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Extending ABB's WirelessHART Tool

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Abstract

Within this decade, wireless technology has been used in process control in various industries. WirelessHART is one of the standards, used for creating communication networks for such purpose. Since the technology is relatively new, there are many known and unknown risks in deploying it in real life applications.

ABB’s WirelessHART Tool is used for generating simulation scenarios that can be used for evaluating the performance of WirelessHART networks under different conditions.

This paper describes in detail, how ABB’s WirelessHART Tool was extended by adding various new functionalities. The topics cover what obstacles we have faced, which solutions were used and why, how our solutions were evaluated and the outcomes. Furthermore, the paper documents the application structure of WirelessHART Tool.

Keywords: WirelessHART, TrueTime, Simulink, MATLAB, Software, Simulator, Networked Control Systems

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Acronyms

IEEE	Institute of Electrical and Electronic Engineers
GUI	WirelessHART tool Graphical User Interface
TDMA	Time Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Detection
MAC	Medium Access Control
WHART	WirelessHART

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1. Introduction

Wireless technology is traditionally used in the communication and telecommunication domain however nowadays it plays an important role in many other disciplines as well. In the last few years, it has emerged in industrial process control to provide an alternative to the already existing wired technology. The advantages are reduced power consumption and weight of the machinery.

ABB is a one of the world’s leading engineering corporations mostly operating in the areas of power and automation. ABB was created in 1988 by merging the Swedish company ASEA (created in 1883) and the Swiss company Brown, Boveri & Cie (created in 1891). In order to supply state of art technology to customers ABB Corporate Research continuously performs research on a number of areas in order to ensure they have the edge in environmental friendliness, sustainability, prices, and quality. One of these research areas is automation networks more precisely wireless automation networks.

WirelessHART (Wireless Highway Addressable Remote Transducer) is one of the standards that are used for building communication networks for process control. It is cost effective and ensures quick and easy installation. Nevertheless, when using WirelessHART for process control, the critical point of the process needs to be anticipated and evaluated from the point of efficiency. The behaviors of the process also need to be predicted in case of packet loss, noise and other disturbances.

WirelessHART Tool is an application created by ABB to automate generating WirelessHART network simulations. WirelessHART Tool was implemented in MATLAB for increasing the speed of creating simulations for WirelessHART networks. It uses Simulink along with a modified TrueTime library as simulation environment, which enables simulation of packet loss and other network related problems.

1.1 Problem Formulation

The problem in the focus of this thesis is how to improve and extend WirelessHART Tool without affecting already existing features.
In order to identify improvements that need to be performed, first the design of the existing WirelessHART Tool has to be discovered and documented.

The contribution of this Thesis is to add two major extensions to WirelessHART Tool.
The first extension is to allow users to build simulations where both a wired and a wireless network coexist.
The second extension is to allow the users to generate networks that use multiple channels in their frequency range to transmit data.

Since before this thesis the application structure was not documented another contribution is that the application structure was exposed and documented.

1.2 Report Outline

Chapter 2 contains information that is crucial for understanding the following chapters. The topics cover process control, wired and wireless network technologies and specifically focusing on WirelessHART. Other topics such as description of the used tools, libraries, simulation environment are also included.
Chapter 3 starts with brief introduction of ABB's WirelessHART Tool and the modified TrueTime library developed by ABB is explained here.
Later, the reader can see a detailed specification and evaluation of ABB's WirelessHART Tool from a software engineering point of view. This includes structure, coding style, functionality etc.
Chapter 4 includes the requirements collected from ABB in order to improve and extend the tool. The scope and limitations of the work is covered here as well.

Chapter 5 contains the solutions for each requirement and the reasons for each of those solutions.
Chapters 6 and 7 describe how the solutions were evaluated, what were the results of those evaluations as well as the explanation of the results.
Chapter 8 concludes the paper and gives suggestions for further improvements for ABB’s WirelessHART Tool and other related appliances.

2. Background

In this section, we describe briefly the fundamental information which was found during research. There are three main areas that the reader should familiarize with before start reading the next chapter. These three main areas are: Networking Technology, Industrial Process Control and Software Development.

Section 2.1 provides a short explanation about process control used in industrial production, focusing on closed loop control systems and a general description of the PID controller.

Section 2.2 talks about the network technologies that were met during development for example Ethernet and a few wireless standards. This subsection also includes a table comparison about each kind of networks.

Section 2.3 focuses on describing the WirelessHART Standard.

Section 2.4 gives a brief introduction on the development tools that were used during the implementation phase.

2.1 Process Control in Industrial Production

Process controllers are used in a large variety of areas such as oil refining, chemicals and power plants. In industrial production, process controllers are used to manage process output and keep it within the desired range. There are different controllers for different kinds of processes.

2.1.1 Closed loop control

There are two major types of process control systems: open loop control systems and closed loop control systems [3]. In this thesis, *only the closed loop control systems are observed.*

A set of common terms used in the automated process control area need to be defined for better understanding. There are some important variables that need to be named and defined in the area of process control systems [1].

The *controlled variable* is the variable, which the process deals with. Sometimes the term “process variable” also refers to the controlled variable.

Setpoint is a desired value of controlled variable. The action of the controller is based on the error between the controlled variable and the setpoint. If the error is not 0, the controller will try to drive the value of the controlled variable towards the setpoint.

Manipulated variable is the input to the actuator. The actuator uses it to affect the process and keep the controlled variable on the desired setpoint.

Error is the difference between the feedback and the setpoint. The error can be either positive or negative. The purpose of any controllers is to minimize an error.

The *feedback* is the input to the sensor (output from the process) that needs to be maintained or controlled at the desired value (setpoint). Feedback control reacts to system and works to minimize the error.

Referring to Figure 1, closed loop control system uses **error** between the **feedback** from the process compare to the desired **setpoint** to make a decision of changing the control signal that drives the system. The feedback is current output from the process that is observed. In the control system term, the error value can be positive or negative. The controller persists to maintain the error to reach the desired state. The error will be adjusted accordingly to the desired setpoint by sending **manipulated variable** to the process. Since closed loop control system can adjust itself, from time to time, it is called automatic control loop system.

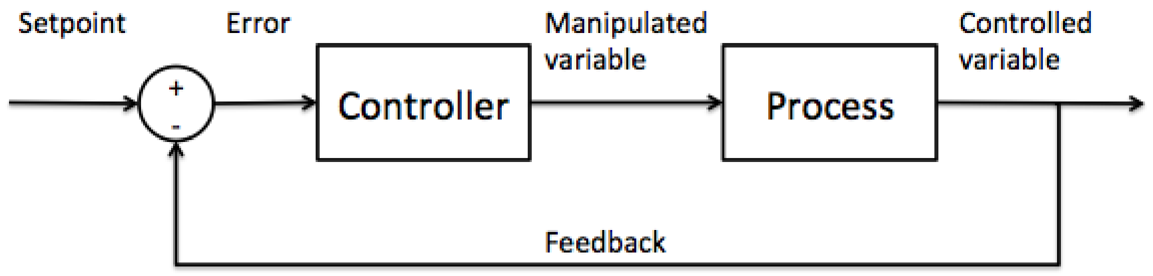


Figure 1: Closed-loop control system

2.1.3 Proportional, Integral and Derivative Controller

The Proportional, Integral and Derivative (PID) controller is the most popular controller used in industry. The PID controller is normally used in closed loop control systems [2]. The purpose of PID controller is to obtain the minimum error, controlled variable and desired setpoint, for a given system by applying three types of control actions. The controller sends the controller output signal to actuator. The actuator acts upon the controller output signal in order to drive a plant.

As shown in equation 2.1.3, PID consists of applying the sum of three types of control actions: Proportional action, Integral action and Derivative action [18].

$$Y(t) = K_P\, e(t) + K_I \int_0^t e(\tau)\, d\tau + K_D \frac{d}{dt}\, e(t) \qquad (2.1.3)$$

Proportional action is used to compensate (increase or decrease) the magnitude of the current error signal.

Integral action increases according to how long the error has existed. This action will affect directly to response time that reaches the setpoint.

Derivative action determines the steepness that is corresponding to the magnitude of the error. The larger the error is, the longer the steepness will be.

2.2 Network Technologies

This section describes general introduction to the Open System Interconnection (OSI) Model and the different Wired and Wireless Network Technologies are presented along with their strength and weaknesses. The general comparison of each type of Wireless Network Technologies will be mentioned here as well.

2.2.1 The Open System Interconnection Model

OSI model is a theoretical framework used for communication between networking devices. The OSI model is just a framework is used to act as guidelines for several network standards. The OSI model has been developed and adopted by the International Organization for Standardization (ISO). Most of the network protocols follow an underlying layer based of the OSI model [6].

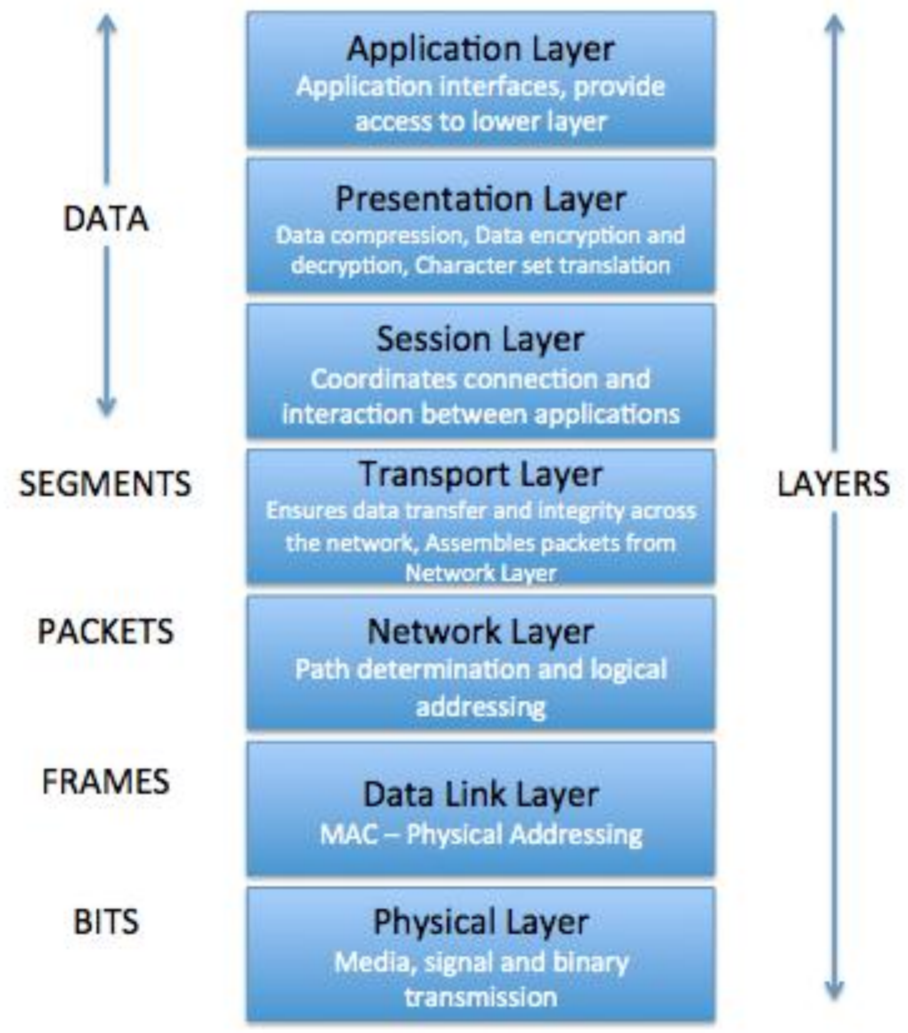

DATA
SEGMENTS
PACKETS
FRAMES
BITS
Application Layer
Application interfaces, provide access to lower layer
Presentation Layer
Data compression, Data encryption and decryption, Character set translation
Session Layer
Coordinates connection and interaction between applications
Transport Layer
Ensures data transfer and integrity across the network, Assembles packets from Network Layer
Network Layer
Path determination and logical addressing
Data Link Layer
MAC – Physical Addressing
Physical Layer
Media, signal and binary transmission
LAYERS

Figure 2: The Open System Interconnection (OSI) model

The OSI model breaks the various characteristics of computer networks into seven separate layers as shown in Figure 2. Each layer of the OSI model is independent from the other layers in its purposes and responsibilities. First three layers from the bottom: Physical Layer, Data Link Layer and Network Layer. The lower layers deal with mechanism of sending information from one computer to another over the network. The Upper Layers are: Transport Layer, Session Layer, Presentation Layer and Application Layer. The upper layers deal with how applications communicate to network through application programming interfaces.

The seven layers in OSI basic structure:

Physical Layer: The bottom-most layer, of OSI model the physical layer defines the link between the devices and either electric wire or radio communication medium (transmission medium). The main functionality of this layer is to convert the data, called "*bits"*, into transmission signals. This transmission can be either analog or digital, both types transmit binary data.

Data Link Layer: The Data Link Layer is used to arrange the raw bits of data from Physical layer into *"frames"*. Reliability term, this layer provides reliable transmission, and is used to identify and correct the errors, that might happen during the transmission from one device to another.

Network Layer: The Network Layer establishes a complete routing path and prepares the data to be transmitted through all nodes, between source and destination. This layer is also responsible for translating the physical address (binary format) to logical address, for example Internet Protocol (IP). Since the transmission has a source and a destination, the Network Layer can work in different responsibility: Fragmentation and Reassembly. An example for this two process would be: the source sends the *packets* down to the Data Link Layer, the packets are needed to be divided into small pieces, the length of the message can be limited if it is too large. Then the small pieces of the packets are to be reassembled when arrives to the Network Layer of destination device.

Transport Layer: This layer provides transparent transfer of data between end computers and responsible for the reliability of the connection. The Transport Layer handles error recognition, data recovery and retransmission. The retransmission may be used when the messages are not delivered to the destination device in a correct manner or the messages get corrupted.

Session Layer: The Session layer allows devices to establish and manage the connection. This layer creates the link or connection between two software applications, and allows them to exchange the data over a period of time.

Presentation Layer: This layer acts as a translator. The reason for this layer is that a network can connect several different computers such as, Macintosh, PC, etc. The Presentation Layer also performs the encryption and decryption to ensure the data security when it conveys down to another layer.

Application Layer: The top-most layer of OSI. The Application Layer provides interface for applications to access to the lower layers.

2.2.2 Wired Network Standards

There are three different wired network models were considered candidate technologies for connecting the wired actuators.

Carrier Sense Multiple Access with Collision Detection (e.g. Ethernet)

CSMA/CD stands for Carrier Sense Multiple Access with Collision Detection. This network model is used to improve the performance by terminating the transmission when the collision is detected. Collision happens when two devices attempt to use the same frequency simultaneously for transmission. Since the verification acknowledgement of sending and receiving is not enough to ensure that the package will ever be sent to the destination due to collision, the method uses a back-off algorithm to try sending at different times. The collision detection state starts after the sender is ready to transmit the package, if the medium is idle and then the sender starts transmitting the package.

The CSMA/CD is a Media Access Control (MAC) method in Data Link Layer, providing the acknowledgement for the source/destination device whenever data has arrived [16].

The back-off technique is an algorithm, used in the sending nodes, which selects a random number for the duration of waiting time in the network to reduce the probability of further collisions.

Time Division Multiple Access (e.g. TTP)

The *TDMA* is a medium access method for shared medium networks. Each network node is given a time slot where it can transmit. The number of time slots is fixed, and nodes transmit in that time slot where they are allocated. The node transmissions are separated and no collision can happen based on time division. The transmission will continue in the next time slot, unless the full frame can be transmitted in a slot. The disadvantage of this technique is that there can be wasted time slots when no data transmission happens [16].

PROFINET IO

The *PROFINET* is an open standard for Industrial Ethernet, it stands for PROcess Field NET. The PROFINET offers two possibilities: PROFINET IO and PROFITNET CBA.
In this thesis, only the PROFINET IO is taken into account.
The working mechanism of PROFINET IO is quite complex. The paragraph written below does not try to describe all PROFINET IO’s parameters and mechanism but rather give a glimpse on them [10].
In PROFINET IO the message sending is divided into three parts:

- Synchronization: no messages are sent. Only clock synchronization happens.
- RT Class 3/IRT (Isochronous Real Time): the messages are sent considering the IRT schedule table (this schedule does not use timeslots). A node only sends the message to the next node on the message’s path.
- RT Class 1: this phase uses user determined transmissions. When the receiving nodes memory is empty, only the address part of the message is read by the receiving node, and the message is immediately transmitted to the next node in the path of the message.

Each PROFINET node can be connected up to four other nodes, thus the solution requires a static node graph of some sort in order to work.

2.2.3 Wireless Network Standards

This subsection is a brief introduction about the Wireless Network Technologies. The wireless network standards are chosen considered their use in both industrial and personal environments. There are many accessible technologies for industrial wireless communication that provide high flexibility and efficient automation solutions. Compared to fixed wired networks, the main advantages of wireless network are the mobility and cost-saving installation [14].

Bluetooth

The reason why Bluetooth standard was developed, is that people needed wireless means for connecting and exchanging information between personal computing devices, such as mobile phones, laptops, printers etc.

Bluetooth technology was adapted for manufacturing applications and other industrial processes [14]. Bluetooth is a standard and protocol primarily considered when low power consumption and short-range are needed. The range of communication is related to the power consumption. The devices communicate with each other at the specified range of 1 meter with 1mW, 10 meters with 2.5mW and 100 meters with 100mW.

Bluetooth operates under Industrial, Scientific and Medical (ISM) radio bands within 2.4 GHz frequency range. The Bluetooth specification is based on frequency-hopping spread-spectrum technique and is enclosed to IEEE protocol 802.15.1.

The radios in Bluetooth hop randomly with 79 different frequencies at nearly 1,000 times per second. In terms of security, on top of the message structure, a 128-bits encryption is provided for high security. The messages are divided into small packets, sending one packet per hop. If the receiver is unable to interpret the packet, the receiver sends a message to the transmitter. The transmitter is responsible to resend the message and reinsert the message in the proper sequence.

Nonetheless, the Bluetooth Wireless Technology provides a low-cost method of wireless connectivity for digital and computing devices. However, the supported data rates are moderate and insufficient for many applications. The short-range communication is also one of the weaknesses for this wireless technology.

Wireless Local Area Network

The use of *Wireless Local Area Network (WLAN)* has been constantly increasing in various domains such as manufacturing, chemical industry, oil refinery, etc. Industrial WLAN operates under mechanisms that are defined in the related IEEE standard. Wireless LAN has many series of extension such as IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, IEEE 802.11n, etc. WLAN was developed in order to provide very high-speed data transmission including both packet and connection-oriented voice, Quality of Service, etc. [17][27]

The goals of developing new series are to provide high throughput and a continuous network connection. The most common variations and extensions of IEEE 802.11, IEEE 802.11 a/b/g, will be described here.

IEEE 802.11a supports bandwidth up to 54 Mbps and signals in a regulated frequency spectrum around 5 GHz. The Physical Layer of IEEE 802.11a is based on multiple carrier system: Orthogonal Frequency Division Multiplexing (OFDM). The high frequency causes a disadvantage to the overall range of IEEE 802.11a compare to IEEE 802.11b/g.

The IEEE 802.11a signals are absorbed very quickly by walls and other obstacles. This is caused by the smaller weave-length, which cannot reach as far as IEEE 802.11b/g. IEEE 802.11a suffers less from interference because regulated frequencies prevent interference from other devices.

IEEE 802.11b has a maximum data rate of 11 Mbps and it uses the original IEEE 802.11 Direct-Sequence Spread Spectrum (DSSS) modulation standard of Media Access Control (CSMA/CA) defined by the IEEE standard. The Physical Layer extension, added IEEE 802.11b provides a faster connectivity to WLAN operating in the 2.4 GHz. The IEEE 802.11b offers the data rates of 1 and 2 Mbps specified by original 802.11 standard. This data rates are backward compatible with the 802.11 standard at 1 and 2 Mbps. The reason for gaining instant popularity is this backward compatibility. The IEEE 802.11b uses different modulations to encode/decode data at different speed. Complementary Code Keying (CCK) is used to encode the information for 5.5 and 11 Mbps. Quaternary Phase Shift Keying (QPSK) is used at 2, 5.5 and 11 Mbps and Binary Phase Shift Keying (BPSK) at 1 Mbps. Besides, the IEEE 802.11 uses Baker Code for 1 and 2 Mbps. The change in modulation allows more information to be transmitted using the same timeframe.

IEEE 802.11g operates at 2.4 GHz, like 802.11b, but it uses the OFDM like 802.11a. The IEEE 802.11g is an extension of 802.11b; the Physical Layer is identical to IEEE 802.11b. The maximum data rate is up to 54 Mbps, excluding forward error correction. The 802.11g is fully backward compatible with 802.11b hardware. Due to being cost-effective, IEEE 802.11g enables companies that have already IEEE 802.11b devices to use them along with the IEEE 802.11g devices on the same network.

Zigbee

Zigbee defines a set of communication protocols and wireless network technologies for short distance, low-data-rate, low complexity, low-power consumption as well as low cost [19]. The Zigbee standard has adopted IEEE 802.15.4 in its Physical Layer and Medium Access Control (MAC) protocols. The MAC protocol used CSMA/CA with initial random back-off time. Therefore, Zigbee devices are compatible with the IEEE 802.15.4 standards as well. Zigbee wireless devices operate in different radio bandwidths: 868 MHz, 915 MHz and 2.4 GHz. The maximum data rate is 250 Kbps. The transmission range can vary depending on factors such as what antenna is used, in which environment, how much is the transmit power and transmission frequency. Zigbee has been used in a variety of domains, such as industrial, public, home or office environments. Zigbee was designed for low power consumption, so it is fit for embedded systems and applications where reliability and versatility is important but not wide bandwidth (high data rate) [30].

