Stability of Positive Systems in WSN Gateway for IoT&IIoT

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Abstract. Modern sensor networks work on the basis of intelligent sensors and actuators, their connection is carried out using conventional or specifically dedicated networks. The efficiency and smooth transmission of such a network is of great importance for the accuracy of measurements, sensor energy savings, or transmission speed. Ethernet in many networks is typically based on the TCP/IP protocol suite. Regardless of whether or not the network transmission is wired or wireless, it should always be reliable. TCP ensures transmission reliability through retransmissions, congestion control and flow control. But TPC is different in networks based on the UDP protocol. The most important here is the transmission speed achieved by shortening the header or the lack of an acknowledgment mechanism. Assuming the network is an automatic control system, it has interconnected elements that interact with each other to perform some specific tasks such as speed control, reliability and security of transmission, just the attributes that define stability being one of the fundamental features of control systems. Such a system returns to equilibrium after being unbalanced. There are many definitions of stability, e.g. Laplace or Lupanov. To check the stability of the sensor network connected to the Internet, different stability criteria should be used. We are going to analyze the stability of a computer network as a dynamic linear system, described by the equations known in the literature. In this paper, we propose the method of testing stability for positive systems using the Metzlner matrix in sensor networks such as IoT or IIoT. We will carry out tests in a place where wide area networks connect to sensor networks, that is in gates.

Keywords: Wireless sensor networks · Network system stability · Industrial IoT · Metzler matrix · Software testing methodology

1 Introduction

The work concerns an important topic which is the stability of computer networks as dynamic systems. Stable network operation allows the construction of efficient, fast and optimally working networks. Stability testing methods are known from the automation literature. The authors propose the use of these methods in computer science, and in particular, in computer networks. The use of sensor networks not only in IoT, but also in industry 4.0 (IIoT) is constantly growing and the research on their reliability should be continued. The proposed method may contribute to improving quality of such networks.

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Networks that rely on the RED algorithm using AQM and packet queuing in routers and its variants do not always give good results. Hence, the methods for testing the stability of such networks is studied. They allow us to compare how the network stability conditions and its parameters will change depending on the method used.

Thus, stability of dynamic systems is an important concept associated with automation. Comparing the computer network to a dynamic system will allow analyzing its stability. Defining stability boundaries will give us the opportunity to design a more efficient and fault-tolerant network. Such studies can be applied to sensor networks. The use of sensor networks not only in IoT, but also in industry 4.0 (IIoT) is constantly growing and research into the reliability of such systems should be improved. One of the methods described in this article is testing the stability of positive systems. Therefore, motivation of this research work is to improve network parameters significantly, i.e. to improve its reliability and overall performance.

LoraWAN network research has been presented in [12–14]. They mainly concern the improvement of network scalability. Works on time synchronization, which plays an increasingly important role in information systems, are described in [15, 16]. However, the research carried out in this article concerns the improvement of network parameters in IoT and industrial IoT networks. They focus on network parameters such as: capacity, number of session and propagation time (capacity, number of sessions or propagation time). The analysis of positive systems will allow to improve the performance and scalability of wireless sensor networks.

When compared to conventional networks, wireless sensor networks (WSN) are arranged much more densely, their topology changes dynamically, additionally they have more limitations like memory or energy resources. Also, WSN creates a distributed measurement network to be applicable to measure air humidity and soil, monitoring traffic, tectonic movement, or avalanches. Other application areas include industry, medicine or the army. Sensors communicate with each other in real time and keep on sending data. The sensor topology is rather unpredictable. As a principle, sensors are divided into groups (clusters). This is a hierarchical network topology. All the measured data is sent to the main nodes and then to the overriding (parent) nodes. The parent nodes play the crucial role in a network gateway. Sometimes the sensors don't see the parent node and the data is sent in steps from one sensor to another always towards the parent node (see Fig. 1).

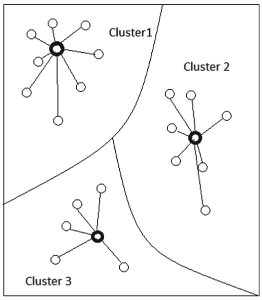

Fig. 1. Clustering and master sensors of WSN

2 LPWAN Networks

Development of IT technologies has a huge impact on smart cities. One of the most important aspects of this development is connectivity or wireless communication. Standards implementing IoT tasks for smart cities are WiFi, BLE, Zigbee, Thread or LoRaWan.

