \leq k)$ are the *components* of longitudinal graph G.

Obviously, each pair of vertices

$$\{x_i, y_i \mid 1 \leq i \leq k-1\}$$

is a cut in graph G. We define *longitudinal cut* in G as set

$$\bigcup_{i=1}^{k-1} \{\{x_i, y_i\}\}.$$

Let $\{x_i, y_i\}$ be a *component* of longitudinal cut, which is also called *cross-cut* of longitudinal graph G. A longitudinal cut of G is *maximum* if no any 2-vertex cut of G can be added to it so that it remains longitudinal. Two cross-cuts $\{x_i, y_i\}$, $\{x_j, y_j\}$ are *adjacent* if $|i - j| = 1$.

For a component G_i, we denote by S_i the set of partitions of the set of longitudinal cut vertices that are in G_i. We use the following notation for a partition:

$$v_1 \ldots v_l | \ldots | u_1 \ldots u_t = \{\{v_1, \ldots, v_l\}, \ldots, \{u_1, \ldots, u_t\}\}. \tag{2}$$

By G_i^{Φ} $(\Phi \in S_i)$ we denote graph G_i contracted by each element of Φ. Thus, if vertices u and v are in the same element Φ, then they are contracted into one vertex in G_i^{Φ}.

During recursively application of formula (1) for longitudinal graph G, we obtain graphs, in addition to G_i, of the following types (Fig. 3, 4):

$$G_i' = \begin{cases} G_i^{x_{i-1}y_{i-1}|x_i|y_i} & , 1 < i < k, \\ G_k^{x_{k-1}y_{k-1}} & , i = k; \end{cases} \tag{3}$$

$$G_i'' = \begin{cases} G_i^{x_{i-1}|y_{i-1}|x_i y_i} & ,1 < i < k, \\ G_1^{x_1 y_1} & ,i = 1; \end{cases}$$

$$G_i''' = G_i^{x_{i-1} y_{i-1}|x_i y_i}, 1 < i < k; \tag{4}$$

$$G_{ik} = \bigcup_{i \le j \le k} G_j, 1 \le i \le k; \tag{5}$$

$$G'_{ik} = G'_i \bigcup_{i+1 \le j \le k} G_j, 1 < i \le k. \tag{6}$$

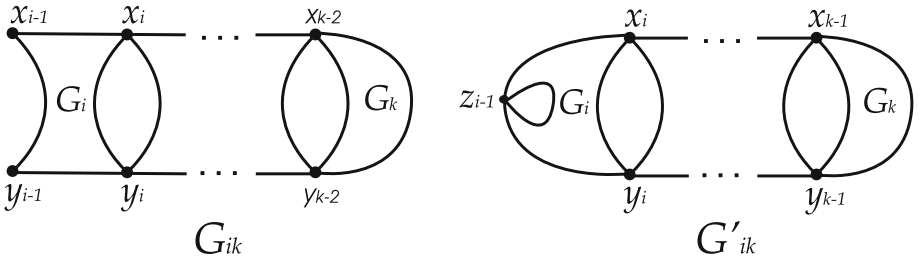

Fig. 3. Intermediate graphs

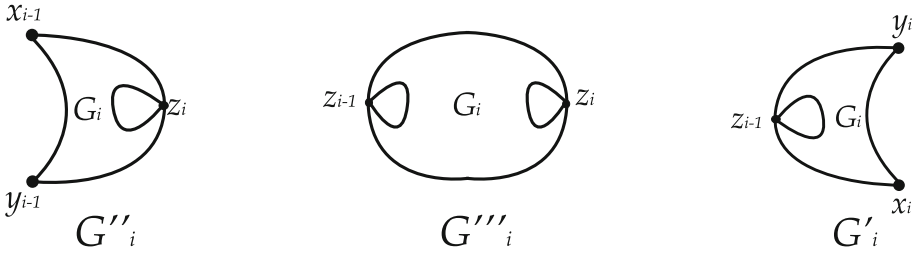

Fig. 4. Intermediate graphs

Let us remark that $R(G_{ik})$, $R(G'_{ik})$ can be calculated recursively:

$$R(G_{ik}) = R(G_i)R(G'_{i+1k}) + R(G''_i)R(G_{i+1k}) - R(G_i)R(G_{i+1k}), \tag{7}$$

$$R(G'_{ik}) = R(G'_i)R(G'_{i+1k}) + R(G'''_i)R(G_{i+1k}) - R(G'_i)R(G_{i+1k}). \tag{8}$$

From the definition of G_{ik} it follows that $G_{1k} = G$, therefore:

$$R(G) = R(G_{1k}). \tag{9}$$

Thus, having previously calculated the values of $R(G_i)$, $R(G'_i)$, $R(G''_i)$, $R(G'''_i)$, we can calculate $R(G)$ using recursive formulas. This results can essentially improve performance of reliability computing.

