

PI-based Transmission Power Control for *WirelessHART* Field Devices^{*}

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Abstract: Wireless networks are gaining space in industrial environments due to the low installation costs and low maintenance. Robustness is also one of the main requirements for these systems to be adopted, and, in this context, *WirelessHART* (WH), ISA SP100.11a, and WIA-PA protocols met these characteristics. In order to provide low maintenance, these protocols must provide reliable radio links while keeping low power consumption to allow battery powered devices. Unfortunately, the standards of these protocols do not impose any RF power modulation technique, which is a form to increase even more the battery endurance of a wireless field device. Instead, RF power levels are fixed and selected by commissioning, and must allow the longest link per device. In this case, devices in closer ranges waste energy during transmissions, as they could save energy by modulating the RF power. This paper presents a RF power modulation technique that employs a proportional-integral controller and allows reduction of energy consumption while keeping the robustness of RF links. A proof of concept of the power modulation technique is implemented and verified showing good results and proving that the proposed controller is feasible. The proposal has the advantage to be fully compatible with the standard.

Keywords: Transmission power control; *WirelessHART* protocol; PI controller; industrial wireless sensor networks

1. INTRODUCTION

The *WirelessHART* (WH) protocol was specifically developed for industrial applications, as well as ISA SP 100.11a and WIA-PA (Song et al., 2008; Chen et al., 2010). All three standards employ IEEE 802.15.4 physical layer, with WH imposing at least three power levels for the field devices, which are -10 , 0 and $+10$ dBm. They reach reliability and security in a way they can replace cable based systems for industrial process control (Doherty and Teasdale, 2006). After WH launch in 2007, several studies were proposed and developed aiming to improve its performance (Zand et al., 2012). One important issue pointed in that study is the power consumption, which should be as low as possible while keeping good radio link characteristics. An industrial wireless field device should work as many years as possible before battery replacement because this is the most important characteristic related to maintenance.

A typical IEEE 802.15.4 transceiver presents several power levels that can be chosen according to the necessary RF link. In WH, the RF power level is adjusted by commissioning and must be carefully chosen based on device position inside the plant to provide a reliable link while keeping power consumption as low as possible.

This can lead to a situation when RF power must be selected to provide the longest links: energy is wasted in short-range communications, as illustrated in Figure 1.

A direct relation between RF power levels and DC power levels can be established as well as a relation between RF power levels and radio range. There is a trade-off between optimal link range and lowest energy consumption: as the RF powers are adjusted by commissioning, they are not optimal concerning all the links between field devices. Therefore it is important to reduce energy consumption that consequently extends battery life by modulating the RF power of each field device in relation to a specific peer. In this work, a power modulation scheme based on a proportional-integral (PI) controller is developed for transmission power control (TPC) in WH field devices.

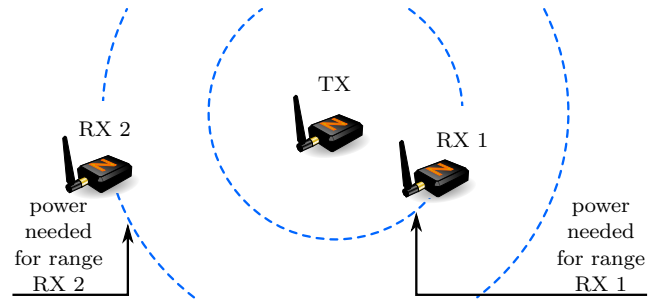


Fig. 1. RF power adjusted by commissioning in a WH network.

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This proposal improves a previous one, which presented a non-linear control system (Muller et al., 2014). The improvement is obtained by the constant power regulation, which was not achieved before. Previous experimental results showed up to 50 % of energy reduction, depending on the communication schedule. Also, the proposal does not change any aspect of the WH standard and therefore is fully compatible with standard commercial field devices.