LPWAN (Low Power, Wide Area Network) is a new category of universal networks with a similar structure to that one used in mobile network. It mostly has a star topology and uses BTS (Base Transceiver Station) as a communication center for network cells. In some standards like Zigbee, it has a mesh topology for whose the central point is a coordinator.

LPWAN enables long distance communication at low bit rates and low power consumption. These networks work based on protocols that have better parameters in terms of resistance to interference and signal loss, at the expense of inferior bandwidth. They work on frequencies belonging to the unlicensed ISM band, which minimizes the costs of their use.

3 WSN Communication

A network layer model is adopted for WSN just like in conventional networks. In addition to the physical layers, data link, network, transport layer and application layer, there are also 4 planes such as energy management plane, displacement plane and two task management planes. All the planes cooperate with each other so that the sensors can share their resources, save energy or route the data [11]. Such a scheme determines efficiency of the network (see Fig. 2).

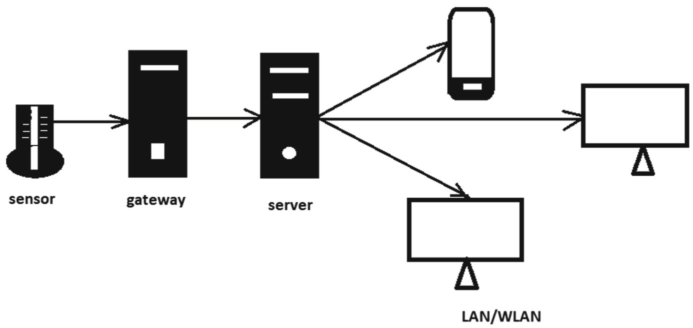

Fig. 2. Communication between WSN and WLA

In this paper, we focus on the transport layer. It serves as a combination of application layer and network layer whose major task is to control the mechanism of traffic congestion. All these tasks are performed by the TCP protocol, however for the sensor networks, they have some variations.

Network traffic moves from the child nodes to the parent node. Reverse traffic channel is used to manage the whole network. Acknowledgment mechanism for the data transfer is not required here for the reasons of network energy savings. However, the mechanism move from the parent node to the user or to the global Internet needs to be supervised for reliability purpose.

4 WSN Gateway

A device connecting the WAN network with the sensor network is a gateway operating in the Ethernet standard (see Fig. 3). The gateway may be a typical sensor, but having much larger RAM and a faster processor, then it is supplied by the power line. Alternatively, the gateway can be a router, as so called a routing network device or a coordinator, just as for example, in the Zigbee standard. WAN Gateway is a data collecting point which transfers them to the Internet. It mainly deals with the data conversion to packets by forwarding them. Packets are then sent to the network servers using conventional TCP/IP based networks.

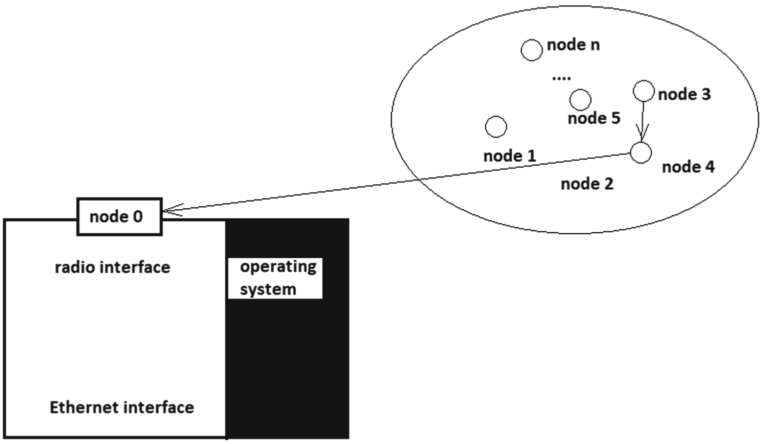

Fig. 3. WSN and WLAN Gateway scheme

5 Industrial Network Standards

Industrial networks, and in particular Industrial IoT (IIoT) networks, are becoming nowadays an inherent element of industrial infrastructure. Efficient data management enables to optimize production processes, whereas standardization of networking supports this objective.

