Control over WirelessHART Network through a Host Application

A WirelessHART Network Control Proposal

Viyils Sangregorio Soto, Ivan Muller, Jean M. Winter
Carlos Eduardo Pereira
Department of Electrical Engineering
Federal University of Rio Grande do Sul
viyils@gmail.com, {jean.winter, ivan.muller}@ufrgs.br,
cpereira@ece.ufrgs.br

João C. Netto
Institute of Informatics
Federal University of Rio Grande do Sul
Porto Alegre, Brazil
netto@inf.ufrgs.br

***Abstract*- The number of wires needed for effecting control increases with the complexity of the automation. In the last years, this has limited the developing of processes in the industry. Wireless networks offer an evolution to these restrictions, regarding wire systems, bringing facilities in reconfiguration and portability to mobile terminals. Meanwhile, some paradigms as, for example, security, reliability and latency, make it difficult for new technologies be inserting into the industrial area. One of the major difficulties in networked control systems is that the delay induced by the network in the control loop may cause degradation of the control performance and can destabilize the plant. This research offers a general view of the WirelessHART protocol for networked control systems, including the necessary mechanisms for an effective control loop through a host application. It also shows that is possible to perform control over WirelessHART networks with the control module placed in a host application using an acceptable working sample period for a process plant in an networked control system.**

Keywords—WirelessHART, automation systems, networked control, process control.

I. INTRODUCTION

In the last decades with the increase of the wires in the industry, the automation has turned more complex and this caused difficulties in the viability of wired systems. The requirements set by the industrial processes made it look for new alternatives and wireless networks turn out to be a good possibility. The use of industrial wireless equipment has increased, bringing some advantages. Some of the main advantages offered by wireless networks are easy installation when compared to wired devices, lower installation and support costs and high scalability. Due to all these advantages, the industry has considered to implement wireless networks for control and supervision of processes. These advantages among others are discussed by [9] and [10] in previous a study.

When the industry needed an alternative for wired, it started studying wireless networks and the focus was set on the monitoring of processes. In June 2010, the International Electro Technical Commission (IEC) certificated a new standard protocol called *Wireless*HART (WH). This brought new alternatives to the industrial area and allowed the use of WH networks for monitoring industrial processes. Wireless network are now established in monitoring applications. The next step is wireless control, as shown in several studies made in the last years such as in [2] [3] [4] [5]. The following question emerges apart from the monitoring: is it possible to replace wires networks on an industrial plant for wireless networks to create control loops?

The insertion of the communication network in the feedback control loop brings important questions that may need to be answered. These new systems are called networked control system (NCS), and they are characterized for sharing communication networks for the information transfer [2]. Not using an exclusive communication network for the execution of the control loop system brings along some disadvantages that influences the process variable in a negative way.

One of the major challenges in the NCS is the network-induced delay that occurs while exchanging data among devices connected to the shared medium. A significant emphasis has been developed on control methodologies to handle the network delay effect in NCS [11] [12]. Network delays can degrade the NCS control performance and destabilize the system. These delays do not necessarily affect significantly an open loop control such as on-off relays in industrial plants. Nevertheless, this configuration is not appropriate for more complex control applications, which requires feedback in order to correct output errors. Traditional control methodologies that handle constant delays are not suitable to be applied in these systems, because these delays are not constant.

Recently in [29] [30] it was proposed the use of a co-simulation framework based on the interaction of TrueTime, together with a cross layer wireless network simulator. In this works, a sample system controlled by a WirelessHART network has been considered in a simulated ambient. This paper presents a proposal for developing a closed-loop control system over WH Network through a host application using a real scenario. It is organized as follows: in section II are shown specifications of the WH protocol; section III briefly presents the problem in wireless control and includes important aspects related to control over WH network. In section IV is discussed how to do control through a WH network by a host application, according to WH specifications; in section V, the conclusions and future works of the paper are presented.

II. The WirelessHART protocol

This section shows specifications of the WH protocol and the main characteristics of a WH field device (FD). The WH devices are configured to work in burst mode for periodical publishing of process data. The characteristics of the WH burst mode are presented in section B.