The remaining of this work is organized as follows: Section 2 provides some context to this work through related works, Section 3 states the control problem, Section 4 presents the theory and the proposed controller, Section 5 describes the experiment used to validate the proposal, in Section 6 an analysis of the experiment outcomes is presented, finally in Section 7 the conclusions and future works are presented.

2. RELATED WORKS

Many works have been published that try to make WH networks more efficient using either data aggregation, packet routing, or link scheduling strategies. See for example (Zhang et al., 2014; Li et al., 2016; Neander et al., 2011), and for more energy saving strategies see (Rault et al., 2014). This proposal have the same goal (which is to save power), however it uses only the transmission power modulation to achieve its goal.

The RF power control has been subject of several researches in different areas. The main idea is to promote reduction of energy consumption while maintaining stable links. Also, power reduction cleans up the spectrum, which is very important in coexistence-based systems. A survey about TPC in wireless networks can be found in Olwal et al. (2010). The paper presents an extensive study about dynamic power control for mesh networks. A closed loop control for power reduction is presented in Dhamdhare et al. (2008) where the authors considered a bio-medical wireless sensor networks (WSN) composed by movable sensor nodes. The impacts in received signal strength indication (RSSI), which varies along the time due to multipath and shadowing phenomena, are explored. An adaptive RF power control for WSN is presented in Lin et al. (2006). The proposed algorithm was tested in MicaZ motes in a real application subject to weather conditions. An RF power control was developed in Cascado et al. (2010) for IEEE 802.15.4 networks that employ beaconing. The authors tested the proposal and found up to 57.7 % of power reduction in a case study. In Son et al. (2004) the authors made an extensive experimental study, where the TPC impact in communication reliability was verified. They proposed a TPC algorithm based on packet error rate and included a blacklisting for unreliable links. In Jeong et al. (2007), the authors verified the effectiveness of an RF power reduction control over WSN. In their study they argued that WSN power control is useful when combined with radio cycling techniques which promote greater reduction in overall consumption. Another work about the issues of power control in WSN was presented in Fu et al. (2012). Control theory was applied to produce a practical power control which was tested in real environment.

All of the previous works are related to WSN and some of their techniques can be incorporated in a WH field device

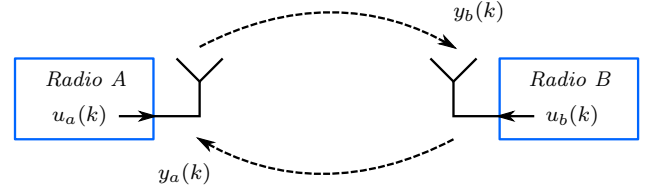


Fig. 2. The unknown LQI problem — each radio only knows the strength of the other radio’s signal.

for RF power control. This can be used to improve WH field devices by changing RF power level, allowing reduction of power consumption and thus increasing battery life. This work is an improvement of a previous one (Muller et al., 2014), employing a proportional-integral controller which allows continuous power modulation, while keeping full compatibility with WH protocol by not transmitting power information directly.

3. PROBLEM STATEMENT

In this work we assume there is a WH network where two radios A and B communicate with each other. We define $u_a(k)$ as the transmission power level of *radio A* and $u_b(k)$ as the transmission power level of *radio B* (both dimensionless), when sending packet k . This levels are configured in the radio firmware, and they are usually integers from 0 to $N - 1$ where N is the number of power levels. Whenever a radio receives the packet k , it can measure the link quality indicator (LQI) which depends on the transmission power and the attenuation of the environment. Fig. 2 shows a basic diagram of the communication, the LQI of a packet with index k received by *radio B* and converted to decibel-milliwatts is denoted $y_b(k)$, while it is denoted $y_a(k)$ if the packet is received by *radio A*, i.e. it is traveling in the opposite way.