5.1 ZigBee Standard

One of the standards created for the purpose of the radio communication in WSN, which does not need very high bandwidth, is the ZigBee standard with the numerous nodes. Usually, it has one of the following topologies: a star, tree, or a mesh topology. ZigBee model is layered, quite similarly to the TCP/IP model. This model is defined as the standard (protocol) of IEEE 802.15.4 [9]. It defines all the layers, out of which the two lowest layers are named: the physical PHY (PHYsical) and the MAC layer (Medium Access Control Layer).

The MAC layer is responsible for access to radio channels using the CSMA-CA (Carrier Sense Multiple Access - Collision Avoidance) mechanism. This layer may also process the transmission of signal beacons, provide synchronization and reliable transmission mechanism.

Radio transmission works on two frequency ranges: 868 MHz (one channel - Europe standard) and 2.4 GHz (16 channels - the whole world).

Access to the network is carried out in two ways:

- beaconing - transmission during operation of devices in a continuous mode,
- non-beaconing - transmission during operation of devices in periodic or random mode.

Two types of nodes have been defined in the IEEE 802.15.4 protocol:

- the node with reduced functionality RFD
- the node with full functionality FFD.

The node that manages the network (coordinator) is the type of FFD [8].

5.2 ZigBee Gateway

Wired connections in industrial automation networks are known as not a very good solution because they are not applicable in industrial companies located on large areas or in places where the temperature is high. Whereas, wireless networks may have adverse effects in the form of interference or signal reflection, automatic routing techniques are aimed to prevent them.

Standard Zigbee enables not only to build new industrial networks, but also to connect new to existing ones. Such network integration is possible thanks to modems and gateways. Ethernet gateways can convert data from Zigbee to TCP/IP and vice versa.

6 IoT Network Standards

We define two major IoT network standards such as LoRaWAN and Sigfox.

6.1 LoRaWAN Standard

The LoRa (Long Range) standard is a wide narrow band long-range network that has been optimized for the lowest possible energy consumption. It provides two-way, simultaneous data transmission. Information exchange takes place via a common medium in both directions. LoRaWAN is the standard for network communication M2M (Machine-to-Machine) and IoT. Also, it can be either an alternative or complement solution to battery supply.

The LoRaWAN network new modulation technique is an asynchronous method of digital modulation based on direct sequence spread spectrum (DSSS). It enables user to choose the diffusion string and bandwidth in order to meet the requirements for the connection.

Regarding energy consumption, three classes of terminal equipment are defined in the LoRa standard [6]:

Class A - the most energy-efficient, downlink devices receive data after sending their own uplink. The data is sent in specific time intervals.
Class B - energy-saving class. Communication is divided into slots and synchronized with network signaling. The nodes in this class send more information than those of class A.
Class C - is the least energy-efficient, the nodes are set to smart watch [7].

6.2 LoRaWAN Gateway

Topology of this network is usually the star, whose gates transmit data between end devices and central servers (or cloud). Gates are connected to servers based on Ethernet or WiFi technology, and communication between the gates and terminal devices is carried out through the LoRaWAN modules. The LoRaWan gate diagram is shown in Fig. 4.

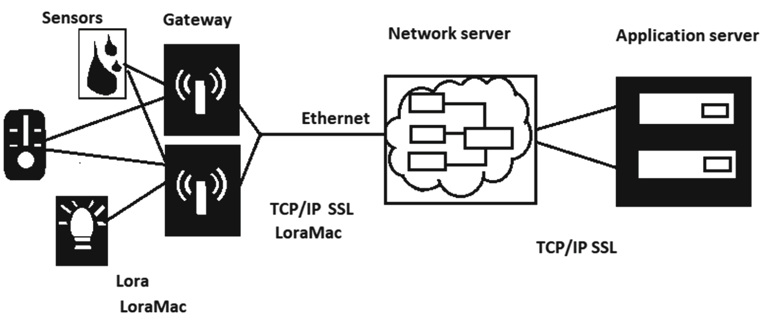

Fig. 4. Architecture of LoRaWAN Source [10]

6.3 Sigfox

Sigfox technology allows low power consumption while transferring a small amount of data. The device sends data up to 12 bytes long, while up to 8 bytes can be sent to the device. Data can be sent in the smart watch window after the device has finished the transmission. Smart watch and data receival by the terminal device is triggered by the action of transmitting data from the device to the base station.