A. WirelessHART

The WH is the first wireless open standard protocol, for measurement and industrial process control applications, certified by the IEC; WH was added to overall HART protocol suite as part of the 7th specification [13]. WH is an extension of the HART protocol created in the 80's and allows compatibility with older HART systems. The two versions of the protocol share the same features on applications layer, according to the OSI model (see Fig. 1). WH protocol stack include five layers mentioned below:

- Physical Layer: Based on IEEE 802.15.4 standard, which uses DSSS (Direct Sequence Spread Spectrum), operating in license-free ISM band through 15 different channels [7]. Its channels are numbered from 11 to 25, with 5 MHz a gap between two adjacent channels . The raw data rate of WH is 250Kkb/s;
- Data layer: Channel hopping with Time Division Multiple Access (TDMA) and time slots of 10ms for Medium access control (MAC). It uses the concept of superframe, which are a group of sequenced time slots. The superframe is periodical and the first slot on the network receives an ASN equal to zero (Absolution Slot Number).
- Network layer: It uses mesh topology, presenting different algorithms for packet routing. The standard uses 128-bits AES Key for encryption;
- Application layer: In WH, the communication between the devices and gateway is based on command requests and responses.

WH components are here described [15]:

- Network Manager (NM): It is the application responsible for forming and configuring the network, scheduling communication between devices, managing the routing in the network, monitoring and reporting the health of the network;
- Security Manager (SM): Application responsible for security management;
- Gateway: It is the link between the host application, NM, SM, and the FDs within the mesh network;
- Field Devices (FD): The devices distributed in the industry process. The FD are used for sensing, actuation, and communication;
- Host applications: user application connected to the network backbone of the industry, which has communication with WH nodes in order to manage process and control data.
- Access point: connect the WH FDs with a gateway;
- Handheld: Mobile devices (wireless or not) for monitoring, configuration, maintenance of WH FD.

OSI Layer	Wireless HART
Application	Commands based
Session	
Transport	Auto segmented transfer of large data sets, reliable stream transport, and Negotiated segmented sizes.
Network	Power- optimized Redundant Path, Mesh to the edge Network.
Data Link	Secure, Time Synched TDMA/CSMA, Frequency Agile with ARQ
Physical	2.4 GHz Wireless, 802.15.4 based radios, 10 dBm TX Power

Fig. 1. WirelessHART OSI model.

The main components in a typical WH network are the NM, SM, and an access point. These components usually reside inside one box. The main characteristic about WH protocol networks is the use of mesh network, in which each device is able to transmit its own data as well as relay information from other devices in the network [13]. The different network topologies can influence the network in several ways depending on different factors such as distance between nodes, number of devices, etc.

B. WirelessHART Burst Mode

The protocol WH allows an adjustment of the time for data process publication by the WH FD, according to the process requirements. A WH FD can be set on burst mode. Depending on the time set in the FD when it is configured in burst mode for data publishing, it is possible to increase the number of links for transmitting data. This represents more opportunities to send a message in a superframe. The NM must ensure sufficient resources for WH devices to propagate their messages with redundant possibilities in case of failure.

Previous studies presented in [14] a WH network proposal to evaluate the use of network resources by modifications on the burst mode. The study shows that NM assigns transmission links before the deadline of messages publication. The number of transmission links increase depending on the burst time assign to each WH FD. Other characteristics were also shown, such as a relation between the number of devices present in the WH network and the amount of links for transmission assigned to each device.

When a FD is in burst mode, it will publish data according to the burst mode configuration [16]. In this paper there were taken into account the results presented in [14] and the requirements of this case of study to set the FD on a burst period equal to one second, which is the minimum update period for the burst messages allowed in the gateway used.

III. CONTROL OVER *WIRELESS*HART NETWORK

This section presents the following topics: the problem about control over wireless networks, a description of a NCS using WH standard, which includes the network-induced delays analysis and a proposal for control over WH Network with the control module placed in a host application.

A. *Control over Wireless Networks*

Usually, there are three application groups executed in a process plant [1], from auxiliary activities up to critical processes. Applications of class A are specified for security, while control and monitoring processes are classified as class B and class C respectively. Application group of class B includes supervisory control, open loop control, closed loop control and critical control. This paper is about the basis of class B applications.

In order to start using wireless networks in control systems, some important issues must be solved, such as security, reliability, safety, throughput, and battery longevity. Table I shows a comparison between wireless networks.

