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TOWARDS RELIABILITY AND SAFETY IMPROVEMENT OF MEASUREMENT AND CONTROL PROCESSES ON SHIPS: IMPLEMENTATION OF WIRELESS HART PROTOCOL

BY

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Abstract. Measurement and control systems in maritime engineering applications are quite similar to those in shore based engineering applications except for some unique features which differentiate between each of them. These features are either related to the specific nature and purpose of the maritime application (Various types of commercial ships, oil/gas rigs and others) or linked to the harsh environmental conditions such as salinity, corrosion and vibration which usually exist in higher levels than shore based applications. Accordingly and due to such a specific nature of maritime engineering applications, more requirements should be considered to ensure reliability and stability for measurement and control process avoiding any negative effects that might be associated with such a unique engineering environment. As was discussed in (Abotaleb, 2021), smart transmitters based on hybrid analogue-digital (HART)

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and digital (Foundation Fieldbus and Profibus PA) communication protocols with additional diagnostic information, they might be a possible wired alternative for analogue transmitters (mostly based on 4-20 mA analogue standard). Similarly, wireless HART protocol can be an alternative for 4-20 mA analogue transmitters. This article will discuss the possibility of replacing classical 4-20 mA analogue transmitters with wireless HART smart transmitters on commercial ships as an example for maritime engineering application. The first section of the discussion will include a theoretical background for the basic principles of wireless HART protocol among other wireless technologies used in industrial automation. The second section of the article will discuss the possibility of utilising wireless HART protocol in the most common measurement and control systems on any commercial ship in order to discover the degree to which wireless HART can be fully or partially integrated with maritime engineering applications. Afterwards, better realization for such a concept will be rendered by an analytical planning case study conducted for tank level measurement system on different types of commercial ships. Based on both the theoretical and the analytical sections, the experimental section will manifest the importance of some of the necessary key elements to implement a reliable wireless HART network. These key elements are RSSI levels, supply voltage stability and the capability of wireless HART adapters to integrate between wired HART protocol and wireless HART network.

Keywords: Gateway; Wireless HART adapter; RSSI; Effective Range; RFI; EMI.

1. Introduction

Control and measurement systems on commercial ships are mostly based on using analogue standards, particularly 4-20 mA analogue standard. Hybrid analogue-digital or digital communication standards are good alternatives to consider for any possible planned system upgrade in the future. These standards provide improved performance as well as secured communication for these control/measurement systems. This article will discuss wireless HART as an example for digital wireless protocols replacing classical 4-20 mA analogue standard on commercial ships. Basic introduction for wireless HART protocol will be rendered at the beginning of the article linking it to other wireless standards dedicated for industrial automation such as ISA100.11a as well as other general use wireless standards such as WiFi, ZigBee and Bluetooth. This introduction will be presented from a perspective related to the possibility of coexistence between any of these standards and wireless HART. Afterwards, the article will discuss the necessary requirements for implementation of wireless HART networks on commercial ships including planning for the network as well as the required preventive measures to avoid possible negative effects from various sources of Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI). The article will also provide a general realization for the different types of measurement/control systems on any commercial ship. Such a realization will indicate the extent to which wireless HART protocol can be integrated with these systems and according to which criteria. Tank level measurement system is an example for such systems. It will be discussed through analysing the possibility of its integration with wireless HART protocol on different types of commercial ships (Container ships, tanker ships and bulk carrier ships). Ultimately, the experimental section of the article will include three parts. The first part will discuss the effect of uniform spacing between wireless HART field devices included in a wireless HART network on the level of Received Signal Strength Indicator (RSSI) at each of these field devices showing higher and fairly distributed RSSI levels at wireless HART transmitters when these transmitters were uniformly spaced. The second part of the experimental section will discuss the effect of reduced level of DC supply voltages at different elements of wireless HART network (Gateways and field devices) showing that successful communication can still be maintained at reduced DC voltage levels at both wireless HART gateway and field devices. The third part of the experimental section will discuss the possibility of using wireless HART THUM adapter to integrate a wired HART multidrop communication loop into a wireless HART network exhibiting that THUM adapter can provide the wireless gateway with identification information of all field devices connected to the wired HART multidrop network, however the measurement and control variables of only a single field device in the multidrop network can be provided to the gateway according to the adapter configuration.

2. Wireless HART

HART protocol was firstly introduced in the 80s as a hybrid analogue-digital protocol based on which many smart transmitters are built. Other than the classical analogue standards adopted in industrial automation, HART protocol rendered additional superimposed digital information to the 4-20 mA analogue current signal. This digital information provided additional features to the measurement/control process such as advanced diagnostics, event notifications and block mode transfers. There are three versions of HART protocol which are HART 5, 6 and 7. Wireless HART was firstly presented at HART 7.1 as an extension for HART protocol. It was approved as a standard which specifies a wireless communication network by the International Electrotechnical Commission (IEC 62591) in 2010. Wireless HART network is a mesh network in which various types of devices are included such as network managers, network security devices, access points, adapters, routers and handheld devices. As an extension for wired HART protocol, wireless HART shares the same application layer with wired HART where three types of HART commands are used (Universal commands, common practice commands and device specific commands) (Chen *et al*., 2010, p. 5-8; Hassan *et al*., 2017; Kim *et al.*, 2008).

Time Division Multiple Access (TDMA) (Chen *et al*., 2010, p. 5-9, p. 19-48; Kim *et al*., 2008) is the mechanism embraced by wireless HART protocol to schedule communication between field devices. Communication tasks are performed in 10 ms time slots which are divided into two types, single time slots and shared time slots. If communication tasks are performed with only one field device during the time slot, it will be called a single time slot, however if multiple field devices performed their communication tasks during the same time slot, it will be called a shared time slot. In order to minimise the probability of collision between messages transmitted from multiple field devices during shared time slots, CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) (Chen *et al*., 2010, p. 139-149) supervises the transmission process from these field devices through using exponential back-off algorithm. Wireless HART protocol has its own Medium Access Control MAC sublayer (Kim *et al*., 2008; Chen *et al*., 2010, p. 8-12, p. 19-25, p. 89-111, p. 139-185; Hassan *et al*., 2017) carrying out assignments of slot timing, link scheduling and administrating communication tables and buffers. Slot timing is provided by a timer module included in MAC layer. Each 10 ms time slot is divided into shorter time intervals based on the type of communication transaction (Transmitting/Receiving) taking place in such a time slot. Therefore, these shorter time intervals in source device time slots differ from those time intervals in destination device time slots. The timer module included in MAC layer indicates the periods of both time intervals at source and destination time slots. Communication tables include four types of tables (superframe table, link table, neighbour table and graph table). The basic principle of link scheduling is to recognise the next time slot that should be serviced by the field device and whether it is receiving (listening for new packet) or transmitting time slot (propagating a packet onward through the mesh network). If a time slot has a packet waiting to be transmitted and receiving a packet at the same time, the priority will be for packet transmission. It would be worth mentioning that link scheduling is not that simple because if a high priority transaction failed to be transmitted, it will be rescheduled to another link that might be designated for lower priority transaction which consequently leads to rescheduling of the lower priority transaction as well. This sequential process might even lead to deleting some superframes.

Frequency Hopping Spread Spectrum (FHSS) (Chen *et al*., 2010, p. 138-139; Shukla *et al*., 2016) as well as Direct Sequence Spread Spectrum (DSSS) (Chen *et al*., 2010, p. 138-151; Deshmukh and Bhosle, 2016) are two important features of wireless HART protocol. DSSS reduces the overall signal interference by increasing its bandwidth. Increasing the signal bandwidth is achieved by using a pseudo-noise (PN) bit sequence in which bit duration is shorter than the bit duration of the signal which will be modulated. The modulation technique adopted by wireless HART is Offset Quadrature Phase-Shift Keying (O-QPSK). FHSS adopts frequency hopping technique in which the modulating signal frequency is continuously changing in a frequency band less than 1 MHz. The pattern according to which the frequency hopping process takes place is determined by a pseudo-random sequence synchronized at both transmitter and receiver sides. Generally, Spread Spectrum (SS) spreads the signal power over a wideband and the overall SNR (Signal to Noise Ratio) is enhanced because only a small part of spread spectrum signal will be affected by interference. Combining both FHSS and DSSS leads to improved privacy, higher immunity levels to interference and multi path fading, increased signal capacity, increased signal to noise ratio in addition to better bandwidth efficiency.

3. Wireless HART and other wireless technologies

The closest competitor for wireless HART protocol is ISA100.11a. They are both quite similar except for some differences which distinguish between both of them. They both share adopting FHSS and DSSS techniques. Wireless HART protocol does not define explicitly the frequency hopping pattern, however ISA100.11a defines 5 patterns for frequency hopping (Petersen and Carlsen, 2011) among which the fifth pattern which is dedicated to the coexistence with wireless HART protocol. From a scalability point of view, both of wireless HART and ISA100.11a protocols can handle up to 50-100 devices depending on the update rate of the devices. Moreover, both protocols adopt nearly the same techniques to render maximised levels of security to the network by similar payload encryption and message authentication mechanisms as well as similar keying models. Counter with Cipher block chaining Message authentication code (CCM) mode as well as Advanced Encryption Standard (AES)-128 are used by both wireless HART and ISA100.11a to ensure data encryption and privacy. Wireless HART protocol uses join key, network key and session key. Similarly, ISA100.11a uses join key, master key, DL (Data Link) key and session key, however using join key in ISA100.11a is optional (Petersen and Carlsen, 2011; Devan *et al.*, 2021). Only wireless HART protocol and ISA100.11a are considered as standalone wireless standards dedicated to wireless communication in industrial automation. Other wireless standards such as WiFi, Bluetooth and ZigBee can be used in household applications as well as industrial automation. On the other hand, these standards don't provide the same security level required for industrial automation applications as rendered by both wireless HART protocol and ISA100.11a. Accordingly, the best use for wireless standards such as ZigBee (Lennvall *et al.*, 2008), Bluetooth and WiFi in conjunction with industrial automation is to coexist with both wireless HART protocol and

ISA100.11a particularly ZigBee and WiFi. This coexistence can be manifested in executing tasks such as collecting groups of wired measurement signals to integrate it with wireless HART protocol or ISA100.11a. (Hassan *et al*., 2017; Devan *et al*., 2021). From an economical point of view and according to a case study, an industrial plant in which 70% of automation systems were based on conventional wired technology while 30% of the automation systems were based on wireless technology, it can achieve up to 48% saving in cost less than a plant that is entirely based on conventional technology (Emerson, 2016).