We also assume that there are *desired* levels for the received strength of the radios, which are denoted $r_a(k)$ and $r_b(k)$, such that *radio A* expects to receive the packets with $y_a(k) = r_a(k)$ and *radio B* expects to receive the packets with $y_b(k) = r_b(k)$. The objective of the TPC is to automatically choose the transmission levels $u_a(k)$ and $u_b(k)$ to ensure that both radios receive the packets with the desired strength level.

The main challenge in choosing the transmission power level is that radio A only knows how strong it is receiving radio’s B signal and vice-versa, as shown in Fig. 2. In other words, radio A only knows y_a but it only have direct control over y_b . The WH does not transmit the LQI information over the network, so in order to do that one should change the protocol. This work aims to develop a transmission power controller that keeps compatibility with the actual technology, therefore any such changes in the protocol are unwanted.

In order to better understand the problem, let us describe the system. Using a WH radio described in (Muller et al., 2010), a simple power consumption model is obtained through measurement. The employed transceivers have a transmission power table with 18 levels, but only the 13 lower levels are available for power adjustment because of

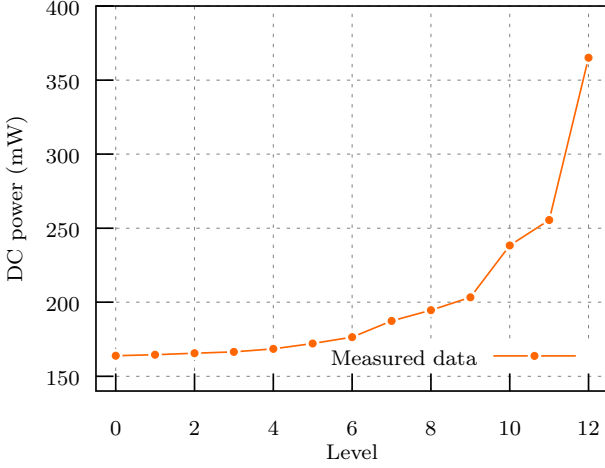


Fig. 3. DC power consumption by level.

hardware limitation (PA saturation). Figure 3 presents the values measured for each level, it shows that a significant power saving is obtained by using the lower levels.

Figure 4 shows a plot relating the transmission power level and the actual power measured at the pre-amplifier output for a WH radio as described in (Muller et al., 2010). When the power is measured in decibel-milliwatts, it can be observed that a linear fitting is a good choice for this model, therefore the fitted curve is presented alongside the measured data in the same plot. Since all the measures are in decibel-milliwatts, and the measure depends on the logarithm of the power, one can write that the LQI

$$y_b(k) = K_a u_a(k) + L_a + \nu_a(k)$$

where L_a and K_a are the offset and slope from the linearized model, and $\nu_a(k)$ is the attenuation of the environment in a communication from *radio A* to *radio B*. Observe that usually $\nu_a(k)$ is negative. Also, regarding a packet from *radio A* to *radio B*, we can write

$$y_a(k) = K_b u_b(k) + L_b + \nu_b(k)$$

where $\nu_b(k)$ is the respective attenuation. For the sake of simplicity, we assume the radios are similar, i. e. we assume $L_a = L_b = L$, and $K_a = K_b = K$ as well.

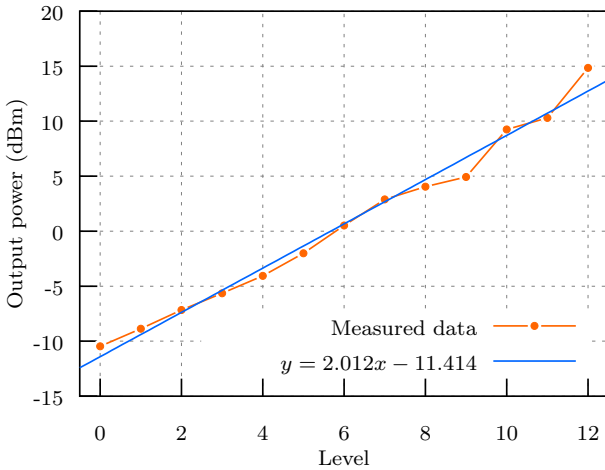


Fig. 4. PA output by level and the linear fit.