TABLE I. COMPARATIVE TABLE OF THE MAIN FEATURES IN WIRELESS PROTOCOLS

	Bluetooth	ZigBee	ISA 100.11a	WirelessHART
Security	Optional	Optional	Very High	Very High
Reliability	Low	Low	Very High	High
Power Consumption	High	Medium	Low	Low
Scalability	Limited Devices	High	High	Limited Devices

To conclude, it is possible to say that WH and ISA 100.11a protocols are the proper solution to fulfill industrial requirements compared to other Wireless protocols, because apart from being good for the industry process, they provide a backward compatibility with the widely used HART technology. In [27] it is shown an effective approach to wireless control with less reliability. It is used an enhanced PID (Proportional, Integral and derivative) enhanced algorithm to treat the adverse conditions in wireless communication. When there is no communication loss, the enhanced PID block acts exactly the same as a standard PID block. Lost data is compensated by the integral component in the enhanced PID block. When communications are reestablished, the derivative component in the enhanced PID block eliminates possible spikes in the output. This proposal could be implemented to obtain reliable results for process control loops.

B. *Networked Control*

The effects of the delay in a networked control have been studied in many works. In [19], it shows a simple stability analysis for discrete-time delayed systems and, in [20], various system formulations for a periodical delay in NCS are presented. The conclusion showed a degradation that can destabilize the system, due to the fact that there is a reduction of the system stability margin. Wireless networks have random delays, which require more complex techniques to be treated. Some modern methodologies have tried to compensate these delays in the last few years, for example, in works [21] and [22]. The first is based on stochastic stability and the second uses stability regions and a hybrid system technique for the analysis.

Fig. 2 shows a general architecture that allows an analysis of many important characteristics of the NCS considering a WH network. The architecture corresponds to Direct Structure [13]. In a wireless networked control system, all communications are made through wireless links. There are two sources of delay that comes from the network. The first network-induced delay occurs in the communication between the sensors and the controller and it is called τ^{SC} .The second one, called τ^{SA} , occurs when the controller calculates the value of the control signal and sends it to the actuators, this one is τ^{SA} The total loop delay can be lumped as showed in equation 1, for analysis purposes.

$$\tau = \tau^{SC} + \tau^{CA} \quad (1)$$

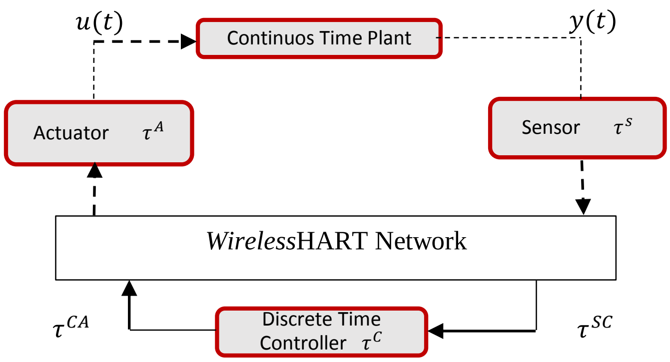

Fig. 2. Single loop NCS.

To include these delay effects in the continuous-time model, let us define the parameter $k^*(t)$ that denotes the index of the most recent control input that is available at time *t* as $k^*(t)$. The NCS model, that considers network-induced delays, consists of a continuous plant:

$$\dot{x}(t) = Ax(t) + Bu^*(t), \quad y(t) = Cx(t) \quad (2)$$
$$u^*(t) = U_{k^*(t)},$$

And a discrete controller,

$$u(kh) = -Kx(kh), \quad k = 0,1,2 \ldots \quad (3)$$

Where, $x \in R^n, u \in R^m, y \in R^p$, and A, B, C, k are of compatible dimensions.

An important topic to be considered is the relation between the maximum delay permitted and the plant's sampling time. The delay cannot be longer than the sample time. When the delay is longer than the sample time, there are modern techniques to solve it. In [28], stochastic optimal controllers of NCS whose network-induced delay is longer than a sampling period are designed, for the two cases of a system with full state information and a system with partial state information. They presented an optimal estimator of the system state when the system has partial state information and network-induced delay is longer than a sampling period.

