Heitor FLORENCIO[1], Adrião DÓRIA NETO[1]

Federal University of Rio Grande do Norte (1)

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Method for Link Stability Evaluation of Industrial Wireless Sensor Networks (ISA 100.11a)

Abstract. *Industrial Wireless Sensor Networks (IWSNs) have been considered as an solution for measurement and control of industrial processes that have deficiencies in the infrastructure of wired networks. The flexibility and allocation of measurement points in locations inaccessible to the operator are the main arguments for integration of wired and wireless instrumentation. Nonetheless, deployment of wireless communication systems presents several problems due to the environment exposed to different types of interference. A way to address this issue is to evaluate the performance of the network through attributes of the communication links. In this work, we propose a method based on the strength signal parameters and the packet delivery rate to evaluate the link stability of IWSN. The proposed strategy considers that received signal strength (RSS) variation and the cumulative packet delivery rate value defines link performance. Two scenarios were selected, among the 15 tests performed with ISA 100.11a networks, to present the results of the method. The results show that the link stability factor generated by the proposed method is able to identify instabilities in the link, enabling the evaluation of network performance.*

Streszczenie. *W artykule analizowano możliwość zastosowania bezprzewodowej Sieci czujników WSNS do pomiaru i sterowania procesów przemysłowych w warunkach gdy zastosowanie sieci przewodowej jest utrudnione. Analizowano najkorzystniejsze usytuowanie punktów pomiarowych. Zaproponowano metodę uwzględniającą siłę sygnału. Zbadano dwa scenariusze wykorzystujące sieć ISA 100.11a.* ***(Metoda poprawy stabilności połaczeń w przemysłowej bezprzewodowej sieci czujników.)***

Keywords: Industrial Wireless Sensor Networks, Sensor Networks, ISA 100.11a, Link Stability
Słowa kluczowe: przemysłowa bezprzewodowa sieć czujników, ISA 100.11a

Introduction

The application of new technologies in the industrial environment provides an increase in the quality and productivity of industries and services. Recently, the application of wireless sensor networks in the monitoring of variables in an industrial environment is greatly intensifying. The flexibility and allocation of measurement points in locations inaccessible to the operator are the main arguments for integration of wired and wireless instrumentation. Wireless instrumentation has not emerged to replace the wired technologies, but the control system integrates wired with wireless instrumentation to include hard-to-reach points.

The scalability of IWSNs facilitates the design and upgrade steps of industrial factory. However, the low installation cost is the most relevant factor to the popularity of wireless instrumentation. Compared to the cabling and maintenance costs of wired networks, the wireless networking technologies offer a very small cost in fraction of a euro for per meter of wireless connectivity [1].

It is mandatory to evaluate the system dependability in monitoring and control domains in order to assess its successful operational behavior through time, although there are relevant challenges to be handled for such assessment. Actually, dependability is a generic concept including attributes as availability, reliability, safety, integrity and maintainability [2].

The probability of an item not failing at a given time interval is the definition of the reliability. However, in the context of industrial networks based on wireless communication protocols, the main difference between the reliability analysis of wired and wireless networks is related to the instability of the means of communication, which is more susceptible to noise [3]. With such contribution, it is noticeable that the stability of a link of communication of wireless networks is an essential factor in the evaluation of the operation of industrial systems with wireless communication.

In this paper, we propose a method to generate the evaluation of the link stability of an IWSN. The method is based on the strength signal parameter and the packet delivery rate to the generation of link stability. Since the data can be collected from the network manager, the method can be automated using the model presented in this work.

Related Works

The stability is not a metric but rather a property of systems. Hence, some published research articles, surveys and studies in the years from 2010 to 2018 were evaluated to identify the methodologies for link stability analysis. There are several parameters being used to define the link stability of a wireless network, such as received signal strength, distance between nodes, node residual energy, link expiration time, link available time, node successful data transmission, packet delivery rate, etc. We analyze the papers according to the parameter used for the definition of stability, and divided into four groups: distance between nodes, link expiration time, packet delivery rate (PDR) and received signal strength (RSS).

From the analysis it is possible to observe that few papers have been developed for industrial sensor networks, just paper [4]. Most of the papers are applied to mobile networks. A brief description of contributions of these surveys and research articles are listed as follow.

Distance between nodes in WVSNs is considered in papers [5], [6] and [7]. The paper [5] considers the distance between two nodes to define the stability of the link. The NBS variable represents stability with values between 0 and 1. In [6], two stability parameters are defined: link stability and path stability. The authors relate the distance between the nodes and the range antenna of the instrument to calculate the link stability metric. The path stability uses the lowest stability value of the links contained in the path. The paper [7] also proposed the use of the concept of distance between nodes to define link stability. However, the link stability is used to create a new content request protocol in vehicular networks (VANETs).

