Influence of Node's Reliability Indicators on the Wireless Sensor Network Operability

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***Abstract*—Wireless sensor network is an excellent tool for gathering data from various sensors scattered over the area. However, reliability requirements applied to the network nodes are generally higher. A variety of factors contributing to the reliability of the network should be taken into account. In the present study, the reliability indicators for both a typical network node and the WSN as a whole will be evaluated. The mathematical models for estimating mean down time, failure rate and availability factor will be constructed. The influence of external factors on the reliability indicators will be clarified. Throughout the entire calculation process, unique Russian software systems will be used. And finally the impact of both sensor nodes and base stations reliability indicators on the operability of the entire network will be estimated.**

Keywords—reliability, modeling, availability, failure rate, faultlessness.

I. Introduction

There has been a rapid development of information technologies during the last decades. Within this process, data transmission networks have become an integral part of people's lives, without which the exchange of information is practically unthinkable. The analysis of existing data transmission networks technical characteristics and the design of new networks considering the given parameters remains one of the most urgent tasks in the field of information technology.

Wireless sensor network (WSN) is a special case of data transmission network when many separate sensors scattered over the area are used for data acquisition and pre-processing. Thanks to the recent advancements in the IoT technologies, the WSNs have gained special popularity not only in industrial, but also in the consumer-grade fields of application [1]. However, the reliability requirements applied to the wireless network nodes are higher.

WSN nodes (or sensors) are physically located in harsh environmental conditions and influenced by increased vibration load, high air humidity, extremely high or low operating temperatures. In addition, the wireless transmission medium itself is considered unreliable, especially when it comes to ultra-low power transmitters and receivers widely applied in WSNs to reduce power consumption.

All of the mentioned problems leads us to the fact that complex reliability indicators including availability factor and mean down time are no less important than consumer-related characteristics such as network performance, latency, and bandwidth. The availability of network services for users directly depends on reliability indicators. In addition, the performance and latency of the WSN are indirectly dependent on network reliability, since the occurrence of networking failures entails retransmission of data blocks, and this ultimately leads to increased latency and decreased bandwidth. Finally, the network reliability indirectly affects the safety of latency-dependent control systems operation. Any network failure may lead to dramatic consequences if the control system is unable to respond in time to changes in vital parameters. In such a situation, the analysis of reliability indicators of wireless sensor networks is an especially urgent problem.

Within the framework of the article, the application of a model for assessing the reliability indicators of recoverable systems consisting of one or several groups of homogeneous objects for a given sensor network topology is considered in order to analyze the availability factor. The model relies on the mathematical apparatus of probability theory. To simplify the final formulas for calculating the availability factor, an assumption is made about the complete independence of objects both within groups and between groups, both in terms of failures and recovery. In addition, to simplify the analysis, the possibility of failure of the communication channels in data transmission networks is not taken into account.

II. Wireless sensor networks general overview

The devices communicating over a certain network are expecting the network to be available and reliable. The reliability of a wireless sensor network on a software level is supported by reliable data transmission protocols, which may include redundancy, error correction codes, data retransmission, and other features. On the other hand, the physical electronic devices comprising the network may be a subject to fail as well. To estimate the probability of such failure, the type, quantity, operational and storage conditions of the electronic devices should be considered.

A typical wireless sensor network includes sensor nodes, or sensors, which are connected to base stations via wireless radio communication. The main purpose of sensor nodes is measuring the specified parameters, pre-processing the acquired data and transmitting the data to the base station [2]. The base station aggregates information received from a variety of sensors connected to it, monitors changes in parameters and their out of range, and provides user access to its data through industrial-grade network protocols such as Modbus or IEC 60870-5-101/104.

The base stations are intended to be placed in steady and protected containers and to be linked via a fixed cable network connection thus to be considered significantly more reliable. On the other hand, sensor nodes are located in harsh environmental conditions, which potentially significantly reduces their reliability.

In addition, the wireless network connection itself cannot guarantee a reliable data delivery. The radio signal can be affected to interference and crosstalk caused by power lines or other industrial machinery located nearby. No software data

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transfer protocol can remain reliable when the physical transmission medium is unavailable.

However, since the base stations are interconnected with a fixed cable link, within the framework of this study the assumption is made about the high reliability of such connection. The only unknown variable left is the reliability of the electronic devices comprising the network. It is possible to estimate the reliability indicators of both sensor nodes and base stations in the WSN using analytical methods for calculating reliability based on exponential distribution law.