6.4 Sigfox Gateway

Transmission acknowledgement mechanism can be implemented but it is not required. Transmission reliability is ensured by several base stations receiving the signal with simultaneous tripled repetition of the transmission by the terminal device. Transmissions are performed on randomly selected frequencies (frequency hopping). The network should be designed in such a way that the client is within a distance of at least three base stations. Sigfox works in the unlicensed ISM band. It needs a communication module working on 868 MHz with DBPSK (Differential Binary Phase-Shift Keying) modulation for the uplink channel and GFSK (Gaussian Frequency Shift Keying) for the downlink channel. Access gates and network applications that ensure the transfer of the network data guarantee the same quality of service.

7 Algorithm for Testing Network Stability

Computer networks have been operating based on standard network protocols for many years. For industrial networks or IoT, we do not have to create new solutions from scratch, it is enough to modify these solutions. We can then use them to improve the network bandwidth, save the end devices or to increase the speed of the connection.

We will apply asymptotic stability of positive systems to our research. Our activities concern creation of an algorithm that improves the network parameters based on traditional network protocols.

For the WLAN network, we have the Ethernet standard and the TCP or UDP transport layer protocol. The TCP protocol with overload control is described by the window size W and the average queue length in buffer q with the equations according to [3].

In order to perform the task, the steps listed should be followed:

<u>Step 1</u> Transform equations describing the size of the window and the length of the queue to the form $x' = Ax$
<u>Step 2</u> Determine if matrix A is the Metzlner matrix
<u>Step 3</u> Prove that the system of equations is a positive system
<u>Step 4</u> Investigate the asymptotic stability of the continuous positive system.

Such a system will allow for the analysis of the stability of real sensor networks as a way to improve the uplink speed and to establish stability boundaries that may contribute to better use of bandwidth or small delays. Network stability on the WLAN side will help reduce queues in buffers allowing consequently to reduce delays in the WSN network caused by a delay in queuing packets in the buffers or their loss caused by too long waiting for the reduction of the network delays.

Wireless sensor networks can accumulate packets in network device buffers, their overflow or queuing delays. Variety of queuing models enable to build a server wakeup model from the idle state as an efficient use of energy in servers.

8 Methodology for Testing Network Stability

There are many methods for testing stability of dynamic systems. They include analytical or graphical methods. Frequency methods (graphical) using the principle of an argument such as the Mikhailov's method (criterion or modified Mikhailov's criterion method) are the most popular methods for testing asymptotic stability at the set parameters of delay. To test such a system stability, the operator's transfer function (transition function) is calculated and the quasi-polynomial is determined. The distribution of quasi-polynomial zeros on the complex plane sets the stability boundaries.

As described in [2], one of them is the zero exclusion method, the uncertain parameter space method and so on. There are also methods for testing stability in which stability does not depend on the amount of the delay.

8.1 Testing Method for Delay-Independent Stability

In this method, on having derived a system of equations describing the network, a quasi-polynomial is determined, and the Hurwitz criterion is used to check the location of the polynomial roots. The designated zero lines of the quasi-polynomial are shown in the Fig. 5.

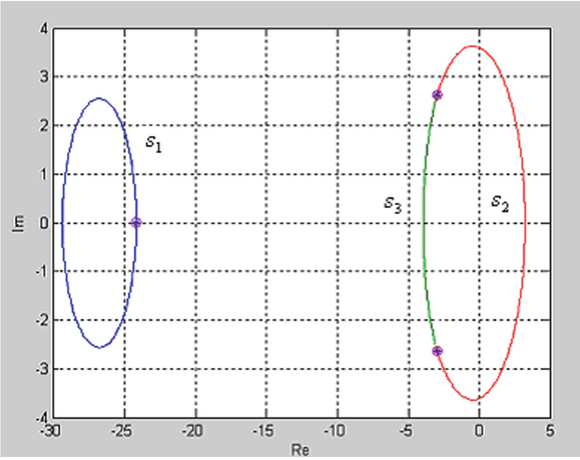

Fig. 5. The lines of the quasi-polynomial zeros

Figure 5 shows the closed curves which intersect the imaginary axis, that is they do not meet the criterion of stability. It means that the quasi-polynomial is not stable regardless of delays. So that in this case, it is necessary to change the network parameters to make the system stable [2].