In [8], in addition to link stability, Energy-Aware metrics were used to define a routing algorithm using multiobjective optimization problem. An important consideration of that paper is the formal definition of the concept of stability. A link between two nodes i and j with transmission range R is established at time instant t when the distance between both nodes is less than R. Otherwise, the link is broken or unstable. However, the authors did not consider that within the transmission range the instrument can suffer attenuation of the environment, which can make the link unstable.

Among the technical articles that use the distance parameter for link stability, the paper [9] presented a relevant method for our work. That paper proposes a new stability evaluation metric which is based on the relative mobility of each node pairs by sampling the relative position. The link stability evaluation value is calculated by two decision factors, which are direct link stability evaluation value, defined from a relation of the free space propagation model, and indirect link stability evaluation value. The stability metric was used in a routing algorithm and, through five evaluation metrics, the results show the advantages of the proposed routing scheme over other routing protocols.

In this work, we propose a method to create the link stability metrics considering the same relation of the propagation model used in [9].

Another parameter used in the definition of link stability is the duration time of the link in the network. The papers [10], [11] and [12] directly use the link duration time or link expiration time in the link stability metric. In [10], the link duration is defined as the period of time where two nodes are within the transmission range of each other.

The authors of paper [11] define link stability in three levels: low, average and high. Stability is classified according to the average value of the maximum duration values of all links in the network. In [12], the authors use the duration time of the links to define the link stability in two ways (s1 and s2). The results showed that the second definition of the link stability assists the AODV algorithm with more robustness in routing selection.

Differently from [11] and [12], the paper [13] uses the concept of link duration to define two stability metrics: persistence and prevalence. Persistence evaluates the amount of time it takes for an observed path between a source-destination pair to change. Prevalence evaluates how often a certain path between two end-points is taken.

However, the works that use the duration time of the link in stability definition are applied to the mobile networks due to the high mobility of the nodes. Models that use link duration or expiration do not consider the instability during the period that the links are active on the network. The instability of the active links in IWSN is caused due to the various forms of signal interference. In our work, we consider the stability of active links from the received signal strength.

The definition of link stability in paper [14] consists of three factors: link quality, safety degree and mobility prediction factor. The link quality factor is calculated from the received signal strength. According to [14], the stability metric is used in the creation of a routing algorithm applied to flying networks Ad-hoc. The results showed that the proposed algorithm increased the packet delivery rate compared to the AODV protocol.

In [4], the link quality parameter was also used to define stability. The work proposes a routing algorithm based on link quality in order to prioritize the dynamics of the link in the route construction. The works [15] and [16] also define link stability from received signal strength.

A routing algorithm that uses residual residual energy, link stability and queuing capacity to classify the routes of a node is proposed in [17]. This paper uses recent RSS data and the Bienayme-Chebyshev inequality principle to calculate variance of RSS values. The RSS variance concept will also be used in our work.

In this work, we propose a method to define the stability of all links in the network from RSS. Our method uses the received signal strength ratio with the variation of the attenuation similar to the work [9]. In addition, the link stability of the method proposed in this work is calculated by the variance according to the paper [17]. However, the model developed in this paper does not consider node mobility because the model is applied to the IWSN, and it also takes into account the PDR parameter.

Industrial Wireless Sensor Networks

In recent years, the use of communication technologies, especially wireless, in the industrial environment has intensified. Nonetheless, industrial networks need to present reliable parameters and high levels of quality to convey confidence to the market. In this paper, the packet delivery ratio in transmitting packets of communication paths in the network devices is considered the essential parameter to be evaluated.

Presently, the major obstacle in the evolution of automation systems is the inclusion of wireless communication at the field level. Mobility, flexibility, cost reduction, and, especially, the deployment of sensing in locations inaccessible to the wired network are the reasons for the inclusion of wireless networks at the field level of industrial automation systems.

Eliminating cabling and its components, such as junction boxes, connectors, distribution blocks, conduits, and signal repeaters, facilitates installation, reconfiguration of the plant, and reduces costs. Installation costs for a wired network can range around hundreds of dollars on an offshore platform [18]. This elimination is essential for the deployment of networks in environments that damage cabling, such as environments that are subject to chemicals, vibrations, and moving parts. In addition, aging causes cable damage and implies the expense of inspection services, testing and problems diagnostics.

Another major impact in the deployment of the IWSN is the low latency and high reliability required by industrial process control. Despite the fact that existing protocols for IWSN establish support for the control of industrial processes, there is still a hesitation in the use of IWSN for process control. The paper [19] presents some research, tests and analysis of control systems with wireless communication in order to spread the theme. An architecture example of a control mesh based on wireless communication is shown in Figure 1.

