LAN-ND, a New Neighbour Discovery Protocol for Mobile WirelessHART Industrial Networks

Sergio Montero and Javier Gozalvez
UWICORE, Ubiquitous Wireless Communications Research Laboratory
Miguel Hernández University of Elche
Avda. Universidad s/n, 03202, Elche, Spain
smontero@umh.es, j.gozalvez@umh.es

Abstract

Wireless industrial communications are expected to represent an essential component of the Factories of the Future. Current industrial wireless standards have been designed for networks with fixed devices, while future systems might require the mobility of certain devices within a factory. The neighbour discovery mechanism is an important feature of wireless standards for facilitating the mobility of devices. WirelessHART includes a contention-based neighbour discovery mechanism that is not particularly suited for efficiently discovering mobile devices. In this context, this paper proposes a new protocol, called Listen Advertise Network Neighbour Discovery (LAN-ND) that improves the neighbours' detection probability of WirelessHART, and reduces the average time needed to detect new neighbour devices.

1. Introduction

Factories of the Future are expected to significantly benefit from the use and deployment of industrial wireless communications. The benefits include increasing productivity and improving the workers' health and safety conditions. An example of such potential is the FASyS (Absolutely Safe and Healthy Factory) project [1] that has been developing ICT-enabled solutions to avoid industrial risks and continuously monitor the working environment and conditions. Some of these solutions are based on the deployment of Wireless Sensor Networks (WSN) within a factory.

Current industrial wireless standards have focused on providing the high reliability levels necessary for industrial applications, but do not include mechanisms to efficiently support the mobility of devices. An interesting review on the impact of mobility in WSN is reported in [2] where several relevant contributions are analyzed, although the focus is on decentralized mobility management. The provision of high reliability and Quality of Service (QoS) levels in industrial environments usually requires a centralized management. In this context, the authors analyzed in [3] the impact of mobility on the performance of industrial wireless communication systems based on centralized management like it is the case of the WirelessHART standard [4]. This study highlighted the need to design new mechanisms that reduce the time required to discover new neighbour mobile devices. In fact, the probability that a mobile device maintains network connectivity as it moves within an industrial wireless network is highly influenced by the speed at which mobile devices can be detected. Several neighbour discovery protocols have been proposed in the literature [5]. However, most of them are contention-based, and therefore require that all devices operate on the same frequency channel. However, WirelessHART allows devices to constantly change the operating frequency channel. In addition, these mechanisms generally do not guarantee reliability levels in the process to detect new neighbour devices within a limited time period. WirelessHART also uses a contention-based scheme to estimate the signal level of a device with its neighbours, and detect new devices entering under its coverage area. This approach was adopted because WirelessHART has been initially designed for static nodes or devices. Other techniques try to guarantee a deterministic discovery performance ([6] and [7]) by sending advertise packets. Several schemes have been proposed to decide when nodes should transmit their advertise packets, and when they should be in reception mode. Some schemes consider a fixed advertising period, while others propose to dynamically modify the advertising period based on the mobility of devices. The deterministic detection schemes proposed in the literature have been traditionally applied to WSNs that do not include a centralized entity in charge of managing the network nodes and the mechanism to detect new neighbour nodes like it is the case of WirelessHART. The future deployment of WirelessHART networks with mobile devices will require mechanisms that guarantee a high probability to discover new neighbour devices in order to ensure the connectivity of devices as they move along the network. In this context, this paper proposes a new deterministic neighbour discovery protocol for the WirelessHART standard (LAN-ND, *Listen Advertise Network Neighbour Discovery*). To the authors' knowledge, this is the first study that proposes a deterministic neighbour discovery protocol for WirelessHART, and evaluates it under mobile conditions. The proposed protocol improves the probability of WirelessHART to detect neighbour devices, and reduces the average time needed for such detection.

