Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 105 (2017) 240 – 247

Procedia Computer Science

2016 IEEE International Symposium on Robotics and Intelligent Sensors, IRIS 2016, 17-20 December 2016, Tokyo, Japan

Application of Wireless Technology for Control: A WirelessHART Perspective

Sabo Miya Hassan, Rosdiazli Ibrahim*, Kishore Bingi, Tran Duc Chung, Nordin Saad

Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS, Malaysia, 32610, Bandar Seri Iskandar, Perak, Malaysia

Abstract

Process monitoring and automation in the industrial sector are hitherto done over wired connection between devices. It is evident that the amount of wires required increased proportionally to the complexity of the industry and their installation is time consuming. The wires used in the industry must withstand the harsh environmental conditions, hence expensive to install and maintain. In the event of loss of connection due to accident or any other reason, the cost incurred as a result of the downtime is high. The highlighted problems necessitated the need for an open, interoperable wireless standard like WirelessHART that can overcome these problems. Three categories of applications running in any process plant with increment of criticality are for monitoring, control and safety. The current application of wireless technology including WirelessHART in the industry so far is limited to monitoring and some attempts are being made to apply it for control. This paper examines the extent to which WirelessHART technology is applied especially for the purpose of control.

Peer-review under responsibility of organizing committee of the 2016 IEEE International Symposium on Robotics and Intelligent Sensors(IRIS 2016).

Keywords: WirelessHART; Gateway; Wireless Control

1. Introduction

Evolution of communication between field devices and control systems in the process and automation industry began with the 4-20mA analogue communication. Then, there comes the hybrid systems using protocols such as highway addressable remote transducer (HART) which combines both the analog and digital signals. This was followed by digital communication technologies such as Foundation Fieldbus and PROFIBUS and finally the wireless technologies such as WirelessHART and ISA100 Wireless standards [1,2].

The importance of wireless technology is becoming more glaring in both the public and industrial sectors [3]. Wireless technology employed in the wireless sensor networks (WSNs) is one of the most demanded technologies in the industry and is guaranteed to provide the same control services or even better than its wired counterpart [4–7]. In ad-

* Corresponding author. Tel.: +6-05-368-7800 ; fax: +6-05-365-7443.
E-mail address: rosdiazli@petronas.com.my (Rosdiazli Ibrahim)

1877-0509
Peer-review under responsibility of organizing committee of the 2016 IEEE International Symposium on Robotics and Intelligent Sensors(IRIS 2016).
doi:10.1016/j.procs.2017.01.217

dition, the WSNs have several advantages over their wired network counterparts[4]. Firstly, the technology eliminates the limitation associated with costly and cumbersome cabling[5]. This in turn will eliminate cable maintenance and greatly reduce the deployment, redeployment, installation and commissioning times of sensor nodes in the network. Secondly, the capability of wired networks can be extended to such areas where cables cannot reach (i.e., environments considered dangerous to run cables)[6]. Another advantage of WSNs is that they are self-organizing[7] with the ability to support large number of battery-powered nodes[8].

However, concerns about security, reliability, safety, device interoperability and integrity have caused great delay in the acceptance, adoption and deployment of the WSNs in the industry[9,10]. The reason being that, none of the available wireless technologies is matured enough to provide for real time performance[11]. Another reason for the slow acceptance and lack of widely adoption of the existing wireless technologies is the absence of an open standard that will ensure customers are not tied to a single supplier and also meets the stringent requirements of the industry[12]. With the coming on board of such open standards, the benefit of wireless technology will dominate the risks posed by uncertainties in deploying the technology in the industry[13].