WirelessHART

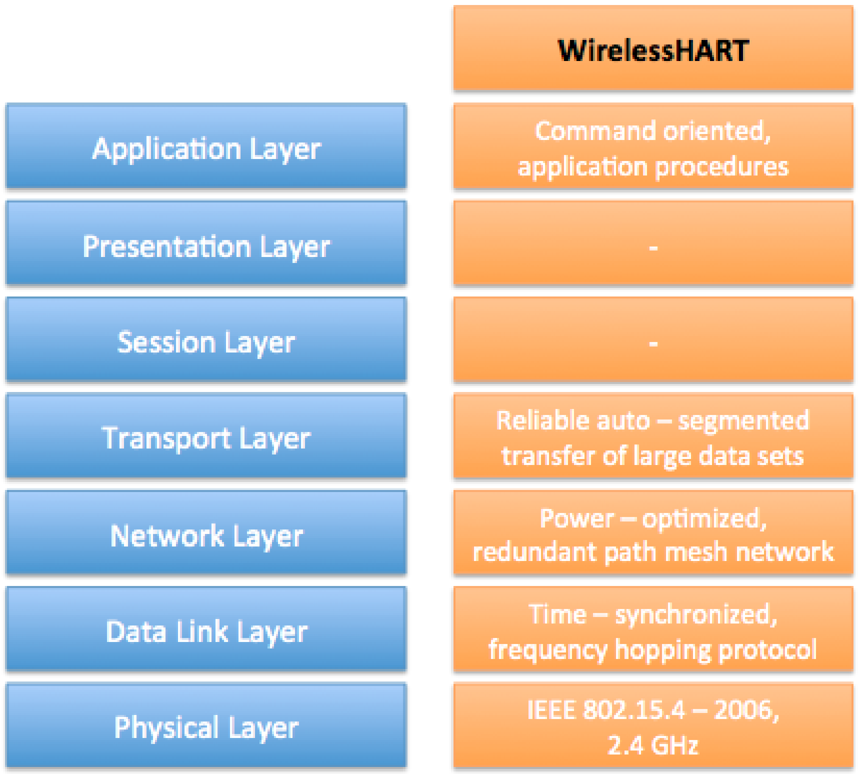

WirelessHART
Application Layer
Command oriented, application procedures
Presentation Layer
-
Session Layer
-
Transport Layer
Reliable auto – segmented transfer of large data sets
Network Layer
Power – optimized, redundant path mesh network
Data Link Layer
Time – synchronized, frequency hopping protocol
Physical Layer
IEEE 802.15.4 – 2006, 2.4 GHz

Figure 3: WirelessHART OSI model

The *WirelessHART* was created based on a set of fundamental industrial requirements such as easy to use and deploy, self-organizing, scalable, reliable, secure and should support existing HART technology [22].

WirelessHART is an extension of the wired HART protocol and its architecture is based on the OSI layer design. Referring to Figure 3, the Physical Layer is underlying IEEE 802.15.4-2006 standard, but other stack layers use new Data Link, including MAC, Transport and Application Layers. The WirelessHART aimed to be secure, ultra-low power and time-synchronized.

WirelessHART uses both TDMA and CSMA/CA techniques. The TDMA schedule uses 10 millisecond timeslots. The use of these two techniques is determined in the MAC layer of the device and depends on how the timeslot is managed. A timeslot can be managed either by dedicating one transmission or shared by several transmissions. The dedicated slots use TDMA technique in MAC and shared slots use CSMA/CA in MAC.

	IEEE 802.11b	Bluetooth	Zigbee	WirelessHART
Throughput	11 Mbps	3 Mbps (EDR, raw data rate)	20 – 250 kbps (raw data rate)	20 – 250 kbps (raw data rate)
(Variable) Packet length	34-2346 bytes	366, 1622 and 2870 bits	0 – 104 bytes	127 bytes
MAC Protocol type	CSMA/ CA	Dynamic TDMA	Slotted and unslotted	TDMA + CSMA/ CA
Frequency hopping	Yes	Yes	Not specified	Yes
Encryption	WEP (802.11i - WPA)	E0 (improved passkey)	Key exchange for AES encryption	AES – 128 block ciphers with symmetric keys
Frequency band(s)	2.4 – 2.5 GHz	2.402-2.450 GHz	868, 902 – 928, 2400 – 2483.5 MHz	2400 – 2483.5 MHz
Effective range	~ 75 m outdoor, ~ 25 m indoor	1 – 100 m	10 m nominal (1 – 100 m based on setting)	1 – 100 m
Supported number of nodes	Practical limitation due to collisions	1 master and up to 7 active slave nodes per piconet	255 devices per network	250 devices per network

Table 1: General comparison about Wireless Network Technologies

From Table 1, *Bluetooth* and *WLAN (IEEE 802.11b)* use the same frequency but different multiplexing methods. The Bluetooth specifications are based on FHSS technique underlying IEEE 802.15.1. On the other hands, WLAN operates under IEEE 802.11 standard so they are not interoperable.

Bluetooth and WLAN are different in a couple of factors: WLAN provides higher amount of throughput, distance coverage, and it consumes more power and requires high cost equipment. The similarities are that both Bluetooth and WLAN operate at lower bandwidths and considered as cable replacements. [15]

Zigbee is a global standard, made by many companies. Zigbee enables reliable, cost-effective and low-power, monitoring and control of processes. Zigbee, comparing to Bluetooth and WLAN, has a lower data rate and lower power consumption. Zigbee also supports star, tree and mesh topologies while Bluetooth and WLAN support very small size topologies such as ad-hoc and point to hub [28][36].

WirelessHART addresses some of main concerns in industrial environment towards Zigbee. WirelessHART supports frequency hopping and retransmissions in order to make the network more reliable. Also, the use of TDMA provides more robustness and power saving because the timeslots prevent the message collision; the message is received when it is scheduled. The WirelessHART is more secure than Zigbee. The security of WirelessHART is mandatory, there is no option to turn it off and it uses 128-block cipher using symmetric keys for the message authentication and encryption [22].

2.3 WirelessHART Technology

HART (Highway Addressable Remote Transducer) is a standard communication protocol for field process instrumentation, which usually communicate at 4-20 mA analog current signal. This protocol is widely used in industry for sending and receiving digital information through wires (analog signal) among field instruments and monitoring system in order to improve plant information management and cost saving [5][6].

WirelessHART is an extension to HART protocol that adds the flexibility of wireless to the existing HART standard. WirelessHART is an open communication standard that drives at the 2.4 GHz ISM (Industrial, scientific and medical) radio brand using Time Division Multiple Access (TDMA).

WirelessHART is designed to address the problem specifically focused on process industry due to the high cost of wiring for a long distance. WirelessHART also allows the channel hopping to avoid interference and reduce multi path fading effects. To support channel hopping WirelessHART allocates its frequency range to multiple channels.
In terms of simplicity, security and reliability WirelessHART standard sets requirements that any network claiming to use the standard needs to fulfill [7].

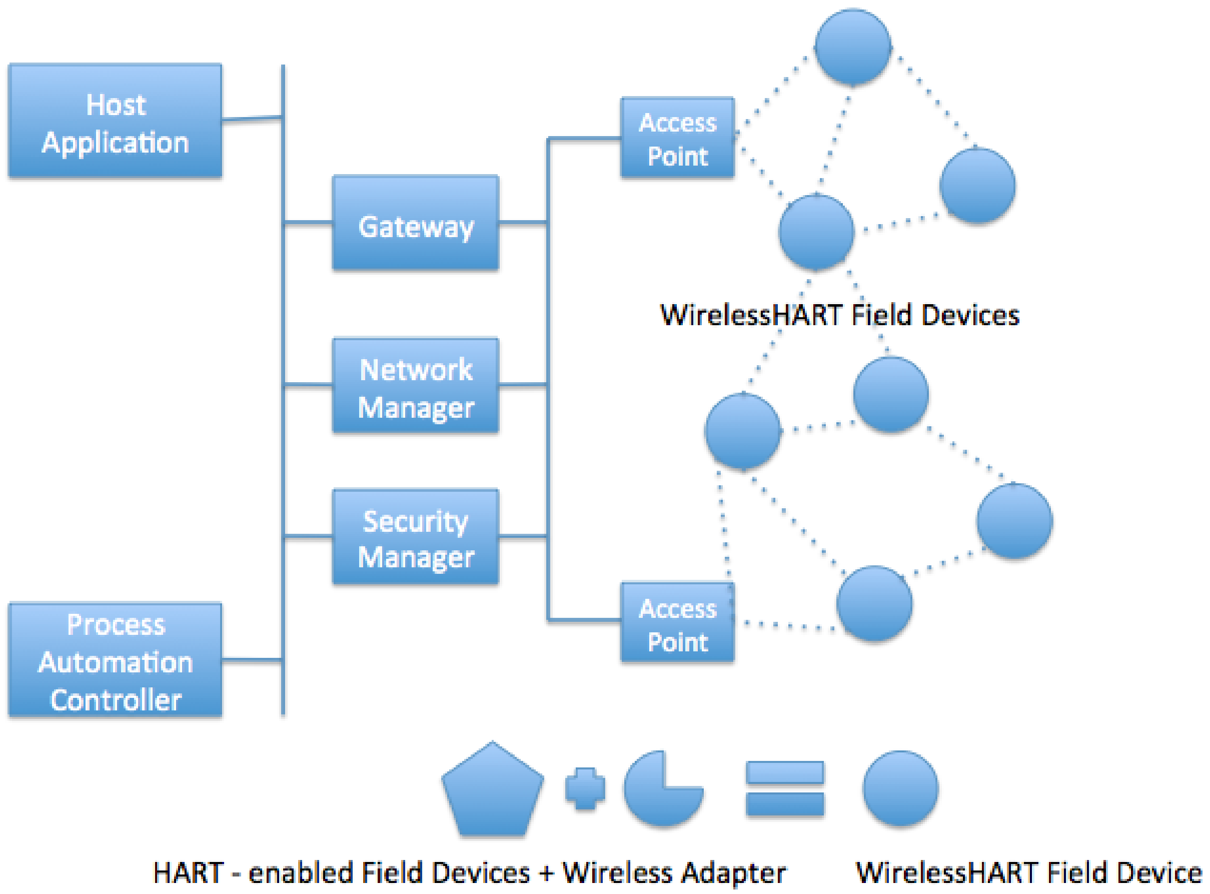
As for simplicity, WirelessHART field devices are easy to install and configure. One significant advantage of using WirelessHART is to enable the reuse of existing HART devices, commands and tools [7][8].

As for security, WirelessHART uses AES-128 (Advanced Encryption Standard). AES-128 utilizes a fixed block size of 128 bits ciphers similar to Zigbee standard.

As for reliability, WirelessHART itself provides great features that can optimize the performance of the process control in an industry, for example, TDMA (Time Division Multiple Access) in the Data Link Layer, standard radio with channel hopping, coexistence with other wireless networks, etc.

2.3.1 Basic Components of WirelessHART

The basic components of WirelessHART can be divided into three types of components [9][23].


Host Application
Gateway
Network Manager
Security Manager
Process Automation Controller
Access Point
Access Point
WirelessHART Field Devices
HART - enabled Field Devices + Wireless Adapter
WirelessHART Field Device
Figure 4: WirelessHART System Architecture

Referring to Figure 4, the **WirelessHART field devices** are used to collect the measured data from the field then forward the data to the gateway node (sensor nodes) and/or the field devices can receive data from the gateway in order to control the process (actuator nodes). The field devices are normally integrated with wireless communication, sensing and computational facilities. As mentioned above, the field device can be either an intelligent WirelessHART device or typical (wired) HART device. Any HART device can be easily upgraded to support WirelessHART by adding a “wired to wireless” adapter.

The *Controller, the Network Manager, and the Gateway* are connected to each other with wires (this network is usually referred as the “host network”). The most commonly used host networks are Modbus, Profibus and Ethernet.

The **Gateway** is the bridge that enables the Controller and the Network Manager to communicate to the WirelessHART Network. It is a device that receives sensor data from the field instruments and forwards it to the Controller for further processing, and sends control data to the actuators.
There is only one Gateway per network however one Gateway can have more than one access points. All WirelessHART nodes are registered to the network through the Gateway.

The **Network Manager** is an intelligent device that creates, manages and maintains the mesh network, each node is connected directly to every other node within their transmission range. The network manager is responsible for configuring and monitoring the network, configuring the schedule (TDMA) and maintaining the routing tables. The slots in TDMA schedule are allocated hop by hop based. Also, the frequencies are allocated in those slots.

2.3.2 Medium Access Control

MAC protocol is a sub-layer of Data Link Layer of OSI model. The main responsibility of MAC protocol is to arrange the packet transmission among multiple stations that share the same channel.

The Design of an efficient and capable MAC protocol is crucial in wireless networks [29]. The MAC protocol in WirelessHART is dealing with the following responsibilities:

- Providing Time Synchronization Approach
- Requesting Identification of devices that need to access the medium
- Acting as interface to transmit messages to Network Layer
- Listen to packets that are transmitted by the neighbors

Time Division Multiple Access

The *TDMA (Time Division Multiple Access)* uses schedules to allow several devices to communicate over the network. The schedule contains different time slots to avoid the collision problem.

The major challenges of TDMA are the *time synchronization and clock drift.* In WirelessHART, the network cycle (schedule) consists of a number of superframes. All of these superframes are created by the Network Manager and stored by each field device. The field devices send notification to the Network Manager about the time slots when they transmit or receive. After that, the field devices must synchronize their clocks to permit the slot communication with neighbored devices [26].

A group of fixed length timeslots (10 milliseconds), accumulates the superframe. A field device must be scheduled in at least one Timeslot for data transmission in a network cycle. The slots in TDMA schedule are allocated point-to-point communication (hopping) [25].

The frequency hopping is combined with TDMA in order to increase the reliability of the network. The frequency hopping is used to avoid interference and reduce multi path fading effects. To support frequency hopping, WirelessHART allocates its frequency range to multiple channels.

The frequency range of WirelessHART is shared between 16 channels. In one timeslot communication between two nodes can happen on any free channels. This allows multiple transmissions happening in the same time slot between on different channels used by different nodes.

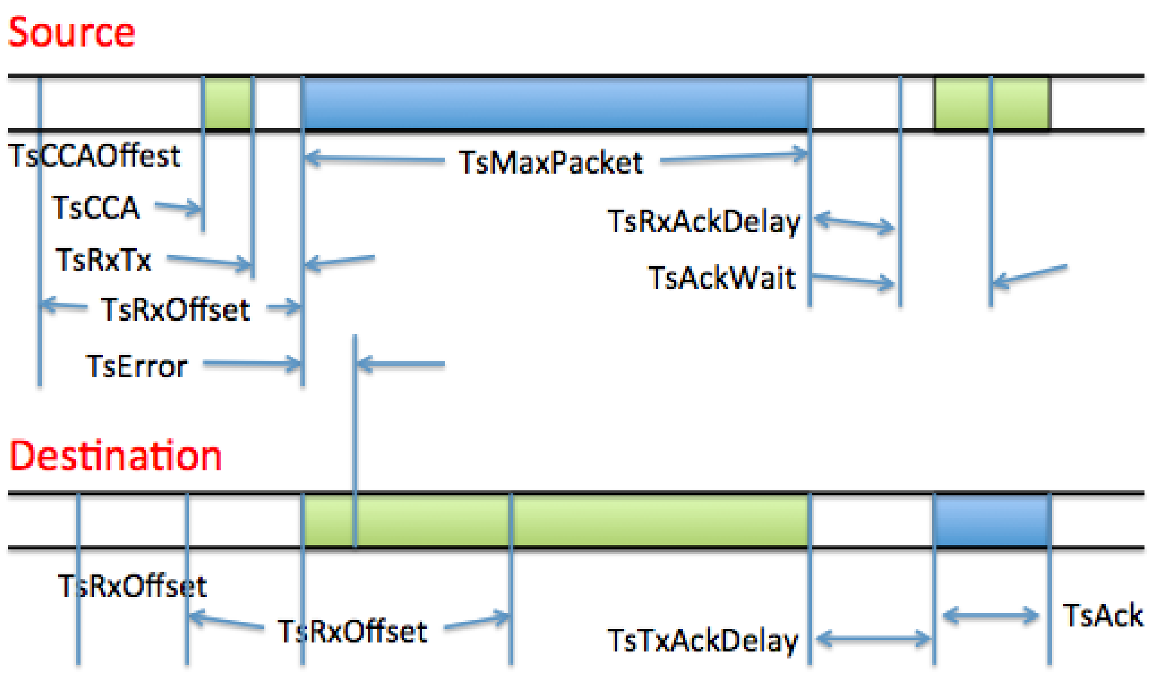


Figure 5: WirelessHART Slot Timing

Referring to Figure 5, in a timeslot, the transmission of the source device starts at a certain point, not right in the beginning of the Timeslot. This short delay allows the source device and destination device to set up their frequency channel and allows the receiver to start listening on the specified channel. Since, there is a delay on clocks, the receiver must start to listen before the ideal transmission starts and continue listening after that ideal time. After the transmission is complete, the destination device indicates by sending an acknowledgement (ACK) to the source device to reporting success, error or overhead [26].

The transmission in Data Link Layer uses packets to send/receive data. These packets are called DLPDU (Data Link Protocol Data Unit Packet).

Data Link Packet (DLP)

This section describes the specific format of the Data-Link packet as presented in Figure 6. The total packet length of each DLPDU (Data Link Protocol Data Unit) is 127 bytes [24]. Each DLPDU contains the following fields:

A single byte set to 0x41

A 1-byte address specifies

The 1-byte Sequence Number

The 2 byte Network ID

Destination and Source Addresses either of which can be 2 or 8-bytes long

A 1-byte DLPDU Specifies

The DLL payload

A 4-byte keyed Message Integrity Code (MIC)

A 2-byte ITU-T CRC16

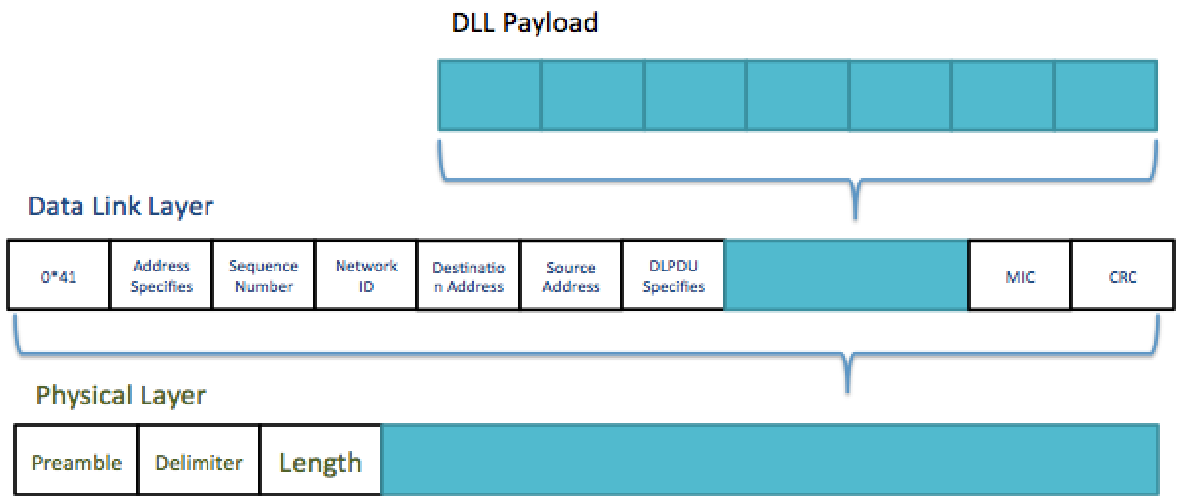


Figure 6: The DLPDU packet structure

To allow MAC the transmission of packets, it has to perform a number of tasks. As shown in Figure 7, the WirelessHART MAC protocol contains six major components: Interfaces, Timer, Communication Tables, Link Scheduler, Message Handling Module and State Machine. [24]

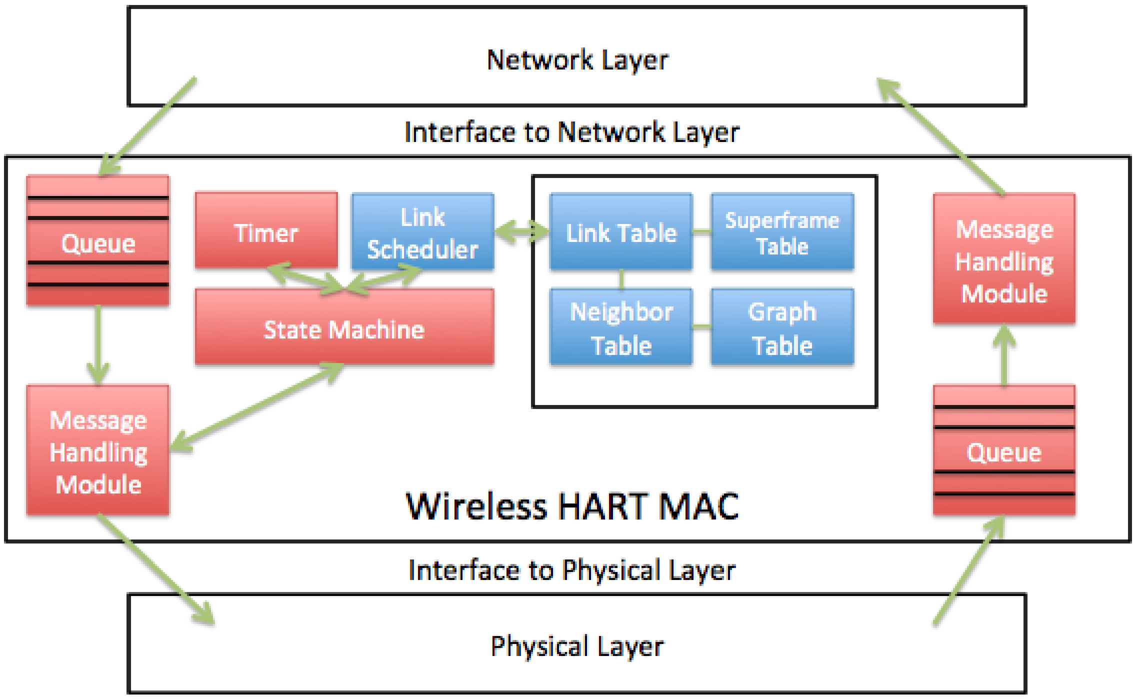


Figure 7: WirelessHART MAC architecture

This thesis only deals with two of the components: *communication tables and link scheduler.*

- Communication tables (table of neighbors, superframes, links, and connection graphs) are responsible for set up the communication between device and its neighbors.
- The Link Scheduler's responsibility is to determine the next time slot to be allocated based on the communication schedule in the superframe table and link table.