2. WirelessHART

WirelessHART is a wireless standard developed for reliable and secure industrial wireless communication. It is based on IEEE 802.15.4 operating in the 2.4GHz band. It adds on top of IEEE 802.15.4 a TDMA medium access mechanism for improved transmission robustness. WirelessHART divides the time into slots, each with a duration of 10ms. During one slot, it is possible to transmit a packet of up to 133 bytes (maximum size for IEEE 802.15.4 packets including 6 bytes of physical header), and receive an acknowledgment if necessary. WirelessHART allows transmitting in up to 15 different frequency channels, but it usually does not allow instantaneously reusing one slot of a given frequency channel for more than one data transmission (there are exceptions for some special cases). Each WirelessHART communications link between two devices is defined by one slot and one frequency channel, and each slot may have up to 15 different links. The *Network Manager* organizes slots into superframes that are periodically repeated. All devices in the network support multiple concurrent superframes (data and management superframes). The management superframe should contain 6400 slots (with a period equal to 64 seconds), while the size of a data superframe may vary. The *Network Manager* is also responsible, among other functions, for allocating links to network devices in order to transmit Data Link Protocol Data Unit (DLPDU). The WirelessHART standard defines five different DLPDUs:

- *Acknowledgment* DLPDUs are the immediate link level response to the reception of non-broadcast DLPDUs from the source device.
- *Advertise* DLPDUs provide information to neighbour devices wishing to join the network.
- *Keep-alive* DLPDUs facilitate connection maintenance between neighbour devices.
- *Disconnect* DLPDUs are used by a device to inform the other that it is leaving the network.
- *Data* DLPDUs are used to transmit data to a final destination device.

The *Network Manager* is also in charge of handling the process for a new device to access the network, as well as the process to discover new neighbour devices. A device that wants to join/rejoin the network must first be in reception mode to receive at least an *Advertise* DLPDU from another network device. The device that is joining the network should then send a *Join Request* in the link specified in the received *Advertise* DLPDU. The *Join Request* message is sent to request access to the network to the *Network Manager*. Once the devices enter the network, the neighbour discovery process allows network devices to detect new devices. This feature is particularly relevant in the case of deployments with mobile devices as it highly influences the capability of the device to be permanently connected to the network.

2.1. WirelessHART Neighbour Discovery

WirelessHART implements a neighbour discovery protocol (referred to in the rest of the paper as *WirelessHART Neighbour Discovery* protocol or WH-ND) that allows devices within the network to be detected by its neighbour devices. WH-ND is based on listening/receiving *Keep-alive* DLPDUs sent by neighbour devices on a *Discovery* link. *Discovery* links are common links shared by all devices in the network. Each management superframe includes at least one *Discovery* link where each network device randomly sends a *Keep-alive* DLPDU or listens to the possible transmission of a *Keep-alive* DLPDU from one of its neighbour devices. When two or more neighbours of a device transmit a *Keep-alive* DLPDU on the same *Discovery* link, their transmission collides, and their presence cannot be detected. The rate at which each device transmits on the *Discovery* link is bounded by the *Discovery_time*. To schedule a *Keep-alive* DLPDU, the device shall select a random waiting time between 0 and *Discovery_time*. When this time expires, the device shall transmit a *Keep-alive* DLPDU at the first available *Discovery* link, and select a new random waiting time until the next *Keep-alive* DLPDU. In order to receive *Keep-alive* DLPDUs sent by neighbour devices, the devices must be in reception mode in all *Discovery* links in which they are not transmitting their *Keep-alive* DLPDUs. Each device maintains its own list of discovered devices in its neighbour table. When a device receives a *Keep-alive* DLPDU from a device that was not initially identified as a neighbour, the device stores it in its neighbour table. Periodically, each device reports its list of neighbours to the *Network Manager*, and the *Network Manager* takes them into account to plan the network and schedule the use of the links.

2.2. WH-ND Analytical Model

In order to analyse the performance of neighbour discovery protocols in WirelessHART, this paper proposes an analytical model to compute the probability that a device i is able to detect a new device j under its coverage range when the device i has H_i neighbours. This requires device i and the H_i neighbours, except device j, to be in reception mode on the link where the detection takes place, and device j to be in transmission mode[1].