Several industrial organizations such as HART Communication Foundation, ISA, WINA and ZigBee have been actively working on improving the application of wireless technologies in industrial automation. As a milestone of such efforts, the HART Communication Foundation released the version 7 of the HART protocol and ratified the WirelessHART in 2007[14,15]. WirelessHART is the first complete interoperable and open WSN standard, specifically designed for process measurement and control applications[16]. WirelessHART assured to maintain the tradition of simplicity and robustness known to users of the earlier versions of the HART protocol. The mesh topology structure of network allows for possibility of each device in the network to be used as a router to neighboring devices, thereby creating redundant routes and extending the range of the network. In case of any incidence of obstruction, interference or interruption in a given route, the self-organizing network simply reroutes the communication to another possible route in the mesh network. This feature of the WirelessHART network ensures increased reliability, up to 99.999%. In addition, the new standard is based on the HART protocol which has about 30 million devices already in operation and it is the most widely used communication protocol in the industry[14,17]. Hence, there will be need for very little training for the plant operators to start using the WirelessHART.

The application of modulation methods of both frequency-hopping spread-spectrum (FHSS) and direct-sequence spread-spectrum (DSSS) and the use of spatial path diversity and retransmission capability of the mesh network ensure high expectation of robust communication in the system. The standard has also taken care of the issue of data security; it has also ensured that the users have the choice of selecting the level of security required for their plant. This was made possible through the adoption of a multi-layered technique for data authentication and the use of well-tested encryption algorithms for encryption[14]. The typical structure of the WirelessHART network is shown in Fig. 1. The WirelessHART network consist of primarily five basic elements which include: (1) Field Devices that are attached to the plant process, (2) Wireless Handheld used for device configuration, diagnostics and calibration, (3) a gateway that connects host applications with field devices, (4) a network manager responsible for network configuration, scheduling and communication management between WirelessHART devices, and (5) a security manager that manages and allocates security encryption keys, and also keep track of devices approved to join the network[12].

The following parts of this paper is organized as follows. In Section 2, a classification and review of some wireless technologies in comparison to WirelessHART is presented. The application of WirelessHART to control both in the simulation and practical environment is discussed in Section 3. Section 4 highlights the challenges and research issues associated with applying the technology in the practical environment. Lastly, in Section 5 a concluding aspect of the paper is presented.

2. Classification of Wireless Technologies

WirelessHART is an improvement to the (wired) HART standard that offers a relatively low speed (e.g., compared to IEEE 802.11g) and cheaper wireless connection. Just like most of the communication standards devised for industrial application, the WirelessHART is based on the Open Systems Interconnection model (OSI) and it adopts the IEEE 802.15.4-2006 as the physical layer as shown in Fig. 2. Moreover, it operates in the near globally available unrestricted 2.4 GHz Industrial Scientific and Medical (ISM) radio frequency band using 15 different channels (11-26). A key difference between WirelessHART and other similar standards like ZigBee is that it specifies its MAC layer

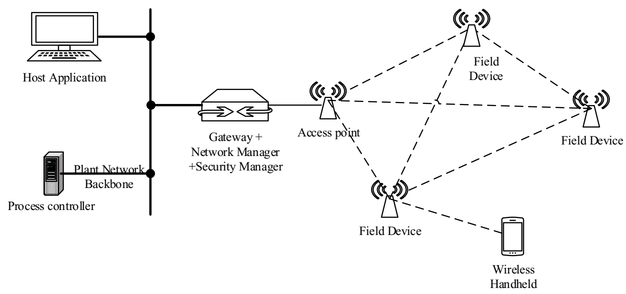


Fig. 1: Typical WirelessHART Structure.

which is time-synchronized. The MAC header is designed to support the co-existence of other networks, such as ISA 100 Wireless, ZigBee, Wi-Fi, WiMax, etc. Additionally, communication between the devices is accomplished using Time Division Multiple Access (TDMA) with a strict 10ms time slots in a super-frame.

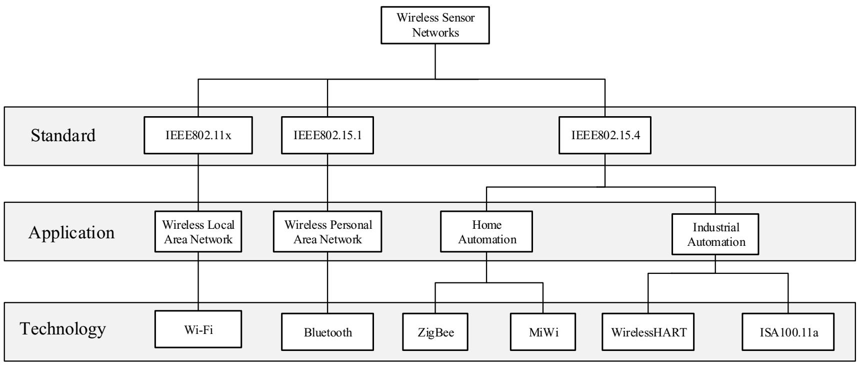


Fig. 2: Classification of some wireless communication standards.