If the attenuation was known, the task of the controller would be very simple: it should only compute the transmission powers using the following equations:

$$u_a(k) = [r_b(k) - L - \nu_a(k)]/K$$

$$u_b(k) = [r_a(k) - L - \nu_b(k)]/K$$

However, both attenuation terms $\nu_a(k)$ and $\nu_b(k)$ are unknown by the radios and change in time. The attenuation depends on several aspects like the distance between the radios, obstacles and other communication that can interfere in the transmission.

Of course, one can always try to estimate the attenuation using the measured LQI and transmission power, computing the equations:

$$\hat{\nu}_a(k) = y_b(k) - K u_a(k) - L$$

$$\hat{\nu}_b(k) = y_a(k) - K u_b(k) - L$$

but this estimation depends on information from both radios, what is unavailable with the WH protocol. Therefore this approach cannot be employed.

4. PROPOSED PI-BASED TRANSMISSION POWER CONTROLLER

In this work, we propose a different approach to the RF power control, using similar ideas of (Muller et al., 2014). Since the LQI in *radio B* is unavailable to *radio A*, we propose a controller algorithm in *radio A* which will try to control the the LQI in *radio A* instead of *radio B*.

Using this idea, the controller A will measure the LQI in the *radio A* ($y_a(k)$) and then try to adjust the transmission level $u_a(k)$ in order to change the communication from A to B and also expecting to change the communication from B to A, and then receiving with the desired LQI. The idea seems counterintuitive but we will show in the sequence that it allows both the radios to communicate, making the LQIs to converge to the desired levels.

A sketch of the closed loop system can be seen in Fig. 5. The controller in *radio A* will use the following feedback action:

$$u_a(k) = C_a(z)(r_a(k) - y_a(k)) = C_a(z)e_a(k)$$

where $C_a(z)$ is the transfer function of the controller, $e_a(k)$ is the receiving error and z is the shift forward operator $zx(k) = x(k+1)$. Also, the *radio B* should use a similar feedback controller

$$u_b(k) = C_b(z)(r_b(k) - y_b(k)) = C_b(z)e_b(k)$$

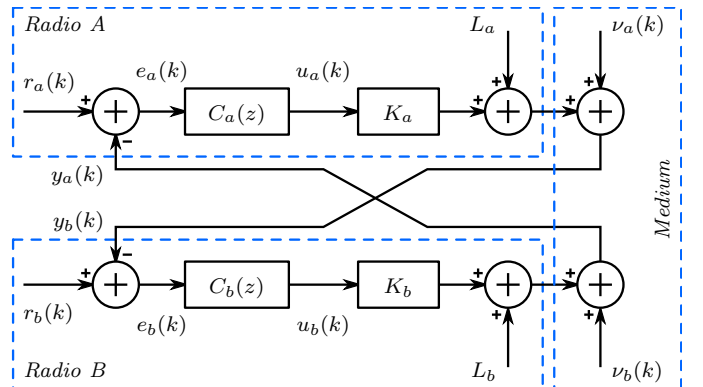


Fig. 5. Closed-loop diagram.

using the similar notation.

Let us compute the closed-loop transfer function, from $r_a(k)$ to $y_a(k)$:

$$y_a(k) = -K^2 C_b(z) C_a(k) (r_a(k) - y_a(k)) \\ + K C_b(z) (r_b(k) + L + \nu_a(k)) \\ + L + \nu_b(k)$$

therefore

$$\frac{y_a(k)}{r_a(k)} = T_a(z) = \frac{-K^2 C_b(z) C_a(z)}{1 - K^2 C_b(z) C_a(z)}. \quad (1)$$

An important property of the closed-loop system is that it presents negative forward gain — an issue that will be addressed latter — and it does not depend on the attenuation of the system.