III. THE MATHEMATICAL MODEL FOR ESTIMATION OF RELIABILITY INDICATORS OF SPECIFIED NETWORK

The considered WSN can be classified as two-tier network with dedicated core [3] (base station) which includes $r \geq 1$ of core-level switches (base stations) and $k \geq 1$ of sensors (nodes). Under these assumptions, the network will have the following parameters:

- All the base stations are connected with each other;
- All the sensors are not connected with each other;
- Each core-level switch (base station) is connected to one or several dedicated sensors;
- Any failure of any sensor, or any failure of wired connection between the base stations is considered as a failure of all the sensor network (failure criterion of the system is a failure of any of its parts);
- The failure rate of the base station is λ_C, and its recovery time is $\mu_C = 4h$;
- The failure rate of the sensor is λ_A, and its recovery time is $\mu_A = 6h$.

Considering the mentioned network parameters and given *r* and *k*, it is possible to design a topological model of the two-tier wireless sensor network (Fig. 1).

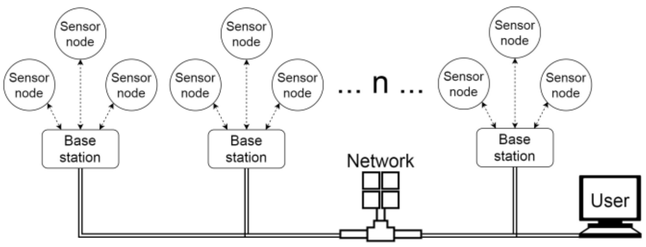

Fig. 1. An example of a sensor network topology with a dedicated core (base station)

Considering that the network topology is two-tiered, from the point of view of the reliability theory, two independent groups of objects can be distinguished, such as a group of base stations and a group of sensor nodes. Thus, the Markov model of a set of independent object groups will have the following form [4] (Fig. 2).

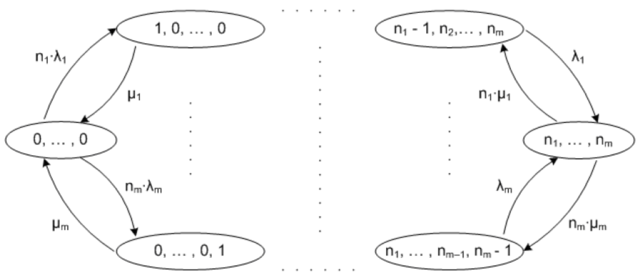

Fig. 2. A graph of independent object groups according to the Markov model

Let there be m independent groups of recoverable objects to be restored with given numbers of objects in groups: $n_1 \dots n_m$. The objects within the group $l = 1 \dots m$ have the same failure rates λ_l and the same recovery rates μ_l.

The objects can independently fail and can be independently recovered without any restrictions.

The general solution of the model (system of differential equations) in analytical form is obtained by direct multiplication of the corresponding probabilities within individual groups (since the groups are independent from the point of view of the reliability model) (Fig. 3).

$$P_{j_1,\dots,j_m}(t)=\prod_{l=1}^{m}\left(C_{n_l}^{j_l}\cdot\frac{\rho_l^{j_l}}{\left(1+\rho_l\right)^{n_l}}\cdot\left(1-e^{-\alpha_l\cdot t}\right)^{j_l}\cdot\left(1+\rho_l\cdot e^{-\alpha_l\cdot t}\right)^{n_l-j_l}\right)$$
$$j_l=0\dots n_l;\quad l=1\dots m$$
$$\rho_l=\lambda_l/\mu_l;\quad \alpha_l=\lambda_l+\mu_l;$$
$$P_{0,\dots,0}(0)=1;\quad \sum_{j_1=0}^{n_1}\sum_{j_2=0}^{n_2}\dots\sum_{j_m=0}^{n_m}P_{j_1,\dots,j_m}(t)=1;$$

Fig. 3. The general solution of the model

Assuming $t \to \infty$, the Markov process becomes steady, and the probabilities no longer change over time [5] (Fig. 4).

$$\lim_{t\to\infty}\left(P_{j_1,\dots,j_m}(t)\right)=\prod_{l=1}^{m}\left(C_{n_l}^{j_l}\cdot\frac{\rho_l^{j_l}}{\left(1+\rho_l\right)^{n_l}}\right)$$
$$j_l=0\dots n_l;\quad l=1\dots m$$
$$\rho_l=\lambda_l/\mu_l$$