8.2 Method of Space of Uncertain Parameters

In the method of space of uncertain parameters for testing the network system stability, it is necessary to determine the stability limits characterizing the operation of the computer network for the given parameters. This method is an extended variant of the classical method of division D, which allows for the appropriate selection of parameters so that the curves resulting from the substitution of the parameter values into the system equations do not exceed the limits set by the parameter deviations [2]. Because direct checking in multidimensional space is not easy, therefore in the case of polynomials it is possible to apply projection of stability boundaries on the plane of two selected uncertain parameters.

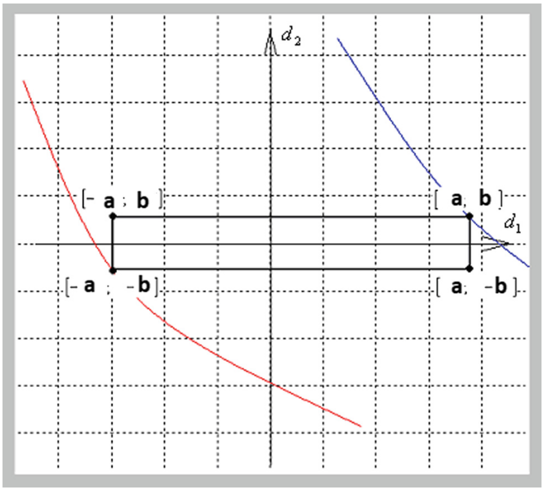

Fig. 6. The resulting rectangle created from the deviations of the values of uncertain parameters, sets the stability limits

Figure 6 shows a rectangle built up of the parameter deviations from their nominal values. To test stability, it is necessary to check whether or not the curves generated when changing the values of the quasi-polynomial parameters on the plane, intersect the rectangle. As the first value, we calculate the limit of complex zeros, that is we solve the system of equations of two variables, and then the limit of real zeros. Then the common part of both sets is determined, which gives the limit of stability of the entire system. We get a graph of three curves that intersect the rectangle formed from the parameter deviations or not. The values of those curves that intersect the rectangle are the values for which the system is stable (see Fig. 7).

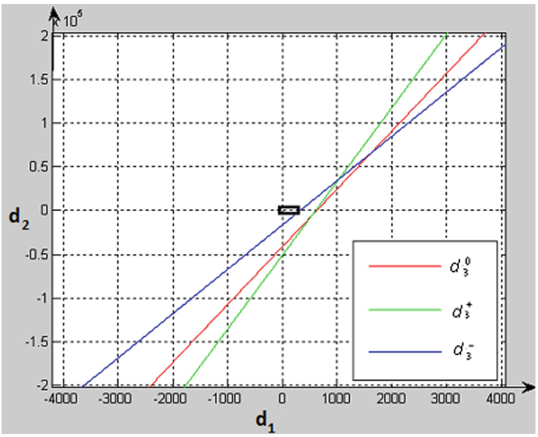

Fig. 7. Curve d_3^- intersects the deviation rectangle

Testing stability of dynamic systems by adopting the method of uncertain parameters and the method of delay independence are included in [4] and [5].

9 Stability of Positive Systems – Fundamental Assumptions

In order to conduct network analysis, we will introduce some fundamental theorems and definitions regarding positive systems. We will also present criteria for their stability [1].

Definition 1
Matrix $A = [a_{ij}] \in R^{nxn}$ is called Metzlner matrix if all its elements lying outside the main diagonal are non-negative, that is, $a_{ij} \geq 0$ for $i \neq ji, j = 1, 2, \ldots, n$

The positive continuous system is described by the equation

$$x' = Ax\, x(0) = x_0 \quad (1)$$

where A is a Metzler matrix.

The solution of Eq. (1) has the form

$$x(t) = e^{At}x_0 \quad (2)$$

Definition 2
A positive system (1) is called asymptotically stable if and only if Eq. (2) satisfies the following condition

$$\lim_{t\to\infty} x(t) = 0 \quad (3)$$

for each *x*.