4. Implementation of wireless HART

4.1. Network Planning

In order to implement a reliable robust wireless HART network, there are many considerations (Emerson, 2016) that should be taken into account. These considerations can be briefly summarised as follows:

1- Fully detailed realization of the location at which the wireless HART network is planned to be installed. This realization should include:

- Knowledge of the detailed infrastructure at the network location provided by updated scaled engineering schematics.
- Knowledge of the environmental conditions at which the network will be installed and to which extent it might influence the network performance (lightning and snow).
- Knowledge of possible sources for EMI (Electromagnetic Interferences) or RFI (Radio Frequency Interference) at the site at which the network will be installed.

2- Identifying the measurement quantities which can be better processed wirelessly and choosing the proper wireless HART transmitters which will be used to measure them (Emerson, 2016; Han *et al*., 2010).

3- Based on the time constant of the selected wireless transmitters, their update rates will be calculated. For monitoring and open loop applications, the update rate should be 3-4 times faster than the time constant, however for regulatory closed control loop applications, the update rate should be 4-10 times faster than the time constant (Emerson, 2016).

4- Calculating the number of gateways required for the network based on the total number of wireless transmitters in the network as well as the assumed spare capacity in the project (40%) (Emerson, 2016).

5- Identification of the exact locations of the wireless transmitters included in the network on the engineering site. Based on these identified locations, the location of the gateway/gateways will be determined. Gateways should be distributed in the network as marshaling panels or junction boxes so that each gateway can cover a specific area section in the network (Segmentation) (Emerson, 2016).

6- In order to achieve maximized levels of robustness and reliability in wireless HART mesh network and also to ensure more possible links between network nodes, 4 important rules (Emerson, 2016) should be taken into account:

- Rule of minimum 5: Each gateway should have at least five field devices within its effective range.
- Rule of minimum 3: Each field device should have at least three neighbour field devices within its effective range.
- Rule of Percentage: For networks with field devices with update rates slower than 2 seconds or networks with 20% of field devices with update rates faster than 2 seconds, each gateway should have at least 25% or 50% of network field devices within its effective range, respectively.
- Rule of maximum distance: For networks with field devices faster than 2 seconds, each field device should be located within the effective range of two neighbour field devices which are both located within the effective range of the gateway.

The previously explained rules are not mandatory to be applied for each wireless HART application as the network in most of the cases can function properly without these rules totally applied (they can be partially applied).The limitations imposed by the infrastructure of the network as well as the inflexible mobility of some wireless transmitters (the exact location of many transmitters either can't be modified or can only be modified to a very limited extent) are two obstacles which might restrict the possibility of full implementation of these four rules. Applying these rules results in:

- Increasing the number of possible links between different nodes in the network.
- Improving the efficiency of link scheduling process between field devices.
- Increasing number of neighbour field devices for each field device.
- Reduction of the power consumed by field devices due to improved efficiency of link scheduling process by adopting shorter (faster) links between nodes which leads to increasing field devices' batteries lifetimes.
- Improving the overall reliability and robustness of the network by the increased number of both neighbour field devices and number of links between nodes which leads to a minimised possibility of network failure due to inactive nodes (damaged field device, for instance) as the network manager will immediately adopt another routing link in which this inactive node will be excluded.
- Reducing latency of the network due to more efficient link scheduling abased on shorter faster routing links.

These 4 rules are strongly dependent on the knowledge of the effective range of different types of field devices (transmitters, repeaters and gateways) in wireless HART network. The effective range of any wireless device is determined by multiple factors such as transmitter signal power, gain of the transmitter antenna, free space loss, return loss, cable loss (in case of using remote antennas) and sensitivity of the receiver antenna. Emerson wireless HART network installation guide defines 4 values for effective range based on the physical obstruction density level in the premises where wireless HART network will be implemented. For high, medium and low physical obstruction density level in addition to clear line of sight, these defined values of effective range are 30 m, 76 m, 152 m and 228 m, respectively (Emerson, 2016).

4.2. Considerations to avoid RFI

Emerson wireless HART installation guide proposed some recommendations to avoid any possible negative influence on wireless HART network induced by Radio Frequency Interference (RFI). These recommendations can be summarised as follows (Emerson, 2016):

- Limiting 802.11N applications to 5.8 GHz ISM radio band.
- Using low-pass filters on all high-power RF systems.
- Putting high bandwidth wireless applications such as security cameras in the 5.8 GHz radio band.
- Ensuring that all RF coaxial cables are properly installed with weather sealant tape or comparable method to mitigate reduction in performance due to exposure to the environmental elements.

Additionally, a description for the most common sources of RFI on commercial ships can render more profound perception while discussing the effect of RFI on wireless HART networks linked to the subject of this article. There are several communication systems on any commercial ship. GMDSS (Global Maritime Distress Safety System), AIS (Automatic Identification System) and X-Band/S-Band radars are examples for such systems. Each of these systems has its own dedicated antenna or group of antennas as in GMDSS. These antennas are usually mounted on the 'monkey Island' above the navigation bridge. GMDSS (Tenese, 2019; Bhattacharjee, 2021) is an automated emergency signal communication system for ships at sea developed by International Maritime Organisation IMO. INMARSAT, NAVTEX and DSC are examples of subsystems included in GMDSS system. NAVTEX (Oruc *et al*., 2022; Mukherjee, 2021) is an acronym for Navigational Telex (Navigational Text messages). NAVTEX devices are used on board to provide short range maritime safety information. NAVTEX receivers works on two medium frequencies of 490 kHz and 519 kHz and can cover an area up to 400 nautical miles. INMARSAT (Tetley *et al*., 1994) is a satellite communication system used to provide services such as telex, telephone and other types of data transaction from ship to ship as well as from ship to shore with high priority given to telex and telephone services from ship to shore rescue centres. The frequency band of satellite communication in INMARSAT system (Tetley *et al*., 1994) is dependent of the version of the system, the location of the ship as well as the type of service provided by communication process at a specific moment whether it was uplink, downlink, ship to ship, shore to ship, ship to shore or others. L-band (1-2 GHz), C-band (4-8 GHz), Ku-band (12-18 GHz), Ka-band (26.5-40 GHz) are the mostly used bands in different versions of INMARSAT system. L-band and C-band are the mostly related to the subject of this article whereas wireless HART adopts a very close ISM frequency band of 2.4 GHz to both of L and C bands. AIS is a universal ship borne Automatic Identification System (Serry, 2017; Slupak, 2014). It is used to provide the most important information about the ship's location and its voyage. It performs such as task by using two types of transponders (Class A and Class B) to send out data packets every few seconds through two marine VHF channels (161.975 MHz and 162.025 MHz). Marine X-band (10 GHz) and S-band (3 GHz) radars (Bhattacharjee, 2021) on commercial ships are used for the purpose of identifying, tracking and positioning for ships. The higher frequency X-band radar provides sharper images and better resolution, while the lower frequency S-Band radar is used more frequently for identification and tracking especially in rough weather conditions such as rain and fog. Similarly to INMARSAT system operating in L-band range of frequencies, S-band marine radars are also operating in a frequency range close to the ISM 2.4 GHz frequency band adopted by wireless HART protocol. If this proximity between the frequency bands of wireless HART protocol and other communication equipment on ships was considered as a possible RFI source, it can lead to possible negative effect on the SINR (Signal-to-Interference-plus-Noise Ratio) as well as degraded throughputs as mentioned in similar research (Ghorbanzadeh *et al*., 2015) on the in-band and out-of-band interference induced by S-Radar into LTE macro and small cells uplinks in the 3.5 GHz band. Moreover, some shore conveyors/cranes are operated wirelessly, which might be a possible source for RFI if these shore loading/discharging equipment adopted wireless technologies in frequency bands close to the 2.4 GHz frequency band.

Narrowband RFI (Ferrara *et al*., 2018), all-band RFI and RFI due to adverse weather conditions are three types of RFI that should be avoided during planning phase of wireless HART network. Low SINR is a possible negative effect induced by Narrowband RFI in 802.11 networks (Gummadi *et al*., 2007). As wireless HART protocol shares a lot of features with 802.11 standards, it can also endure the same negative influence. Considering the fact that maritime engineering applications are installed in very harsh environmental conditions, wireless HART network might suffer attenuation induced by RF interference associated with heavy rain conditions. In addition to the heavy rain, high temperatures as well as high relative humidity levels can lead to decreased RSSI levels in 2.4 GHz frequency band as was concluded in (Amajama, 2016; Umar *et al*., 2015).

4.3. Considerations to avoid EMI

EMI on commercial ships exists in extremely high levels manifested in numerous sources widely spread in various locations on board. Synchronous AC generators, high power AC motors and different converters are main sources of EMI on any commercial ship. They are mostly located in engine room except for some motors located on main deck which are dedicated to cargo operation (Cargo Cranes) or berthing/anchorage operation (windlass and anchorage winches). The negative impact of EMI induced by large electric motors on industrial wireless networks (Chilo *et al*., 2009) can take stronger forms in frequency bands lower than 200 MHz where not many wireless communication standards are located. Similarly, in frequency range of 1880-1890 MHz (Close range to the 2.4 GHz frequency band), high EMI levels were also noticed. If EMI was considered from a perspective related to industrial automation systems sharing both wired and wireless technologies in the same plant, it is recommended that both wired and wireless technologies adopted in the plant would share the same communication protocol which renders more resistance to EMI (Gaj and Mackowski, 2020). In other words and for ensured lower levels of EMI, if the majority of wired field devices in a specific plant were based for example on HART protocol, it will be recommended to use wireless HART (not ISA100.11a) field devices in case of planned upgrade for the plant to wireless technology.