In recent works, as in [31], it is presented a discrete-time model that incorporates time-varying sampling interval. In this study was considered to implement a controller which first reads the process variable's value. This value is available in the clock-driven sensor. As soon as the value is available in the application host, it calculates the value of the control signal and sends it to the event-driven actuator. Once the control signal's value is received, the actuator changes. Once this process is done, the cycle is repeated.

C. Control over WirelessHART trough a host application.

To study this proposal, a real test bed was implemented and the system was applied to control a valve position that is usually used in oil and gas industries. Fig. 3 illustrates the block diagram for a control loop through host application over WH networks. There are three types of control, depending where the control module is placed [17]. It was considered to place a control module in a host application, as it is possible to see in Fig. 3. The WH gateway provides Hart UDP interfaces [8] that are used for the host application to communicate with the WH gateway [7].

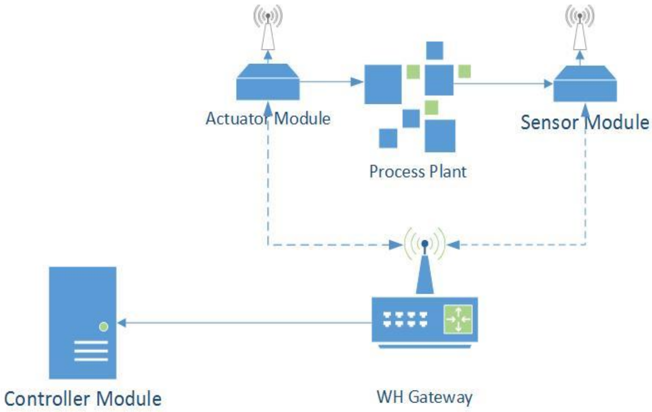

Fig. 3. Basic communication structure of the host application.

The sensor node contains a periodic time-driven task, with an execution time of $s(k)$ that performs a sampling process, converting analog to digital data. The actuator node is event-driven, running a task that is activated by a coming message from the controller node, containing a control signal for the digital to-analog conversion. The controller node can be either event-driven or clock-driven.

The WH application layer is based on commands. All commands requests require command responses. When the response commands are confirmed, the next step is available. The implemented host application works in the following way: First the <<controller>> sends the command to read process variable, sends to the <<gateway>> which forwards to <<sensor node>> in order to read the process variable value. After this, the <<controller>> receives the process variable value and computes the control signal. Thus, the value is sent to the <<actuator>> through the <<gateway>> using the command Write Process Variable and the actuator writes the value in the valve actuator. Then, this sequence is repeated along the time.

IV. CONTROL OVER *WIRELESS*HART NETWORK

Related studies about control in WH networks propose to insert function block of the control module in the Gateway for the control loop execution[17], in this work is inserted the control module in the host application. This includes some topics about networked control over wireless network. The developed proposal is used in acomercial valve actuator for valve positioning. It also presents statistics about the network-induced delay.

A. Architecture

The software was developed using C# language. It imports two DLL "dynamic link library" created in C++, which contains the frames for UDP commands, the function for delivering messages, validation of the received data and the commands structures.

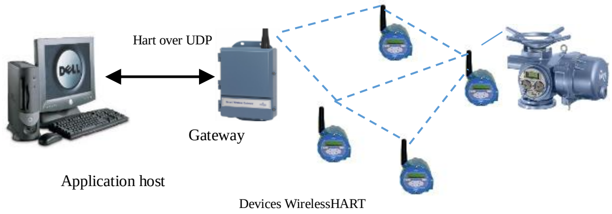

Fig. 4. Connections among the computer, gateway and WH field devices.

The communication structure between a host application and a WH network is presented in the Fig. 4. In this scenario, a commercial gateway, Emerson model 1420A and four developed WH FDs are used for the analysis of this proposal. All communications from WH network passes through the gateway which forwards the messages to the specific destination. The software is based on threads, which get information from the network and creates the control loop. For this study, it was used a WH FD developed in [18], and a commercial valve actuator which has a WH communication interface.

Fig. 5 illustrates the sequence diagram of the proposed architecture, in which it is shown how is measured the network-induced delays in the control loop. It is possible to measure $\tau^{SC} and\ \tau^{CA}$ but considering (1), the delay loop τ_k it was measured.