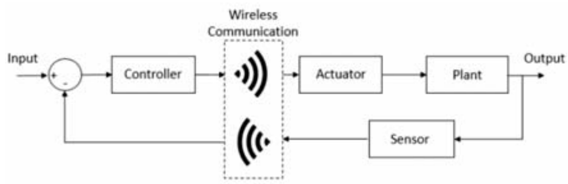

Fig. 1. Control architecture with wireless communication.

As the industrial applications may involve close loop control systems and critical processes automation, the primary research focuses in IWSNs reliability, real-time data delivery and deterministic network designs. Hence, to ensure this incorporation of technology, protocols that define the rules and techniques for wireless communication at the sensor, actuator, and controller level, such as IEC 62591 (WirelessHART), IEC 62734 (ISA 100.11a), and IEC 62601 (Wireless Networks for Industrial Automation-Process – WIA-PA) have been developed since 2010.

Protocols developed in recent years present some similarities in communication stack and network architecture. All three cited implement the physical layer based on the IEEE 802.15.4 standard, in the 2.4 GHz range. In addition, they also use IEEE 802.15.4 standard in the media access layer. However, each protocol reinforces the network against failure, incorporating other techniques such as channel hopping, time division multiple access, graph routing, source, superframe and static, tunneling, object oriented application, among other techniques. Both WirelessHART and ISA 100.11a protocols define the following techniques: Frequency Hopping Spread Spectrum (FHSS), Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA).

Besides the similarities in the physical layer, WirelessHART, WIA-PA and ISA 100.11a also present similarities in the definition of the elements that form the architecture of the network. In this work we use ISA 100.11a networks to test the proposed evaluation method.

Architecture of ISWN: ISA 100.11a

The ISWNs architectures contain elements that perform information transmission, information routing, and network management at different levels. Each network is formed with nodes, composed of processing unit, radio, memory, data acquisition board and battery. Currently, regardless of topology, all networks need a central element to concentrate information from all nodes: the network manager. The manager receives and sends the data packets to the nodes, and manages all links formed in the network. Within an end-to-end communication, at least one of the elements is the manager, either by receiving the packet from a measuring element or by sending the packet to an actuation element.

Acording to the IEC 62734 standard, the network manager is responsible for managing device and network link settings, managing link tables and neighbor tables, scheduling communication between nodes, defining routes for information traffic and generating network performance, devices, and communication links reports.

However, the network manager is not responsible for the junction authorization of a new device to the network. The task of managing security keys, such as authenticating, generating, and storing, is the responsibility of the security manager. Physically, the two managers are integral logical parts of the gateway element.

Figure 2 show the ISA 100.11a network architecture. It is possible to observe that the gateway provides an interface between the wireless field network and the plant network, which connects the various controllers to the data and supervision stations. The wireless network instruments communicate with the gateway and therefore with the managers through one or more access points. The ISA protocol 100.11a define the backbone router for the element containing the radio which forms the links with the instruments.

Figure 2 show that a field instrument can communicate with one or more backbone routers (access points). Communication with more than one backbone routers increases system redundancy. Acording to [20], multiple backbone routers provide similar benefits, including reducing data traffic congestion, reducing latency, and increasing network reliability.

Due to the application of IWSNs in industrial plants with kilometers of monitoring area, routing instruments were defined for the packet traffic of instruments that can not maintain direct communication with the manager. A network node can also become a router in order to transmit its data and its neighbors data to the manager. In addition, the ISA 100.11a protocol also allows a level of routing in the network backbones.

The use of routers in networks increases redundancy and availability due to alternative paths generated. In most cases, a router can be inserted next to a node that has a

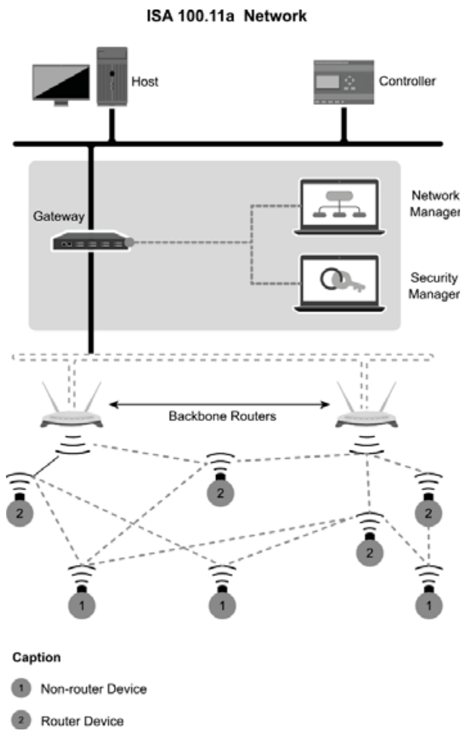

Fig. 2. ISA 100.11a Network Architecture.

weak signal to the manager. Inserting routers can reduce packet loss, however caution is necessary to not increase the installation cost for little increase in network performance. The insertion of routers influences the creation of network links and, consequently, the stability of the network.