5. Application of Wireless HART in Maritime Engineering (Commercial Ships)

5.1. General Criteria

Commercial ships vary in their types according to the nature of cargo handled by each type of these ships. In this article and while discussing the possibility of applying wireless HART protocol on commercial ships, three types of ships will be taken into account: bulk carriers, container ships and chemical tankers.

Control and measurement systems on these types of ships are quite similar except for some features that distinguish between similar systems on different ships. Most of control and measurement systems on any commercial ship are centralised at Engine Room (ER) except for several systems dedicated to navigational or safety purposes (Autopilot and Fire Alarm systems) which are centralized at the bridge. In order to classify control and measurement systems on any commercial ship from a perspective related to the application of wireless HART protocol in the maritime field, the following considerations should be taken into account:

- The location at which control/measurement system is centralized and to which degree it is widely spread all along the vessel.
- The type of control/measurement signals (Digital input, digital output, analogue input or analogue output) used in the system and the purpose to which they are dedicated (remote monitoring, in-plant monitoring, safety, open loop control, closed loop control)(Emerson, 2016; Han and Aloysious, 2010).
- The degree of difficulty that might be associated with mounting process of wireless HART transmitters replacing wired transmitters especially these dedicated to a particular system and if it will be easily fitted in such a system or not.
- The expected economic efficiency of upgrading a system based on wired technology to wireless HART and if it will achieve a considerable saving in the cost of installation and commissioning.

Accordingly, it is highly recommended that wireless HART will operate more efficiently in systems where:

1. Signals processed are digital inputs, digital outputs or analogue inputs.
2. Signals processed are dedicated for monitoring purposes (Not control or safety purposes which requires higher speed and reliability levels)
3. Signals processed are widely spread over large areas with less density of ship metallic infrastructure.
4. Signals where wireless HART transmitters can be easily mounted to replace wired transmitters without the need for many modifications in system structure.

Table 1

Classification of Safety, Control and Monitoring signals at the most Common Measurement/Control systems on Commercial Ships and possibility of their integration with wireless HART Protocol (Rough Estimation according to 1st author practical experience)

System	Safety	Control	Monitoring	Location	W. HART Integration Possibility
M/E Safety and Control	*50%*	*30%*	*20%*	*ER*	*Average*
A/E Safety and Control.	*40%*	*40%*	*20%*	*ER*	*Average*
Alarm Monitoring System.	*0*	*0*	*100%*	*Widely Spread*	*High*

PMS	*45%*	*45%*	*10%*	*ER*	*Low*
Boiler	*50%*	*45%*	*5%*	*ER*	*Low*
Incinerator	*50%*	*45%*	*5%*	*ER*	*Low*
Sewage Treatment Plant	*30%*	*30%*	*30%*	*ER*	*High*
Tank Level Measurement	*0*	*0*	*100%*	*Widely Spread*	*Very High*
Valve Remote Control	*30%*	*45%*	*25%*	*Widely Spread*	*Average*
Fire Alarm	*50%*	*20%*	*30%*	*Widely Spread*	*Low*
Water Mist Fire Extinguishing	*50%*	*30%*	*20%*	*ER*	*Low*

A general economical factor should be considered when it is planned to integrate wireless HART protocol into a wired control/measurement system that is already installed. The basic principle of such a factor is that if an installed working wired transmitter is extremely cheaper than its alternative wireless transmitter, it will not be recommended to replace it. It would be better to include it among a group of wired transmitters which will be integrated into the wireless network using a single device such as an adapter. According to the brief illustration in table 1, it can be observed that fully integration of wireless HART protocol is limited to tank level measurement system which is a purely monitoring system, however wireless HART can still be partially integrated into systems such as AMS (Alarm Monitoring System) which collects monitoring signals (digital inputs or analogue inputs) from all the previously mentioned systems. In all systems, there will be always a monitoring signal or group of signals dedicated for AMS. Examples for these signals are:

- Exhaust gas temperatures at M/E (Main Engine) and A/E (Auxiliary Engine).
- Cooling fresh water temperatures at M/E and A/E.
- Cooling sea water temperatures at M/E and A/E.
- Lubrication oil temperature alarm for A/E.
- Lubrication oil low pressure alarm for A/E.
- Voltage, current and power levels at generation units as well as at main switchboard in Power Management System (PMS).
- Boiler water level, steam pressure and exhaust temperature.
- Exhaust temperature of incinerator system.
- High / low tank level of sewage treatment plant.
- Fire alarm from different zones on the ship.

If these signals were planned to be transmitted to AMS using wireless HART, this can be performed using the following options:

- Replacement of wired transmitters with wireless HART transmitters.
- If the original signal is a wired HART signal, a wireless HART adapter can be used to convert this signal into a wireless HART signal. Wireless HART adapter is connected in series with HART 4-20 mA current loop to provide wireless communication using wireless HART protocol. An example for such a case can be applied for exhaust gas temperature transmitters in A/E where exhaust temperature transmitters are usually TC or Pt100 transmitters with probes able to measure temperatures up to 400-500 Celsius degrees. The terminals of these TC or Pt100 transmitters can be connected to wired HART R/I transducers forming a single current loop including wireless HART adapter in a multidrop communication topology (Emerson, 2017).
- Converting classical analogue signals into a 4-20 mA HART signal using devices such as Temperature Concentration Module (TCM) (Moore, 2020) to convert analogue measured signals from different types of temperature transmitters into HART communication signal which can be easily integrated into wireless HART network using wireless HART adapter.
- The possibility of coexistence between wireless HART and other wireless HART standards (WiFi, ZigBee or ISA100.11a) allows for possible implementation of microcontroller based electronic modules which are capable of collecting several wired signals to transmit it wirelessly with identified addresses using wireless standards other than wireless HART. The collected wirelessly transmitted information can be integrated later into wireless HART network using software based tools implemented particularly for such a purpose which is a point of a great interest that will be subjected to detailed future analysis.

For monitoring signals dedicated to Main Engine (M/E), they are usually the output signals of signal conditioners or splitter units the inputs of which are those signals coming directly from transmitters mounted on the engine. This technique is usually used with M/E exhaust gas temperature transmitters as well as cooling water temperature transmitters in order to obtain two 4-20 mA current signals out of the same transmitter, one is dedicated for safety and control (activating slowdown of Main Engine in case it exceeded a preset limit) and the other is dedicated for monitoring. Therefore, the 4-20 mA current signals dedicated for monitoring in M/E are coming from a control panel which includes these signal conditioners or splitters. In most of the cases, this control panel is located very close to AMS system in control room, which makes it impractical as well as economically non efficient to use wireless technology in such a close proximity, however if this control panel was located somewhere in engine room close to the transmitters, it would be practical as well as cost effective to consider using wireless HART with the option of grouping these signals in one HART current loop including a wireless HART adapter.

In addition to using wireless HART adapter with wired HART signal, there are other possible techniques to integrate wired HART signal or group of signals into wireless HART network. These techniques (Raza and Voigt, 2010) are:

1. Using HART-to-Wireless HART Gateway as a PC card in the same PC board where HART modem is plugged in.
2. Using the gateway as a part of HART input/output subsystem. Each I/O system must have one or more cards and each card must have one or more channels. Gateway can be plugged in as a card in the I/O system.
3. Using serial communication interface (recommended RS485 full duplex multidrop serial interface), gateway can be connected to Field Transmission Assembly (FTA) or I/O system.
4. Using Wireless HART Integrator (WHI) to connect with wireless HART field devices and gateway through IEEE 802.15.4 wireless interface and also to connect with wired HART master using RS485 interface or Ethernet. Unlike WHI, wireless HART adapter connects with HART field device using 4-20 mA current loop and connects with wireless HART field devices and gateway through IEEE 802.15.4 wireless interface. The HART master can be I/O system, Distributed Control System (DCS), field controller, or a Field Transmission Assembly (FTA).

5.2. Tank Level Measurement System (Analytical Planning Case Study)

Tank level measurement system is a monitoring system the purpose of which is to measure fluid levels in different types of tanks on the ship. Brief description for the system on a bulk carrier ship as well as the problems associated with the system was presented in (Abotaleb *et al*., 2021). The system is based on using classical 4-20 mA analogue pressure transmitters. As explained in (Abotaleb *et al*., 2021), most of the problems linked to the system were related to the measurement of sea water levels in ballast water tanks (double bottom tanks and top side tanks). If a partial integration of wireless HART protocol into the system was considered, radar level transmitters (Rosemount 3308) will be used to replace 4-20 mA classical transmitters immersed in the bottom of the top side tanks. For double bottom tanks which can be accessed only through pipe tunnel, it will be extremely difficult to use a wireless HART transmitter for each tank due to the specific nature of the tanks' accessing area (Pipe Tunnel or Duct Keel).

Pipe tunnel area (Fig. 1) is an extremely narrow area located at lowest vertical level of the ship extending horizontally along the ship's length from the forward station to the engine room. This area includes extremely high density of piping as well as metallic structure, which minimizes the possibility of any uniform RF propagation in this area especially that these sections dedicated for mounting the transmitters are separated with high thickness metallic frames (Agarwal, 2021).