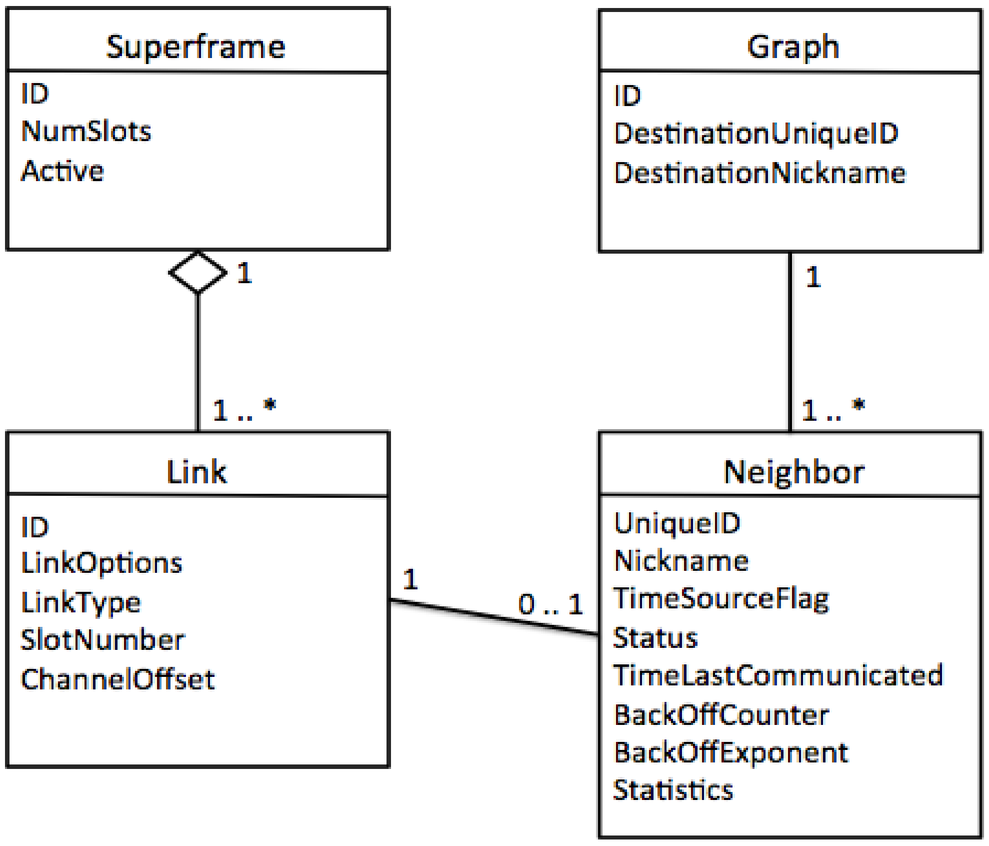


Figure 8: The communication tables

<u>Communication Tables</u>

Referring to Figure 8, each device maintains a number of tables in Data Link Layer. These tables manage the communication carried out by the device and collect information to create statics about the communication. There is four table activities: Superframe table, Link table, Neighbor table and Graph table [24][25].

The responsibility of the **Superframe table** is to provide solid base for communication between a device and its neighbors. The superframe table consists of three columns: SuperframeID, NumSlots and ActiveFlag.
As mentioned above (section 2.3.1), the Network Manager is in charge to generate and provide the superframes in the network.

The purpose of **Link table** is to arrange the communication between the device and its neighbor. There can be more than one link within a superframe. A link specifies the communication with particular neighbor or broadcast group of neighbors.
The Link table consists of five columns: LinkID, LinkOptions, LinkType, SlotNumber, ChannelOffset.

The *LinkID* is the unique identification for the link, it is provided by the Network Manager within a superframe and all entries in the table. The *LinkOptions* determines the meaning of the Link; it can be either transmitter link (TX) or receiver link (RX). The *LinkType* indicates the type of link (normal, broadcast, join or discovery link). The *SlotNumber* is a foreign key that provides the connection between the superframe table and the Link table. The SlotNumber represents which timeslot within the superframe is going to be used for communication with neighbor.
The *ChannelOffset* represents which frequency will be used for transmission.

Neighbor table contains the list of nodes that the device can reach. Since each link has a reference to one neighbor, the neighbor table contains the statics and properties of itself.
The Neighbor table consists of eight columns: UniqueID, Nickname, TimeSourceFlag, Status, TimeLastCommunicated, BackOffCounter, BackOffExponent and Statistics.

The Neighbour table has one unique key (*UniqueID*) which is used to connect with the Link table.
The *Nickname* is a foreign key that connects to the Graph table.
TimeScourceFlag determines the device should take time synchronization from the neighbor or not. *Status* determines the status information relating to this neighbor. *TimeLastCommunicated* determines the last time communicated with this neighbor. *BackOffCounter* decides the value of standby countdown for shared link. *BackOffExponent* decides the number of back-off exponent for shared link. *Statistics* contains the statistics communicated with this neighbor.

Graph table is used by the Network Layer and stores the routing information from source and destination. There are three columns in Graph table: GraphID, DestinationUniqueID and DestinationNickname.

The *Graph table* is maintained by the Network Manager, the information is added on Network Layer Protocol Data Unit packet (NPDU).

The MAC protocol can use *GraphID* to point the DLPDU packet towards its final destination. The Graph table has two foreign keys: DestinationNickname and GraphID. The *DestinationNickname* is used to connect with the Neighbor table. Another foreign key is GraphID as output from the Graph table to NPDU packet.

Link Scheduler

Link scheduler determines the next slot, which will be used (receiving or transmitting slot) based on the communication schedule in the Superframe table and Link table.

In order to transmit a packet, the Link scheduler evaluates the packet that is coming from Network Layer to the MAC protocol. MAC protocol determines the Absolute Slot Number (ASN), which will be the Timeslot used to send the packet.

The received links contained in a superframe should be checked to determine the first Absolute Slot Number (ASN) that can be used to receive a packet. [24][25]

2.4 Development Tools and Simulation Environment

2.4.1 MATLAB

The term MATLAB (Matrix Laboratory) covers a programming language and computing environment for specific purpose numerical computing. Both the programming language and the computing environment are developed by MathWorks [31]. MATLAB computing environment provides a large set of computations for different instances in mathematics such as matrix manipulations, statistics, numerical analysis, control theory, etc.

The computing environment also allows design of user interfaces and allows interaction with code written in other programming languages.
MATLAB is used by researchers in many different disciplines starting from engineering, science and economics.

Moreover, MATLAB computing environment also provides an additional package “Simulink” to create graphical multi-domain simulations. Simulink package can be used for sub tool modeling, simulating and analyzing Model-Based Design of different types of systems.

For this thesis, MATLAB 2011b was used. The tool was provided by ABB.

2.4.2 Simulink

Simulink is a commercial tool for modeling, simulating and analyzing dynamic systems of various domains. It is an additional package of MATLAB and it is usually included in MATLAB [32].
Simulink was used to create the static model of the wireless and wired networks system. To represent and build various modules in the system different types of graphical blocks were used. Simulink allows the users the possibility to create custom made blocks save them in “libraries” (model files) and use them in a number of projects.
Developers can customize and configure the Simulink blocks through their parameters or programming in a MATLAB script file.

Simulink is a tool for modeling embedded and control systems, which need more dynamic and complexity of coding for each block therefore it is a great tool for modeling “custom made” system and it is essential in any engineering disciplines for simulating new inventions before real life tests or observing behavior of complex systems in any scientific field.

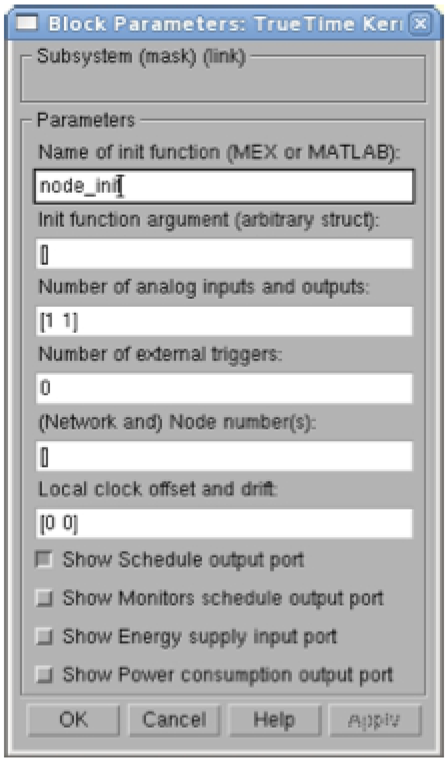
2.4.3 TrueTime

TrueTime library is a library extension of Simulink developed at Lund University. The blocks are modifiable, discrete, MATLAB Simulink functions written in C++.
TrueTime 2.0 library was used during the implementation phase of the project. This version of TrueTime allows designing networked control systems simulation, by using real-time kernels blocks, network transmission blocks (wired and wireless networks). All information here was gathered from the TrueTime Manual [10][35]. The parameters, which are not described in the TrueTime manual, were studied through tests.

The original block library consists of the following blocks:

- **TrueTime Kernel Block (programmable):** simulates a node in the network. This node simulation executes user defined tasks.
- **TrueTime Network Block:** acts as a communication medium and simulates the behavior of a wired network by allowing nodes to transmit packets to each other through this block. The internal behavior of the block is the following: the message is taken as input from the input port that relates to the sending node, then the message is pushed to the output port which relates to the receiving node.
- **TrueTime Wireless Network Block:** simulates the behavior of a wireless network by allowing nodes to communicate with each other through this block.
- **TrueTime Ultrasound Network Block:** this block simulates networks that use ultrasound signals for communication.
- **TrueTime Send Block:** pre-configured node block acts as a sender node on the network.
- **TrueTime Receive Block:** pre-configured node block acts as a receiver node on the network.
- **TrueTime Battery Block:** this block can be used to simulate battery.

In this thesis, only the following nodes were used: TrueTime Kernel Block, TrueTime Network Block, and TrueTime Wireless Network Block. Below their parameters give an insight of how they are used.



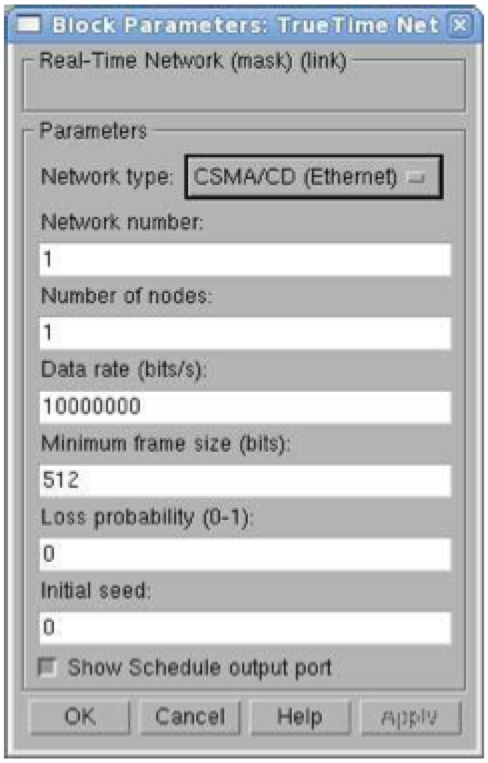
Name of init function (MEX or MATLAB):
node_init
Init function argument (arbitrary struct):
[]
Number of analog inputs and outputs:
[1 1]
Number of external triggers:
0
(Network and) Node number(s):
[]
Local clock offset and drift:
[0 0]
☑ Show Schedule output port
☐ Show Monitors schedule output port
☐ Show Energy supply input port
☐ Show Power consumption output port

Figure 9: TrueTime Kernel Block Parameters.

TrueTime Kernel Block has the following configuration parameters that can be set through its Simulink Mask interface in Figure 9.

- **Name of init function (MEX or MATLAB):** this property refers to the MATLAB script which contains the initialization code.
- **Init function argument (arbitrary struct):** the input of the initialization function.
- **Number of analog inputs and outputs:** determines the amount of external analog inputs and outputs what the block possesses. The format of the input is an array with two values where the first value is the number of inputs while the second value is the number of outputs.
- **Number of external triggers:** these ports can be used to activate the block.

- **(Network and) Node number(s):** the input is an array where the first element determines which network does the block belong to the second element determines the ID of the node on the corresponding network.
- **Local clock offset and drift:** this is input again takes an array where the first element defines a constant delay compared to the simulation time, while the second element defines a percentage of how much the time is "faster" for the block compared to the simulation time.
- **Show Schedule Output port:** allows the user to visualize schedule.
- **Show Energy Supply Input port:** this configuration parameter was not used.
- **Show Power Consumption Output port:** this configuration parameter was unused.


Block Parameters: TrueTime Net

Real-Time Network (mask) (link)

Parameters

Network type: CSMA/CD (Ethernet)

Network number: 1

Number of nodes: 1

Data rate (bits/s): 10000000

Minimum frame size (bits): 512

Loss probability (0-1): 0

Initial seed: 0

Show Schedule output port

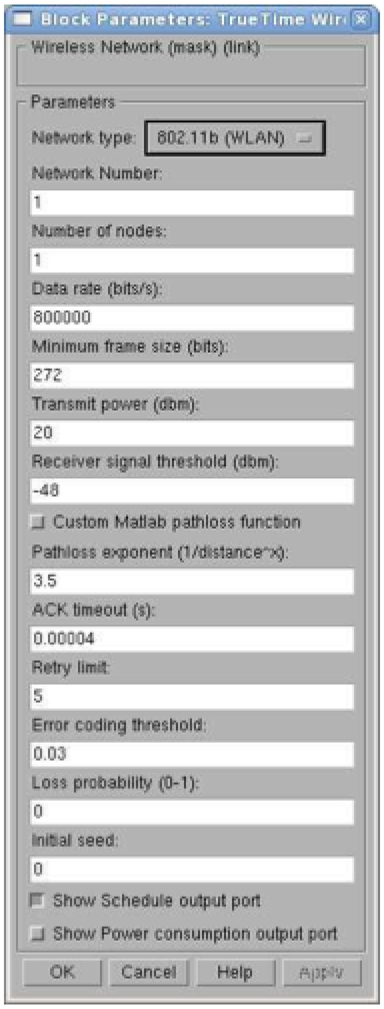
Figure 10: TrueTime Network Block Parameters.

The TrueTime Network Block has the following parameters that can be set in its visual interface in Figure 10.

- **Network type:** determines the network technology simulated by the block. The following network types are supported: CSMA/CD, CSMA/AMP, Round Robin, FDMA, TDMA, Switched Ethernet. Different types of networks have different configuration parameters. In here only the general configuration parameters are described.
- **Network number:** determines the ID of the network.
- **Number of nodes:** determines the number of nodes which belong to the network represented by this block.
- **Data rate (bits/s):** determines the speed of the network.
- **Minimum frame size (bits):** determines how long the smallest possible message frames are.
- **Loss probability (0-1):** determines the chance of a message not arriving to the receiving node.
- **Initial seed:** The numbers of variables which can put the network block in a random state.
- **Show Schedule Output port:** allows the user to visualize schedule.

TrueTime Wireless Network Block has the following parameters that can be set in its visual interface in Figure 11.

- **Network type:** determines the network technology simulated by the block. The following network types are supported: 802.11b (WLAN), 802.15.4 (Zigbee), NCM_WIRELESS
- **Network number:** determines the ID of the network.
- **Number of nodes:** determines the number of nodes which belong to the network represented by this block.
- **Data rate (bits/s):** determines the speed of the network.
- **Minimum frame size (bits):** determines how long the smallest possible message frames are.
- **Transmit power (dbm):** determines the range of the network.


Block Parameters: TrueTime Wir
Wireless Network (mask) (link)
Parameters

Network type: 802.11b (WLAN)

Network Number:
1

Number of nodes:
1

Data rate (bits/s):
800000

Minimum frame size (bits):
272

Transmit power (dbm):
20

Receiver signal threshold (dbm):
-48

☐ Custom Matlab pathloss function

Pathloss exponent (1/distance^x):
3.5

ACK timeout (s):
0.00004

Retry limit:
5

Error coding threshold:
0.03

Loss probability (0-1):
0

Initial seed:
0

☐ Show Schedule output port

☐ Show Power consumption output port

Figure 11: TrueTime Wireless Network Block Parameters.

- **Receiver signal threshold (dbm):** minimum signal strength that the receiver can detect.
- **Pathloss function:** user defined path loss function.
- **Pathloss exponent (1/distance^x):** determines how fast the signal gets weaker in the transmission environment.
- **ACK timeout (s):** determines how long the sending node waits for the acknowledgment of the receiver, before it considers the message lost.
- **Retry limit:** the maximum number of retransmissions allowed.
- **Error coding threshold:** determines the limit of errors when decoding signals.

- **Loss probability (0-1):** determines the chance of a message not arriving to the receiving node.
- **Initial seed:** determines the pattern of randomization that is used to put the network block in a “random” state.
- **Show Schedule Output port:** allows the user to visualize schedule.
- **Show Power Consumption Output port:** allows the user to visualize power consumption.

One disadvantage is that the separate blocks cannot truly be tested by themselves. In case of a complex system, looking for problems in separate blocks can cause some delay.

It is necessary to initialize kernel blocks, network blocks, to create tasks, interrupt handlers, timers, events, monitors, etc. before executing the model. The initialization code and the code that is executed during simulation must be written in MATLAB or C++ programming language.

Another disadvantage is the absence of resources such as supporting documents and examples. There is a manual, but it is unclear, in some places outdated, and unfinished.

3. ABB’s WirelessHART Tool

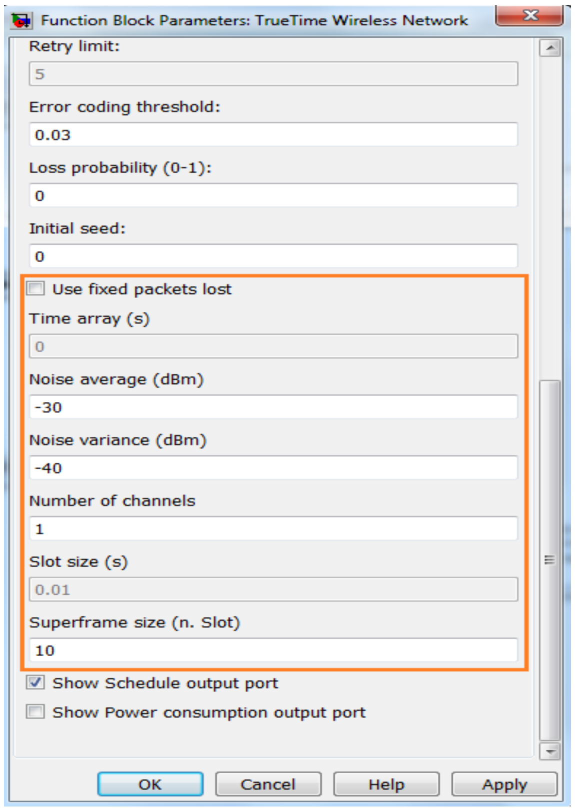
The ABB’s WirelessHART Tool was developed in order to ease and speed up the process of creating simulations. The first version of WirelessHART Tool allowed the users to generate models to simulate a single WirelessHART control network, add and remove nodes to the network, set up a simple schedule for communication and set up a single PID controller to control all the processes

Before the development of the WirelessHART Tool began, there had been a major project to build some static WirelessHART simulations in MATLAB and Simulink and add WirelessHART support to TrueTime.

3.1 TrueTime Upgrades

This section describes how the WirelessHART has been implemented in TrueTime by a group of ABB’s researchers. Since this thesis was not dealing with changing or extending TrueTime, the TrueTime library was only explored briefly. However there are a couple of upgrades that need to be mentioned.
The WirelessHART MAC protocol has been developed with C++ functions together with MATLAB *MEX-interfaces*. The MEX-interface is an adapter between C++ and MATLAB. The MEX interfaces of the Blocks are connected to the Mask Interface of the Blocks. [33] All the information which is required to simulate a WirelessHART network can be entered on the mask, but not all data is used by functions, thus not all WirelessHART features work correctly.