Other features of the WirelessHART include channel hopping to evade interferences and minimize multi-path fading effects, channel blacklisting, and for security of the network it employs the use of industry standard AES-128 ciphers and keys. Discussions and analysis on the security features of the standard have been conducted[4,18] and it was revealed that despite some limitations due to its wireless nature, the standard is strong enough security wise to be used in the industrial process control environment[18,19]. The self-organizing and self-healing mesh networking nature of the WirelessHART is supported by the network layer. Through graph routing and source routing, as monitored and controlled by the network manager, efficient and uninterrupted communication is ensured between devices.

Although Wi-Fi standard operates on the same 2.4GHz unrestricted ISM radio frequency band as the WirelessHART, the two operate on two different standards of IEEE 802.11 for the former and IEEE 802.15.4 for the later. However, Wi-Fi is targeted at WLAN, it consumes a lot more power and uses only one channel hence not support channel hopping like WirelessHART that uses 15 channels[6]. Furthermore, Wi-Fi supports star topology as against WirelessHART mesh (and or star, cluster)[7] topology thus making the Wi-Fi unreliable and therefore unsuitable for industrial environment as well.

The Bluetooth was ratified as IEEE802.15.1 standard in 2002 as against WirelessHART standard of IEEE 802.15.4[20]. The technology targets mainly Personal Area Networks (PAN) with a range of up to 60 meters. Although both technologies support time slots and channel hopping, Bluetooth only supports star type network topology, and one master support a maximum of 7 slaves only [16]. The restriction imposed by the size of the Bluetooth network makes it impractical to be used in large industrial automated systems and the constrained of being a star topology only network makes it not robust enough and therefore highly unreliable. On the contrary, the topology of a WirelessHART network can take the form of a star, a cluster or a mesh, thereby allowing for better scalability and reliability [16].

Released firstly in 2004 and improved in 2006, the ZigBee standard network operates on a single channel and does not allow for hopping between channels throughout its lifespan. This limitation exposes the network to noise and signal interference [21]. As such the standard is still not suitable for industrial application characterized by harsh environments. In 2007, an attempt to make the standard robust enough for Industrial application was made with the introduction of ZigBee PRO into the market. The ZigBee PRO has an added feature of improved security and is specially made to allow for complete network to change operating channel in the event of poor communication caused by either noise or interference or both. This ability to change channel is referred to as frequency agility [4]. Even with the frequency agility features of the ZigBee PRO, it can still not match the frequency hopping ability of the WirelessHART. ZigBee Alliance prefers to adopt the IEEE 802.15.4 specification in its entirety; hence not ready to engage in any attempt to modify the IEEE 802.15.4 MAC layer. Modification of layer is a requirement to achieve the frequency hopping ability [22].

On the other hand, the ISA100 Wireless is the closest competitor to the WirelessHART standard for industrial wireless automation applications. While WirelessHART has been approved by the International Electrotechnical Commission (IEC) as a first global wireless standard and designated as IEC 62591 since 2010, the ISA100 Wireless has been approved with the same status by the IEC late 2014 and is designated as IEC 62734. The two standards adopt a simplified version of the OSI model with some adjustment to some of the protocol layers. The physical layer of both the ISA.100 Wireless and WirelessHART is also based on the IEEE 802.15.4 standard. They both operate on the 2.4HGz radio frequency band and on 2MHz bandwidth, 5Mhz equally spaced channels 11-25 and an additional optional channel 26 for ISA.100 Wireless only. The two standards both specify their MAC layers; they employ the TDMA technique and use both the DSSS and the FHSS for modulation. While WirelessHART provides for one frequency hopping scheme and specifies fixed 10ms time slot, the ISA100 Wireless allows for up to three channel hopping techniques and a time slot range of 10-14ms [23,24]. Another difference between the two standards also is on the area of device functionality. In the WirelessHART, all field devices (and/or adapters) acts as routers that can forward and receive data to and from other field devices [23,25]. Furthermore, they can also enable new devices seeking to join the network hence the adoption of the mesh topology structure of the network. On the other hand the devices in the ISA 100 Wireless network are defined based on their roles as either input or output devices. It is on this basis that these devices can be configured as end nodes with or without routing capability. By implication, unlike WirelessHART, not all devices can enable other devices to join the ISA100 Wireless network except those configured to do so. This informs the decision for the standard to be of a star, mesh or star-mesh structure [23].