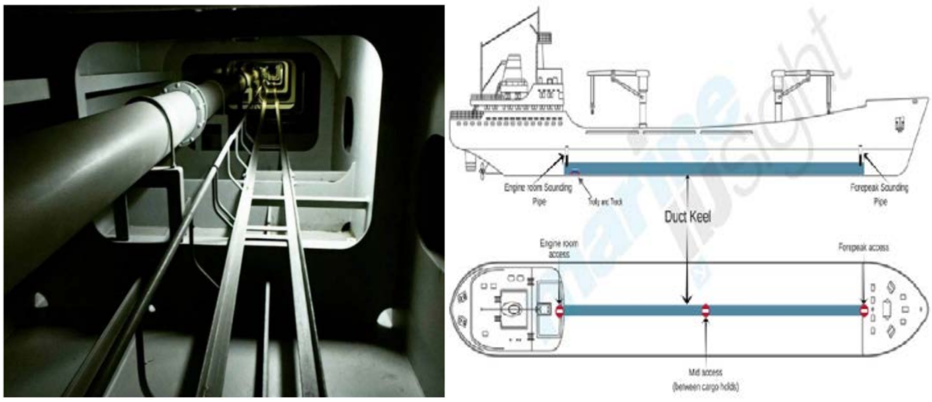


Fig. 1 – Duct Keel or pipe tunnel (Agarwal, 2021).

Therefore and in the case of double bottom tanks, wireless HART protocol can be implemented using wireless HART adapters to be connected in series with 14 HART transmitters using multidrop communication topology. The location of the wireless HART adapter is recommended to be close to either forward station or to the engine room. If the wireless gateway communicating with wireless transmitters dedicated for top side tanks is located at forward station, the wireless HART adapter should be located close to the forward station. On the other hand, if the wireless HART network was extended to include more wireless HART transmitters or wirelessly integrated signals inside the engine room, the wireless HART adapter dedicated for double bottom tanks can also be mounted in a position close to the engine room. Remote antenna option can be used in such a case where ship's metallic structure might be a possible obstacle for RF propagation. Accordingly, wireless HART adapter can be included in the multidrop communication loop in pipe tunnel measuring double bottom tank levels and connected to a remote wireless antenna located at the forward station or the engine room using LMR-400 cable. There is another alternative which can also be considered to integrate double bottom multidrop communication loop into wireless HART network. This alternative is based on using two wireless HART adapters; the first of them will be mounted close to the forward station while the second will be mounted at the end of the pipe tunnel close to the engine room. Each of these two adapters will be included in a multidrop communication loop in which 7 HART transmitters are included. In other words, there will be 2 multidrop communication loops; each of them consists of 7 HART pressure transmitters plus a wireless HART adapter. If the second alternative solution was taken into account, two remote antennas will be mounted on forward station as well as in engine room.

The possibility of integrating wireless HART protocol into tank level measurement system on different types of ships might confront additional obstacles mostly related to the attenuation induced on wireless HART signals by the continuously changing density of metallic obstructions on each type of these ships during operational conditions. The following three examples will render more practical perception for the possibility of integrating wireless HART protocol into tank level measurement system on most common types of commercial ships.

5.2.1. Container Ships

The extremely dense existence of metallic obstructions on container ships (Fig. 2) nearly eliminates any possibility for mounting any wireless HART transmitters, gateways or even repeaters on the ship's main deck. These metallic obstructions include loaded containers and cargo cranes (if available). Containers are loaded in multi-vertical (can reach a height up to 20 meters or more) as well as multi-horizontal levels according to the ship's capacity. The height of each container is almost 3 meters while the length differs from 6 to 12 meters for 20 feet and 40 feet containers, respectively (Hapag-Lloyd, 2016). Additionally and other than the attenuation induced on RF wireless signals by this high density of metallic objects, extremely harsh loading/discharging operational conditions (lashing and stowing) can also be considered an obstacle in the way of applying wireless HART technology on container ships. Due to lashing/stowing operations, there can be high possibility of damaging any wireless devices mounted on the main deck. Pressure transmitters dedicated for measuring sea water ballast tank levels on container ships are usually mounted either in void spaces or in pipe tunnel in order to avoid any possible physical damage due to operational conditions.

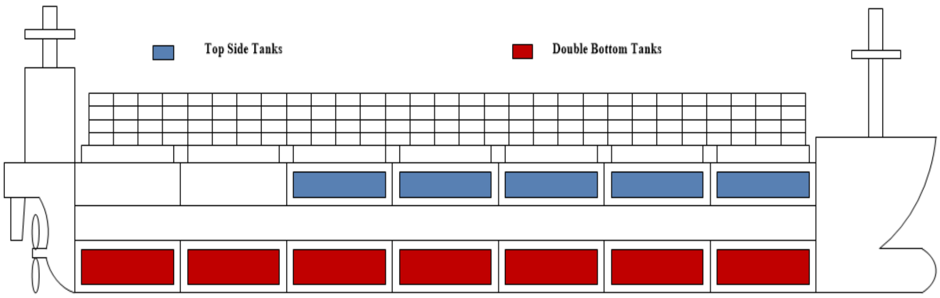


Fig. 2 – Top Side and Double Bottom Ballast Water tanks in container ship.

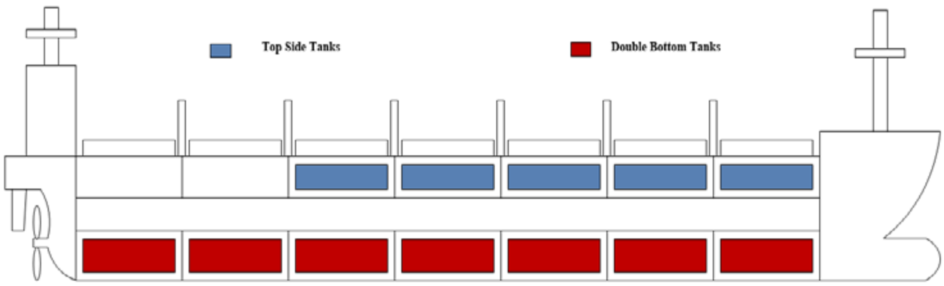
5.2.2. Tanker Ships

The nature of structural as well as operational conditions in tanker ships allows for very high possibility of applying wireless HART protocol in tank level measurement system. If a partial integration of wireless HART protocol on a tanker ship was considered to measure ballast water tank levels using wireless HART transmitters, it will not be difficult to mount different types of wireless HART equipment (gateways, field devices or repeaters) on the main deck due to very low density of metallic obstructions which is limited to piping and pumping equipment at a height level of 4-5 meters. Moreover, smoother loading/discharging operations than both container and bulk carrier ships result in higher effective range of wireless HART equipment as well as less restrictions on mounting wireless equipment on the main deck.

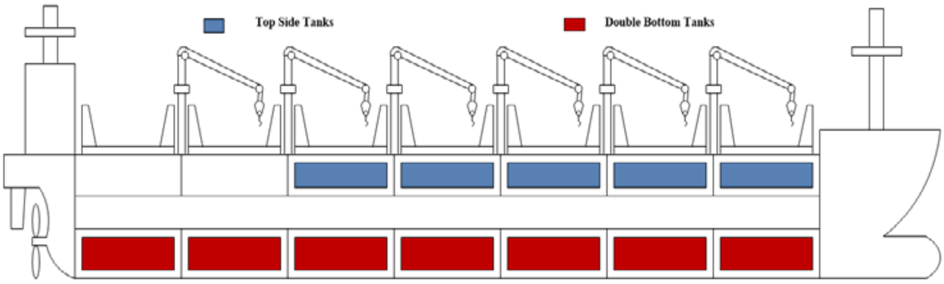
5.2.3. Bulk Carrier Ships

On bulk carrier ships and in order to provide more practical perception for the extent to which wireless HART protocol can be partially integrated into tank level measurement system (Measuring only ballast water tank levels wirelessly), three operational conditions should be taken into account:

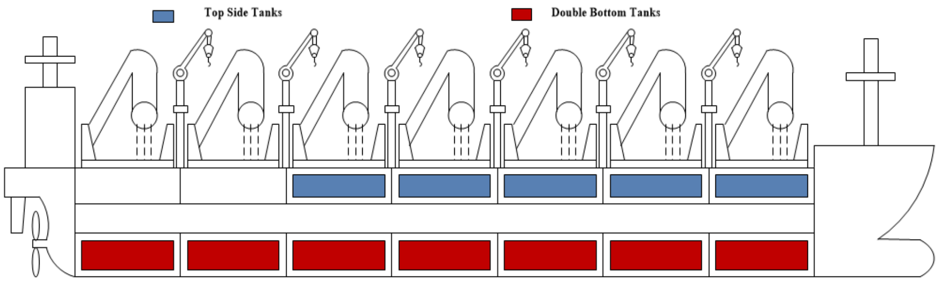
- No loading/discharging operations. (Assumed effective range: 152 meter)
- Loading/discharging operations using ship's cranes. (Assumed effective range: 76 meters)
- Loading/discharging operation using shore equipment (conveyors or cranes) without using ship's cranes. (Assumed effective range: 30 meters).



(a)



(b)



(c)

Fig. 3 – Top Side and Double Bottom Ballast Water tanks on bulk carrier ship in conditions of no loading/discharging, loading/discharging on ship's cranes and loading/discharging using shore cranes sorted from (a) to (c), respectively.

The partial integration of wireless HART protocol into tank level measurement system is based on using wireless HART radar transmitters such as (Rosemount 3308) for measuring water level in top side ballast tanks. For double bottom tanks and as was previously explained, the partial integration of wireless HART protocol will be based on using wireless HART adapter in a multidrop communication loop including HART pressure transmitters (Rosemount 3051S) dedicated for double bottom tanks. Assuming that time constant of wireless transmitters is 500 ms (Santos *et al*., 2017), the update rate of wireless HART radar transmitter will be from 1.5 to 2 seconds. Based on the calculated update rates of the transmitters, maximum capacity of gateway will be indicated. For 1420 wireless HART Emerson gateway, maximum number of field devices is 12 or 25 devices for update rates of 1 or 2 seconds, respectively (Emerson, 2020). According to the gateway capacity and number field devices in the network with assumed spare gateway capacity of 40%, the number of gateways will be calculated using Eq. (1).

$$No. of\ Gateways = Roundup\ [D/C(1 - S)] \tag{1}$$

Where: D is the number of field devices, C is the gateway assumed capacity and S is the gateway assumed spare capacity percentage.