Fig. 4. The steady model for estimating the state of the objects group

The given wireless sensor network model requires the connection of all the base stations to each other via a common network medium. Considering the mentioned model for evaluating a group of base stations, the network is considered to be operational if at least one base station in the group of stations is operational. The probability of this is equal to the sum of the probabilities from the zero state to the penultimate state in the Markov reliability model of a group of *r* objects (Fig. 5)

$$P_{net}(t)=\left(1-\left(\frac{\rho_C}{1+\rho_C}\cdot\left(1-e^{-\alpha_C\cdot t}\right)\right)^r\right)\cdot\left(\frac{1+\rho_A\cdot e^{-\alpha_A\cdot t}}{1+\rho_A}\right)^k$$

Fig. 5. Probability of faultless operation of the network core

Then, the stationary availability factor of the two-level network is equal:

$$K_{net} = \lim_{t\to\infty} P_{net}(t) = \frac{(1+\rho_c)^r - (\rho_c)^r}{(1+\rho_c)^r \cdot (1+\rho_A)^k}$$

Finally, the mathematical model for estimating the down time (per year) considering the above model for estimating K_{net} will be as follows:

$$T_d = 8760 \cdot (1 - K_{net})$$

IV. The Mathematical Model for Estimation of Reliability Indicators of Electronic Devices

At this point, it is very important to mention that all the components of the network are electronic devices, which consists of a finite set of discrete electronic parts including capacitors, resistors, integrated circuits, printed circuit boards, welding points and others. The failure rate of separate electronic parts can be estimated using methods from reliability handbooks.

A failure rate is a basic unit for interdisciplinary reliability indicators estimation. Electronic components of similar type shares the same mathematical formula for failure rate estimation. A general view for the specified formula is the following:

$$\lambda_i^k = \lambda_b^k \cdot \prod_j K_j^k$$

λ_i^k is a failure rate of any component within a specified group, λ_b^k is a mean basic failure rate, similar for all the components in the group, K_j^k is a correction factor.

The reliability handbooks such as “Reliability-2006” or MIL-HDBK-217F [6] provide a set of formulas for estimating the failure rate of any component in any group. For example, the formula for estimating the failure rate of a resistor is listed below:

$$\lambda_i^R = \lambda_b^R \cdot K_t \cdot K_P \cdot K_S \cdot K_Q \cdot K_E$$

As shown by the specified formula, the failure rate of a resistor depends on mean basic failure rate of all the resistors of similar type, and several correction factors that take into account the influence of electrical and environmental conditions, as expected.

It is widely known that any electronic component inevitably generates heat during its operation. A resistor is a great example of this process, as its main function is to convert electrical energy into thermal energy. Reliability handbooks can be used to calculate the required correction factors for any discrete electronic component. As an example, the MIL-HDBK-217F reliability handbook is prudently provided with a separate section for assessing the temperature correction factor of resistors. The figure 6 shows that the temperature correction factor of a resistor is a function of its case temperature, which sequentially depends on the ambient temperature, power dissipation, and operational mode power.

Temperature Factor - π_T

T_C (°C)	π_T	T_C (°C)	π_T
25	1.0	80	8.3
30	1.3	85	9.8
35	1.6	90	11
40	1.9	95	13
45	2.4	100	15
50	2.9	105	18
55	3.5	110	21
60	4.2	115	24
65	5.0	120	27
70	6.0	125	31
75	7.1		

π_T = $\exp\left(-4056\left(\frac{1}{T_C + 273} - \frac{1}{298}\right)\right)$

T_C = Case Temperature (°C)

Fig. 6. Temperature correction factor of a resistor, as shown by [6]

The failure rate of other discrete electronic components can be estimated using similar formulas from reliability handbooks. After that, the failure rate of the entire electronic device (λ_C or λ_A) is calculated as a sum of failure rates of its parts:

$$\lambda = \sum_{i=0}^{n} \lambda_i$$

The stated approach is mostly applicable for simple electronic devices consisting of a small number of discrete components. However, wireless sensor networks are composed of complicated electronic devices, which designed for simultaneous implementation of many disparate functions. As a consequence, they include a vast number of discrete components, which makes manual calculation of failure rate for each component a tedious process. To avoid manual calculations, the stated approach should be automated using computer-aided design systems.

V. Estimating the Reliability Indicators of Specified Wireless Sensor Network

To date, a certain number of software solutions for estimating the reliability indicators of electronic devices has been developed. A Russian computer-aided design software “ASONIKA-K”[7] has been applied at the present study. It combines computational models, data, and basic failure rates for groups of components from reliability handbooks such as “Reliability-2006”, MIL-HDBK-217F [6], GJB/z 299B, and others. This software makes it possible to introduce a cross-cutting methodology for estimating reliability indicators of solitary or complex electronic devices given that their components are known.