3.1.1 TrueTime Network Block

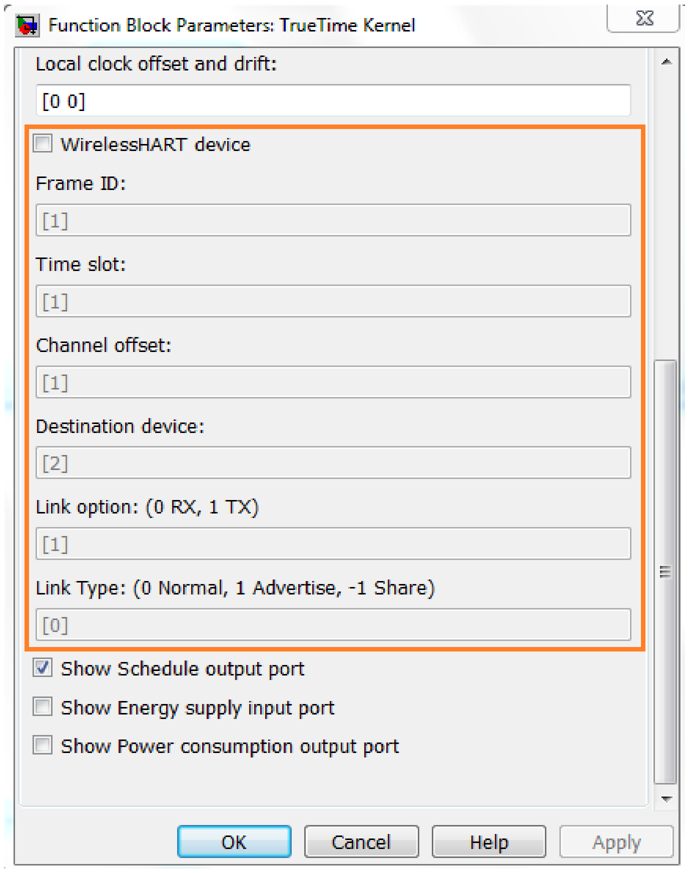


Retry limit:
5
Error coding threshold:
0.03
Loss probability (0-1):
0
Initial seed:
0
[ ] Use fixed packets lost
Time array (s)
0
Noise average (dBm)
-30
Noise variance (dBm)
-40
Number of channels
1
Slot size (s)
0.01
Superframe size (n. Slot)
10
[✓] Show Schedule output port
[ ] Show Power consumption output port

Figure 12: New fields in the TrueTime Wireless Network Block Mask, supported Multi-Channel

- **Fixed Packet Loss, Time Array(s):** when the box is ticked user can enter (in the Time Array) the beginning and the end of one or more time interval(s), during which all the packets sent on that network are lost.
- **Noise Average (dBm):** determines the average disturbance on the network.
- **Noise Variance (dBm):** shows how much the disturbance can differ from the average.
- **Number of Channels:** defines how many channels can be used for communication on the network.
- **Slot Size (s):** determines the length of one Time Slot (0.01 s for WirelessHART).
- **Superframe Size (n. Slot):** determines the number of slots contained in a superframe.

3.1.2 TrueTime Kernel Block


Function Block Parameters: TrueTime Kernel

Local clock offset and drift:
[0 0]

- [ ] WirelessHART device

Frame ID:
[1]

Time slot:
[1]

Channel offset:
[1]

Destination device:
[2]

Link option: (0 RX, 1 TX)
[1]

Link Type: (0 Normal, 1 Advertise, -1 Share)
[0]

- [✓] Show Schedule output port
- [ ] Show Energy supply input port
- [ ] Show Power consumption output port

Figure 13: New fields in the TrueTime Kernel Block Mask, supported Multi-Channel

- **WirelessHART Device check box:** determines whether the WirelessHART parameters of the node are available or not.
- **Frame ID:** determines which message is sent/received on which Superframe.
- **Time Slot:** determines which Timeslots are used for sending/receiving messages.
- **Channel Offset:** determines which channels are used for sending/receiving the messages.
- **Destination Device:** determines the origin/recipient nodes of the messages.
- **Link Option:** determines whether the message is received by the node or sent from it.

- **Link Type:** determines whether a link is normal, shared or advertised.

<u>Implementation of Device Communication Tables</u>

As mentioned in the background (section 2.3.2), the TrueTime has been modified based on the WirelessHART MAC protocol theory. The Devices Communication Tables together with Mask interface of TrueTime Kernel block have been implemented in order to support all communications [25].

FrameID	TimeSlot	ChOffset	DevAddress	LinkOpt	LinkType
{1… Nbrframes}	{1…NbrSlots}	{1…Nbrch}	{1…NbrNodes}	0 = RX 1 = TX	0 = normal 1 = advertisement -1 = shared

Table 2: Logical Device Tables in Upgraded TrueTime.

The information of the device table contains six columns: FrameID, TimeSlot, ChOffset, DevAddress, LinkOpt and LinkType.

- **FrameID:** indicates the unique identification number of a Superframe. Each WirelessHART device supports multiple Superframes.
- **TimeSlot:** contains a list of slots where the device needs to communicate.
- **Channel Offset (ChOffset):** determines in which channel that the device use to communicate in particular Timeslot.
- **DevAddress**: indicates the destination device that will receive the transmission.
- **Link Option (LinkOpt):** determines two types of communication: RX (0) and TX (1). The zero (0) value means that the device must receive, while the one (1) value means that the device must transmit.
- **LinkType:** indicates the link types of slot, the slot can be either reserved, shared slot or dedicated.

Implementation of Time Synchronization

In order to achieve and fulfill an efficient TDMA communication technique, the time synchronization of clocks between devices in the network is critical. This is because each device has their local clock. This allows during the synchronization of two stations that each one should be able to estimate the local time of each other. [25]

When TrueTime was upgraded, the above described problem was taken into account and the MAC protocol was modified based on ASN (Actual Slot Number) technique to find the actual Timeslot for sending and receiving messages.

In the implementation, the device reads the actual simulation time from the MATLAB environment, and then the actual simulation time value is used to compute the actual Timeslot using the following formula (3.1.2):

$$ActualSlotNumber = \left(\frac{ActualSimTime + exextime}{SlotSize} \;\%\; SuperframeSize\right) + 1 \qquad (3.1.2)$$

where the exectime is the execution time of the active device. The Slotsize is fixed to 10 ms in WirelessHART. The SuperframeSize is the number of slots contained in a Superframe.

3.2 Application Structure

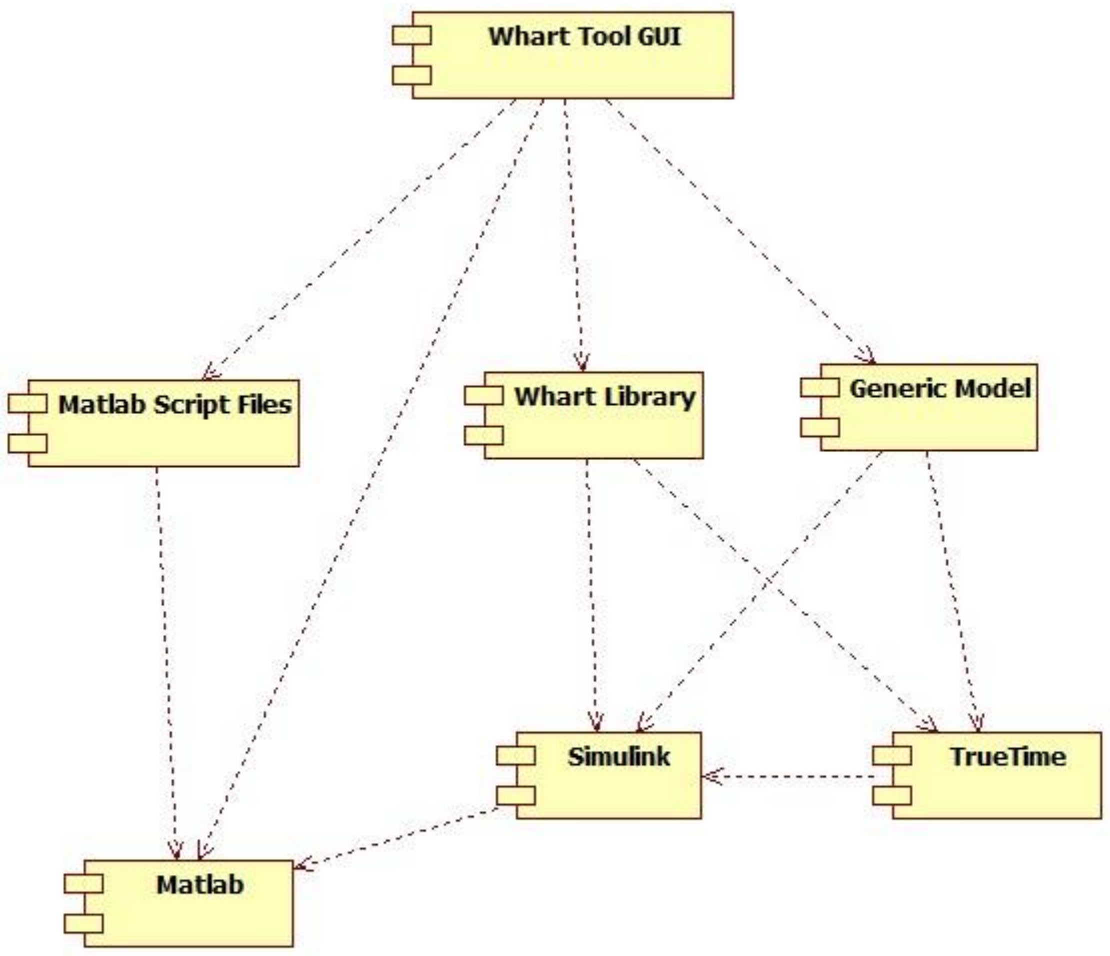


Figure 14: Application Structure Design

Referring to Figure 14, the structure of the application does not follow any conventional software engineering structure or architecture. It was decided that in order to show the application structure the uses structure must be displayed.

The uses structure uses the “requires the correct presence of” relation between the elements of the structure, thus shows which elements need which other elements in order to function as expected. The arrows represent this relation on the diagram [20][21].

The diagram uses UML (Unified Modeling Language) notation.

7 main elements build up the application structure. These elements are defined through code inspection, research and testing.

GUI: The purpose of the GUI is to allow users to set up different simulation scenarios fast and without getting lost in the details. The UI creates 17 global variables for communication between different functions. These global variables store data about the transmission schedule and the nodes in it.

Generic Model: is a saved Simulink model. The Generic Model is used as template when generating the simulation model. Generic Model contains TrueTime blocks such as TrueTime Kernel Blocks, TrueTime Wireless Block, etc.
An advantage of generic model is to allow changing basic structure quickly without the need of coding.

WHART Library (whart_lib): is a saved Simulink Model that stores an important TrueTime Simulink blocks that are used to build the simulation model. These blocks are: Actuator block, Sensor block, the Position block and Intermediate block. When generating the simulation model the WHART_lib is opened and the required nodes are copied into the simulation model.

Simulink: is a MATLAB extension and library. It is used to take general purpose blocks into the model and is responsible running the general simulation mechanism.

<u>Structure Organization</u>

Both the Generic Model and the WHART_lib were constructed from blocks that can be found in Simulink as well as blocks from the TrueTime library. The Sensor, Actuator, Intermediate, Controller and Gateway Blocks are special from the viewpoint that they are programmable using MATLAB Script Files (this connection is not shown on the diagram because it is dynamic). These Script Files implement functions in order to determine the runtime behavior of the blocks.

During runtime, the Script Files are using the global variables created by the UI in order to determine what behavior they should simulate (connection is not shown because it is dynamic).
The TrueTime library uses some building blocks from the Simulink library as well as, so called S-Function (System-function) files. The S-Function files are compiled files that are included in the library itself that is why the authors choose not to display them. [33]

3.3 User Interface & Functionality

WirelessHART GUI (Graphical User Interface) was created using GUIDE (GUI Development Environment of MATLAB). GUIDE is a tool for designing and programming GUIs.

GUI components are building blocks of the GUI. Each GUI component has its own callback. The “callback” is a function that developer can implement and connect to the specific GUI component. The callback controls the GUI or component behavior by performing a task or action.
The callback is activated by an event of its component. An event is a previously defined user interaction with the GUI component.
There are several callbacks provided by GUIDE, for example ButtonDownFcn, KeyPressFcn, Callback etc. [12]

For instance, the Delete Button is the GUI component. The Delete button uses “Callback” as its callbacks property type. The “Callback” is one kind of a callback property. In this case, the Delete Callback will be activated when the user pushes the Delete Button. Whenever the Delete Callback is activated, the function code contained by the delete callback will be executed.

As shown in Figure 15 and 16, the components and their functions were grouped on the GUI considering their purpose. For grouping the components on the GUI panels were used [11][13].

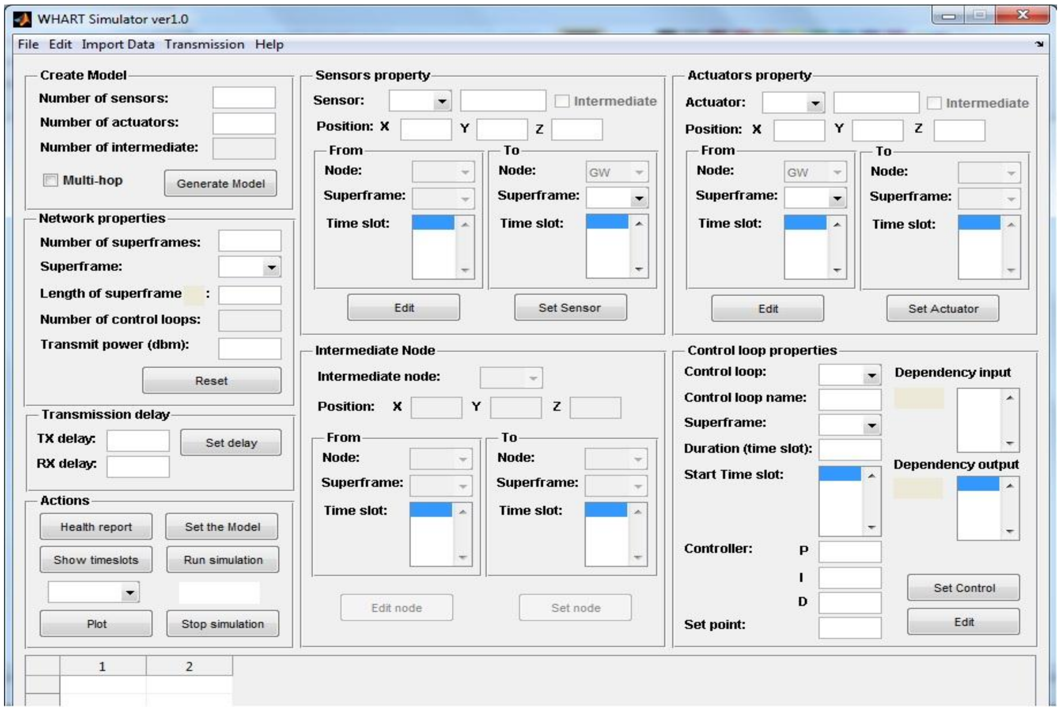


Figure 15: WirelessHART Simulation ver1.0 interface

The GUI is used to open/ call the generic model and WHART_lib when the user gives the input to generate the model.

After the Simulink model has been generated, the user is able to configure the necessary parameters in the global variables and then set them in the model.

3.3.1 Create Model

This group of components deals with specifying the parameters of the simulation model, which need to be specified before generating the model. The create model panel has three fields and one check box that the user can fill in. The implementation differentiates between two types of networks single hop and multi hop. In any case, the user needs to specify the number of sensors and number of actuators. The number of sensors and the number of actuators are limited to 100 (100 sensors and 100 actuators).

Until the model is generated, all other functionalities of the UI are restricted. The Intermediate Panel, the Actuator Property Panel’s components which are responsible for scheduling data transmission and the Sensor Property Panel’s components which are responsible for scheduling data receiving, are only enabled if the user selects the multi hop communication option. The WirelessHART Simulator allows the sensor and actuator nodes to act as intermediate node when the multi-hop communication is enabled.

There is a difference between how the UI counts the nodes and how the Simulation model numbers them.
In Simulation model all the node IDs use the same numbering, while the UI splits them by functionality to Sensor nodes, Actuator Nodes, Intermediate Nodes, Gateway and Controller. The solution to the problem is presented here:
The Sensor nodes from the UI come first, the Actuator nodes come second, The Intermediate nodes third, then the Gateway and finally the Controller, when the numbering of nodes in Simulation model. For example, in case of: there are 3 Sensors, 2 Actuators, 1 Intermediate. In Simulation model the Sensor nodes number are the nodes from 1-3, the Actuator nodes are 4 and 5, Intermediate Node is 6, Gateway is 7 and Controller is 8. [11]

3.3.2 Network Property

After generating the model, the user can proceed to the Network Properties Panel. On the Network Property Panel the user can assign the network properties such as number of superframes, length of superframes, number of control loops and transmit power of the network.
The *Superframe Number property* determines how many superframes are in use on the WirelessHART network.
The *size of a superframe* must be multiples or common divisors of each other. The reason for this is a common real-time scheduling problem that they must be compatible on a longer timescale.

The *Number of Control Loop field* determines how many control loops are run by the Controller.

The *Transmit Power* is used to determine the strength of the transmissions signal. The transmit power will be defined at 10 dbm as a default if not specified.

The *Reset button* in Network Property panel is used to clear all options on the GUI, and allows the user to generate a new model.

This network property will be enabled only after the model is generated, generated_flag global variable is used to check whether the model is generated or not.

The Superframe is a global variable (array in this case), with the length of 1 which is changed accordingly to Length of Superframe field. If the value in the Length of Superframe field is incorrect, the user is not allowed to set the Control Loop number.

3.3.3 Sensor Property

Sensor Node: primarily these nodes only send data. When Multi Hop is enabled, the sensor nodes can act as intermediate nodes thus send and receive data.

Through the *Sensor Property panel* the user can determine in when a specific sensor sends data and in which superframe. First, the user must select the desired sensor from the drop-down list. The user can also assign a specific name for the signal of each sensor. The *X-Y-Z position* is used to set the position of the node in a 3D space. This 3D coordinates are used to compute the area where the signal can be received from that node.

The “*Set Sensor*” button is used to store the values of the sensor in the virtual tables of the UI and the sensor also appears on the Schedule Table of the UI.

The “*Edit button*” removes all information of the sensor from the virtual tables of the UI and also deletes it from the Schedule Table of the UI from the scheduler table and clear the sensor table.

In case of single hop communication all sensors send data directly to the gateway, thus only the gateway node will visible on “To” drop-down list.

In case of multi-hop communication the “To“ drop-down list the receiving node can be selected by the user.

3.3.4 Actuator Property

Actuator Node: primarily these nodes only receive data. When Multi Hop is enabled, the actuator nodes can act as intermediate nodes thus send and receive data.

The *Actuator Property panel* is almost identical to the Sensor Property panel. The only difference is that when the user does not use multi hop communication, all of the actuators receive the data from gateway, thus the “GW” node will be the only option on “*From*” panel.

3.3.5 Intermediate Node

Intermediate Node: these nodes can only be used when Multi Hop is enabled. They can both send and receive data.

The *Intermediate Node panel* is only enabled if the multi-hop option was checked in the before generating the model.

The GUI components included in this panel are identical to those in the “Sensor Property” and “Actuator Property” panels as well as their purpose.

3.3.6 Control Loop Properties

In the control loop panel, the user is able to select the desired control loop and set various properties for it.

The name of the control loop can be specified in a *control loop name field.* The user must set the *timeslot* and the *superframe* of control loop.

The *Duration* determines how much time (measured in timeslot) the process will require for completing the calculations. The default value of duration is 1 timeslot.

Each control loop has separate *PID control values* and a *Setpoint* that the user can assign. The default PID control values are P=10, I=0, D=0 respectively. The default setpoint is 1. The *dependency input and output* show which sensor and actuator is related to the currently selected control loop. The user can assign more than one sensor and/or actuator for the selected however only the most recent ones are displayed.

The control loop properties will be stored in the virtual tables and displayed on the WirelessHART Tool UI after the “*Set Control*” button was pressed.
The “*Edit*” button clears the selected control loop from the virtual tables as well as from the UI.

3.3.7 Transmission Delay

WirelessHART tool simulator can simulate the transmission delay for the host network. The Transmission Delay panel provides two types of delay: TX delay (Transmit), RX delay (Receive). The default value of both TX and RX delay is zero and the maximum value of each of them cannot exceed 0.005 second.
TX (Transmission Delay) functionality is implemented to provide a time delay when transmitting the data from the Controller to Gateway. On the other side of the Controller, *RX (Receive Delay)* functionality is implemented to provide a time delay when receiving the data from Gateway to Controller.

3.3.8 Actions

The actions panel contains five different functionalities: Health report, Set the model, Show timeslots, Run/ Stop Simulation and Plot.

After all nodes (sensor, actuator, intermediate) properties and control loop property are set, the user can verify and check the schedule of the whole network Using the “*Health Report*” button. The Health report provides the several errors and warnings if something is incorrect in the schedule setup.
The simulation cannot be started if there is the error or warning in the Health report.
In case the settings are correct, the displayed message says “Scheduling successful”.

The “*Show Timeslots*” button is built in order to refresh the Schedule Table on the UI.

The “*Set the Model*” button is used to copy all node parameters and values from the virtual tables into the Simulink Model. The model cannot set those values into the model if there are any warnings or errors in the Health report. If the user does press the “Set the Model” button while there are still error(s) in the schedule, a dialog box will appear warning the user that there are still errors.

“*Run/Stop Simulation*” buttons are used to control the when simulation should start and stop. The user can see the simulation time displayed on the UI in seconds.