Also, observe that

$$\frac{y_b(k)}{r_b(k)} = T_b(z) = T_a(z),$$

so that both closed-loop transfer functions $T_a(z)$ and $T_b(z)$ have the same transfer function. This indicates that the closed loop performance of the both closed loops is similar using the proposed strategy. We will then use these properties of the closed loop system to design both $C_a(z)$ and $C_b(z)$.

In this article we propose the use of proportional-integral (PI) controllers, because they are very simple to be implemented in the radio firmware and permit good closed loop performances, with null steady-state errors. The controllers are parametrised by K_p (proportional) and K_i (integral) gains, such that

$$C_a(z) = K_{pa} + K_{ia} \frac{z}{z-1}$$

while

$$C_b(z) = K_{pb} + K_{ib} \frac{z}{z-1}.$$

Now, we need to choose the four parameters K_{pa} , K_{ia} , K_{pb} , and K_{ib} to ensure closed loop stability and good transient performance. Observe in (1) that both controllers $C_a(z)$ and $C_b(z)$ affect the closed-loop transfer function $T_a(z)$ in a way that they can not be adjusted separately. Both controller should be adjusted together and an efficient procedure to design the controllers is still under development.

In this work, we decided to simplify the analysis and choose the parameters as:

$$K_{ia} = -0.85 K_{pa} \\ K_{ib} = -0.85 K_{pb}.$$

Since the closed loop system presents negative forward gain, we must choose opposite gains in order to ensure stability of the closed loop system. It is not possible to obtain a stable closed-loop using the same transfer function in both controllers $C_a(z) = C_b(z)$. Therefore we have chosen $K_{pa} = -K_{pb}$.

We have chosen similar gains for both radios to simplify the implementation of the codes. By doing so, it is simple to implement the code in a practical environment because both radios can be programmed with the same controllers and then just use opposite gains. A simple algorithm to determine the sign of the gains uses the radios unique network addresses that they both know. The radio with the

greater address has positive gains, the other has negative ones. Therefore the controller gains in one radio may be different for each link. Also, there is a table that holds the controller states for each link. This scheme allows the algorithm to scale to a larger n -node network. Also, to keep the implementation compatible with WH protocol, the algorithm prevents the PI controller to operate over broadcast and advertisement WH links, therefore when transmitting over those links the commissioned power level is used instead.

In the sequence we will present a case study where this proposed algorithm is implemented.

5. CASE STUDY

An experiment is carried out to validate the proposed controller using a WH network that has two WH nodes, as those described in (Muller et al., 2010), programmed with a firmware running the TPC algorithm plus an Emerson Rosemount 1420 WH network manager. However, since the algorithm does not control the transmission power during communications with the network manager, this could be any ordinary one.

The aim of this paper is to show the feasibility of this approach, therefore the controller parameters were tuned experimentally, resulting in those presented in Table 1.

Table 1. PI controller parameters

Parameter	Radio A	Radio B
K_p	0.2	-0.2
K_i	-0.17	0.17

During the experiment the radios are connected to a computer through a USB cable and a USB/serial converter in order to log the packets information for posterior analysis and further processing. Each packet exchanged between the radios has its related information (absolute slot number, source, destination, and LQI or TX level) stored in the respective radio file. After a certain amount of packets is exchanged, the system passes the transitory state and the transmission power level of each radio converges, as also does the received signal power, towards the setpoint chosen, in this case -65 dBm.

Since each sensor node logs only its own data, the data related to transmission and reception of each packet is split in two different files. Therefore the files are combined to relate each packet's transmission data to the respective reception data.

6. RESULTS

Figures 6 through 11 show the experiment results. Figure 6 shows the relation between the transmission power level at A, $u_a(k)$, and the perceived signal strength at B, $y_b(k)$, during the transitory state.