The WirelessHART has an edge over the ISA100 Wireless standard when it comes to issue of interoperability, flexibility, simplicity and acceptability [26]. Furthermore, whereas the WirelessHART is the first to be released and to attain a global (IEC 62591) standard position with around 30 million HART devices [27] already installed globally while the ISA 100 Wireless standard is still in the process of getting approval from the IEC. This gives the WirelessHART a clear lead for the moment in the industry [23].

Table 1 shows a further comparison between features of some selected wireless standards. The factors considered here is the application of these standards for industrial monitoring and control.

Table 1: Comparison between features of some selected wireless standards.

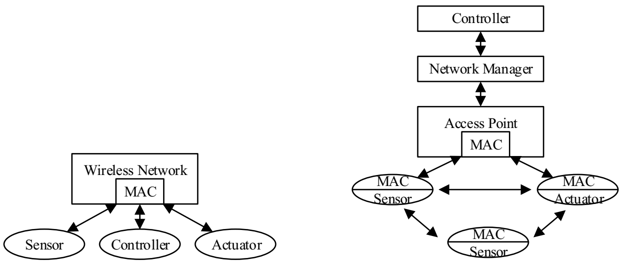
	Wi-Fi	**Bluetooth**	**ZigBee**	**ISA100.11a**	**WirelessHART**
Security	Low	Optional	High	Very High	Very High
Reliability	Low	Low	Very Low	Very High	High
Power Consumption	High	High	High	Low	Low
Scalability	Medium	Limited	Medium	High	High
Network Topology	Star	Star	Star, Tree, or Mesh	Mesh, star	Mesh
Data rate	High 11- 105Mbps	Medium 1Mbps	Low (20-250)kbps	Low -up to 250kbps	Low upto 250kbps
Channel Hopping	No	Yes	No	Yes	Yes

3. Control Techniques for WirelessHART

3.1. Simulation Environment

The three categories of applications running in any process plant as defined by ISA [14] (and considering increasing order of criticality) are for monitoring, control and safety. Wireless technology has been applied for monitoring purpose and attempts are being made to apply it to the control aspect [15]. The WirelessHART is the first open standard that has been proposed for monitoring and control applications in the industry. Most of the work done on WirelessHART so far is based mostly on the development, analysis, performance evaluation of the standard, interoperability test and the implementation in the simulation environment [14,19,28].

The first attempted application of the standard for control purpose started with the True-Time; a wireless simulation software specifically designed for simulation of networks supporting IEEE802.11 and ZigBee networks [29,30]. In the True Time software, the execution of MAC protocol for all devices is done in the wireless network block, since it is based on ZigBee and WLAN as shown in Fig. 3a. This situation is a deviation from reality. In reality, every device in the network has own sub layer of MAC (see Fig. 3b). To reflect this scenario, which has been already supported by WirelessHART, the capability of the software was extended by the authors [29,30]. The standard was then simulated for process control subject to two conditions of clock drift and packet losses [31,32].



(a) (b)

Fig. 3: (a) MAC Protocol location in original True Time [32]; (b) MAC protocol location in a real environment as supported by WirelessHART [32].