Above the “Plot” button there is an “*actuator drop-down list”*. The user can chose from this list which actuator’s results they wish to plot.

The “*Plot*” button is used to display the results of the previously ran simulation. There are two plot windows appearing. The first plot window shows the actuator output, the second window shows the plant output and the setpoint. Both plots correspond to the drop-down list above where the user can select the process for display.

3.3.9 Schedule Table

The *Schedule table* is used for displaying the current schedule of the WirelessHART network. There is no interaction possible with the UI component however it does display warnings when collisions occur.

3.3.10 Menu

3.3.10.1 Import and Export

The WirelessHART Tool also allows the users to import saved and export the generated Simulink model and network configuration from/ to excel sheet.

3.3.10.2 Add and Remove node

The *Add and Remove node menu* allows the users to add or remove node(s) from and to the network.

3.3.10.3 Retransmission

The *retransmission* is a separate option, placed on the menu. The WirelessHART tool allows the users to retransmit messages in empty Timeslots.

3.4 Simulation Model

This section describes the block organization of the simulation model, the internal block architecture of Sensor, Actuator and Intermediate blocks as well as the properties of the included Simulink blocks [34].
The block organization shows the interconnections between the blocks and how the data is transmitted and received on the entire network in Figure 17.

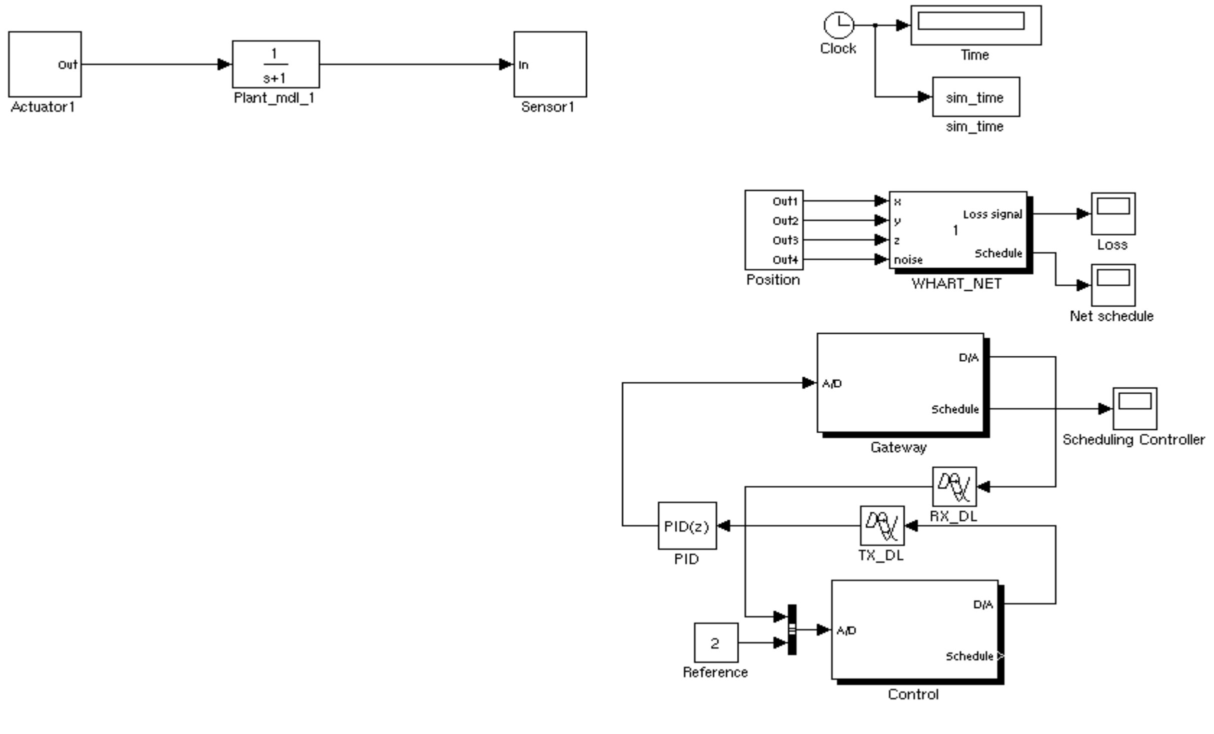


Figure 17: The completed Simulation Model of WirelessHART Tool

Blocks

The *Network block (WHART_NET)* contains several parameters as shown in TrueTime section. The Loss Signal output and Schedule output allow the users to plot the Packet

Loss of the network and the schedule of each node. The Network block is attached with Position block.

The *Position block* contains the physical location (X, Y, Z) of nodes that belong to the network as well as the noise of the environment of the particular node. The users can specify the physical position of each node in the network through the WirelessHART Tool interface. In case of the noise, the value will be zero (0) constant since the UI does not have options to set or change it.

Gateway block (Gateway) is connected to Control block (Control) using an analog output. Between them, a delay block can be found. The Gateway block has one input port and two output ports. The Gateway schedule output is provided by TrueTime, in case of studying the Gateway behavior.

RX Delay, as shown in the Figure 17, is the Receiving Delay block. The RX_DL block can be specified by the users through the WirelessHART Tool interface.

The *Control block* has two input and two outputs. The two inputs are combined with “Mux” block that converts several input signals into a vector.
Two block interface ports (output) are similar to Gateway block’s output ports. The first output interface uses Digital to Analog converter of TrueTime to transmit the data to Gateway block. The second can be used to plot the schedule of the block.

The *Reference* is a Constant block from Simulink. This block generates a constant value. The users are able to set the Reference value through the Setpoint field of the Control properties panel of the GUI (#6).

TX Delay contains the functionality of Transmission Delay is similar to RX_DL, but TX_DL is performed when the analog signal is transmitted to Gateway.

PID block processes the incoming data and then forwards the results to Gateway block. On default, the PID is chosen to be *discrete-time.* The internal parameters of PID consist of Proportional value, Integral value, Derivative, Sampling Time and Filter Coefficient. The value of the Filter Coefficient is 0 on default, and the Sample Time is 0.01s on default. The GUI makes only the P, I and D values available for input.

The simulation time of the model is controlled by a group of Simulink blocks which are: Clock Simulink, Sink Display Simulink and “to Workspace” Simulink (sim_time) blocks.

Clock block controls the current simulation time. The length of simulation time runtime can be specified by the users in the Simulink run-time interface. The simulation time in default set as “inf” which means the simulation will run until the users stops it.

Display block shows the value the input from the Clock Simulink block.

sim_time block is used to write the signal data to MATLAB workspace. When the simulation is completed or paused, all data created by the simulation is written to the workspace. The users can specify how to save the data, from several formats such as time-series, array, structure and structure with time.

Plant refers to “Transfer Fcn” Simulink block is used as a “Plant” for processing and transforming the data. The Transfer Fcn has two parameters: *Numerator coefficients and Denominator coefficients.* The Numerator coefficients and Denominator coefficients can be a vector or matrix expression. The default transfer function is the following formula (3.4):

$$\frac{1}{S+1} \tag{3.4}$$

The default of Numerator coefficients is one (1) and Denominator coefficients is [1 1].

Actuator block can be expanded to see how it is built from sub-blocks as shown in Figure 18. The Internal architecture of Actuator Sub-blocks consists of one TrueTime Kernel block and three Simulink blocks.

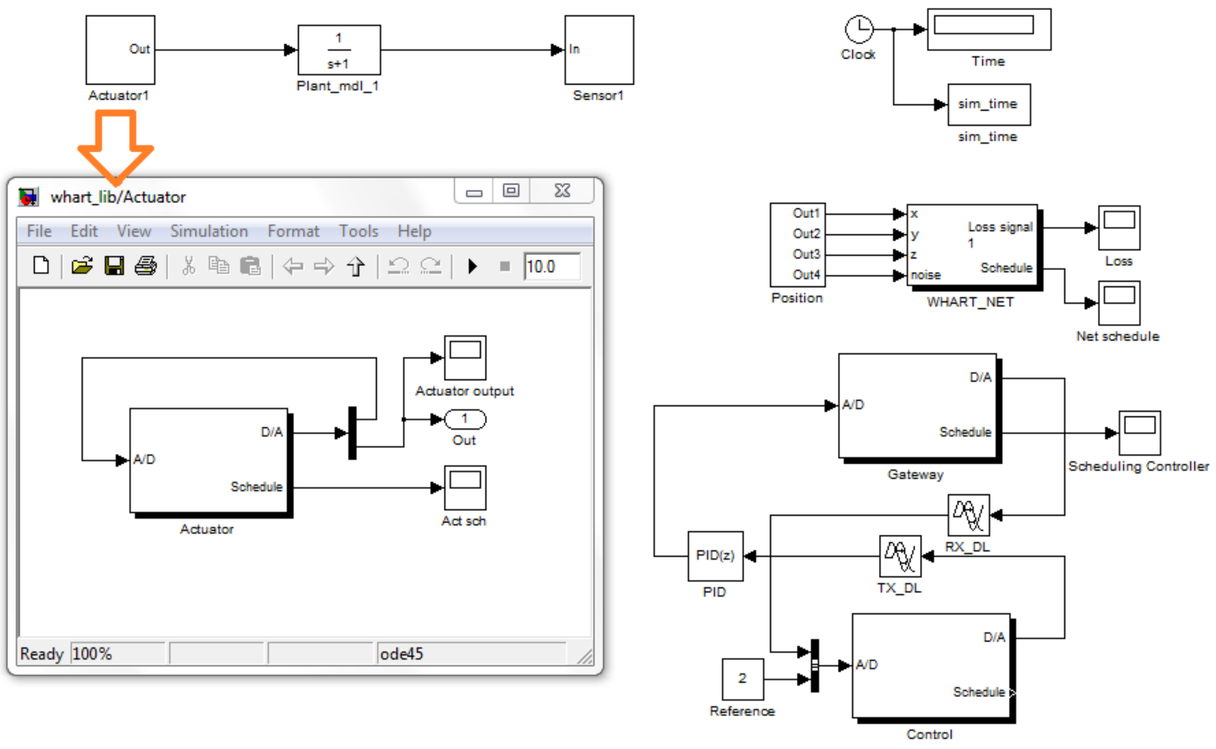


Figure 18: The completed Simulation Model of WirelessHART Tool with Actuator Sub-blocks

The *TrueTime Kernel block* represents the core of the actuator node. This core has two output ports. The D/A output port is connected to the Actuator output scope and the to the Plant through “Outport” Simulink block, while the Schedule output port is connected to the “Act sch” scope.

The connection from D/A to A/D acts as a feedback (buffer). This connection is only used when the Actuator block is used as Intermediate node.

Sensor block receives the data from the “Plant”. When expanded it is discovered that the block contains an Inport, a Constant block, a TrueTime Kernel block and two scope blocks as presented in Figure 19.

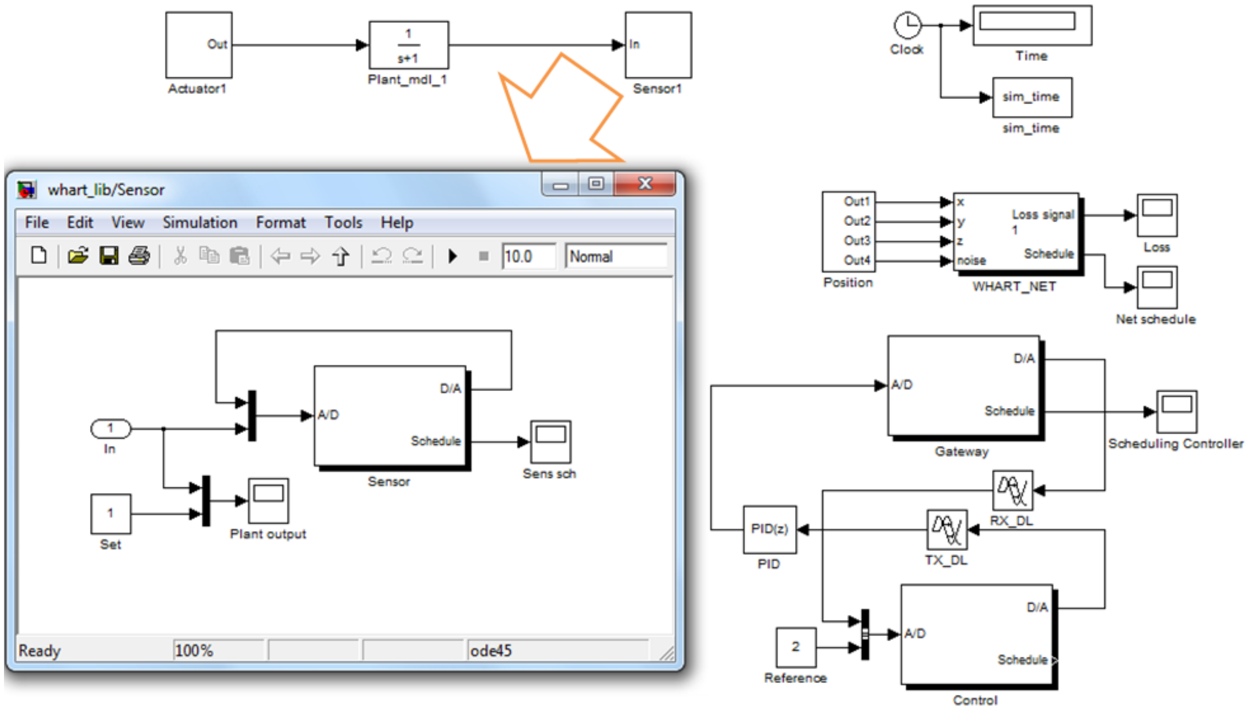


Figure 19: The completed Simulation Model of WirelessHART Tool with Sensor Sub-blocks

The *Constant Simulink block* called “Set” represents the value of the control setpoint. One scope plots the Plant output and the setpoint of the control loop while another scope displays the sensor’s schedule on the network.

In case of the sensor is used as an intermediate node, the sensor node sends data backwards to A/D input.

Intermediate block does not have input or output port from its high level view. The *“buffer”* acts as a feedback the same way as it does when the actuator or the sensor nodes are used as intermediate nodes.

Block Organization

The simulation model was generated based on the input of the user, through GUI such as number of sensor, number of actuator, etc. The Figure 17 shows the completed simulation model of WirelessHART tool with one Wireless Sensor and one Wireless Actuator. The Network block is attached with Position block.

Two incoming inputs to Control block are Analog to Digital input from Gateway and Reference (setpoint). Between the Controller and the Gateway blocks, the TX_DL and the PID blocks can be found.

The Gateway block transmits the data through the Digital to Analog Converter (D/A) port of the Kernel TrueTime block to the Control block. RX_DL is the Receiving Delay block; this block is organized in between Gateway block and Control block towards the delaying of receiving data.

3.5 Code Readability

The code for the functions of the UI was included in one MATLAB script. There is also a lot of repetition in the code, meaning that whenever two functions are have some common code it is copied and pasted in both.
All the project files are included in one folder. Since there are a lot of files that are used during runtime, it becomes very confusing to navigate inside the folder.
The above described, style of code writing prevents from the application to accommodate good maintainability, extensibility, changeability and response time. The style of code writing also goes against pragmatic programming: Don’t repeat yourself, File and Folder Organization, Avoid Deep Nesting [4].

4. Extensions to WirelessHART Tool

This section provides requirements specification. These requirements were requested by customers in order to improve the capability of the tool. The limitations of the thesis can be found in this section.

4.1 Requirements

4.1.1 Wired actuator

The customer needs the WirelessHART Tool to be able to simulate control systems where the *actuators are wired* and the sensors are wireless.

4.1.2 Multiple Channels

The purpose of utilizing *Multiple Channels* is to enable devices to split the frequency range of the network into multiple channels. These channels covering different frequencies can allow the nodes to communicate simultaneously.
The customer needs the WirelessHART Tool to allow users to generate networks that use multiple channels in their frequency range to transmit data.

4.1.3 Toggle switch for sensor, actuator, intermediate panel

The WirelessHART tool displayed three different panels together on the GUI: sensor, actuator and intermediate panel. This approach resulted that the user interface was and difficult to follow, especially considering that each panel had similar configuration panel such as nodes selection, time slots selection, edit and delete nodes button and etc.

4.1.4 Using the same color pattern for each control loop

The customer wanted to be able to see which sensors, actuators, and control loops belong to the same control loop on the schedule table. The solution was to give the same color to these entities in the schedule if they belong to the same control loop.
Note that intermediate nodes are in our consideration due to they do not belong to any specific control loop.

4.1.5 Remove node on scheduling table by using Delete Key

One of the customer's wishes was to be able to delete nodes from the schedule by selecting them in the schedule and deleting them using the "Delete" key.

4.1.6 Improving the correctness of Controller

There were several demonstrations for the customer when the simulation mechanism of the controller was discovered to be incorrect. Some of these problems were solved as part of the thesis and others were too complex and not considered in the scope of this work.
It was discovered that the block organization of the PID controller and TX_DL was incorrect. The on the way from the Controller Block the PID has to come first, then the TX_DL and then the Gateway.

Another problem was that only one PID was used to calculate for all the actuators. After a short discussion, it was decided that one PID is to be added for each actuator.

When testing with different schedule combinations, some of them produced unexpected and incorrect results. In order to identify the problem the code was inspected and it was found that the gateway does not know what data is to be sent to which node. Since in the simulation the user acts as the Scheduler, it was obvious that when they create the schedule they know what data is to be sent to which node. Consequently, the user needed to have more control over the Gateway.

4.2 Limitations

4.2.1 Internal Limitations

These limitations define what is excluded from the scope of the thesis by the authors with the consent of the customer.

- The redesign of the software architecture was out of work’s scope.
- The thesis did not address perfecting the controller.
- The thesis did not address modifying the TrueTime library.
- The above mentioned reasons set limitations in extra-functional requirements: execution speed, extendibility, modifiability. The thesis did not focus on improving any of those.

4.2.2 External Limitations

These are the limitations that could not be controlled by the authors.

- TrueTime does not support multiple channels.

5. Solution

This section presents the appropriate solutions for the requirements in section 4. The descriptions contain the choices the authors made and the reasons for those choices. It is also shown how the problems solved, based on what the authors have learned during their research.

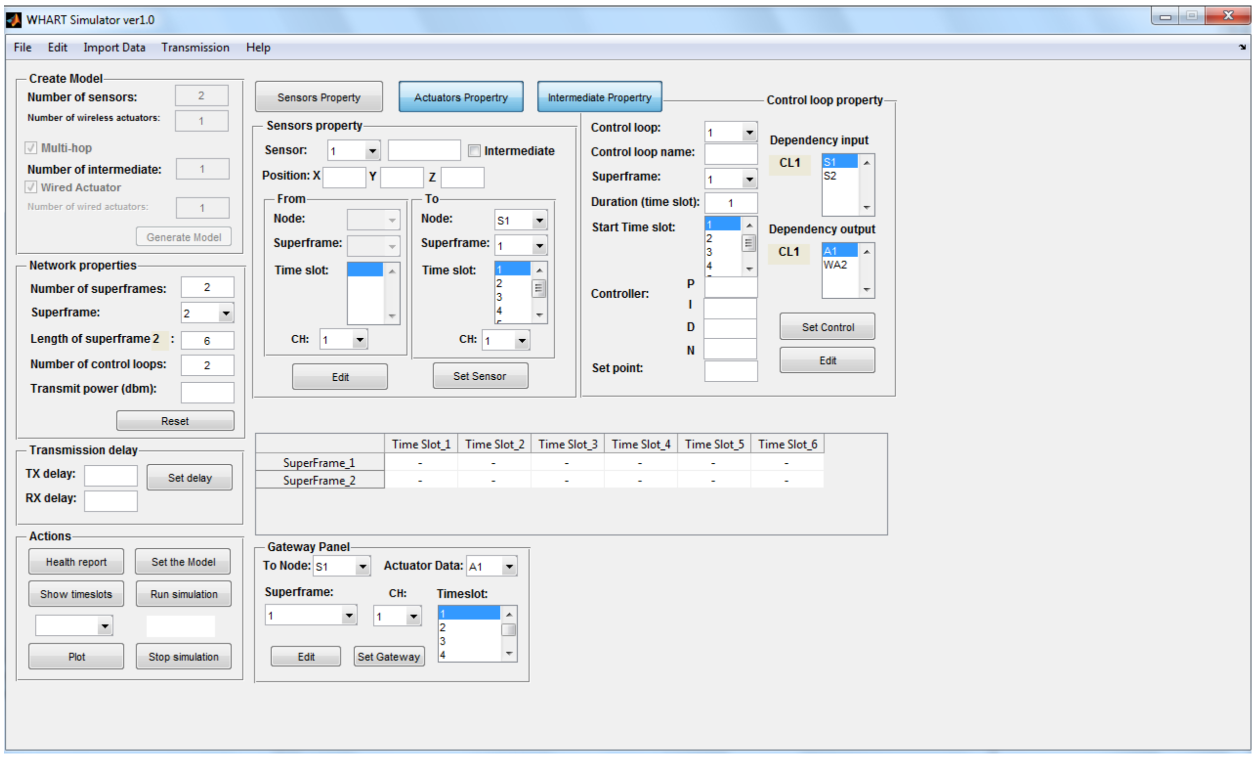
The upgrades of WirelessHART Tool architecture, GUI, and Simulation Model are described here in order to give a better understanding of the changes. The section is broken to subsections using the same organized paper as in Section 3. The subsections only describe the new functionality to allow easier comparison between the new and the old WirelessHART Tool.

5.1 Application Structure

The Application Structure Design has not been changed because of time limitation and customer's request. For the existing application structure, please see Section 3.2.
It was decided to follow the existing application structure and utilize its elements as a means to avoid any effects on the existing functionality of WirelessHART tool. The new functionalities were mapped carefully on the existing elements of structure then implemented to avoid adding extra elements and to avoid complicating the structure.