According to the previously mentioned operational conditions, effective range of field devices will be indicated. Based on the assumed effective range of field devices, it will be decided whether to fortify the network by adding repeaters or not. A very important factor should be considered when planning for a wireless HART network on a bulk carrier ship where field devices will be located on main deck. This factor is that the space designated for mounting the field devices (transmitters and repeaters) is limited to the sideways of the ship and the space between cargo holds where mast houses are located. The main cause for such a limitation is to avoid possible damage of the field devices due to extremely rough operational conditions during loading/discharging. Therefore, the existence of mast houses between cargo holds plays an important role in fortifying wireless HART network whereas repeaters can be mounted on the mast houses or inside the mast houses with remote antennas installed on the top of it. Another important factor linked to the nature of tank level measurement system (in relation to Ballast Water Tanks) is that system is mostly needed during loading /discharging operations where ballasting/de-ballasting operations take place. During sailing, ballast tanks on a bulk carrier ship are either completely filled (empty cargo holds), totally empty (fully loaded cargo holds) or partially filled (partially loaded cargo holds). Sailing and anchorage periods might extend from several days to few months with ballast water tanks having the same sea water level, however during cargo operation, sea water levels in the tanks are rapidly and continuously increasing or decreasing to compensate discharging or loading operations, respectively. Based on such factors, it can be affirmed that tank level measurement system is mostly needed when transmitters are continuously sending data during cargo operations. The effective range of the field devices will be 152 m, 76 m or 30 m corresponding to conditions of sailing, loading/discharging operations by ship's cranes or loading/discharging operations by shore cranes, respectively.

Considering the case when the effective range is 152 meters (Fig. 3a), the rule of minimum 5, the rule of minimum 3 and the rule of percentage will all be fulfilled as illustrated in Fig. 4. Therefore, there will be no need to add any repeaters to the network.

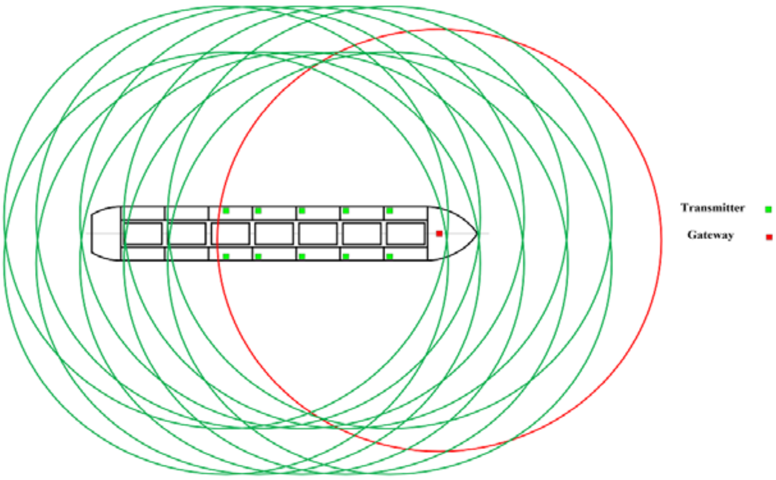
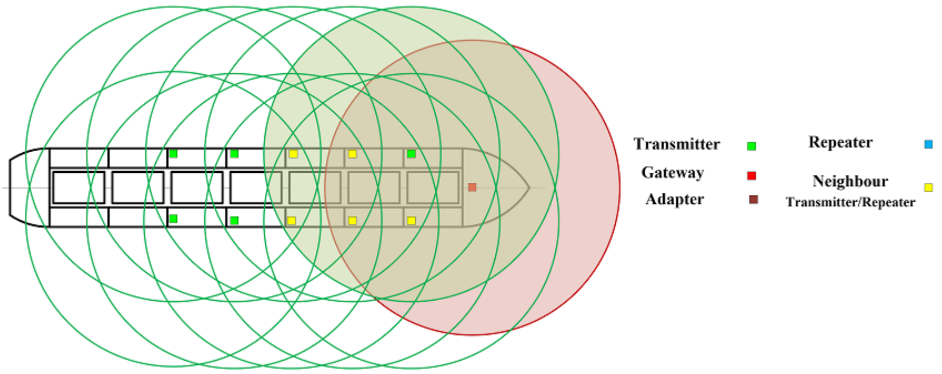
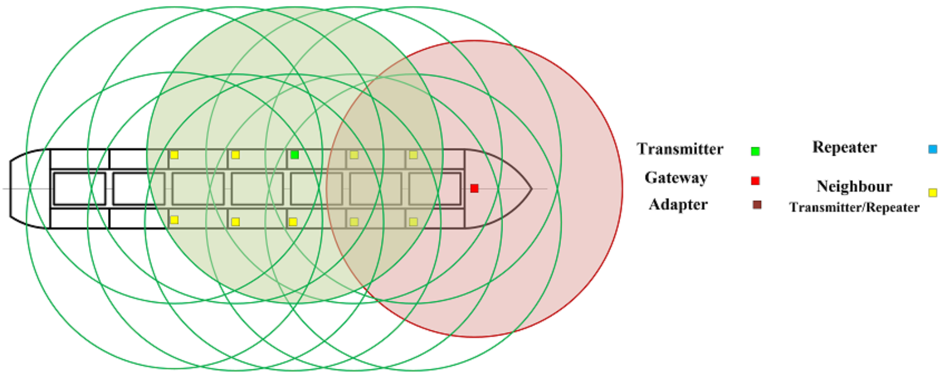


Fig. 4 – Wireless HART network for Top Side Ballast Tanks with effective range of 152 meters.

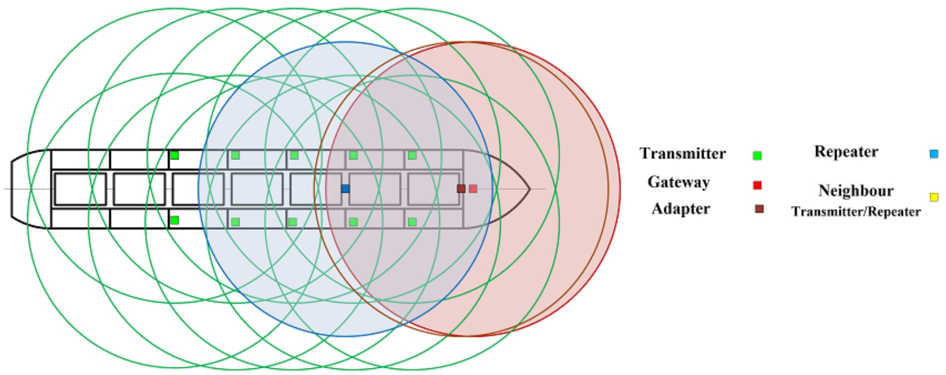
Considering the case when effective range is 76 m (Fig. 3b), the first rule of minimum five won't be fulfilled as gateway has only 4 transmitters in its effective range, however the second rule of minimum three neighbors in the effective range of each transmitter will be fulfilled as each field device in the network will have from 5 to 9 field devices (Figs. 5a and 5b). If the update rate of each field device was considered 2 seconds, the rule of percentage will be applied as more than 25% of field devices in the network are in the effective range of the gateway (4 field devices are more than 3 field devices which are 25% of 10 field devices in the network). It is not necessary that these rules should be applied perfectly as one rule can compensate the other providing more possible links between the nodes in the network. In this condition, the higher number of neighbors for each field device (rule of minimum 3) has compensated the less number of field devices within the effective range of the gateway (rule of minimum 5), however adding a wireless repeater to fortify the network as indicated in figure 5-cwill fulfill the rule of minimum five. If a wireless HART adapter (communicating with wired HART transmitters for double bottom tanks) or its remote antenna was mounted at forward station, this will result in further fortification for the network as more than 5 field devices will be in the effective range of the gateway. Additionally, the gateway is recommended to be installed as far as possible from any source for RFI or EMI, that's why, it would be a better option to mount the gateway at the forward station with a remote antenna mounted at forward mast. It is also recommended to avoid mounting the gateway between cargo holds to avoid possible non uniform RF propagation due to open hatch covers and also to avoid possible EMI that might be induced by cargo crane motors.



(a) 5 neighbor devices and 4 devices in gateway effective range.



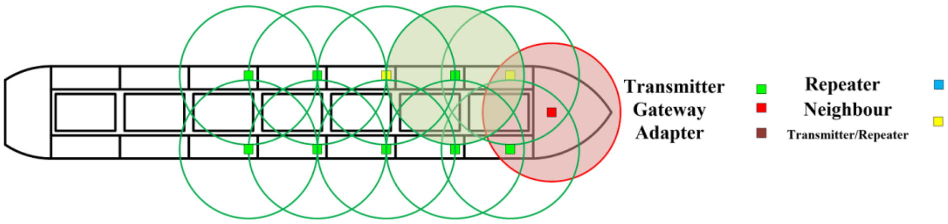
(b) 9 neighbor devices and 4 devices in gateway effective range.



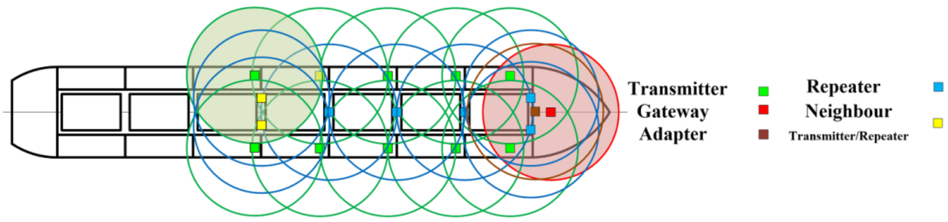
(c) 6 devices in gateway effective range using repeater and wireless HART adapter from double bottom measurement multidrop communication loop.