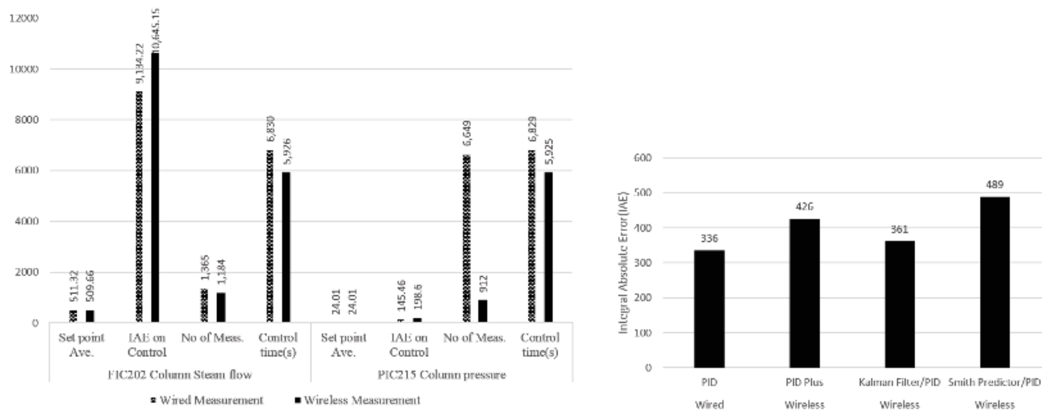
A methodology for co-design of communication scheduling and controller for control systems operating over WirelessHART system was proposed aimed to address issues relating to time optimal convergecast scheduling of data and dissemination, end-to-end reliability subject to packet loss and controller performance [33]. A simulator and a design process support tool targeting WirelessHART for process control was also presented [34]. The simulator specifically targets efficient communication and processing scheduling, but it must be extended to take care of multi-hop communication and also to take care of all the 15 channels. A hybrid simulation approach based on COOJA and Contiki operating system to evaluate the performance of WirelessHART network and WirelessHART enabled devices was presented [35]. Another co-simulation technique based on the interaction of True-Time and OMNET++ was proposed. In this work, a simple control loop involving a DC servomotor was used. Results obtained from that simulation framework justifies the suitability of WirelessHART for closed loop control [36].

3.2. Practical Application

For practical purpose, few applications of the WirelessHART for real time control were reported. It was reported that the measurements collected over wireless using WirelessHART network used for control purpose can rival those collected using wired network [37]. Moreover, WirelessHART transmitters were placed alongside wired transmitters and measurements collected on both sides were used for both column-pressure and heater steam-flow control using a modified PID algorithm for the wireless communication. The control performance of the wired and wireless measurements is compared in Fig. 4a. From the results it can be seen that the two results are comparable.

It was concluded that control over WirelessHART is achievable after comparing the performance of a simple control loop with that of wired Foundation Field Bus[38]. Here a simple control loop to control an LED was set up using WirelessHART devices the same way as with Foundation Fieldbus. However, this method only considers star topology thereby not reflecting the mesh nature of the WirelessHART network. An attempt was also made[39] to implement WirelessHART for liquid level control for industrial tank, however, the technology was only used for detecting liquid level not actually control. Three control strategies for WirelessHART networks were proposed by Han et al[40], they are: Control in the Host, Gateway and in the Field[40]. However, the WirelessHART only partially supports control in the field, thus, the gateway control was recommended since it is fully supported by the WirelessHART and will have less delay compared to the control implemented in the Host. Here the gateway is modified by adding a function block application layers similar to those in Foundation Fieldbus to facilitate configuration and execution of control modules. Even with this attempt, the control scenario has not yet been applied to a real system.

An improved PID algorithm to take care of slower measurement updates, non-periodic measurements and loss of communication imposed by wireless transmitters (e.g., WirelessHART transmitters) called PIDPlus algorithm was presented[41]. Here, two other PID control approaches namely with Kalman filter observer and smith predictor both modified for wireless measurements were presented the performances of these two approaches were compared to the performance of the PIDPlus algorithm. It was found that while the Kalman filter observers performance was better than that of the PIDPlus algorithm, the latter is much better than the Smith Predictor in terms of the error. As shown in Fig. 4b. Moreover, the WirelessHART transmitters were only used for measurement in the feedback loop, the feedforward loop remained wired. Currently, work is on going in developing control strategies for wirelessHART control some of which has been reported in[42–44].