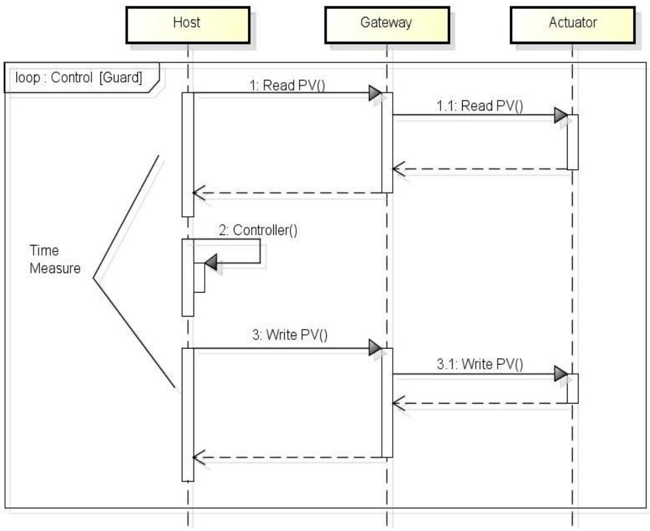

Fig. 5. Sequence Diagram of the proposed architecture.

B. Results

In this section are presented the captured message delays in the architecture mentioned above and the practical experiment with a valve control system. For the analysis, the following is considered: It is possible to divide the delay on the control loop within the presented architecture. Fig. 6 illustrates the different delays presented in the experiment. The first delay τ_1 refers to the delay during executing time for the Hart Control application task; the second delay τ_2 occurs between the time of communication among the application and the WH gateway; the last delay τ_3 is caused by the wireless network.

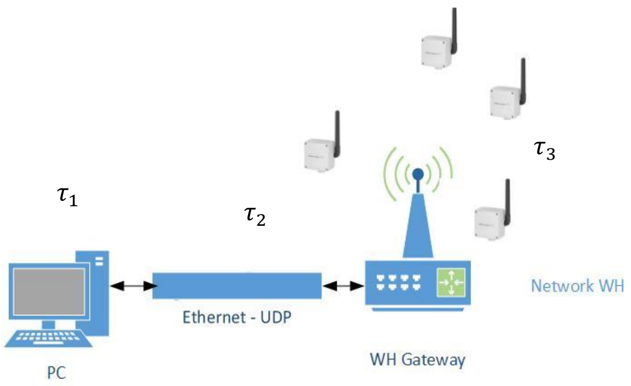

Fig. 6. Representation of the delays in the architecture proposal.

In order to analyze the influence of $\boldsymbol{\tau_1}$ and $\boldsymbol{\tau_2}$ delays, an experiment has been made by sending command 3 through UDP messages. This command reads the value of the dynamic variable of the process which is already saved in the gateway's cache memory. Fig. 7. shows the measured time after 1000 samples. An average delay of 1.6 ms was obtained, with a jitter of 0.5 ms.

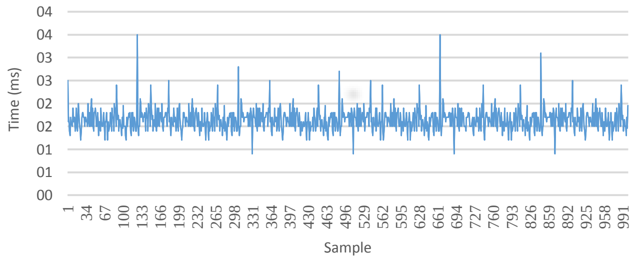

Fig. 7. Delay $\tau_1 + \tau_2$ in the control loop.

Any computational controller delay can be absorbed into either τ^{SC} or τ^{CA} without loss of generality [23]. For fixed control law (time-invariant controllers), the sensor-to-controller delay and controller-to-actuator delay is considered τ_{k} and included $\tau_1 + \tau_2$. Fig. 8 illustrates the measured time for a control loop. With an 1000 samples of control loop time, an average delay of 9.87s with a jitter media of 1.57s was obtained (shown in Fig. 9). As a general rule that can be applied in a large number of cases, the period of samples must be at least five for a time constant τ of the system [24]. Feedback controlled plants can tolerate a certain amount of variable delay. Therefore it is valuable to determinate whether the system is stable as a function of the maximum variable delay τ_k.