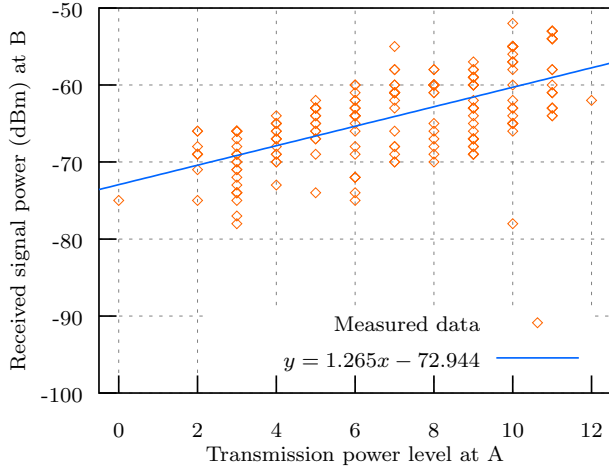


Fig. 6. Reception signal power at *radio B* by transmission power level at *radio A*.

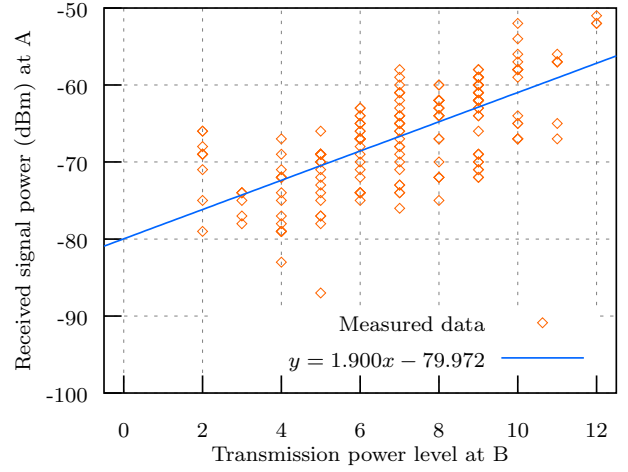


Fig. 9. Reception signal power at *radio A* by transmission power level at *radio B*.

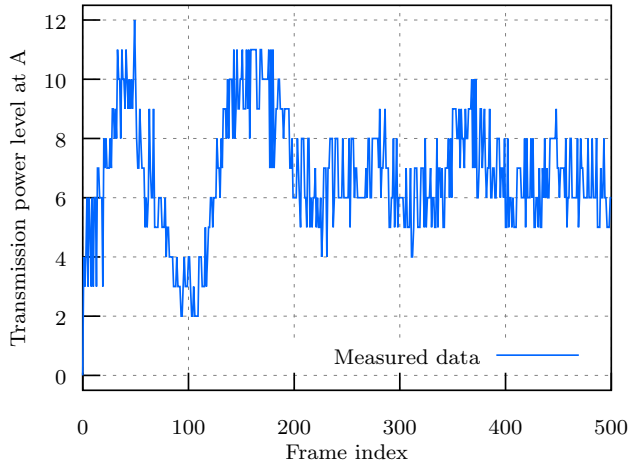


Fig. 7. Transmission power level at *radio A* by frame index.

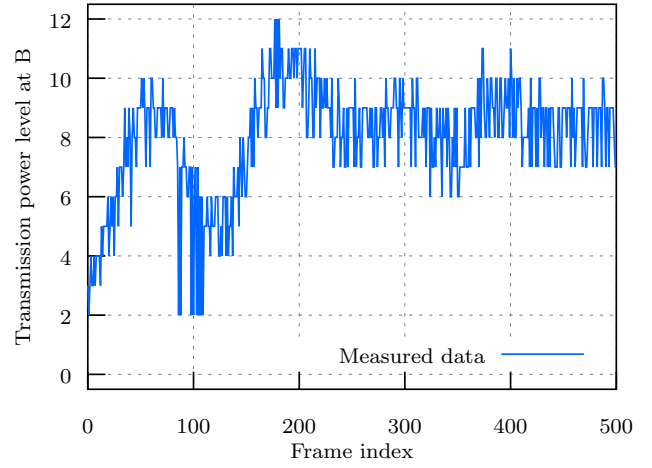


Fig. 10. Transmission power level at *radio B* by frame index.