Fig. 5 – Wireless HART network for Top Side Ballast Tanks with effective range of 76 meters.

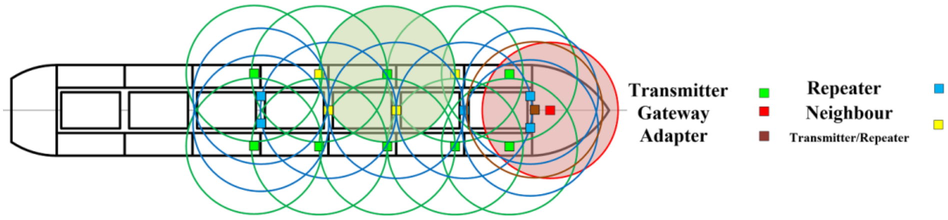
Considering the case when the effective range of the field devices and the gateway is only 30 meters (Fig. 3c), neither the rule of minimum 5 nor the rule of minimum 3 nor the rule of percentage will be fulfilled if the network was not fortified by additional repeaters as illustrated in Fig. 6a. If repeaters were added in the space between cargo holds as illustrated in Fig. 6b, this will increase the field devices in the network (including repeaters) to 17 field devices. The capacity of the gateway is 25 field devices for 2 seconds update rate, which means that the spare capacity of the gateway will be 8 devices (32% of full capacity). Less than 40% spare capacity of the gateway can be accepted if adding field devices will lead to more robust, reliable and stable network. The added repeaters in Fig. 6b will only fulfill the rule of minimum three as number of neighbor devices for each transmitter will be 4, however the rule minimum 5 is still not fulfilled as number of field devices within the effective range of the gateway will be 4. On the other hand, the rule of percentage is still not fulfilled as 4 field devices within the effective range of the gate way is less than 25% of total number of field devices in the network (5 devices). HART pressure transmitters dedicated for double bottom tanks will be connected in a multidrop HART communication loop including a wireless HART adapter the remote antenna of which is mounted at the forward station. Therefore, adding wireless HART adapter to the network will fulfill the rule of minimum five as well as the rule of percentage as illustrated in Fig. 6c.



(a) 2 neighbor devices and 2 devices in gateway effective range.



(b) 3 neighbor devices and 5 devices in gateway effective range by adding repeaters and wireless HART adapter.



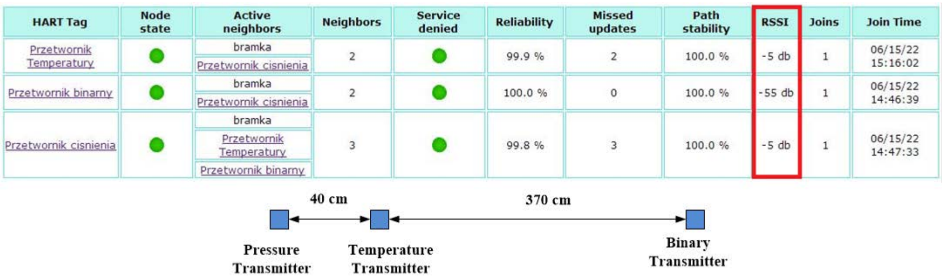
(c) 4neighbor devices and 5 devices in gateway effective range by adding repeaters and wireless HART adapter.

Fig. 6 – Wireless HART network for Top Side Ballast Tanks with effective range of 30 meters.

6. Experimental Section

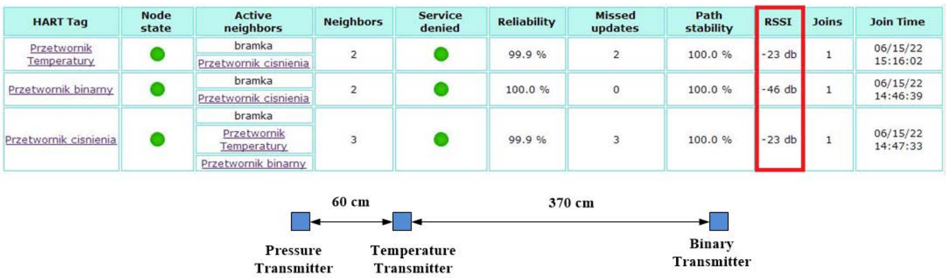
6.1. Received Signal Strength Indicator (RSSI)

Received Signal Strength Indicator (RSSI) is an important parameter in any wireless network measuring the capability of a specific device in the network to detect the RF signal transmitted from a gateway, an access point or a repeater. In wireless HART protocol, wireless AMS gateway software is continuously monitoring three important parameters for each field device included in the network. These parameters are path stability, signal reliability and RSSI. Both of signal reliability and path stability are dependent on the RSSI level. On the other hand, RSSI as a parameter is the first parameter negatively affected by any possible source of interference in the network such as RFI or EMI (Dong and Dargie, 2012; Daiya *et al*., 2011). The minimum acceptable level of RSSI at any device is -70 dbm lower than which the wireless network might not be as robust as planned. RSSI level between -30 dbm and -60 can be considered as a very good level to ensure robust communication in a wireless network (MetaGeek, 2022). A small wireless HART network consisting of 3 field devices (wireless HART pressure transmitter, wireless HART temperature transmitter and wireless HART binary transmitter) and a gateway was implemented to explore the relation linking the spacing between field devices in the network with the RSSI level at each of them. The results of the experiment revealed that the more uniform was the spacing between field devices; the better was the RSSI level at all field devices in the network. In other words, if 2 field devices were close to each other and the third device was further away from them (Figs. 7a, 7b), this will lead to very high RSSI levels at the devices close to each other and extremely lower RSSI level at the far device, however if the spacing between field devices was almost equal (Fig. 7c), RSSI level will be almost in the same level (fairly distributed) at all field devices. The explanation of such a result is that uniform spacing between field devices is simply a reflection for links of close distances between nodes in the mesh network which leads to almost equal energy consumption levels to propagate the data between these nodes. Therefore the energy loss in propagating the data from the gateway to each field device will be almost similar and consequently the energy levels of the received RF signals at each field device will be of close values. If this result was linked to applying wireless HART protocol in tank level measurement system on a bulk carrier ship, it will reflect the fact that the uniform spacing between wireless HART radar transmitters used at top side tanks (as discussed in section 5.1) will lead to more equally distributed RSSI levels at each transmitter which leads to more robust and stable network.



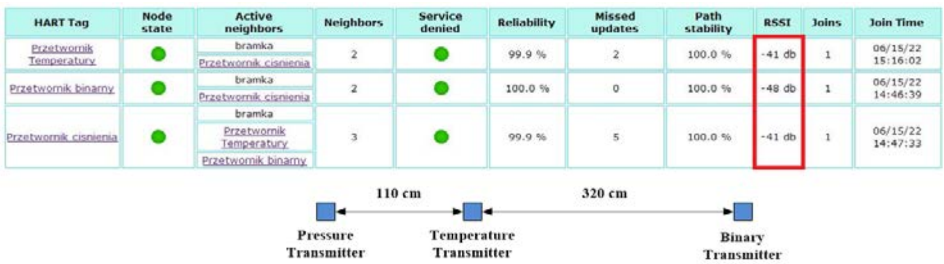
HART Tag	Node state	Active neighbors	Neighbors	Service denied	Reliability	Missed updates	Path stability	RSSI	Joins	Join Time
Przetwornik Temperatury	●	bramka; Przetwornik cisnienia	2	●	99.9 %	2	100.0 %	-5 db	1	06/15/22 15:16:02
Przetwornik binarny	●	bramka; Przetwornik cisnienia	2	●	100.0 %	0	100.0 %	-55 db	1	06/15/22 14:46:39
Przetwornik cisnienia	●	bramka; Przetwornik Temperatury; Przetwornik binarny	3	●	99.8 %	3	100.0 %	-5 db	1	06/15/22 14:47:33

(a)

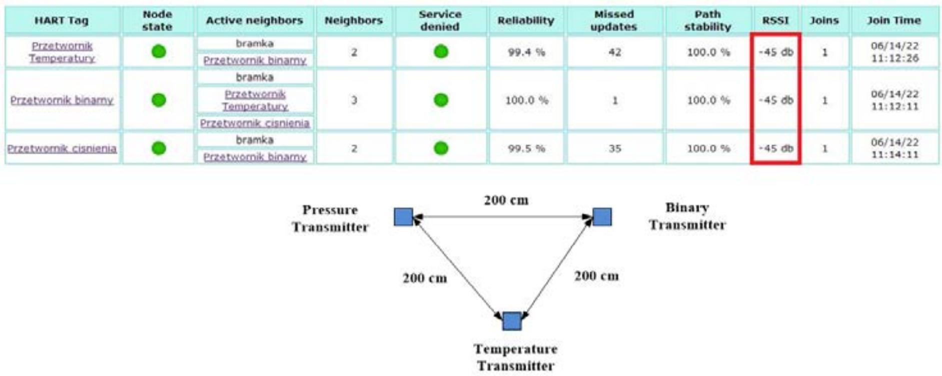


HART Tag	Node state	Active neighbors	Neighbors	Service denied	Reliability	Missed updates	Path stability	RSSI	Joins	Join Time
Przetwornik Temperatury	●	bramka; Przetwornik cisnienia	2	●	99.9 %	2	100.0 %	-23 db	1	06/15/22 15:16:02
Przetwornik binarny	●	bramka; Przetwornik cisnienia	2	●	100.0 %	0	100.0 %	-46 db	1	06/15/22 14:46:39
Przetwornik cisnienia	●	bramka; Przetwornik Temperatury; Przetwornik binarny	3	●	99.9 %	3	100.0 %	-23 db	1	06/15/22 14:47:33

(b)



HART Tag	Node state	Active neighbors	Neighbors	Service denied	Reliability	Missed updates	Path stability	RSSI	Joins	Join Time
Przetwornik Temperatury	●	bramka; Przetwornik cisnienia	2	●	99.9 %	2	100.0 %	-41 db	1	06/15/22 15:16:02
Przetwornik binarny	●	bramka; Przetwornik cisnienia	2	●	100.0 %	0	100.0 %	-48 db	1	06/15/22 14:46:39
Przetwornik cisnienia	●	bramka; Przetwornik Temperatury; Przetwornik binarny	3	●	99.9 %	5	100.0 %	-41 db	1	06/15/22 14:47:33



HART Tag	Node state	Active neighbors	Neighbors	Service denied	Reliability	Missed updates	Path stability	RSSI	Joins	Join Time
Przetwornik Temperatury		bramka Przetwornik binarny	2		99.4 %	42	100.0 %	-45 db	1	06/14/22 11:12:26
Przetwornik binarny		bramka Przetwornik Temperatury Przetwornik cisnienia	3		100.0 %	1	100.0 %	-45 db	1	06/14/22 11:12:11
Przetwornik cisnienia		bramka Przetwornik binarny	2		99.5 %	35	100.0 %	-45 db	1	06/14/22 11:14:11

(c)

Fig. 7 – Different cases of spacing between field devices and their correspondent effect on RSSI levels.