5.2 User Interface Design

This section presents the description of upgrades made on the GUI. The GUI was reorganized in order to accommodate the required changes as presented in Figure 20 and 21.



Create Model
Number of sensors: 2
Number of wireless actuators: 1
☑ Multi-hop
Number of intermediate: 1
☑ Wired Actuator
Number of wired actuators: 1

Network properties
Number of superframes: 2
Superframe: 2
Length of superframe 2 : 6
Number of control loops: 2
Transmit power (dbm):

Transmission delay
TX delay:
RX delay:

Actions

Sensors property
Sensor: 1
☐ Intermediate
Position: X Y Z
From
Node:
Superframe:
Time slot:
CH: 1
To
Node: S1
Superframe: 1
Time slot: 1 2 3 4
CH: 1

Control loop property
Control loop: 1
Control loop name:
Superframe: 1
Duration (time slot): 1
Start Time slot: 1 2 3 4
Controller: P I D N
Set point:
Dependency input
CL1 S1 S2
Dependency output
CL1 A1 WA2

	Time Slot_1	Time Slot_2	Time Slot_3	Time Slot_4	Time Slot_5	Time Slot_6
SuperFrame_1	-	-	-	-	-	-
SuperFrame_2	-	-	-	-	-	-

Gateway Panel
To Node: S1
Actuator Data: A1
Superframe: 1
CH: 1
Timeslot: 1 2 3 4

Figure 20: New WirelessHART Tool User Interface.

5.2.1 Changes in Create Model

Wired Actuators

There were two new items added on the panel, both dealing with the wired actuators. The *wired actuator checkbox* has been added because there are major differences in what the Simulation model includes with and without the wired actuators.

The *number of Wired Actuators* has been separated from the number of Wireless Actuators because during when setting the model and during simulation, it would be difficult to track which node has what number on what network in the model and in the *Global Variables.*

5.2.2 Changes in Sensor/Actuator/Intermediate Property

Toggle buttons

The chosen solution to the above described problem is to place toggle buttons each node property (Sensor, Actuator and Intermediate) which display only one panel at a time. This allows the user to follow easier what is happening when setting up the simulation. For example, if the user is focusing on sensor configuration, the user would click at the sensor toggle switch, and then only the sensor configuration panel would be displayed.

The *toggle buttons* were selected to separate one big panel of Sensor, Actuator and Intermediate.

The concept is to split the big panel into small panels. The panels are controlled by the three toggle buttons. The starting point will be clear panel, unless the user clicks on any buttons. The sensor panel will appear when the users click on Sensor toggle button. If the users click on Actuator toggle button, the actuator panel will appear on the UI.

The *controller panel* was not included between the toggles because it does not belong to the network nodes.

Multiple Channels

It was discovered that TrueTime library does not fully support the use of multiple channels communication. TrueTime’s mask interface is prepared by the channel offset input field, however it only gets the input data, but there is no function connected to process or use that data.

After discussing with the customer, the customer’s wish was to design to prepare the WirelessHART tool for supporting multiple channels, in case the functionality would be added in TrueTime. This meant updating the user interface for selecting the channels, adding a new global variable where channel communication is stored, and implemented algorithms to display the multiple channel communication in the Schedule Table and to verify the schedule.

Thus, the logical idea for multiple channels was built on top of the GUI. The concept was to add a dropdown list element for each node devices (Sensor, Actuator,

Intermediate node Gateway), which can identify the different channels. The channel dropdown list was added for both data sending and receiving on the panels.
The 16 channels can be chosen only after the superframes are generated. Then users are able to specify the channel for each transmission. In order to detect collision in the schedule a new algorithm was designed. The reason is that the old algorithm was not designed in a way to allow extensions. This algorithm considers Timeslots, channels and nodes when checking the schedule for transmissions.

There is a collision in the schedule in 3 cases:

- In the SAME Timeslot, the SAME Channel IS USED MORE THAN ONCE
- In the SAME Timeslot, the SAME Node IS USED (for transmit or receive) MORE THAN ONCE
- In the SAME Timeslot, the SAME Superframe IS USED MORE THAN ONCE

5.2.3 Changes in Control Loop Property

Improving the Correctness of Controller
In order to be able to configure the PID block correctly, an additional field was placed on the Control Loop Property panel. The user can use the N field to set the Filter Coefficient in the PID Simulink block.
The P, I, D input fields were also fixed to take the input with better precision than before.

Wired Actuator
The Control Loop Property panel includes yet another change. When Wired Actuators are used and the user selects them as dependency for the control loop, the Wired Actuators will appear in the schedule in the same Timeslot with the Control Loop.

However, since they are on different network (with different communication mechanism) it is not entirely true. Since the *Ethernet Network* is much faster than the *WirelessHART*: on the Ethernet in a timeframe of 10 millisecond, and more than 400 messages (with the same size as in WirelessHART) can be sent. The authors of this thesis assumed (and got permission from the customer) that the difference in communication could be overlooked.

5.2.4 New Gateway Panel

Improving the Correctness of Controller

The Gateway panel was added into the new GUI in order to solve the problem of knowing destination device when the gateway transmits data to an intermediate node. The cause is that the Gateway does not know what register to take the data from in case it is not sent directly to the destination node.

This solution was created because this allows the user to fully take control of the data transmission.

The Gateway panel has similar properties to sensor and actuator panel properties. The only different feature is the users are able to specify which actuator will be the using the data that is sent. The Gateway panel only appears if intermediate nodes are allowed. There was one global variable added to resolve the problem.

5.2.5 Change in Schedule Table

Using the same colors for each control loop

The following solution was used to fix the colors in the schedule. The color of control loop is generated by randomized number of RGB pattern, Red Green and Blue main pattern, from 0 to 255 bit pattern of each main color. The idea is to identify unique color for process and color the belonging sensor, actuator node and control loop to the same color.

The randomized functionality was used to generate 256 random numbers, between 0 - 255. The reason for this is that in the WirelessHART specification, one network can have only 250 nodes, and there are fewer possibilities to generate the same color for each group of sensor - control loop - actuator.

In order to show the color, the *color tag* is applied into a cell in scheduling table. The color tag needs to be defined by a *color name* or in *RGB code*. The RGB code is more efficient as means to identify many colors. The RGB code represents three variables, each variable contained by number in between 0 - 255.

After the random numbers were generated, they were stored in different variables representing R, G and B. Then, the containing variables are put as the color tag. For example, rgb(x,x,x) function contains R = 0, G = 0, B = 0, this represents rgb(0,0,0) which means black color.

Delete Key

In order to provide a more visual way to remove transmissions from the schedule, an alternative way is provided, where users can select the desired transmission on the Schedule Table and remove them by pressing the "*Delete*" key.

The *CellSelectionCallback* is used to get the right row and column of selected cell on the table. The Delete Key button is represented by number of "*127*" in ASCII number. In the event of the Delete Key is pressed, the specified row and column of that cell will be read in order to check what node is in inside that cell, and remove them from the corresponding tables.

Multiple Channels

The Schedule Table's Cell format for was changed in order to show what channel the transmission is taking place on. The channel number was prefixed before the nodes of the transmission and given the same color as the transmission.

5.3 Simulation Model

Improving the Correctness of Controller

On a real WirelessHART network the Gateway and the Controller use registers for exchanging data. The Gateway knows which register belongs to which sensor on the input side of the controller; the Controller knows which input register to read from and which input register to write to, for each Control Loop, then the Gateway knows again which transmission (towards the actuators) will use which register (controller output) data.

The previous version of the model did not consider registers on the Gateway and the Controller. This resulted that when the simulated network had many sensors and actuators, as well as many control loops, the schedule had to be very specific in order to work.

The problem was that both the Gateway and the Controller blocks had only one analog input where messages arrived.

For example when there are two control loops with the following dependencies:
CL1: Sensor1, Actuator1
CL2: Sensor 2, Actuator2

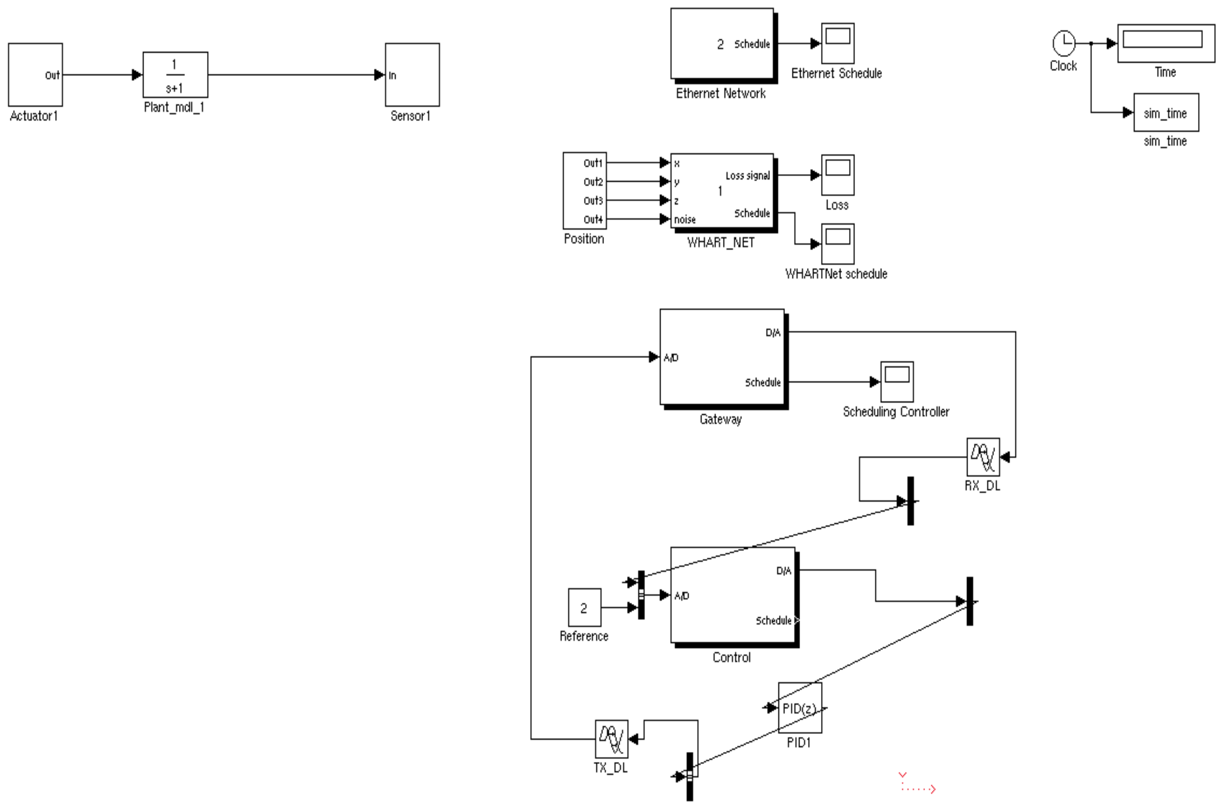


Figure 22: Simulink Model of both Wireless Sensor and Wireless Actuator

The transmissions of control loop order of each control loop must not be mixed:

Timeslot 1	Timeslot 2	Timeslot 3	Timeslot 4	Timeslot 5	Timeslot 6
S1->GW	CL1	GW->A1	S2->GW	CL2	GW->A2

Table 3: Example of Schedule table

In the schedule seen above, Table 3, we can change the patterns (control loop + transmissions) of the whole control loop with the other but we cannot change the individual transmissions or control loops place in the schedule. For instance if we put GW->A2 in Timeslot 3 and GW->A1 in Timeslot 6 instead, the output of both processes would be incorrect.

In order to simulate registers we have decided to use analog connection.

Referring to Figure 17 in section 3.4, where the PID block was organized after TX_DL block, this method created some confusion and after short discussion, it was decided that that PID should come before the TX_DL as in Figure 22. The reason was that the delay before the PID controller might distort the calculation of the PID. Another reason was that the PID and the Controller block were supposed simulate the control together, while the delay was used to simulate the delay on the way back from the Controller to the Gateway.

During the investigation, other problems were found such as single PID served all the control loops. The PID controller block “remembers” old data, in case of one PID and more than one control loop this leads to the controller working ineffectively and incorrectly.

The simulation model has been changed according to the single PID controller problem by adding the number of PID controllers in accordance with number of actuators. After the PID controllers are generated, they are connected to a “Mux” and a “Demux” Simulink blocks.

In order to improve the PID controller behavior, the new parameters inside PID controller block were changed based on customer requirement. The Sample time of PID controller was not changed.
The solutions in the controller might also raise some issues; however the Controller is “more correct” then the previous. It needs to be mentioned that there were a number of solutions considered for the problems and all of them had their defects.

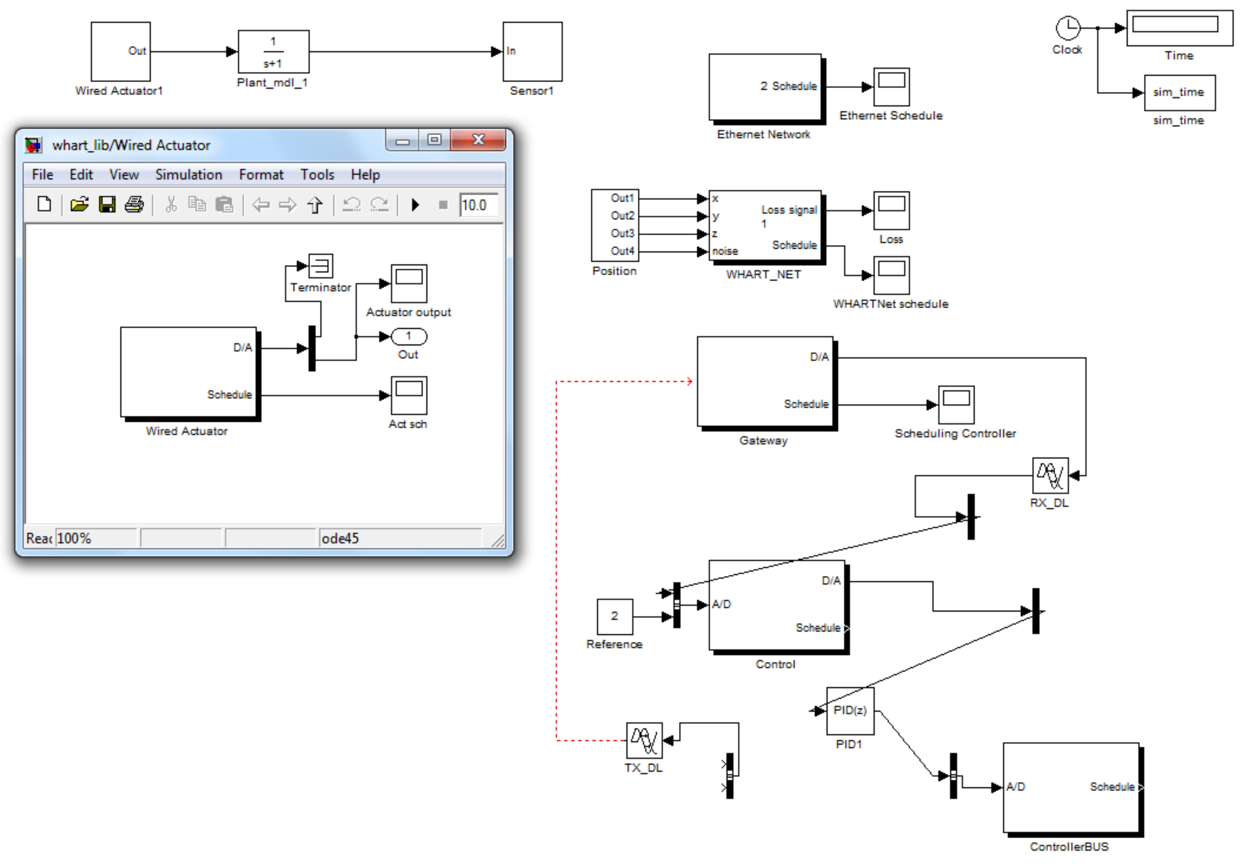


Figure 23: Simulation Model of Wireless Sensor and Wired Actuator

Wired Actuator

As shown in the Figure 23, this model was created as a means to determine the requirement of Wired Actuator (section 4.1.1).

In the real world, the Actuator can be either Wireless Actuator or Wired Actuator. The previous stage of WirelessHART tool did not consider this functionality. So, in this thesis we extended an advance communication of two networks coexist. The purpose was to investigate and evaluate the performance of the data transmitting though both networks.

The first network is WirelessHART and is responsible for communicating data from sensors to controller through a gateway. The second network is wired, it uses Ethernet (CSMA/CD) protocol and this network is responsible for communicating data from the controller to actuators. The Wired actuators were requested to appear in the schedule.

The in the real plant the wired actuators will use a *PROFINET* solution, however the implementation of PROFINET in TrueTime makes it quite difficult to automate the generation of such network. Since the primary objective of this tool is to simulate WirelessHART networks, it was decided that PROFINET would not be used. *FDMA* was another considered solution, but it was dropped since its behavior was not suitable.

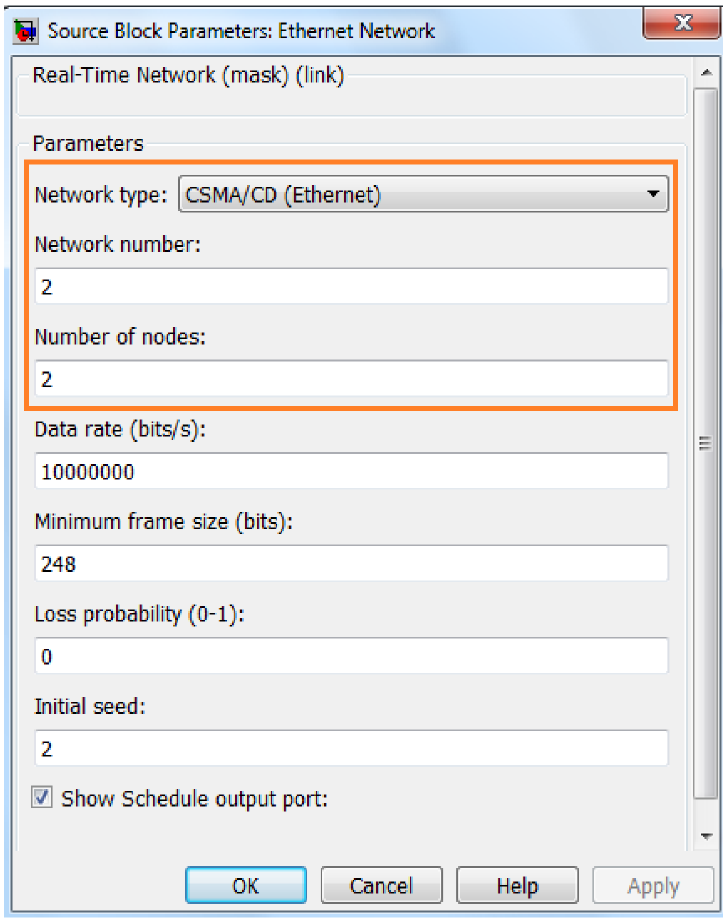
TDMA had quite unclear description in the TrueTime manual about how the static schedule is to be used, so it was decided to move forward with another solution.

The Ethernet (CMSA/CD) network was chosen to interact with WirelessHART network in the system because of simplicity in implementation and well matching behavior with the WirelessHART.

In case of *sensor node is Wireless and actuator node is Wired*, the Wired Actuator block will be copied into the Simulation Model instead of Wireless Actuator block. The Figure 23 shows the different block organizations of Simulation model when actuator is Wired. There are three important blocks that are added in this Simulation model: Wired Actuator block, Ethernet Network block and ControllerBUS block.

The Wired Actuator block is connected to “Plant” and send the data over the “Outport” Simulink block. The internal block design of Wired Actuator block is similar to Wireless Actuator block. The Wired Actuator could not be used at all on WirelessHART Network thus no uses such as intermediate node behavior scenario. Therefore, there is no feedback from output port coming into the input port. The feedback output is terminated by using the “Terminator” Simulink block.

The Ethernet Network block is a TrueTime Network block in which specified type is “Ethernet”. This TrueTime Network block is used in order to simulate a wired network when such actuators are used. Both the Ethernet Network block and the WHART_NET block have their own Network Number which can be defined in mask interface of TrueTime, the WHART_NET block was specified as a network number “1” and Ethernet block is “2” respectively as presented in Figure 24.


Source Block Parameters: Ethernet Network

Real-Time Network (mask) (link)

Parameters

Network type: CSMA/CD (Ethernet)

Network number: 2

Number of nodes: 2

Data rate (bits/s): 10000000

Minimum frame size (bits): 248

Loss probability (0-1): 0

Initial seed: 2

[✓] Show Schedule output port:

Figure 24: Mask interface of Ethernet Network, TrueTime Network Block

Since the Wired Actuator does not belong to the WirelessHART network (WHART_NET block), their positions are not indicated in the Position block.

The ControllerBUS is a TrueTime Kernel block; this block is used to collect the data from PID controller block and forward the data directly to Wired Actuator.

Consequent problem/ solution

Since the model has two networks, which are WirelessHART network and Ethernet network. There was a problem with the controller block. The problem was that in the model the Controller block could belong to only one network. The question was which network?

There were two different versions created one where the Controller belonged to the Ethernet network and one where it belonged to the WirelessHART network. Both versions were demonstrated to the customer who decided to move on with the version where the Controller block is part of the WirelessHART network. The reason was that the Control loops should be scheduled in the WirelessHART schedule.