Link Stability

Network or links stability is a property of the system. However, this property directly influences the reliability of the system and can be used as an important Key Performance Indicator (KPI) for industrial systems with IWSN. In this work, we define a metric for the property of links stability.

Link evaluation is essential to evaluate network performance. There are links that are part of the primary route and others of the secondary route. In these cases, the routing algorithm needs to know link information to include or not in preferred routes. In addition, link stability also affects the power consumption of the node. A node with an unstable link consumes more power, either due to high packet loss or link breaking when the attenuation is high.

According to [21], "link stability indicates how stable the link is and how long it can support communications between two nodes". And the paper [16] stated that "link stability means the link will sustain long time and does not break regularly". However, there are many links that remain on the network with high packet loss. The length of stay of a link in the network, by itself, can not characterize the stability.

The definition of the paper [10] encompasses several important factors for ownership of a stable link. "Link stability is defined as the stable behaviors in the link failures, channel sensing rate, packet loss and many other factors comes in link stability" [10].

In mobile networks, the distance variation between nodes clearly represents link instability, since this variation causes a variation in the received signal strength (RSS). The nodes in IWSN are fixed and have distances between nodes fixed. Therefore, the distance between nodes should not be a parameter considered in the definition of links stability.

Even with fixed positions, there is a variation in RSS due

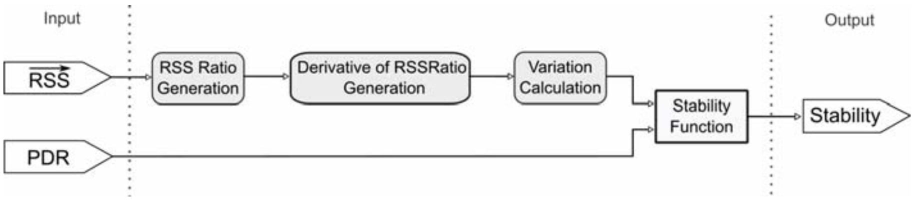

Fig. 3. Overview of the method for Link Stability Evaluation.

to link attenuation. The factors of wireless signal degradation cause a variation in RSS, which represents a level of instability in the link. In this work, link stability is defined by the variation of received signal strength (RSS) and packet delivery rate (PDR).

An unstable link presents high variation of signal attenuation and low packet delivery rate. While a stable link has no signal attenuation variation and has a high packet delivery rate. Next section will presente the method to generate link stability metrics according to the stable and unstable link definitions formulated.

Method

The main objective of the paper is to provide a method to generate the evaluation of the link stability of a IWSN, in order to provide valuable information to the network designer enabling it to develop robust applications and increase reliability. The method is based on the received signal strength and the packet delivery rate parameters for the generation of stability.

The generation of link stability will be based on the variation of the received signal strength. Unlike the cases applied to mobile networks, the variation of signal strength in industrial networks indicates a variation of link attenuation. The greater the attenuation variation, the greater the link instability. However, it is necessary to create a factor that indicates how degraded the signal is to calculate this variation. This factor will be generated from previous samples of received signal strength and current value.

The link stability will be based on a linear function proportional to the link attenuation variation and the packet delivery ratio (PDR) within a set of samples. The main assumptions considered in the method are as follows:

- **Network manager:** we assume that the network manager is responsible for the continuous acquisition of all network information. Mainly, the information of links and network nodes, such as received signal strength, PDR and table of active links in the network. The manager's data acquisition rate is variable.
- **Sample window:** the manager is responsible for storing a set of continuous samples. This set forms a sample window of size defined by the user in the implementation of the method.
- **Link:** when one of the nodes is disconnected the link is deactivated from the network. In this case, all values contained in the sample window are removed.

Other network factors, such as topology, baud rate, redundancy or routing algorithms, are not established in the method. Flexibility of these parameters makes the method applicable to several IWSN configurations.

Figure 3 presents an overview of the proposed method. The procedure starts by generating the signal attenuation factor: $RSSRatio$. This factor indicates the ratio of the current value of RSS and the best RSS signal in the last samples. The lower the value of the $RSSRatio$ factor, the greater the link attenuation value at the current instant.

After collecting the values of $RSSRatio$, the method proposes the analysis of the instantaneous variation rate (derivative) of the factor $RSSRatio$ in order to verify the increase or decrease in attenuation. According to the stability definition proposed in this work, the attenuation or degradation of the signal is totally related to the link stability. Thus, a decreasing value of the derivative at the current instant indicates an increase in instability, while an increasing value indicates a reduction in link instability. Because the objective is to collect the variation of this attenuation, the next step calculates the mobile variance of the data set generated in the previous step. Finally, the last step of the method is define a function to generate link stability from the value of the variance and the PDR.