Eigenvalues s_1, s_2, …, s_n of matrix A are the roots of the equation $\det[Is - A] = 0$ whereas a set of these eigenvalues is called the spectrum of matrix A.

Theorem 1
The positive system (1) is asymptotically stable if and only if when the coefficients a_{ij} of the characteristic polynomial

$$w_A(s) = \det[Is - A] = s^n + a_{n-1}s^{n-1} + \ldots + a_1 s + a_0 \quad (4)$$

are positive ($a_{ij} > 0$) [1]

Quite often, the problem of positive system stability can be resolved by using the following sufficient condition of instability [1].

Definition 3
A positive system is unstable if at least one element on the main diagonal of matrix A is positive.

10 The Network Model

The gateway device is the intermediate device between the Ethernet network and the sensor network. Flow control mechanisms should be implemented in the gateway. They are not as restrictive as in conventional TCP. The packet flow window size does not have to be very large. In the sensor networks nowadays, data flow is fast enough because the data itself is relatively small. However, sometimes, the packets cannot be regained very quickly by the retransmission.

The window size is limited. It does not generate the appropriate number of duplicate acknowledgments pointing out to the packets outside the queue.

There exist some solutions which ensure reliable transport simply because the base station sends the entire window. The advantage of this approach is that there is no need to wait for confirmation of receipt of each packet.

Stability is a feature of dynamic systems. Computer network is an example of such a system. It can be described, like in [3], with differential equations. In TCP there is so-called Congestion Window. However, we need to modify this model to be applicable to the gates for sensor networks. Thus, if we assume that the base station (gateway) sends the whole window, then retransmissions will occur only after sending the entire window. Consequently, we should skip RTT time and replace it with propagation time. Following the feedback proposed in [3] the equations have a negative sign, which does not allow testing the system described by the equations for testing stability of positive systems. Yet, this feedback is not a must, as we will not regulate the transmission before the entire window is broadcast. Such that the equations should allow study the stability of positive systems.

According to the equations in the network model [3], we get equations

$$\delta W'(t) = -\frac{N}{R_0^2 C}(\delta W(t) + \delta W(t - R_0)) - \frac{1}{R_0^2 C}(\delta q(t) - \delta q(t - R_0)) - \frac{R_0 C^2}{2N^2}\delta p(t - R_0) \tag{5}$$

$$\delta q'(t) = \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \tag{6}$$

where:

q - is an average queue in the gateway,
R - is propagation time,
C - denoted throughput,
p - is probability of the lost packet,
N - is a number of packets.

We aim to obtain a positive continuous system from Eqs. (5) and (6)

$$f(t-t_0)=f(t)-f'(t)t_0-\frac{1}{2}f''(t)t_0^2+\dots \tag{7}$$

$$\begin{aligned} &f(t-t_0)=f(t-t_0)^2, f(t-t_0)=t^2-2(t-t_0)t_0-\frac{1}{2}2t_0^2 \\ &=(t-t_0)^2 \end{aligned} \tag{8}$$

Then we have

$$\begin{aligned} \delta W'(t) &= -\frac{1}{R_0 C}\delta q(t)+\frac{1}{R_0^2 C}\delta q(t)-\frac{1}{R_0^2}\delta q'(t)R_0 \\ &-\frac{N}{R_0^2 C}\delta W(t)+\frac{N}{R_0^2 C}\delta W'(t)R_0-\frac{1}{2}\frac{R_0 C^2}{N^2}\left(\delta p(t)-\delta'(t)R_0\right) \end{aligned} \tag{9}$$

$$\delta q'(t)=\frac{N}{R_0}\delta W(t)-\frac{1}{R_0}\delta q(t) \tag{10}$$

For $\delta W(t)=x_1(t)$, $\delta q(t)=x_2(t)$ we obtain

$$\begin{aligned} &\begin{pmatrix} 1-\frac{N}{R_0 C} & \frac{1}{R_0 C} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} x_1'(t) \\ x_2'(t) \end{pmatrix}=\begin{pmatrix} -2\frac{N}{R_0^2 C} & 0 \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{pmatrix}\begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} \\ &+\begin{pmatrix} -\frac{1}{2}\frac{R_0 C^2}{N^2}(\delta p(t)-\delta p'(t)R_0) \\ 0 \end{pmatrix} \end{aligned} \tag{11}$$