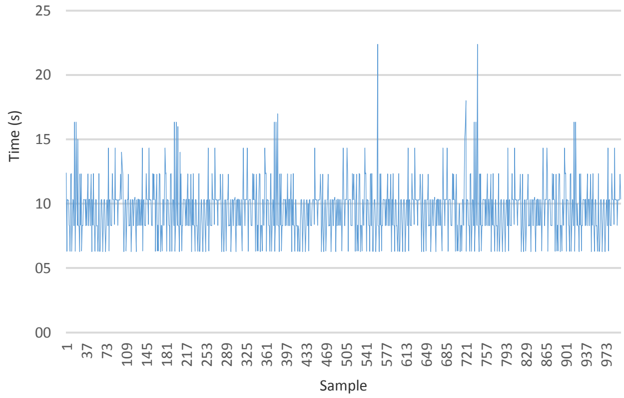

Fig. 8. Delay in the control loop $\boldsymbol{\tau_k}$.

Fig. 8 presents the obtained delays within the control loop induce by the WH network. In this case, it was performed a simple procedure for positioning the actuator in a desirable value using the sequence presented in Fig. 5.

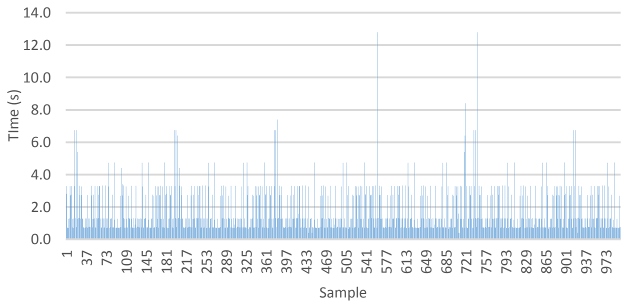

Fig. 9. Jitter τ_k in the control loop.

Taking into account the proposal in section C, the methodology sequence demonstrated in Fig. 5 was emplyed. It was used a time-based PID controller presented in [28]. Results can be seen in Fig. 10, which shows the actuator position versus time with bases on this simple controller.

A practical WH network as presented in Fig. 5 is deployed in a laboratory environment for test this proposal. In Fig. 10, the position of the valve and the position of the control signal is illustrated. When the controller has the value of the actual position available, it calculates the new control signal and it sends the calculated value to the actuator, with a τ^{CA} delay. Fig. 10 shows the control signal and actuator position, where it is possible to appreciate that the actuator reaches the position of the control signal after τ^{CA} delay. To calculate the control signal, the controller works with a different frequency to ensure that the actuator received the value and is positioned on the value sent by the controller. The measure of the actual position of the actuator was made by sending the command of the read process variable. This next measure is obtained when the previous measure is done. This occurs repeatedly.

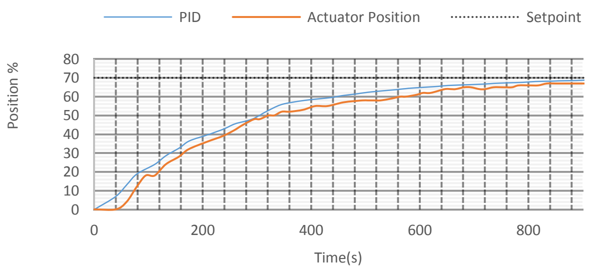

Fig. 10. Temporal response of the valve position

V. Conclusion and Future Work

This work presented the main problems of the networked control over wireless network and the implementation of the valid architecture for effective control through a host application over WirelessHART networks.

In order to show the feasibility of the proposed approach, a practical WH network is deployed in a laboratory environment and including a time-based PID control loop. The proposal presented in this paper can be useful to compare different architectures that are considered to place the control module in the gateway. According to studies such as [26] where it is established a general rule sample time and [12] where stability regions and the delays, the work showed that is possible effecting control on process plant that can be stable with the restriction of the sampled time and delays, given by the architecture. This work show that is possible to apply this proposal in control systems that can work with the sample time restriction offered by the proposed architecture.

For future works, the goal is the development of more complex controller to see the improvements and the answer to the system, taking into account the existing delays, proving different control algorithms to analyze how they affect the performance of the system. A further step in this work is implement an event-based PID controller [25], where the sampling period is variable sample to sample. This variation can be compensated by adjusting the controller coefficients for every sample. The price of implementing more complex algorithm, is an increase on the computation time.

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