The presented method steps shown Figure 3 must be executed for all links in the network and in a cyclic way which means a new execution at each instant. As the network manager is the element responsible for collecting the input information of the method, he is also responsible for the execution of the method. In addition to having more processing, the manager is also responsible for routing and scheduling algorithms, which can be optimized with the use of the link stability parameter. The steps shown in Figure 3 are detailed in the following subsections.

RSS Ratio Generation

The first step of the method receives a set of RSS samples to generate a factor that relates the current RSS signal to the previous values. The purpose is to relate the current strength value to the signal attenuation in the last samples.

In order to relate the signal strength with the degradation suffered by the link, we used the propagation model in the free space of Friis to characterize the industrial environment. This model is widely applied to systems with wireless sensor networks.

Friis models relates the transmitted and received strength with the attenuation of the signal in space, as presented by the equation 1.

$$Pr = \frac{Pt}{Lp} \tag{1}$$

The variable Pt represents the strength of the transmitted signal, Pr the strength of the received signal and Lp the attenuation or loss in the free space. In this work, the values of the transmitted and received signal strengths are represented, respectively, by $RSSt$ and $RSSr$.

The IWSN protocols allow the transmission strength change, as the WirelessHART protocol contains a command to change the value of the radio transmission strength. However, it is not a frequent action in industrial systems. For the method presented in this paper, the value of $RSSt$ is fixed and the same for all transmitters in the network. Hence, the equations 2 and 3 show the proportionality between $RSSr$ and Lp.

$$RSSr \propto \frac{1}{Lp} \tag{2}$$

(3) $$Lp \propto \frac{1}{RSSr}$$

According to the equation 3, a minimum attenuation value (Lp_{min}) is related to a maximum received strength value ($RSSr_{max}$), as shown by the equation 4.

(4) $$Lp_{min} \propto \frac{1}{RSSr_{max}}$$

Considering the attenuation and power values at any time i (Lp_i and $RSSr_i$), it is possible to make a relation between the minimum attenuation and the attenuation at time i.

(5) $$\frac{Lp_{min}}{Lp_i} \propto \frac{RSSr_i}{RSSr_{max}}$$

The ratio shown in the equation 5 indicates the proximity of the attenuation value measured at time i in relation to the lower signal attenuation in the sample set. The following statements indicate the value of the equation 5.

- The higher the ratio of the left side of equation 5, the lower the signal attenuation value.
- The lower the ratio of the left side of equation 5, the higher the signal attenuation value.

Because the link attenuation value is not provided by the network manager, we use the proportionality described in equation 5 to generate the first variable of the method proposed in this work. Equation 6 presents the ratio ($RSSRatio$) that will be used in the next step of the method.

(6) $$RSSRatio = \frac{RSSr}{RSSr_{max}}$$

Derivative of the Ratio

The analysis of the instantaneous rate variation allows a forecast of the behavior, increasing or decreasing, of the factor $RSSRatio$. This behavior points to the situation of the spectrum where the link is located. At this stage, we adopt the same principle of derivative action used in control systems. The rate value is represented by the derivative as shown by the equation 7.

(7) $$\frac{\partial Ratio}{\partial t} = RSSRatio(t) - RSSRatio(t-1)$$

If the set of values of $\partial Ratio$ presents increasing behavior, the link stabilization tends to get worse. The trend of improvement in link stability occurs when the derivative $\partial Ratio$ has a decreasing behavior.

When the trend shows a high variation between increasing and decreasing behavior, it is evident that there is an instability in the link.

Variation Calculation

The larger the variation of the instant packet loss, the greater the oscillation of the $\partial Ratio$ values. Therefore, the objective of this step is to identify the large oscillations of the data obtained in the previous step.

The measure of dispersion or variation used is the standard deviation ($StdRatio$), as shown in the equation 8.

(8) $$StdRatio = \sqrt{\sum \frac{(\partial Ratio_i - \partial \bar{Ratio})^2}{n}}$$

The values resulting from the equation 8 are presented in the range of 0 to 1. If the value of dispersion measure ($StdRatio$) is close to 1, it indicates little variation in the data set obtained. The lower the value of $StdRatio$, the greater the variation of the sample window.

The $\partial \bar{Ratio}$ is the mean value of the n samples. The use of the derivative of the $RSSRatio$ factor can amplify an outlier in the same way as with process control techniques that use derivative terms to calculate the control action. Therefore, we calculated the moving average of the standard deviation values ($MeanStdRatio$) of the last samples to reduce the influence of the outlier highlighted. $MeanStdRatio$ is the factor that represents the variation of RSS in the generation of link stability.

Stability Function

After generating the variation factor of the instability of the received signal strength, it becomes possible to generate the function that represents the link stability in the network. As discussed earlier, we chose two factors to represent link stability: the RSS variation and the current PDR value. The first factor is generated from several steps as shown in the flowchart of Figure 3, while the second factor is collected by the manager in the current sample.