Both base stations and sensor nodes of the network are constructed of various sets of active or integral (microcontrollers, transistors, operational amplifiers, other ICs) and passive (resistors, capacitors, connectors, welding, soldering) components which that contribute to the device reliability. The list of components, supplemented by the working, storage and environmental conditions, acts as the input data for the ASONIKA-K system (Fig. 7).

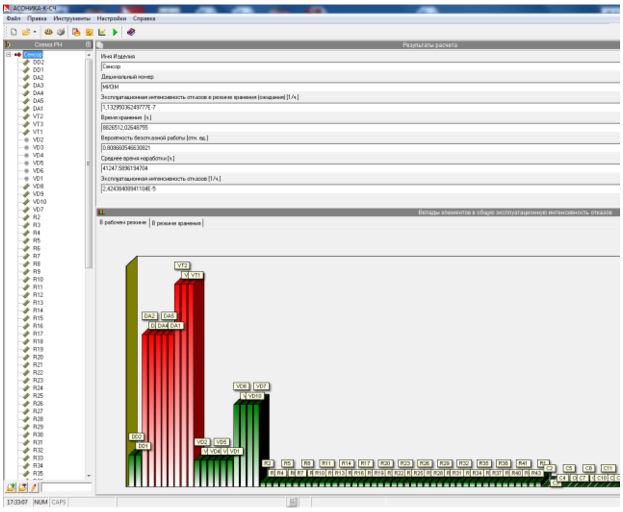

Fig. 7. Estimation of reliability indicators using ASONIKA-K

The calculations are built upon analytical reliability estimation methods and exponential distribution law. The output results from the ASONIKA-K system indicate that $\lambda_A = 2.42 \cdot 10^{-5}$ and $\lambda_C = 1.97 \cdot 10^{-6}$ $[h^{-1}]$, which allows us to estimate the availability factor K_{net} and down time T_d of the wireless sensor network:

$$K_{net} = 99.9565[\%]\,;\, T_d = 3.81\ [h/year]$$

It is noticeable that the base station failure rate is significantly lower than the sensor node failure rate, as expected from the theoretical implications. Sensor nodes contribute the most to the failure rate of the entire network, while the impact of base stations failure rate is relatively negligible. It has also been estimated that the down time of the given wireless sensor network is as low as 3.8 hours per year, which is generally a good result.

Since the main contributor to the network failure rate is discovered, it is necessary to investigate the factors affecting its reliability. Since the sensor nodes are located in the environment, they are mostly affected by temperature. The ASONIKA-K system allows altering the failure rate calculations by changing the operational temperature. The results are presented as a graph (Fig. 8). The figure shows that the failure rate of a sensor node increases exponentially with deteriorating environmental conditions.

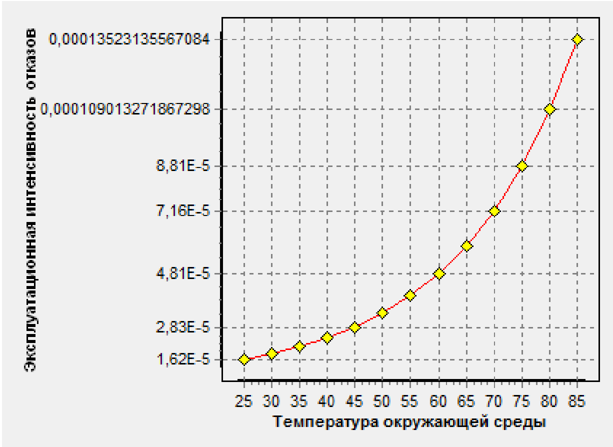

Fig. 8. Failure rate vs temperature chart (ASONIKA-K)

VI. Conclusion

The paper proposed a methodology for estimating the reliability indicators of a two-tier wireless network. This includes a mathematical model for estimating the down time and availability factor of the network in addition to the design route for accessing the reliability indicators of electronic devices included into the network using the ASONIKA-K software system.

The results obtained by the proposed mathematical model indicates that the sensor nodes brings the most impact to the operability of the network, while the sensor nodes themselves are mostly affected by environmental conditions such as operational temperature. On the other hand, the influence of the base stations failure rate on the network operability can be neglected. However, if the reliability of the base stations were on par with the failure rate of the sensor nodes, it should be seriously taken into account as well.

The proposed mathematical model is applicable for two-tier WSNs with various quantity of base stations and sensor nodes, as well as the presented method for accessing the reliability indicators of electronic devices can be used outside the broad area of wireless networks.

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