(a) (b)

Fig. 4: (a) Wired and wireless control provided comparable results[37]; (b) Wireless control Versus PID wired[41].

4. Challenges and Research Issues

In the process industry, automation and monitoring are very important. Process automation and monitoring are hitherto achieved using wired connection between devices only. As the complexity of the industry increases, so does the amount of wires required to monitor its respective units and to control its processes. The wires usually required for the industry application are expensive since they must withstand the harsh environments. The time for installation, commissioning, redeployment, decommissioning and maintenance is high. In the event of disruption of connectivity as a result of damage to the installed cables the cost incurred due to downtime is high. A lot of information about the system is also lost due to lack of accessibility of hazardous environments, since physical presence is required to collect data and calibrate field devices using wired systems. By exploring the wireless capability provided by WirelessHART to monitor and control plant process in the industry, the cost will be minimized. Furthermore, reliability and robustness will significantly be improved. More information about systems will be collected over wireless therefore; control and calibration can be done wirelessly.

Looking at the available literature in the area of application of wireless technology in the Process and Automation Industry, it can clearly be deduced that the application stops mainly at the supervisory and monitoring aspect without given due consideration to control. This then, was as a result of lack of an open and interoperable standard that will withstand the stringent requirement of the industries in terms of robustness, safety, and security. With the approval of WirelessHART in 2010 by IEC, and with the ISA100 Wireless approved in 2014, a sigh of relief was at the corner. But still, as shown from the literature, application to control is still not fully exploited. Research to exploit control using wireless technology with WirelessHART especially in the industry will greatly benefit the industries. Even when fully exploited, it will not be without challenges. The challenges are due to lack of adequate infrastructure, also due to introduction of wireless transmitters in the forward and feedback routes[45]. The signals transmitted are delayed compared to those transmitted using wired connections; there is also loss of communication sometimes and non-periodic update of measurement. Since wireless transmitters will only transmit measurements if there is significant change from previous values. Another challenge to be faced is lack of synchronization between devices in the network. Moreover, conventional PID algorithms used in wired control presume input/output paths to be reliable and measurements are received periodically. If used in wireless control and the input is temporarily lost, the PID controller will accumulate error based on the last received value causing a spike at the output and a possibility of large process oscillations once the communication is restored. Problems are also inevitable if the output communication is interrupted. Research to tackle these challenges will significantly benefit the industry.

5. Conclusion

In this paper a survey of major wireless technologies was conducted with regards to application in the industry. The level of application of WirelessHART, the first industrially acceptable and interoperable standard for monitoring and control was also examined for both practical and simulation environment. The challenges of applying the technology were highlighted and a proposal was made to address these challenges. In the future we will report the progress of this proposal and any other development in that regard.

Acknowledgment

The authors acknowledges the support from the Universiti Teknologi PETRONAS for the award of the Yayasan UTP Research Grant Scheme (YUTP-FRG) No.: 0153AA-A74.