The packet delivery rate is a factor that symbolizes the influence of packet loss stability. However, there may be cases of links that have high PDR values before losing communication with the network manager. In this work, we relate the RSS variation ($MeanStdRatio$) to the PDR according to the equation 9.

(9) $$Stability = PDR * (1 - 0.04^{MeanStdRatio})$$

The purpose of using an exponential function with fixed base and $MeanStdRatio$ exponent is to soften the factor that multiplies the PDR. For example, the values of $MeanStdRatio$ between 0.6 and 1.0 are converted to values between 0.85 and 1.0. This softening avoids the generation of very low values of stability.

Computational results indicate that values above 0.04 can provide a very high factor variation, which makes it impracticable for the supervisory operator's perception. The purpose of the equation 9 is to smooth out the large variation of $MeanStdRatio$ in some situations of high pertubation in short periods of time in the communication channel.

The network manager needs to get two input parameters: the RSS sample window and the current PDR value. After executing all steps, the function returns the value of the link stability in the range from 0 to 1, and can be easily converted from 0 to 100 %. Even following the assumptions presented at the beginning of this section, there are still some information processing limitations that are discussed in the next section.

Results

In this section we present some results obtained after the use of the method proposed for link stability factor generation in IWSN. Our main objective is to highlight some of the features of the proposed method, regarding the identification of periods of link instability from the proposed factor. These instabilities are characterized by high variations in the degradation of received signals and in the links packet delivery rate.

In order to analyze the data generated by the method, 15 tests were carried out with 7 measurement instruments and 1 access point of an ISA 100.11a network. Among these 15 tests, 4 links will be presented in 2 scenarios.

The tests duration is variable in the range of 24 to 48 hours with a sampling period of approximately 15 seconds. However, since the instruments were set at 60-seconds transmission rate, samples with repeated values were eliminated from the tests. The characteristics of the nodes used in the test are described below.

Characteristics of the test network nodes:

- Function: Temperature and differential pressure transmitters.
- Manufacturer: Yokogawa Electric Corporation.
- Protocol: ISA 100.11a.
- Update rate: 60s.

Access to the ISA 100.11a network from the network manager and gateway is performed through the backbone router YFGW510 (Yokogawa Electric). And the network manager, security manager and gateway are implemented in a single management station: YFGW410, as shown in figure 4.

Fig. 4. Management station YFGW410 *Yokogawa Electric* and backbone router YFGW510. *Fonte:* [22].

Data collection was performed through GSAP (Gateway Service Access Point) specifications sent to the network manager. New link stability values were generated for each manager's response. The method receives a window of RSS samples ($listRSS$) to analyze the oscillations in the last samples. Therefore, the data collection station must store the samples for a predetermined period of time in the method. In the tests performed in this work, we used a sample window of 15 minutes.

In order to discuss the results of the proposed method implementation, we chose two scenarios from the tests performed. Each scenario has a different mesh topology and a link is chosen to analyze stability behavior. As discussed in section, the PDR is one of the parameters used in some researches. Thus, the following analyzes are based on the following proposition: the variations in the instant packet delivery rate represent a link instability and are detected by link stability, but are not detected by the PDR.

Scenario 01:

Figure 5 presents the topology of the instruments in the test selected for the first scenario.

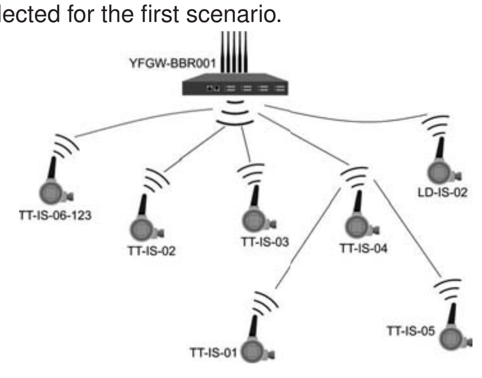

Fig. 5. Topology of the scenario 01.

We chose a link between the TT-IS-06-123 node and the network manager (YFGW-BBR001) to analyze the execution of the method. Among all links in the network, the link chosen was the one that presented the most signal received oscillations periods during the test.

Initially, we observed the relationship between the packet delivery rate (PDR) and the instant packet delivery rate (PDRi), as shown in figure 6. It is possible to observe that the occurrence of packet loss in several instants of the test is not detected by the PDR factor, since it remained practically constant. Hence, we conclude that the use of only the PDR factor does not characterize the link stability.

The link stability factor generated by the proposed method presents oscillations in the same periods of PDRi variations. Figure 7 shows the behavior of the link stability factor. Unlike the PDR, the link stability was able to detect the oscillations and indirectly indicate an anomaly in the means of communication between the devices.