Finding the maximum longitudinal cut is a separate task. A natural way to construct it is a recursive search for 2-cuts in the components, into which the graph is decomposed by already found 2-cuts. The main problem is that obtained by such procedure a 2-cuts set remains a longitudinal cut. This problem can be easy solved for components G_1, G_k, because any of their 2-cuts can be chosen to complement an already formed longitudinal cut. The only condition for check is the difference between each vertex from new 2-cut in G_1 or G_k and the nodes $\{x_1, y_1\}$ or $\{x_{i-1}, y_{i-1}\}$, respectively.

For an internal component G_i $((2 \leq i \leq k-1))$, not any its 2-cut can be added to a current longitudinal cut

$$\bigcup_{i=1}^{k-1} \{x_i, y_i\}.$$

Let there be a cut $\{x, y\}$ in the component G_i, dividing it into subgraphs H_1, H_2. Obviously, the longitudinal cut remains longitudinal due to location of vertices from neighboring cross-cuts with numbers $i, i-1$ to different subgraphs: H_1, H_2. That is,

$$\bigcup_{i=1}^{k-1} \{x_i, y_i\} \bigcup \{x, y\}$$

is also a longitudinal cut if nodes $\{x_{i-1}, y_{i-1}\}$ are in one subgraph H_i, and the nodes $\{x_i, y_i\}$ are in another. Thus, having a longitudinal cut C in the graph and wanting to complete it to the maximum longitudinal cut, we find an arbitrary two-vertex cut $\{x, y\}$, check where the nodes from neighboring cross-cuts are, and determine whether the cut is longitudinal.

By using formula 2-Cuts algorithm with a sequential enumeration of the components of the longitudinal cut, we have to calculate reliability of

$$2 + 2^{k-1} + 4 \sum_{i=0}^{k-3} 2^i$$

such graphs, with the middle cut choice—about 2^k graphs. Thus, the proposed method is significantly faster than the calculation by the traditional way.

Comparison of the calculation time is given below, including for calculating without cut decomposition, i.e. for calculating by factoring method *Factoring* [18] improved by series-parallel transformation at each step [11] and termination of recursive calls when reaching 5-vertex graphs [15]. The decomposition method uses this way to calculate the reliability of components. Finding the maximum longitudinal cut by the procedure above requires the enumeration of all pairs of nodes with checking the connectivity of graph obtained by removing each pair of nodes, that is, $O(MN^2)$ operations.

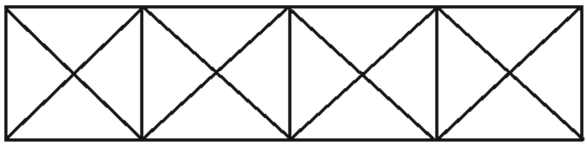

Fig. 5. Graph K_4^5

Numerical experiments were conducted on graphs obtained by the recursive procedure of joining to an already formed longitudinal graph of a complete graph on 4 vertices K_4, provided that two vertices of these graphs coincide. K_4 is also taken as an initial graph. The longitudinal graph obtained by this procedure of union of $k-1$ graphs K_4 we denote by K_4^k (Fig. 5). For each edge of such a graph, we set its reliability value equal to 0.9.

Table 1 shows the execution time of algorithms for calculating the reliability of three graphs K_4^k and the calculated network reliability value with an accuracy of 6 decimal places. 4-core CPU (2.4 GHz) was used. It can be seen that as k grows, it is no longer possible to calculate network reliability by factorization. The decomposition approach makes such a calculation quite fast, while the use of longitudinal cuts additionally speeds up the calculation.