References

1. Henk, B.V.D.. Full redundant field wireless automation solutions based on the isa100.11a standard. *Flow Level Pressure* 2014;**2014**:14–15.
2. Flammini, A., Ferrari, P., Marioli, D., Sisinni, E., Taroni, A.. Wired and wireless sensor networks for industrial applications. *Microelectronics Journal* 2009;**40**(9):1322–1336.
3. Willig, A., Matheus, K., Wolisz, A.. Wireless technology in industrial networks. *Proceedings of the IEEE* 2005;**93**(6):1130–1151.
4. Alcaraz, C., Lopez, J.. A security analysis for wireless sensor mesh networks in highly critical systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 2010;**40**(4):419–428.
5. Baillieul, J., Antsaklis, P.J.. Control and communication challenges in networked real-time systems. *Proceedings of the IEEE* 2007; **95**(1):9–28.
6. Muller, I., Netto, J.C., Pereira, C.E.. Wirelesshart field devices. *IEEE Instrumentation & Measurement Magazine* 2011;**14**(6):20–25.
7. Al Agha, K., Bertin, M.H., Dang, T., Guitton, A., Minet, P., Val, T., et al. Which wireless technology for industrial wireless sensor networks the development of ocari technology. *IEEE Transactions on Industrial Electronics* 2009;**56**(10):4266–4278.
8. Menezes, M.. Wireless hart® minimizes cost of new energy measurements. *Energy Engineering* 2015;**112**(1):69–77.
9. Åkerberg, J., Gidlund, M., Björkman, M.. Future research challenges in wireless sensor and actuator networks targeting industrial automation. In: *2011 9th IEEE International Conference on Industrial Informatics*. IEEE; 2011, p. 410–415.
10. Öztürk, C., Karaboğa, D., GÖRKEMLİ, B.. Artificial bee colony algorithm for dynamic deployment of wireless sensor networks. *Turkish Journal of Electrical Engineering & Computer Sciences* 2012;**20**(2):255–262.
11. Zhao, G.. Wireless sensor networks for industrial process monitoring and control: A survey. *Network Protocols and Algorithms* 2011; **3**(1):46–63.