6.2. Decreased Power Supply Levels at Gateway and Field Devices

In a maritime engineering environment such as commercial ships, power failures or instability of generation units are more common failures than land based engineering applications. Wireless gateway is the only element in wireless HART network supplied by wired power source other than field devices which are powered by 7.2 VDC batteries. Accordingly, the DC voltage range in which wireless HART gateway will still be properly functional (even if it was supplied with a voltage level less than its rated voltage) is an important factor when analysing implementation of wireless HART protocol on commercial ships. Experimental results showed that Emerson1420 wireless HART gateway was still able to communicate with field devices when its supplied DC voltage was decreased from 24 VDC to 12.5 VDC. At 12 VDC voltage level, there was an immediate communication failure with all field devices in the network. Similarly to decreasing supplied voltage to the gateway to simulate instability of power sources on the ship, also the field devices were supplied with decreased DC voltage than its rated level of 7.2 VDC to simulate battery aging conditions inside field devices. Decreased supply voltage level to the field devices revealed the following results:

- Minimum voltage required at the field device so that the gateway will be able to detect its existence is 3 VDC regardless of the gateway supply voltage.
- When the voltage level at the field device is 3 VDC, the gateway will be able to perform basic communication tasks with the field device including detection of voltage at its terminals and temperature of the field device (HART tertiary and quaternary variables), however it will still give an error

as it will not be able to communicate with the sensor unit in the field device to get its primary and secondary variables.

- The minimum voltage required for the field device so that it can fully communicate with the gateway providing all its HART variables (PV, SV, TV and QV), is 5.5 VDC even if the voltage at the gateway was reduced to 12.5 VDC (Fig. 8).

HART Tag	HART status	Last update	PV	SV	TV	QV	Burst rate
Przetwornik Temperatury		06/21/22 16:28:57	118.193 DegC	NaN DegC	24.000 DegC	5.563 V	4
Przetwornik binarny		06/21/22 16:28:59	0.000	0.000	24.500 DegC	5.387 V	4
Przetwornik cisnienia		06/21/22 16:29:00	1.833 bar	25.063 DegC	24.250 DegC	5.581 V	4

Fig. 8 – Successful HART communication with decreased supply voltage of 12.5 VDC at the gateway and 5.5 VDC at field devices.

6.3. Integration between wireless and wired HART network

As explained in the analytical planning section of tank level measurement system, double bottom tanks will be integrated into wireless HART network using wireless HART adapter in one or two multidrop communication networks. Emerson wireless HART THUM adapter (Emerson, 2017) is an example among other wireless HART adapters produced by different manufacturers. THUM adapter can provide only limited integration for a wired HART multidrop communication loop into a wireless HART network. THUM adapter can detect all the field devices connected to the multidrop HART bus. It can also send their identification information to the wireless network manager (Device type and HART tag); however HART variables (PV, SV, TV and QV) of only one field device are sent to the wireless network manager. Discovery mode of THUM adapter determines which device in a multidrop HART bus will perform full communication with the adapter and the wireless gateway. Discovery mode includes three options, firstly found, fixed address and fixed tag name. In order to overcome such a drawback, additional software or hardware tools can be added to the network carrying out task of switching between different addresses connected to the multidrop bus which will be discussed in a future research.

7. Conclusions

This article provided a preliminary strategy of how to implement wireless HART protocol on commercial ships. This strategy indicated which systems are more suitable to adopt wireless HART technology than others. It also specified different possible sources of EMI and RFI on these ships and techniques suggested for avoiding their effect by other authors in previous literature. Additionally, this strategy introduced different proposed mechanisms to coexist between conventional analogue or hybrid analogue-digital standards and wireless HART standard. Less complicated techniques are basically based on the idea of converting classical analogue 4-20 mA measurement signals into a HART signal to be integrated with wireless HART network. More complicated techniques are based on the idea of conjunction between wireless HART protocol and other wireless standards such as ZigBee or Wi-Fi which can be used to convert a group of wired analogue signals into a wireless signal integrated with wireless HART protocol. Further perception for such a strategy was rendered by an analytical planning example for tank level measurement system on a bulk carrier ship among other commercial ships such as container and tanker ships. This example suggested the use of wireless HART radar transmitters (Rosemount 3308) to measure sea water level at top side ballast water tanks, while using wireless HART adapters to integrate between multidrop HART communication loops dedicated for double bottom tanks and wireless HART network. This planning example also discussed the possibility of applying the rules recommended by Emerson wireless HART network planning guide for successful implementation of the network. Application of rule of minimum five, rule of minimum three and rule of percentage was taken into account in this planning example based on calculated update rate of field devices with assumed time constant of 500 ms. Forward station of the bulk carrier ship was proposed as the best location to mount the wireless HART gateway in order to avoid different sources of EMI and RFI on board. Moreover, this planning example illustrated the possibility of using wireless HART repeaters as well as wireless HART adapters to fortify the network in case any of the previously mentioned rules was not fulfilled. In general, using wireless HART technology can provide more accurate readings in monitoring systems such as tank level measurement system other than conventional wired technology in which additional measurement errors might be induced by improper termination, aging of cables or deteriorated conditions of junction boxes due to rough environmental conditions.

The first part of experimental section was based on a simple wireless HART network dedicated to test the effect of uniform spacing between wireless HART field devices on RSSI levels at each device. Results depicted that the more uniform was the spacing between field devices in network, the higher will be the RSSI levels at all field devices through in the network.

The second part of the experimental section was dedicated to test the possibility of supply voltage reduction at both of the gateway and field devices. The purpose of such a test was to simulate the effect of battery aging at field devices and also to simulate instability of supplied power to the gateway particularly that power instability of generation units is a more common failure in maritime engineering applications than land based applications. Results depicted that minimum voltage required for the field device to be detected by the gateway is 3 VDC, however the minimum voltage required for the field device to fully communicate with the gateway providing all its HART variables is 5.5 VDC. On the other hand results showed that Emerson 1420 gateway can still maintain successful operation as well as successful communication with field devices at a voltage level not less than 12.5 VDC even if the voltage at the field devices was 5.5 VDC. The possible effect of reduced supply voltage on the effective range of both gateways and field devices will be presented in a future research.

The third part of the experimental section was dedicated to discover the capability of which wireless HART THUM adapter can be used to provide integration between multidrop communication HART bus including multiple field devices and wireless HART gateway. Results showed that THUM adapter can identify all the field devices on the multidrop network sending their identification information (Device type and HART tag) to the wireless HART network manager, however it can fully communicate only with a single field device according its configuration setting. A detailed research will be conducted in the future discussing the possible techniques proposed to overcome such a limitation.

REFERENCES

Abotaleb M., Mindykowski J., Dudojc B., Masnicki R., *Digital Communication Links Cooperating with the Analog 4-20 mA Standard for Marine Application*s. Bulletin of the Polytechnic Institute of Iași, Electrical Engineering, Power Engineering, Electronics Section, 2021, Volume 67, 21-44, DOI: https://doi.org/10.2478/bipie-2021-0002.

Agarwal M., *Importance of Ship's Keel and Types Of Keel*, 2021, https://www.marineinsight.com/naval-architecture/importance-of-ships-keel-and-types-of-keel/amp/.

Amajama J., *Impact of Weather Components on (UHF) Radio Signal*, International Journal of Engineering Research and General Science, Volume 4, Issue 3, ISSN2091-2730,2016, https://www.academia.edu/28948219/Impact_of_Weather_Components_on_UHF_Radio_Signal.

Bhattacharjee S., *Marine Radars and Their Use in the Shipping Industry*, March 2021, https://www.marineinsight.com/marine-navigation/marine-radars-and-their-use-in-the-shipping-industry/.

Bhattacharjee S., *Introduction to Global Maritime Distress Safety System (GMDSS) – What You Must Know*, May 2021, https://www.marineinsight.com/marine-navigation/introduction-gmdss-global-maritime-distress-safety-system/.

Chen D., Nixon M., Aloysius M., *WirelessHART Real Time Mesh Network for Industrial Automation*, Springer Science Business Media 2010, New York, USA, 5-12, 19-48, 89-111, 138-151, https://link.springer.com/book/10.1007/978-1-4419-6047-4.

Chilo J., Karlsson C., Angskog P., Stenumgaard P., *EMI disruptive effect on wireless industrial communication systems in a paper plant*, IEEE International Symposium on Electromagnetic Compatibility, Austin, TX, USA, 2009, DOI: 10.1109/ISEMC.2009.5284581.