The study considers that each management superframe includes a single *Discovery* link (periodicity of T_N seconds). This study also considers that the transmission between two devices is correct if they are within each other's transmission range, they operate on the same frequency channel, and no other devices within

[1] The developed model supports situations where the number of neighbours of each device changes over time. However, the analytical model here presented has been simplified to scenarios where such changes do not occur.

their coverage range simultaneously transmits on the same frequency channel.

The maximum number of *Discovery* links between two consecutive *Keep-alive* DLPDUs in device i is defined as DL_i and can be expressed as:

$$DL_i = \left\lceil \frac{Discovery\_time}{T_N} \right\rceil \qquad (1)$$

The number of *Discovery* links until device i transmits a *Keep-alive* DLPDU is defined as DLN_i. This parameter is an integer value with equal probability within the range [1, DL_i]. The average number of *Discovery* links until device i transmits a *Keep-alive* DLPDU is defined as $\overline{DLN_i}$, and can be obtained as:

$$\overline{DLN_i} = \frac{DL_i + 1}{2} \qquad (2)$$

The probability that a device i transmits a *Keep-alive* DLPDU in one *Discovery* link (P_i) is obtained as the inverse of the average value of $\overline{DLN_i}$:

$$P_i = \frac{1}{\overline{DLN_i}} = \frac{2}{DL_i + 1} \qquad (3)$$

and the probability that a device i is in reception mode in one *Discovery* link (R_i) can be expressed as:

$$R_i = 1 - P_i = \frac{DL_i - 1}{DL_i + 1} \qquad (4)$$

The probability that a device i receives a *Keep-alive* DLPDU from another device j without collision from its other H_i neighbouring devices can be expressed as:

$$P_{i,j}^{H_i} = P_j \cdot R_i \cdot \prod_{\substack{h=1 \\ h \neq j}}^{H_i} R_h \qquad (5)$$

where $\prod_{\substack{h=1 \\ h \neq j}}^{H_i} R_h$ represents the probability that all H_i neighbours, except device j, do not transmit a *Keep-alive* DLPDU in the *Discovery* link under evaluation. As shown in Figure 1, the probability $P_{i,j}^{H_i}$ is highly influenced by the number of neighbours H_i. In fact, when all devices have equal DL_i the value of DL that maximizes the $P_{i,j}^{H_i}$ probability depends on H_i (Figure 1). It is also possible to define the probability that one device i receives at least one *Keep-alive* DLPDU in k *Discovery* links from j without collision ($P_{i,j}^{H_i,k}$) as:

$$P_{i,j}^{H_i,k} = 1 - \left(1 - P_{i,j}^{H_i}\right)^k \qquad (6)$$

Following the definition of $P_{i,j}^{H_i}$, it is possible to compute the discovery probability between two neighbour devices (i and j). This probability can be defined as the probability that one of the two devices receives a *Keep-alive* DLPDU from the other one without collision during a *Discovery* link. This probability is defined as $P_{i,j}$, and can be expressed as:

$$P_{i,j} = P_{i,j}^{H_i} + P_{j,i}^{H_j} = P_j \cdot R_i \cdot \prod_{\substack{h=1 \\ h \neq j}}^{H_i} R_h + P_i \cdot R_j \cdot \prod_{\substack{h=1 \\ h \neq i}}^{H_j} R_h \qquad (7)$$

where $P_{i,j}^{H_i}$ and $P_{j,i}^{H_j}$ can be added directly to obtain $P_{i,j}$ since both probabilities are mutually exclusive (they cannot occur at the same time). Similarly to the way $P_{i,j}^{H_i,k}$ was defined in (6), it is also possible to define the discovery probability between two neighbouring devices (i and j) at least once in k *Discovery* links $P_{i,j}^k$ as:

$$P_{i,j}^k = 1 - \left(1 - P_{i,j}\right)^k \qquad (8)$$

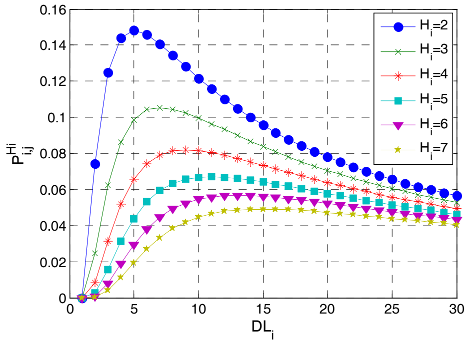

Figure 1. Probability of device *i* correctly receiving a *Keep-alive* DLPDU from *j* as a function of DL_i in the presence of H_i neighbours.