Now we compute inverse matrix

$$\begin{pmatrix} 1-\frac{N}{R_0 C} & \frac{1}{R_0 C} \\ 0 & 1 \end{pmatrix}^{-1}=\begin{pmatrix} \frac{1}{1-\frac{N}{R_0 C}} & -\frac{R_0 C}{1-\frac{N}{R_0 C}} \\ 0 & 1 \end{pmatrix} \tag{12}$$

we multiply both sides of Eq. (11) by (12) and obtain

$$\begin{aligned} &\begin{pmatrix} x_1'(t) \\ x_2''(t) \end{pmatrix}=\begin{pmatrix} -\frac{3N}{\left(1-\frac{N}{R_0 C}\right)R_0^2 C} & \frac{1}{\left(1-\frac{N}{R_0 C}\right)R_0^2 C} \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{pmatrix}\begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} \\ &+\begin{pmatrix} -\frac{1}{2}\frac{R_0 C^2}{N-\frac{N^2}{R_0}}(\delta p(t)-\delta p'(t)R_0) \\ 0 \end{pmatrix} \end{aligned} \tag{13}$$

$$\begin{pmatrix} x_1'(t) \\ x_2'(t) \end{pmatrix} = A \begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} + B \quad (14)$$

$$\lim_{t \to \infty} W(t) = 0 \quad (15)$$

We assume that the coefficients of Eq. (14) are positive, that is B > 0, and that the matrix A is a Metzlner matrix. As we can see, the window size decreases with the transmission time, thus we can say that we have constructed a positive system model

$$A = \begin{pmatrix} -\frac{3N}{\left(1-\frac{N}{R_0 C}\right) R_0^2 C} & \frac{1}{\left(1-\frac{N}{R_0 C}\right) R_0^2 C} \\ \frac{N}{R_0} & -\frac{1}{R_0} \end{pmatrix} \quad (16)$$

Matrix A meets Definition 1 and is a Metzlner matrix because all its elements lying outside the main diagonal are non-negative that is $a_{ij} \geq 0$.

11 Analysis of the Results

If we assume that the number of packets sent and received is a known number for a given gateway, the final result is affected by the propagation time of the given network and its capacity (throughput). In matrix A, the elements outside the main diagonal must be positive, that is

$$a_{21} = \left(1 - \frac{N}{R_0 C}\right) R_0^2 C \geq 0 \quad (17)$$

And

$$a_{12} = \frac{N}{R_0} \geq 0 \quad (18)$$

If the network traffic is smooth, then the inequality (18) is always satisfied, while in the inequality (17) the result depends on the first factor of the product, because the second factor is always positive. After transformation, we get inequality

$$\frac{R_0 C - N}{R_0 C} \geq 0 \quad (19)$$

Then we have

$$R_0 C \geq N \quad (20)$$

Assuming that propagation time is a fixed value, it looks like the link capacity exceeds the number of packets sent through the network of a given window size. Following Definition 3 it shows that the positive system is unstable if at least one element on the main diagonal of matrix A is positive. In our case this is not the case, therefore we can say that Eq. (14) describing the particular configuration of the WLAN network is a continuous positive system, which is an asymptotically stable system.

12 Conclusion and Future Work

Determining stability limits of dynamic systems will allow designing wireless or sensor networks as more efficient, faster and resistant to errors related to imperfections of transmission media. Application of the equations proposed in the paper to the IoT or IIoT networks will allow these technologies to be improved.

Our model proposed meets the new challenges from the perspective that it shows how to set the parameters for particular network to ensure its stability in order to achieve the performance quality required for the environment where it is planned to work.

For the future, computer network models with queuing algorithms will be analyzed even further. These studies will cover sensitivity of stability to changes in network parameters and how to improve the environment of the network to maintain its stability depending on other methods used and depending on the type of queuing.

The research will also address the networks based on the UDP protocol. We will create another mathematical model of the network and test it for stability under some specific environment requirements. We will try to analyze the UDP-based network and compare it to the TCP-based model. Then, we will propose some new solutions for the IoT and IIoT infrastructure.

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