Daiya V., Ebenezer J., Murty S.A.V.S., Raj B., *Experimental analysis of RSSI for distance and position estimation*, International Conference on Recent Trends in Information Technology (ICRTIT), Chennai, India, 2011, http://dx.doi.org/10.1109/ICRTIT.2011.5972367.

Deshmukh S., Bhosle U., *Performance Evaluation of Spread Spectrum System Using Different Modulation Schemes*, International Conference on Computational Modeling and Security (CMS 2016), Procedia Computer Science 85 (2016) 176-182, http://dx.doi.org/10.1016/j.procs.2016.05.207.

Devan P.A.M., Hussin F.A., Ibrahim R., Bingi K., Khanday F.A., *A Survey on the Application of WirelessHART for Industrial Process Monitoring and Control*, Sensors, 2021, https://doi.org/10.3390/s21154951.

Dong Q., Dargie W., *Evaluation of the reliability of RSSI for indoor localization*, International Conference on Wireless Communications in Underground and Confined Areas, 2012, https://doi.org/10.1109/ICWCUCA.2012.6402492.

Emerson Process Management, System Engineering Guidelines IEC 62591 WirelessHART, February - 2016 Revision 04, https://www.emerson.com/documents/automation/engineering-guide-system-engineering-guidelines-iec-62591-wirelesshart-en-79900.pdf.

Emerson Wireless 1420 Gateway, Product Data Sheet, 00813-0200-4420, Rev GC, April 2020, https://www.emerson.com/documents/automation/product-data-sheet-emerson-smart-wireless-gateway-en-73684.pdf.

Emerson Wireless 1420 Gateway, Reference Manual, 00809-0200-4420, Rev HE, September 2020, https://www.emerson.com/documents/automation/manual-smart-wireless-gateway-en-87246.pdf.

Emerson™ Wireless 775 THUM™ Adapter, Reference Manual00809-0100-4075, Rev CDJuly 2017, https://www.emerson.com/documents/automation/manual-smart-wireless-thum-adapter-en-87168.pdf.

Ferrara N.G., Bhuiyan M.Z.H., Soderholm S., Ruotsalainen L., *A New Implementation of Narrowband Interference Detection, Characterization, and Mitigation Technique for a Software-defined Multi-GNSS Receiver*, GPS Solutions, 2018, https://doi.org/10.1007/s10291-018-0769-z.

Gaj P., Mackowski M., *Electromagnetic compatibility issues in hybrid wired and wireless industrial networks*, PLoS One. 2020; 15(5): e0232405, https://doi.org/10.1371/journal.pone.0232405.

Ghorbanzadeh M., Visotsky E., Yang W., Moorut P., Clancy C., *Radar In-Band and Out-of-Band Interference into LTE Macro and Small Cell Uplinks in the 3.5 GHz Band*, 2015, DOI: 10.1109/WCNC.2015.7127746.

Gummadi R., Wetherrall D., Greenstein B., Seshan S., *Understanding and Mitigating the Impact of RF Interference on 802.11 Networks*, Conference on

Applications, Technologies, Architectures, and Protocols for Computer Communications, 2007, 385-396, https://doi.org/10.1145/1282427.1282424.

Han S., Zhu X., Aloysious M., *Control over WirelessHART*, Project: Wireless HART: Real-Time Low-Power Wireless Mesh Networks for Industrial Sensing and Control Applications (2010), DOI: 10.1109/IECON.2010.5675278.

Hapag-Lloyd, *Container Dimensions*, Hapag-Lloyd Container Specification, Hapag-Lloyd AG, Hamburg, Germany, 2016, https://www.hapag-lloyd.com/content/dam/website/downloads/press_and_media/publications/15211_Container_Specification_engl_Gesamt_web.pdf.

Hassan S.M., Rosdiazli I., Bingi K., Chung T.D., Saad N., *Application of Wireless Technology for Control: A WirelessHART Perspective*, Procedia Computer Science, vol. 105, 220-247 (2017), https://doi.org/10.1016/j.procs.2017.01.217.

Kim A.N., Hekland F., Petersen S., Doyle P., *When HART Goes Wireless: Understanding and Implementing the WirelessHART Standard*, IEEE International Conference on Emerging Technologies and Factory Automation, Hamburg, Germany, 2008, https://doi.org/10.1109/etfa.2008.4638503.

Lennvall T., Svensson S., Hekland F., *A comparison of WirelessHART and ZigBee for industrial applications*, IEEE International Workshop on Factory Communication Systems, Dresden, Germany, 2008, DOI:10.1109/WFCS.2008.4638746, Corpus ID: 16112292.

MetaGeek., 2022, *Understanding RSSI*, https://www.metageek.com/training/resources/understanding-rssi/.

Moore Industries, *Temperature Concentrator System TCS*, User’s Manual No. 238-713-01L, 2020.

Mukherjee P., July 2021, *NAVTEX on Ships: Working, Types of Messages and Advantages*, https://www.marineinsight.com/marine-navigation/navtex-on-ships/.

Oruc A, Gkioulos V., Katsikas S., *Towards a Cyber-Physical Range for the Integrated Navigation System (INS)*, Sensors, 2022, https://doi.org/10.3390/jmse10010107.

Petersen S., Carlsen S., *Wireless HART versus ISA100.11a*, IEEE Industrial Electronics Magazine, December 2011, https://doi.org/10.1109/MIE.2011.943023.

Raza S., Voigt T., *Interconnecting WirelessHART and legacy HART networks*, IEEE International Conference on Distributed Computing in Sensor Systems Workshops (DCOSSW), Santa Barbara, CA, USA, 2010, https://doi.org/10.1109/DCOSSW.2010.5593285.

Santos R.C.D., Periera I.M., Justino M.C., Silva M.C., *Time Response Measurements of Rosemount Pressure Transmitters (Model 3154) of Angra i Power Plant*, International Journal of Nuclear Energy Science and Technology, 2017, https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/009/49009668.pdf.

Serry A., *The automatic identification system (AIS): a data source for studying maritime traffic: The case of the Adriatic Sea*, International Maritime Science Conference), Split, Croatia, 2017.

Shukla V., Raman S., Garg S., Verma A., Pratap D., *Frequency Hopping Spread Spectrum for Improved Security*, International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE), ISSN: 2278 – 909X, 2016.

Slupak T., *Influence of Automatic Identification System on Safety of Navigation at Sea*, the International Journal on Marine Navigation and Safety of Sea Transportation, 2014, http://dx.doi.org/10.12716/1001.08.03.02.

Tenese S., *Global Maritime Distress and Safety System (GMDSS) Next Generation*, GMDSS Next Generation, Port Elizabeth, South Africa, 2019.

Tetley L., Calcutt D., Aloysius M., *Understanding GMDSS The Global Maritime Distress and Safety System*, Springer Science Business Media 1994, New York, USA, 178-195.

Umar R., Ibrahim Z.O., Mokhtar W.Z.A.W., Sabri N.H., *Radio frequency interference: The study of rain effect on radio signal attenuation* Malaysian Journal of Analytical Sciences; ISSN 1394-2506; Worldcat; v. 19(5); p. 1093-1098, 2015.

Yang D., Youzhi X., Gidlund M., *Wireless coexistence between IEEE 802.11- and IEEE 802.15.4-basednetworks: A survey*, IEEE International Conference on Distributed Computing in Sensor Systems Workshops (DCOSSW), Santa Barbara, CA, USA, 2010, http://dx.doi.org/10.1155/2011/912152.

SPRE O ÎMBUNĂTĂȚIRE A FIABILITĂȚII ȘI A SIGURANȚEI PROCESELOR DE MĂSURARE ȘI CONTROL PE NAVE: IMPLEMENTAREA PROTOCOLULUI HART FĂRĂ FIR

(Rezumat)

Sistemele de măsurare și control din aplicațiile de inginerie maritime sunt destul de asemănătoare cu cele din aplicațiile de inginerie de la țărm, cu excepția unor caracteristici unice care diferențiază fiecare dintre ele. Aceste caracteristici sunt fie legate de natura și scopul specific al aplicației maritime (diverse tipuri de nave comerciale, platforme de petrol/gaz și altele), fie legate de condițiile dure de mediu, cum ar fi salinitatea, coroziunea și vibrațiile care există de obicei la niveluri mai mari decât în aplicațiile de pe țărm. În consecință și datorită naturii atât de specifice a aplicațiilor de inginerie maritimă, ar trebui luate în considerare mai multe cerințe pentru a asigura fiabilitatea și stabilitatea procesului de măsurare și control, evitând orice efecte negative care ar putea fi asociate cu un astfel de mediu ingineresc unic. Transmițătoarele inteligente bazate pe protocoale de comunicație hibride analog-digital (HART) și digitale (Foundation Fieldbus și Profibus PA) cu informații suplimentare de diagnosticare, ar putea constitui o posibilă alternativă în transmisiile cu fir ce folosesc transmițătoarele analogice (în mare parte bazate pe standardul analogic 4-20 mA). În mod similar, protocolul HART fără fir poate fi considerat o alternativă pentru transmisiile bazate pe standardul analogic 4-20 mA. Acest articol va discuta posibilitatea de a înlocui transmițătoarele analogice clasice 4-20 mA cu transmițătoare inteligente HART fără fir pe nave comerciale, ca exemplu de aplicație a acestui protocol în ingineria maritimă. După prezentarea noțiunilor teoretice privind rețelele de tip HART fără fir și a unui studiu analitic de implementare a unei astfel de rețele pentru măsurarea nivelului în compartimentele diverselor tipuri de nave maritime, lucrarea arată în partea experimentală importanța unora dintre elementele cheie necesare

implementării unei rețele HART fără fir de încredere. Aceste elemente cheie sunt nivelurile RSSI, stabilitatea tensiunii de alimentare și capacitatea adaptoarelor HART fără fir de a face legătura între rețelele ce utilizează protocolul HART cu fir și rețelele ce utilizează protocolul HART fără fir.