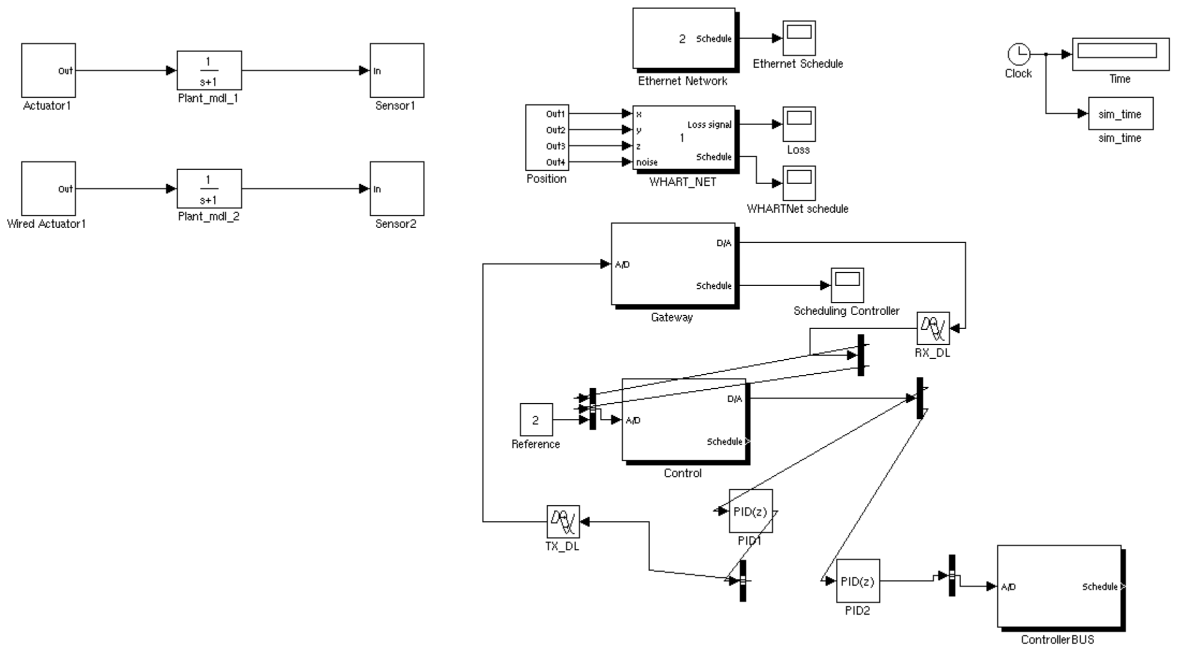


Figure 25: Simulink Model of two Wireless Sensors, one Wired Actuator and one Wireless Actuator

According to the Wired Actuator requirement, the customer can generate more advanced system, where two networks coexist and the system uses both Wired Actuators and Wireless Actuators.

Figure 25 shows the completed simulation model of two Wireless Sensors, one Wired Actuator and one Wireless Actuator. As mentioned above the number of PID controller Simulink block will be added in accordance with number of Actuator whether it is the Wireless Actuator or it is the Wired Actuator. The PID1 connects to Gateway block, this PID controller responsible to control the Wireless Actuator via Gateway block, while the PID2 connects to ControllerBus block. The PID2 controller is responsible to control the Wired Actuator.

6. Evaluation and Results

6.1 Testing the Application

All tests presented here were conducted to ensure that the application still works with the changes made.

6.1.1 The Reference Model

Referring to Figure 26, the tests all used a simple model of a Servo System as reference. This model was provided by ABB, to test against. The model was added to the each Simulation and joined in the Plant Output scopes in order to have a stable trace on the graphs.
The *controller of the reference model* is always set with the same parameters as the networked controller. The *step of the reference model* was set in a way to minimize the time delay between the two graphs. The *plant (Transfer Fnc)* was set to [1] and [3 1 0] for Numerator coefficients and Denominator coefficients respectively*.* The *RX_DL block* in the reference model was set to 0.0005 s just like the RX delay of each simulation.

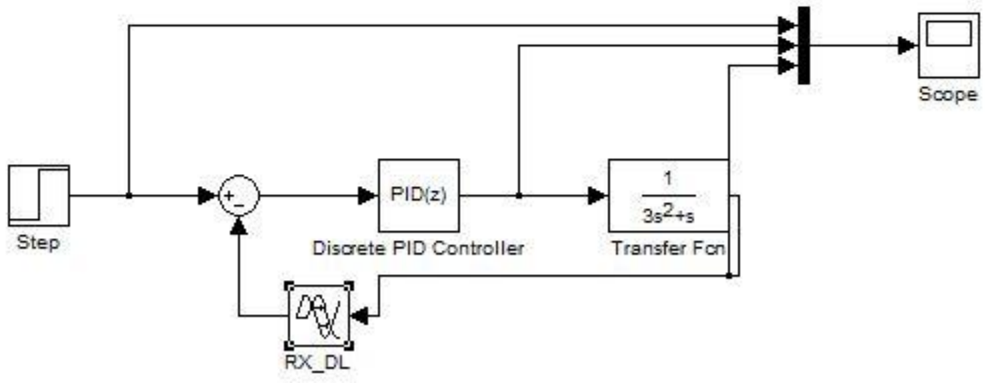


Figure 26: Servo System Model

6.1.2 Test 1: The performance of the Old WirelessHART Tool and New WirelessHART Tool

The reason for this test was to see how different the old tool performs compared to the new tool.
The plant output was recorded in order to see the difference between the two applications. The PID´s and all settings from the GUI were set identically. However, the Filter Coefficient (N) in the PID was set in case of the new Tool. Figure 27 and 28 show the simulation setup model and schedule table of the old version of WirelessHART tool.

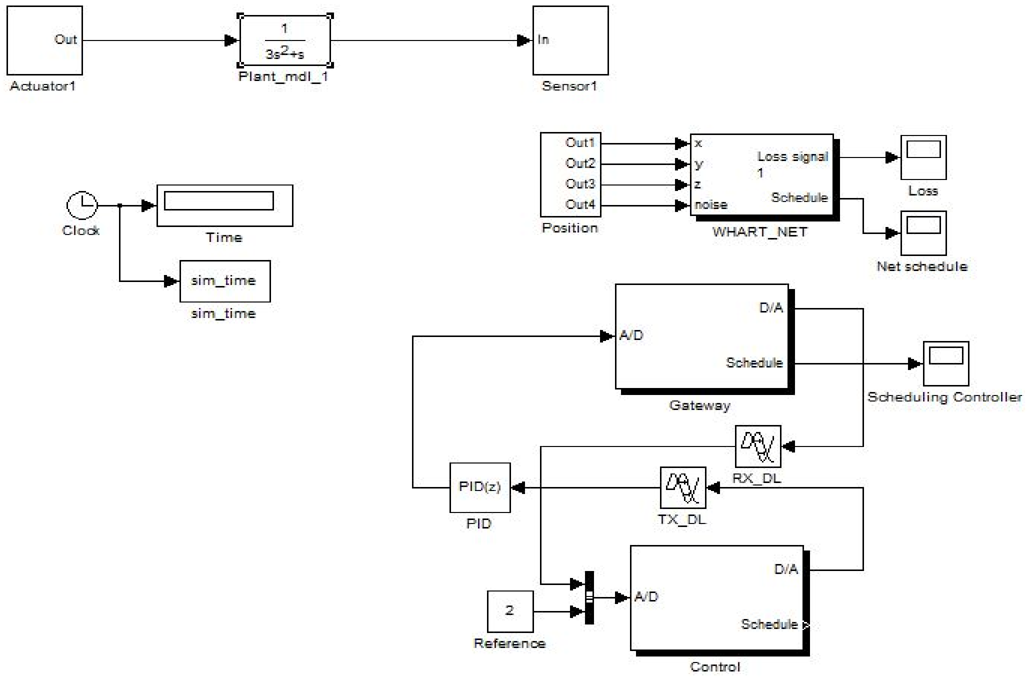
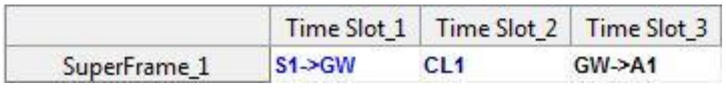


Figure 27: Old WirelessHART Simulation Setup Model



	Time Slot_1	Time Slot_2	Time Slot_3
SuperFrame_1	S1->GW	CL1	GW->A1

Figure 28: Schedule table of Old WirelessHART

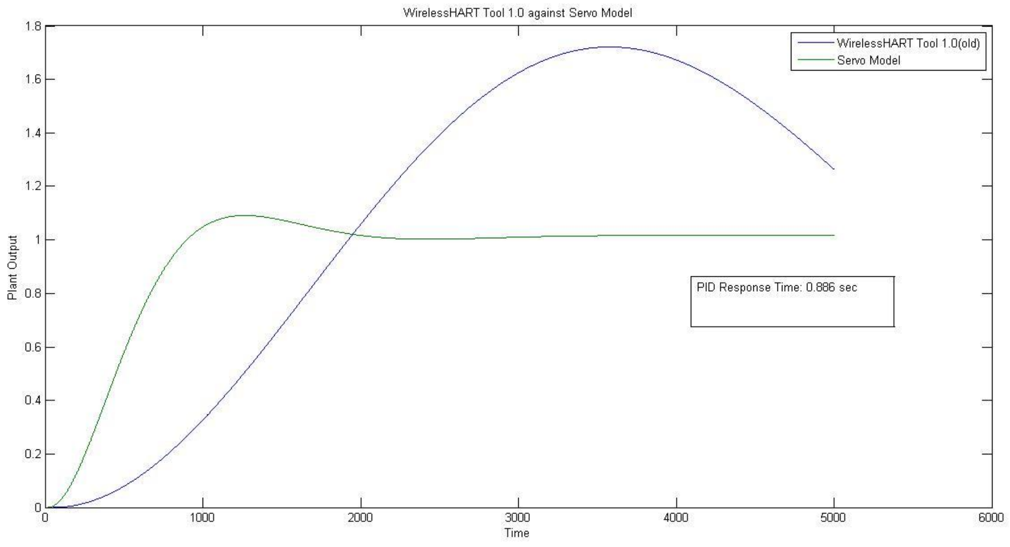


Figure 29: WirelessHART Tool 1.0 (old) against Servo Model

Figure 29 shows the result of the first version of the WirelessHART tool against the Servo Model. The PID values were tuned in a way that they were supposed to stabilize plant outputs in the observed time period. The respond time was set to 0.886 sec. It can be very well seen that the old version of WirelessHART produces a very different result from the reference model.

The expectation was that the WirelessHART Tool curve should follow the Servo Model's curve with a short (approximately 0.03 - 0.04 s) delay with a very slight difference in the output values. It was also expected that the WirelessHART plant output would stabilize in the 5 seconds frame what was used for the experiment, but there is no sign of that, moreover it would be difficult to predict when would it stabilize.

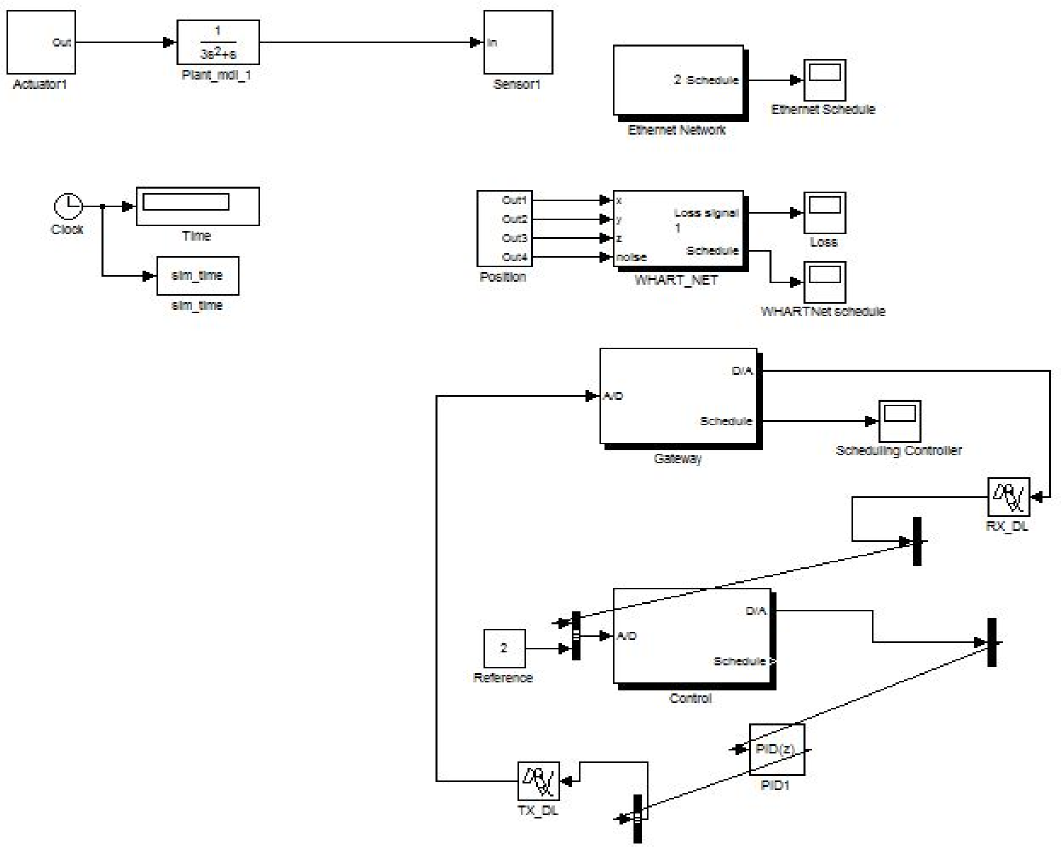
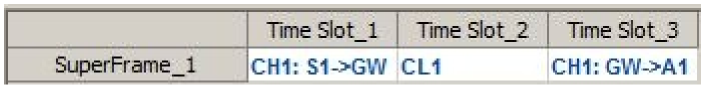


Figure 30: New WirelessHART Simulation Setup Model



	Time Slot_1	Time Slot_2	Time Slot_3
SuperFrame_1	CH1: S1->GW	CL1	CH1: GW->A1

Figure 31: Schedule table of New WirelessHART

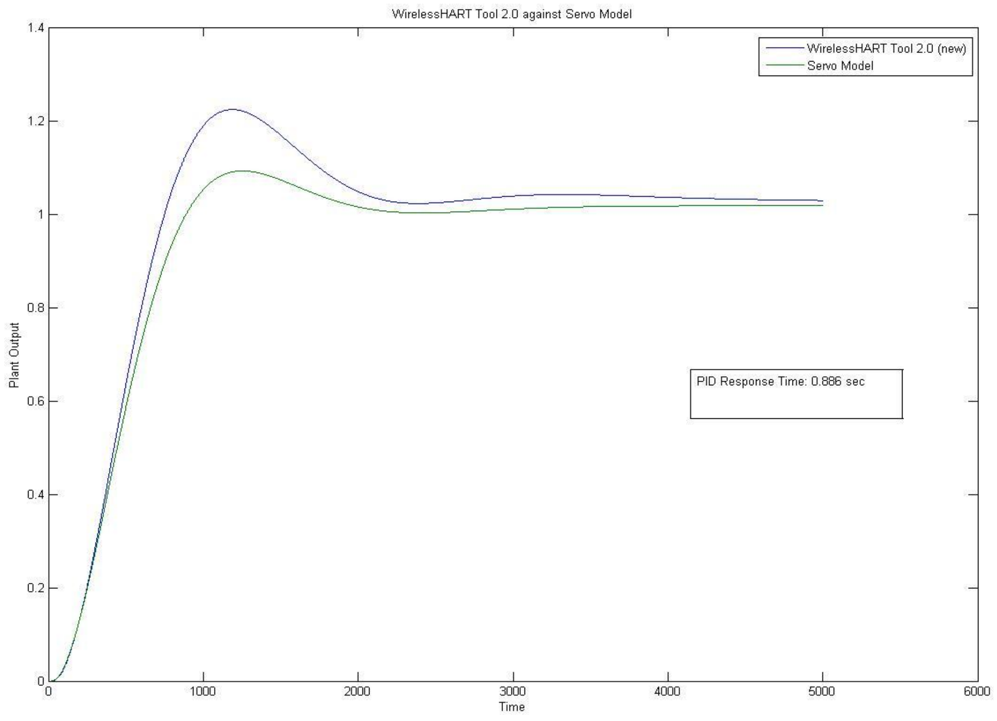


Figure 32: WirelessHART Tool 2.0 (new) against Servo Model

Figure 32 shows the result of the new version of the WirelessHART tool against the Servo Model. The same PID response time was used as in the previous case. The new version of WirelessHART Tool did perform as predicted before the experiment. The curves are similar, they both stabilized and the slight difference between the stabilized lines can be the result of the rounding when the measures are converted to integers and placed in the network messages.

6.1.3 Test 2: The performance of Wireless Actuator and Wired Actuator

The reason for this test was to see how different does the plant perform with wired and with wireless actuators.

The settings of the networks are the same however in case of the wired actuators, there was one timeslot less used, to utilize its speed advantage, as shown in Figure 34 and 37.

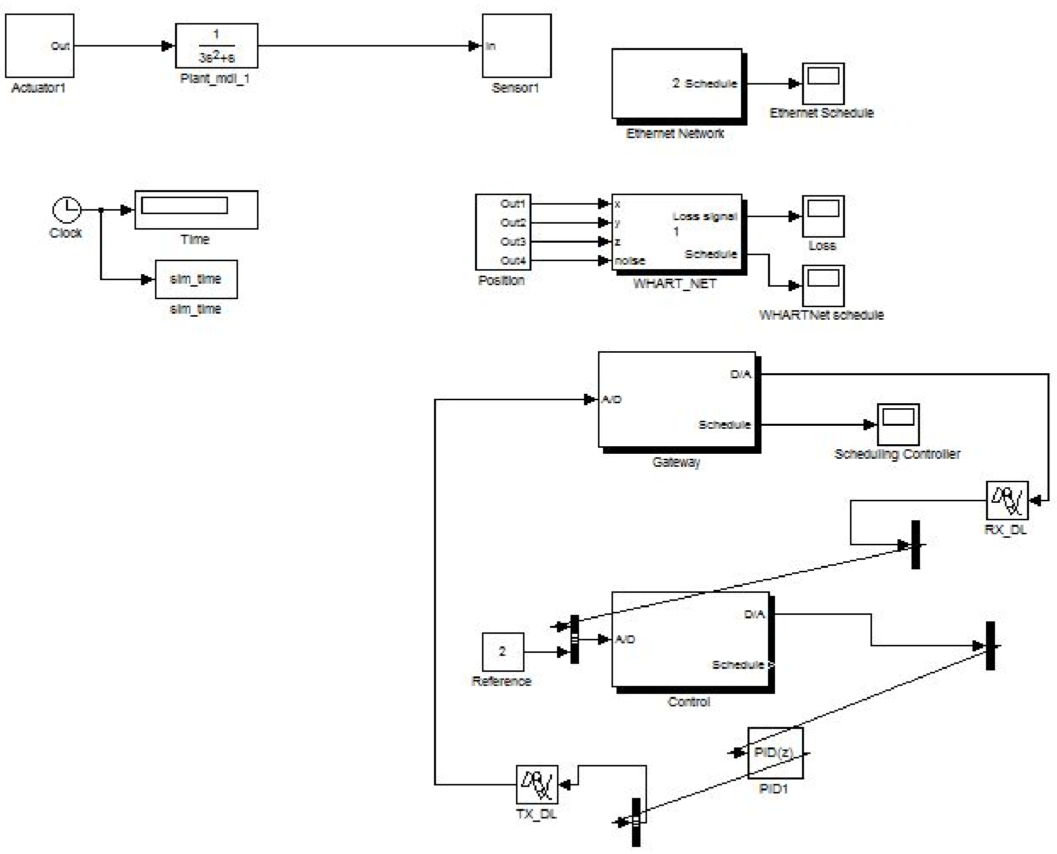
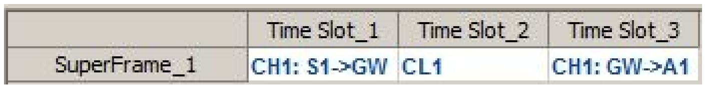


Figure 33: Wireless Actuator, New WirelessHART Simulation Setup Model



	Time Slot_1	Time Slot_2	Time Slot_3
SuperFrame_1	CH1: S1->GW	CL1	CH1: GW->A1

Figure 34: Schedule table of New WirelessHART

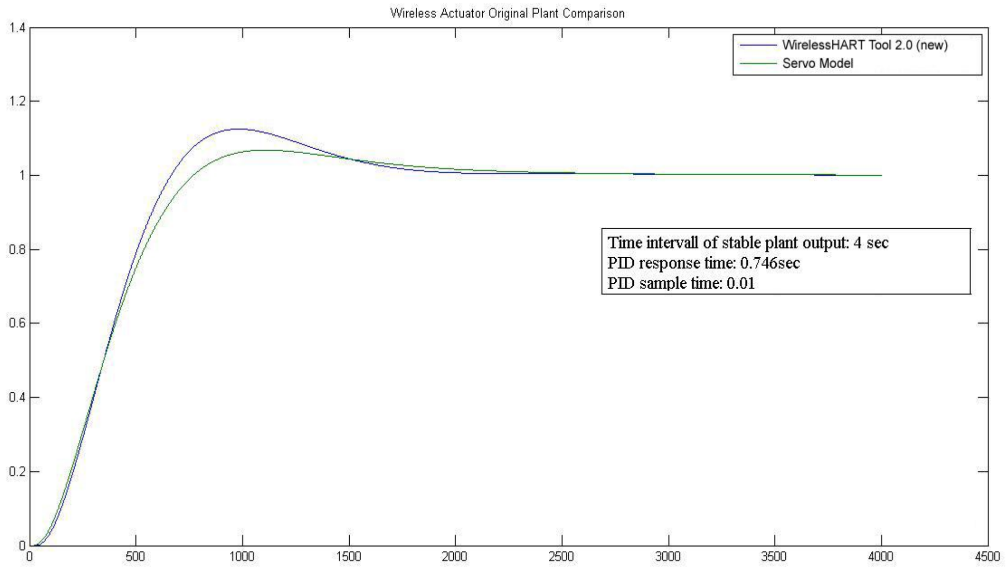


Figure 35: Wireless Tool 2.0, Wireless Actuator against Servo Model

Figure 35 shows the result of the wireless actuator against servo model in new version of WirelessHART tool. The PID values were tuned in a way that they were supposed to stabilize plant outputs in the observed time period. The respond time was set to 0.746 sec. The wireless actuator case did perform as expected closely following the Servo Model's performance and stabilizing.