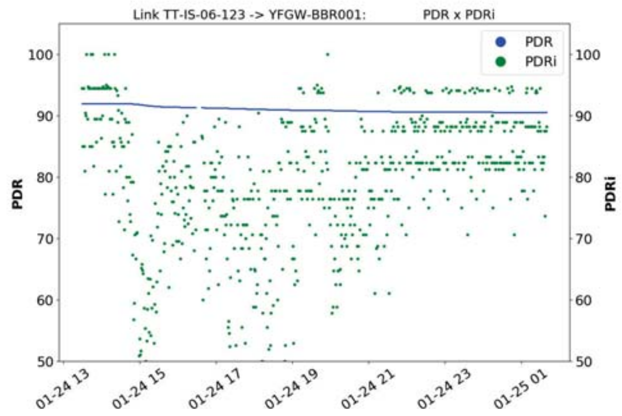

Fig. 6. Scenario 01: PDR versus PDRi - Link TT-IS-06-123 and YFGW-BBR001.

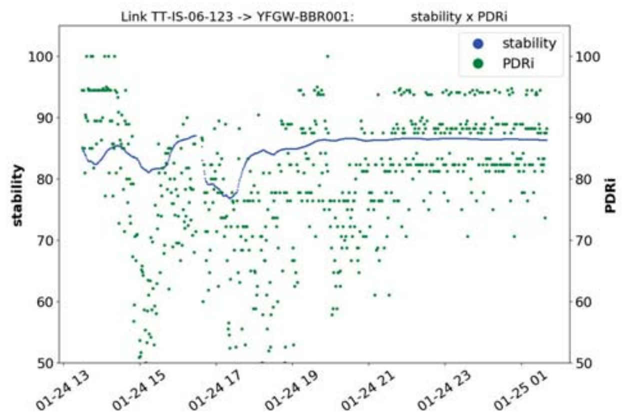

Fig. 7. Scenario 01: stability versus PDRi - Link TT-IS-06-123 and YFGW-BBR001.

In addition to the link between TT-IS-06-123 and YFGW-BBR001, the link between TT-IS-02 and YFGW-BBR001 also presents a satisfactory result regarding the use of the stability factor. It is observed in the figure 8 that the factor can identify the oscillation periods in the communication channel.

Scenario 02:

In the second scenario, we present a case where link attenuation was purposeful. The topology of this scenario is shown in Figure 9 and we chose the link between TT-IS-03 and the network manager (YFGW-BBR001).

Figure 10 presents the relationship between the PDR and the PDRi of the chosen link. In order to restart data collection, the TT-IS-03 node was disconnected from the network at the beginning of the test, between 14 and 17 hours

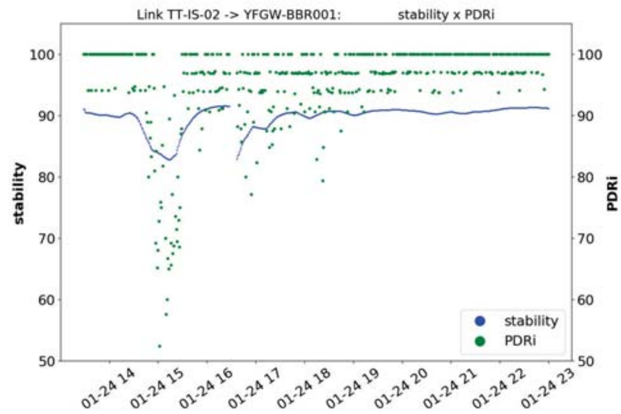

Fig. 8. Scenario 01: stability versus PDRi - Link TT-IS-06-123 and YFGW-BBR001.

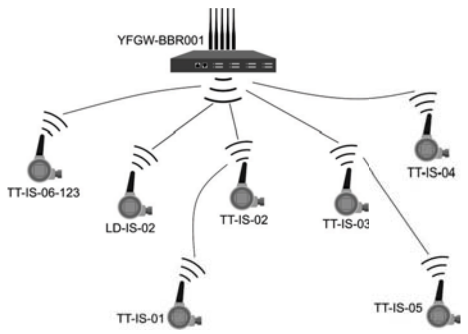

Fig. 9. Topology of the scenario 03.

on 03-23. At about 11 o'clock on 03-24, we applied a degradation in the signal with the insertion of obstacles of metallic material, which present high reflection and absorption potential of radiofrequency waves, to promote the packats loss in instants.

Unlike the PDR behavior in Figure 10, the link stability detected the link instability at the time the signal was degraded, as shown in Figure 11.