12. Åkerberg, J., Gidlund, M., Neander, J., Lennvall, T., Björkman, M.. Deterministic downlink transmission in wirelesshart networks enabling wireless control applications. In: *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*. IEEE; 2010, p. 2120–2125.
13. Kim, A.N., Hekland, F., Petersen, S., Doyle, P.. When hart goes wireless: Understanding and implementing the wirelesshart standard. In: *2008 IEEE International Conference on Emerging Technologies and Factory Automation*. IEEE; 2008, p. 899–907.
14. Chen, D., Nixon, M., Mok, A.. Why wirelesshart. In: *WirelessHART¢*. Springer; 2010, p. 195–199.
15. Petersen, S., Carlsen, S.. Performance evaluation of wirelesshart for factory automation. In: *2009 IEEE Conference on Emerging Technologies & Factory Automation*. IEEE; 2009, p. 1–9.
16. Song, J., Han, S., Mok, A., Chen, D., Lucas, M., Nixon, M., et al. Wirelesshart: Applying wireless technology in real-time industrial process control. In: *Real-Time and Embedded Technology and Applications Symposium, 2008. RTAS'08. IEEE*. IEEE; 2008, p. 377–386.
17. Habib, G., Haddad, N., El Khoury, R.. Case study: Wirelesshart vs zigbee network. In: *Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE), 2015 Third International Conference on*. IEEE; 2015, p. 135–138.
18. Raza, S., Slabbert, A., Voigt, T., Landernäs, K.. Security considerations for the wirelesshart protocol. In: *2009 IEEE Conference on Emerging Technologies & Factory Automation*. IEEE; 2009, p. 1–8.
19. Nawaz, F., Jeoti, V.. Performance assessment of wirelesshart technology for its implementation in dense reader environment. *Computing* 2016;**98**(3):257–277.
20. Bluetooth, S.. Specification of the bluetooth system, core, vol 2, version 1.2, november 2003 at h ttp. *bluetooth org* 2011;.
21. Lennvall, T., Svensson, S., Hekland, F.. A comparison of wirelesshart and zigbee for industrial applications. In: *IEEE International Workshop on Factory Communication Systems*; vol. 2008. 2008, p. 85–88.
22. Egan, D.. The emergence of zigbee in building automation and industrial control. *Computing & Control Engineering Journal* 2005; **16**(2):14–19.
23. Petersen, S., Carlsen, S.. Wirelesshart versus isa100. 11a: the format war hits the factory floor. *IEEE Industrial Electronics Magazine* 2011; **5**(4):23–34.
24. Gustafsson, D.. Wirelesshart-implementation and evaluation on wireless sensors. *Masters's Degree Project, KTH University, Electrical Engineering, Apr* 2009;**1**.
25. Akyildiz, I.F., Wang, X., Wang, W.. Wireless mesh networks: a survey. *Computer networks* 2005;**47**(4):445–487.
26. Nixon, M., Round Rock, T.. A comparison of wirelesshart¢ and isa100. 11a. *Whitepaper, Emerson Process Management* 2012;:1–36.
27. Hartfoundation. `http://en.hartcomm.org/`. 2016. Accessed: 2016-09-30.
28. Nobre, M., Silva, I., Guedes, L.A.. Performance evaluation of wirelesshart networks using a new network simulator 3 module. *Computers & Electrical Engineering* 2015;**41**:325–341.
29. Andersson, M., Henriksson, D., Cervin, A., Arzen, K.. Simulation of wireless networked control systems. In: *Proceedings of the 44th IEEE Conference on Decision and Control*. IEEE; 2005, p. 476–481.
30. Cervin, A., Henriksson, D., Lincoln, B., Eker, J., Årzén, K.E.. How does control timing affect performance? *Control Systems Magazine* 2003;**23**(3):16–30.
31. De Biasi, M., Snickars, C., Landernäs, K., Isaksson, A.J.. Simulation of process control with wirelesshart networks subject to clock drift. In: *COMPSAC*. 2008, p. 1355–1360.
32. De Biasi, M., Snickars, C., Landernäs, K., Isaksson, A.J.. Simulation of process control with wirelesshart networks subject to packet losses. In: *CASE*. 2008, p. 548–553.
33. Pesonen, J., Zhang, H., Soldati, P., Johansson, M.. Methodology and tools for controller-networking codesign in wirelesshart. In: *2009 IEEE Conference on Emerging Technologies & Factory Automation*. IEEE; 2009, p. 1–8.
34. Shah, K., Seceleanu, T., Gidlund, M.. Design and implementation of a wirelesshart simulator for process control. In: *International Symposium on Industrial Embedded System (SIES)*. IEEE; 2010, p. 221–224.
35. Konovalov, I.. A framework for wirelesshart simulations 2010;.
36. Ferrari, P., Flammini, A., Rizzi, M., Sisinni, E.. Improving simulation of wireless networked control systems based on wirelesshart. *Computer Standards & Interfaces* 2013;**35**(6):605–615.
37. Seibert, F., Blevins, T.. Wirelesshart successfully handles control. *Chemical Processing* 2011;.
38. Zhu, X., Lin, T., Han, S., Mok, A., Chen, D., Nixon, M., et al. Measuring wirelesshart against wired fieldbus for control. In: *IEEE 10th International Conference on Industrial Informatics*. IEEE; 2012, p. 270–275.
39. Morakinyo, S., et al. Implementation of wireless hart technology for liquid level control and monitoring 2013;.
40. Han, S., Zhu, X., Aloysius, K.M., Nixon, M., Blevins, T., Chen, D.. Control over wirelesshart network. In: *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*. IEEE; 2010, p. 2114–2119.
41. Blevins, T., Nixon, M., Wojsznis, W.. Pid control using wireless measurements. In: *2014 American Control Conference*. IEEE; 2014, p. 790–795.
42. Chung, T.D., Ibrahim, R.B., Asirvadam, V.S., Saad, N.B., Hassan, S.M.. Adopting ewma filter on a fast sampling wired link contention in wirelesshart control system. *IEEE Transactions on Instrumentation and Measurement* 2016;**65**(4):836–845.
43. Hassan, S.M., Ibrahim, R., Saad, N., Asirvadam, V.S., Chung, T.D.. Setpoint weighted wirelesshart networked control of process plant. In: *Instrumentation and Measurement Technology Conference Proceedings (I2MTC), 2016 IEEE International*. IEEE; 2016, p. 1–6.
44. Chung, T.D., Ibrahim, R., Asirvadam, V.S., Saad, N., Hassan, S.M.. Internal model control for industrial wireless plant subject to measured round trip delays. In: *Instrumentation and Measurement Technology Conference Proceedings (I2MTC), 2016 IEEE International*. IEEE; 2016, p. 1–6.
45. Zhu, X., Han, S., Mok, A., Chen, D., Nixon, M.. Hardware challenges and their resolution in advancing wirelesshart. In: *2011 9th IEEE International Conference on Industrial Informatics*. IEEE; 2011, p. 416–421.