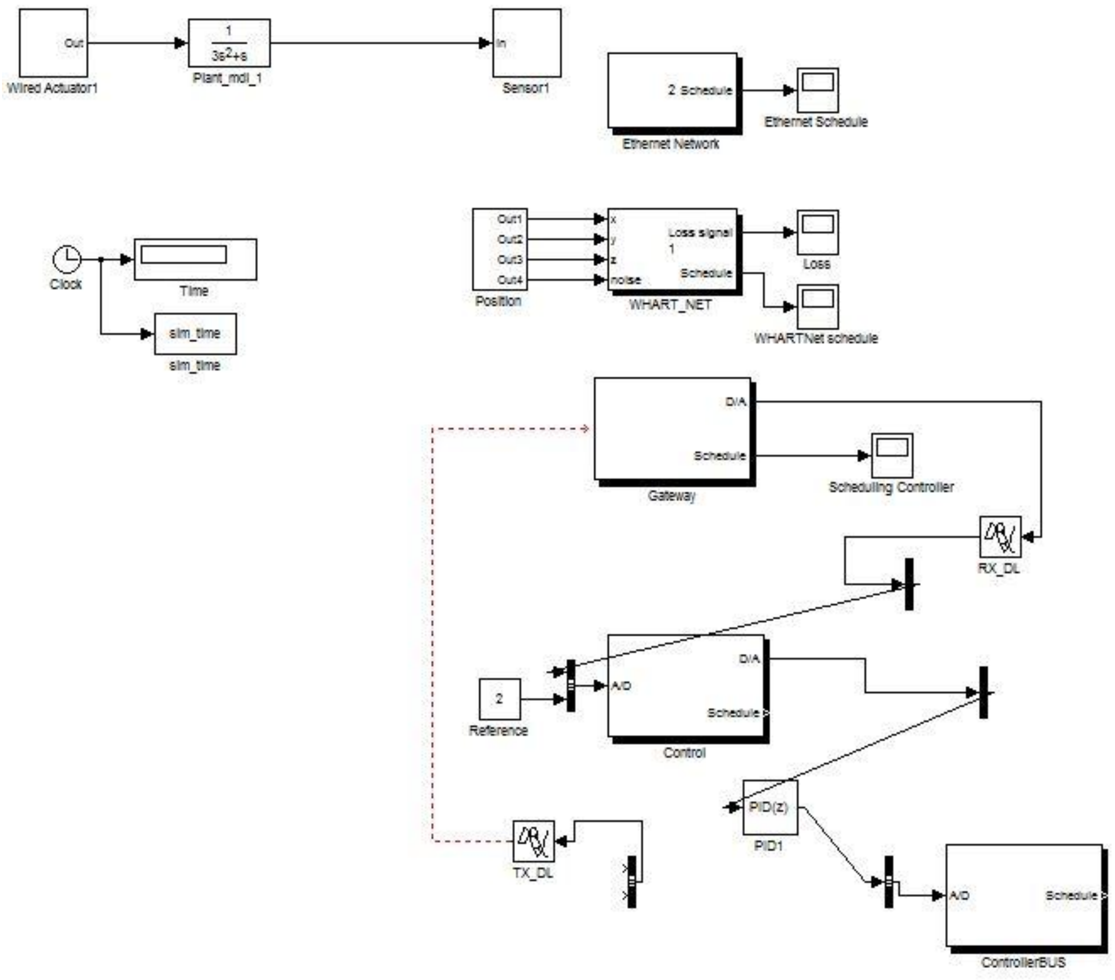
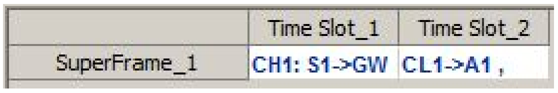


Figure 36: New WirelessHART Simulation Setup Model



	Time Slot_1	Time Slot_2
SuperFrame_1	CH1: S1->GW	CL1->A1 ,

Figure 37: Schedule table of New WirelessHART

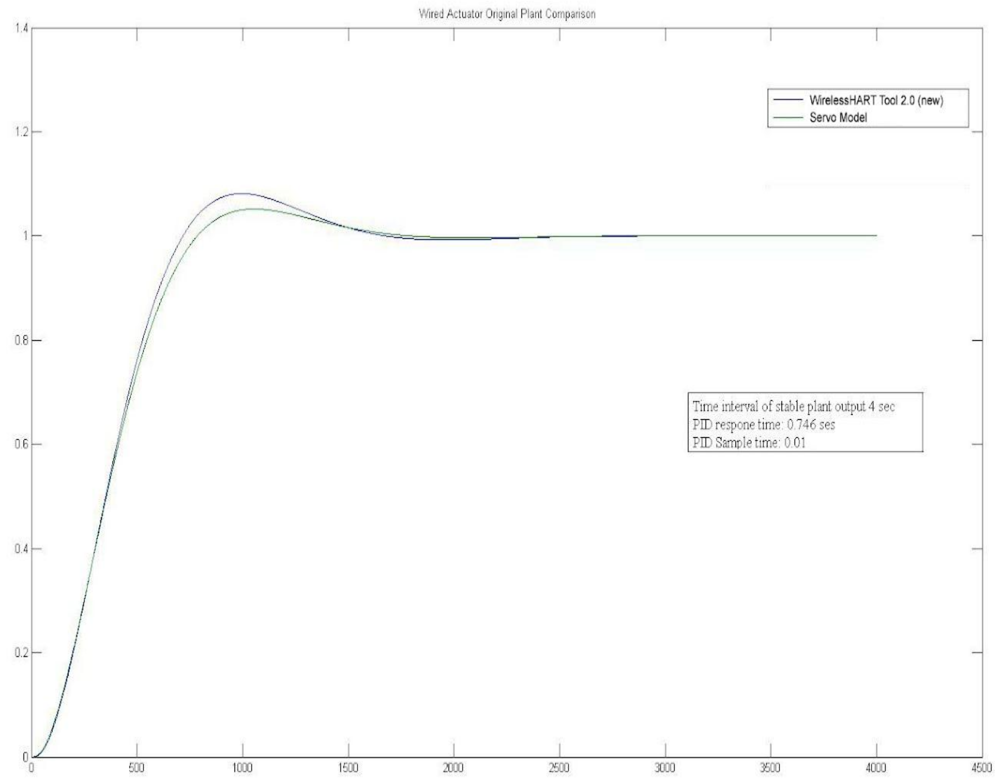


Figure 38: WirelessHART tool 2.0, Wired Actuator against Servo Model

Referring to Figure 38, the same PID response time was used as in the previous case. The Wired Actuators gave the expected results just slightly differing from the results of the Servo Model.

6.1.4 Test 3: The performance of Multi Channel and Single Channel

The test was conducted in order to assess the advantages of multi channel communication compared to the single channel communication. As shown in Figure 40 and 42, the scenario was utilizing the shorter schedule in multi channel communication. In both cases, the same model setup was used, as shown in Figure 39.

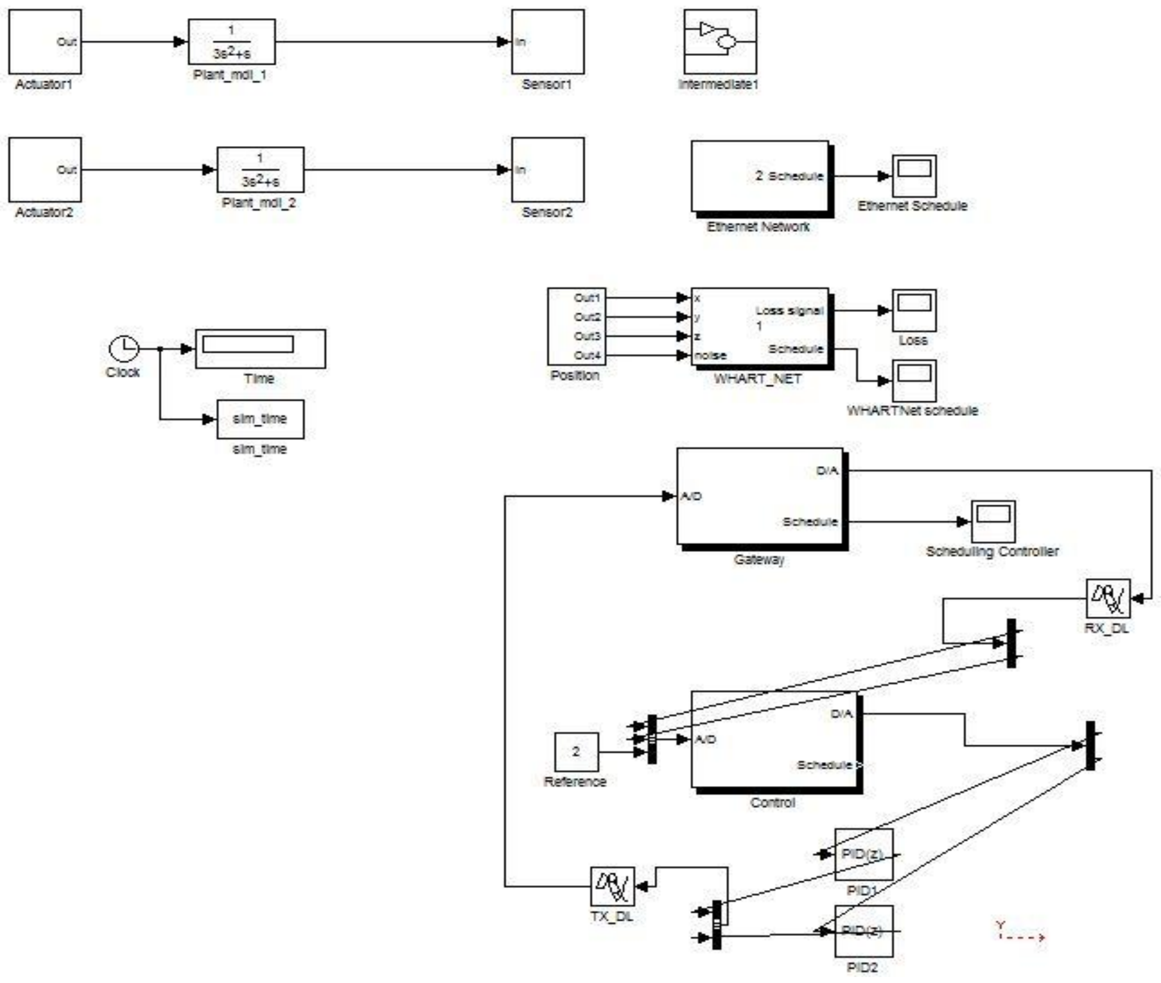
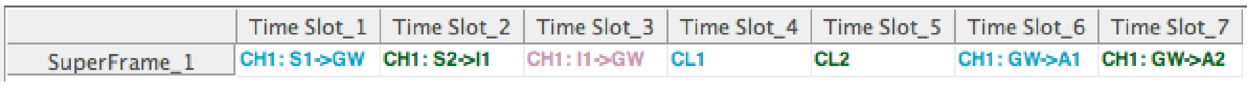


Figure 39: New WirelessHART Simulation Setup Model



	Time Slot_1	Time Slot_2	Time Slot_3	Time Slot_4	Time Slot_5	Time Slot_6	Time Slot_7
SuperFrame_1	CH1: S1->GW	CH1: S2->I1	CH1: I1->GW	CL1	CL2	CH1: GW->A1	CH1: GW->A2

Figure 40: Single channel in Schedule table

The result of the experiment was expected in Figure 41. Because of the long superframe, (0.07 sec) the two control loops were not expected to follow the Servo Model very closely, but they were expected to produce a similar result to the Servo Model. It was also predicted that the two control loops results would be very similar since they used have the same schedule turnaround time (superframe: 0.07 sec).

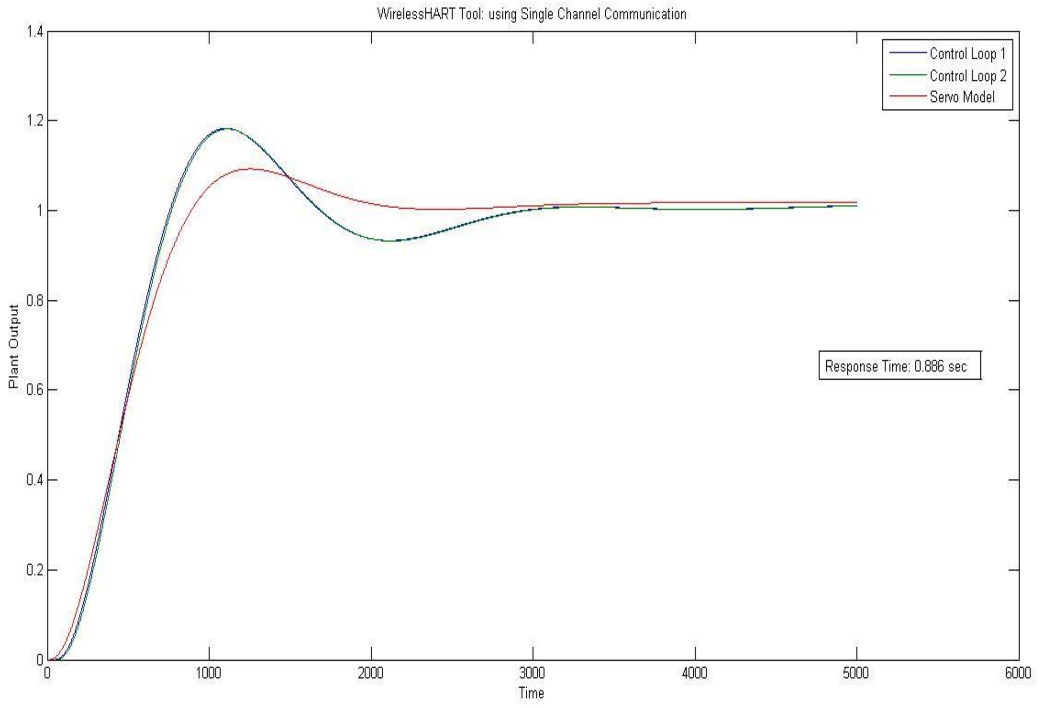
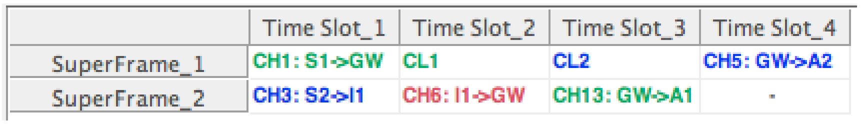


Figure 41: Result of single channel



	Time Slot_1	Time Slot_2	Time Slot_3	Time Slot_4
SuperFrame_1	CH1: S1->GW	CL1	CL2	CH5: GW->A2
SuperFrame_2	CH3: S2->I1	CH6: I1->GW	CH13: GW->A1	-

Figure 42: Multiple channels in Schedule table

As shown in the Figure43, the result of the Multi channel test was completely unexpected. The expected result was that both control loops would produce very similar result to the Servo model, but the two control loops just take off without giving a sign to turn towards the setpoint. The test results show that something was not right with simultaneous multi channel communication on the WirelessHART network. Since the actuators did produce outputs, the only explanation is that the messages did not arrive from the sensors after they were sent. The reason is that TrueTime does not support multiple frequency (channels) communication.

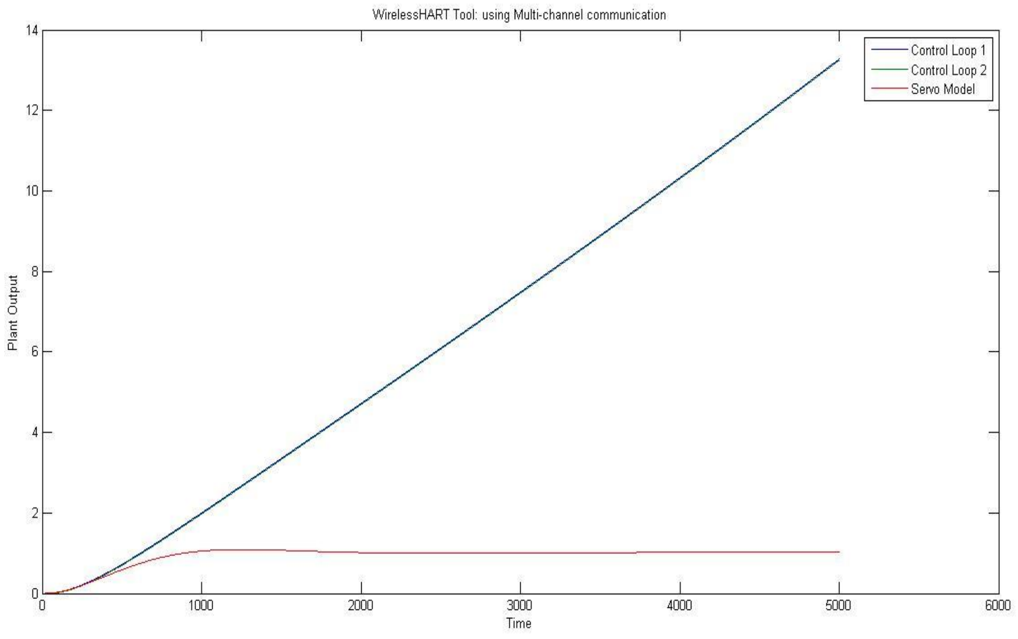


Figure 43: Result of Multiple channels

7. Discussion of Results

Test 1: The improvement of the WirelessHART Tool performance

When comparing the performance of the old tool and the new tool, the expectations were that the plant output using the new tool would be more similar to the plant output of the Servo model than when using the old tool.
The expectations were right the new Tool was way closer when comparing the results. The reasons for the performance difference are most likely to be the updates to the controller (both on the GUI and in the Simulation Model), since there were no changes made to the network or TrueTime.

Test 2: The performance of Wireless Actuator and Wired Actuator

The expectations in the second test were that the wired actuators would outperform (get closer) results to the Servo Model than the wireless actuators.
The forecast for test was right; the simulation using wired actuators did give a plant output closer to the Servo Model than the simulation using the wireless actuators. The reason is for the result is that the schedule turnaround time (superframe length) is shorter when using wired actuators.

Test 3: The performance of Multi Channel and Single Channel

The assumption before the test was that the plant output of the simulation utilizing the multi-channel functionality would get closer to the plant output of the Servo Model. The reason for making this assumption is that shorter superframes could be used and were used for the simulation with the multi-channel functionality.
The assumptions were wrong. The messages, which were sent in the first timeslot and contained the sensor values, did not arrive on the receiving node. After a short investigation, it was found that the multi-channel functionality was not implemented in TrueTime for WirelessHART.

8. Conclusion and Future work

The goal of this thesis was to evaluate the existing WirelessHART Tool, add new functionality without affecting already existing features and attempt to improve where problems are found.

Before the implementation started, the authors had to familiarize themselves with topics such as network theory, WirelessHART standard etc. and get to know the existing application structure of WirelessHART Tool in order to be able to map the new functionality.

There were many questions unanswered after the conducting research. In order to be able to proceed with the implementation, the unanswered questions were discussed with the customer and the appropriate solution was chosen. Each specific solution was evaluated and developed. In order to verify the correctness of the whole application, a few test specifications were created, used to assess the application and the results along with the specifications were demonstrated to the customer.

Some of these tests can be found in this paper. The results of the test comparing the old application to the new application have full-filled the expectations. The comparison of the wired and wireless actuators has given the expected results as well.

The test, comparing the multi-channel and single channel communication gave a surprising result. The multi-channel communication turned out not to be working at all. After a short investigation, it turned out that the problem was in the TrueTime implementation of WirelessHART. The problem was taken into discussion with the customer, who decided that there was not to correct the functionality in TrueTime.

Considering the documentation, the missing parts about the application structure, and functionality were added.

There are some suggestions, which should get priority when considering future work, on WirelessHART Tool.

First of all, there is possibility to implement object-oriented design in MATLAB. If the tool was implemented that way, it would be easier to extend, maintain, and respond faster.
Another suggestion is to reorganize the old code. Use different folders for files and move out the body of the callbacks from the GUI's callback file into different files.
The application needs additional testing of all its functionality and the simulation results need to be compared to some real life scenarios to see how reliable the tool is. TrueTime has to be modified in order to support multi-channel communication in WirelessHART. Since the feature in WirelessHART Tool is already implemented, there is no reason why it could not be used as soon as TrueTime is modified.

Otherwise, WirelessHART Tool proved to be a useful application with plenty of potential for other functionality such as, creating interface for testing automatic scheduler algorithms, an interface to allow easy replacement of the controller by external controllers in order to test their performance etc.

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