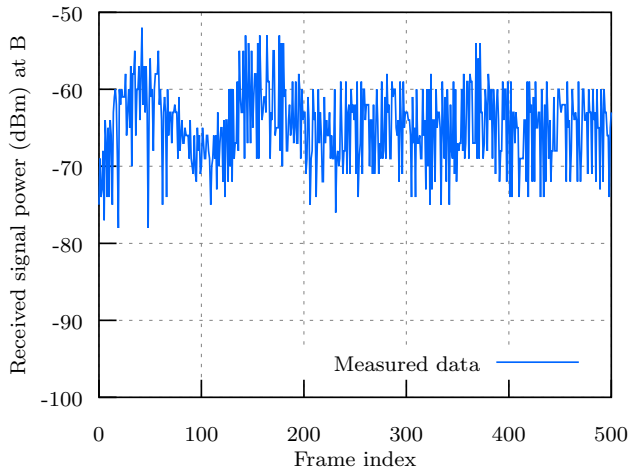


Fig. 8. Reception signal power at *radio B* by frame index.

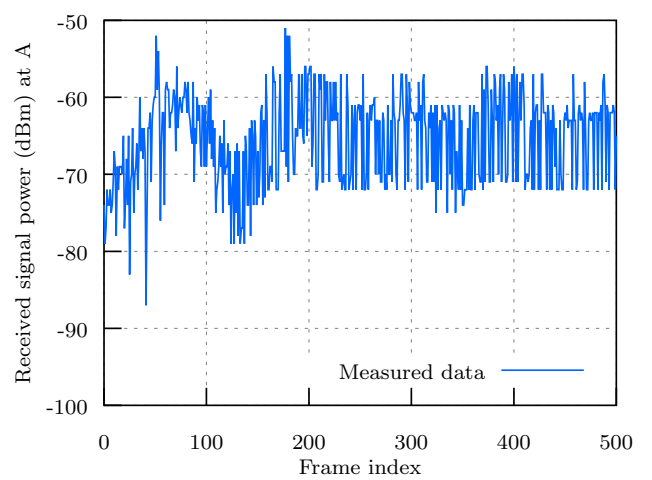


Fig. 11. Reception signal power at *radio A* by frame index.

The straight line is a linear fit that can be thought as a linear model: the channel attenuation and radio offset are related to the negative offset, and the radio gain, to the slope. Figure 7 shows the evolution of $u_a(k)$, and Fig. 8 shows the evolution of $y_b(k)$ through time, represented here by the packet index k .

Figures 9, 10, and 11 are their counterparts related to the other end. The plots show that the proposed set of controller gain works and have a settling time of approximately two hundred packets, in this case.

Analyzing Fig. 3 and comparing with the results presented in Figs. 7 and 10, they indicate a 49% power saving for *radio A* (level 7 corresponds to 187.3 mW in comparison with 365.1 mW at level 12) and 47% for *radio B* (194.6 mW at level 6).

7. CONCLUSIONS

This paper presented a RF power modulation scheme for WirelessHART protocol which is able to reduce the power consumed by the network nodes. To be fully compatible with the standard, no modifications on the protocol were done and a device that is able to modulate its power can operate together with legacy devices, by not modulating its power when communicating with them.

RF power reduction was verified along experiments and DC power saving can be directly related by means of RF to DC power relation, obtained from the radio model. A complete power saving model can be obtained by the analysis of communication scheduled by the network manager. This is done by the observation of link types and periodicity of TDMA scheduling. Peer-to-peer links will have RF power modulated by the algorithm and other types, such as advertisement links, will not.

As a future work another stage will be developed in order to deal with saturation problems that can interfere with the proper controller operation.

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