Table 1. Running time of algorithms for calculating the reliability of graphs K_4^k

Graph	*Factoring*	*2-Cuts*	Reliability value
K_4^{20}	4.3 s	1 s	0.993445
K_4^{25}	2 m 7 s	1 s	0.992753
K_4^{100}	24 h	2 s	0.982438

4 Discussion and Conclusion

In this paper we provide preliminary results of ongoing research in the area of reliability improvement for critical infrastructure monitoring network. We consider long pipeline monitoring networks to detect events of interest (leaks, unauthorized access, special states of the system and transported product, etc.). We are focused on developing a tool for jointly optimizing the structural reliability of WSNs used for pipeline monitoring and optimizing the functional reliability of WSNs for this purpose. To achieve this goal, we use sub-models that characterize the reliability of the channels during their operation, and then, we obtain the reliability of the entire network, taking into account its topology. The results obtained can be used to solve a number of the following practical problems: finding a compromise between minimizing the costs of a critical infrastructure monitoring system and improving the functional and structural reliability of this system. In future works, we will use the properties of the longitudinal cut

to implement an algorithm outperforming 2-Cuts. Also, we will develop technique to maintain quality of service and quality of experience (QoS, QoE), that increases the profitability of IoT technologies.

References

1. Sunhee, Y., Wei, Y., Heidemann, J., Littlefield, B., Shahabi, C.: SWATS: wireless sensor networks for steamflood and waterflood pipeline monitoring. IEEE Netw. **25**(1), 50–56 (2011)
2. Phelan, B., et al.: Should I stay or should I go? Maximizing lifetime with relays. In: Proceedings of the IEEE DCOSS 2012, pp. 1–8 (2012)
3. Mohamed, N., et al.: Failure impact on coverage in linear wireless sensor networks. In: Proceedings of the SPECTS 2013, pp. 188–195 (2013)
4. Colbourn, C.J.: The Combinatorics of Network Reliability. Oxford University Press, New York (1987)
5. Petingi, L.: Introduction of a new network reliability model to evaluate the performance of sensor networks. Int. J. Math. Models Meth. Appl. Sci. **5**(3), 577–585 (2011)
6. Migov, D.A., Shakhov, V.: Reliability of ad hoc networks with imperfect nodes. In: Jonsson, M., Vinel, A., Bellalta, B., Belyaev, E. (eds.) MACOM 2014. LNCS, vol. 8715, pp. 49–58. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-10262-7_5
7. Sun, F., Shayman, M.A.: On pairwise connectivity of wireless multihop networks. Int. J. Secur. Netw. **2**(1/2), 37–49 (2007)
8. Shazly, M., et al.: On area coverage reliability of wireless sensor networks. In: Proceedings of IEEE Conference on Local Computer Networks (LCN 2011), Bonn, Germany, pp. 580–588 (2011)
9. Ball, M.O.: Computational complexity of network reliability analysis: an overview. IEEE Trans. Reliab. **35**(3), 230–239 (1986)
10. Shakhov, V., Koo, I.: Graph-based technique for survivability assessment and optimization of IoT applications. Int. J. Softw. Tools Technol. Transf. **23**(1), 105–114 (2020). https://doi.org/10.1007/s10009-020-00594-9
11. Shooman, A.M., Kershenbaum, A.: Exact graph-reduction algorithms for network reliability analysis. In: IEEE Global Telecommunications Conference GLOBECOM, vol. 91, pp. 1412–1420 (1991)
12. Pérez-Rosés, H.: Sixty years of network reliability. Math. Comput. Sci. **12**(3), 275–293 (2018). https://doi.org/10.1007/s11786-018-0345-5
13. Wood, R.K.: Triconnected decomposition for computing K-terminal network reliability. Networks **19**, 203–220 (1989)
14. Migov, D.: Methods of network reliability calculation based on the use of vertex cuts. Comput. Technol. **13**, 425–431 (2008)
15. Rodionov, A.S., Migov, D.A., Rodionova, O.K.: Improvements in the efficiency of cumulative updating of all-terminal network reliability. IEEE Trans. Reliab. **61**(2), 460–465 (2012)
16. Migov, D.A., Rodionova, O.K., Rodionov, A.S., Choo, H.: Network probabilistic connectivity: using node cuts. In: Zhou, X., et al. (eds.) EUC 2006. LNCS, vol. 4097, pp. 702–709. Springer, Heidelberg (2006). https://doi.org/10.1007/11807964_71
17. Burgos, J., Amoza, F.: Factorization of network reliability with perfect nodes I: introduction and statements. Discr. Appl. Math. **198**, 82–90 (2016)
18. Page, L.B., Perry, J.E.: A practical implementation of the factoring theorem for network reliability. IEEE Trans. Reliab. **37**(3), 259–267 (1998)