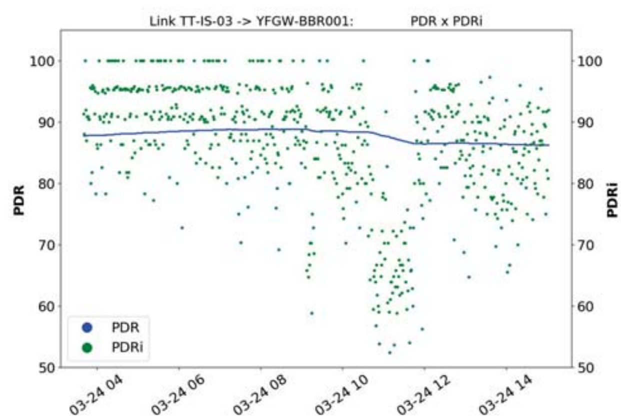

Fig. 10. Scenario 02: PDR versus PDRi - Link TT-IS-03 and YFGW-BBR001.

Another example of the same scenario is shown in Figure12. The link between TT-IS-05 and TT-IS-03 shows a high signal degradation in the period between 14:03 and 14:13 which is detected by the stability factor.

According to the two scenarios analyzed, we made use of the method proposed to analyze the IWSN links. In this work, we implemented the method in a data acquisition and supervision station. This implementation generated a higher processing demand for SCADA (Supervisory Control and

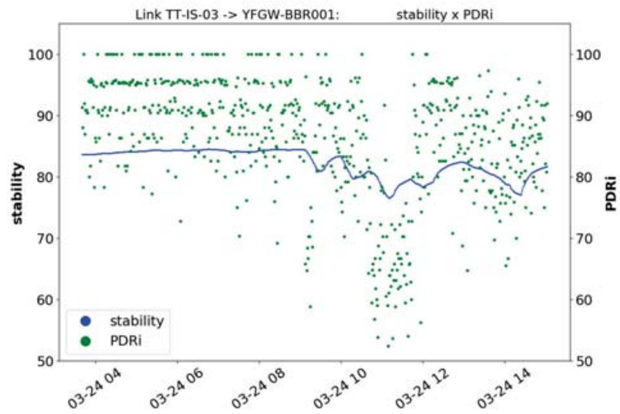

Fig. 11. Scenario 02: stability versus PDRi - Link TT-IS-03 and YFGW-BBR001.

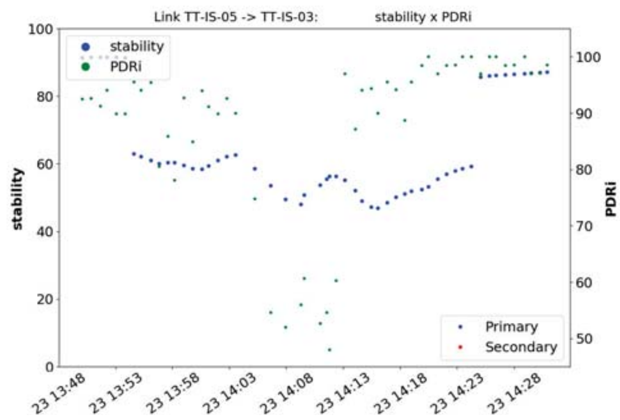

Fig. 12. Scenario 02: stability versus PDRi - Link TT-IS-05 and TT-IS-03.

Data Acquisition), which depends on the following factors: number of network nodes and sample window size. The increase in sample window size causes an increase in the processing time of the method due to the repetition structure.

However, we propose that the method should be implemented in the network manager itself. The commercial versions of the gateway, which incorporates network and security managers, present high processing performance to perform all network tasks. The manager already performs tasks from collecting network nodes information from the formation of links, to the scheduling and routing algorithms. In this sense, it becomes feasible and appropriate to execute the method to generate the link stability in the network manager.

Conclusions

In this paper, we proposed an method to evaluate the performance of network links, considering the parameters of the links available by the network manager. All the steps of the algorithm of the method were described in the paper and the theoretical principles of the link stability factor were discussed in order to justify the use of the selected parameters.

To validate the proposed method, we select four links in two scenarios from fifteen tests with ISA100.11a networks. The results presented in these scenarios show that the link stability factor can identify instability situations in the link, relating this instability to the variation of the received signal strength. In order to compare, the results show graphs indicating that link stability detects anomalies that are not only detected by the PDR parameter.

The main contribution of the factor generated by the proposed method in this work is to enable the detection of instabilities, which cause random variations in packet loss, and may even predict an increase in degradation of the communication path. The link stability can be used as a fundamental parameter routing and scheduling algorithm but also in the evaluation of the application of IWSN for systems control. Such remarks will be considered in future works.

***Authors**: Ms. Heitor Medeiros Florencio, Postgraduate Program in Electrical and Computer Engineering, Federal University of Rio Grande do Norte, Natal/RN, Brazil, ZIP 59072-970, e-mail heitormflorencio@gmail.com; Prof. Ph.D. Adrião Duarte Dória Neto, Department of Computer Engineering and Automation, Federal University of Rio Grande do Norte, Natal/RN, Brazil, ZIP 59072-970, e-mail adriao@dca.ufrn.br*

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