3. LAN Neighbour Discovery

This paper presents a new neighbour discovery protocol called LAN-ND (*Listen Advertise Network Neighbour Discovery*) that has been designed to reduce the time needed to detect new neighbour devices and improve the neighbours' detection probability in WirelessHART. The proposed scheme is based on the idea of listening DLPDUs transmitted by other devices. However, rather than trying to listen DLPDUs on *Discovery* links, LAN-ND proposes listening for *Advertise* DLPDUs on the *Advertise* links. This proposal is due to the fact that devices that are already part of the network are configured by the *Network Manager* to send *Advertise* DLPDUs to facilitate new devices joining the network. In fact, *Advertise* DLPDUs transmit information on how and when new devices should try accessing the network in *Advertise* links dedicated to a single device, therefore avoiding potential collisions. As a result, this information can be valuable to improve the detection of neighbour devices. LAN-ND requires the *Network Manager* to send each device that accesses the network the information about all *Advertise* links (a list with all the links – slot within a superframe and frequency channel- where each network device sends its

Advertise DLPDUs). This information needs to be sent also when the *Network Manager* changes one or more *Advertise* links. The *Network Manager* has to program the devices to be in reception mode when other network devices send their *Advertise* DLPDUs; *Advertise* DLPDUs are sent in broadcast mode. To this aim, the *Network Manager* uses *ADD_LINK* commands to add broadcast links in reception mode to the table of links maintained at each device. It then uses *DELETE_LINK* commands to remove them. Each device includes at the data link layer a link scheduler that determines the next slot at which the device needs to receive or transmit a packet. The link scheduler takes its decisions based on the information available at the device's superframe table and link table. Our proposal works properly if the *Network Manager* programs for each device the links at which they have to operate in reception mode in order to receive the *Advertise* DLPDUs sent by other devices.

This study also considers that the transmission between two devices is correct if they are within each other's transmission range

3.1. LAN-ND Analytical Model

In order to analyse the performance of our proposed protocol, this section presents the analytical model to compute the probability that a device i is able to detect a new device j under its coverage range when all devices employ the LAN-ND protocol. The LAN-ND analytical model also considers that the transmission between two devices is correct if they are within each other's transmission range. In addition, the LAN-ND analytical model considers that each device has only one *Advertise* link in every management superframe to send its *Advertise* DLPDUs.

In WirelessHART, a device transmits its *Advertise* DLPDU without collision in each one of its *Advertise* link. In this context, the probability of LAN-ND that the device i transmits an *Advertise* DLPDU in its *Advertise* link (P_i) can be defined as:

$$P_i = 1 \qquad (9)$$

If all *Advertise* links are programmed adequately, all devices, except the one transmitting the *Advertise* DLPDU, are in reception mode when a device transmits its *Advertise* DLPDU. The probability that a device i is in reception mode at the corresponding frequency channel when the other devices transmit their *Advertise* DLPDUs is then:

$$R_i = 1 \qquad (10)$$

In LAN-ND, the probability that a device i receives an *Advertise* DLPDU without collision from another device j (in the *Advertise* link of j) considering that both devices are under each other's coverage area and device i has H_i neighbour devices is[2]:

[2] Assuming the same radio transmission conditions as in Section 2.2.

$$P_{i,j}^{H_i} = P_j \cdot R_i = 1 \qquad (11)$$

It is important highlighting that differently from WH-ND in WirelessHART, this probability is independent of H_i. The probability that one device i receives at least an *Advertise* DLPDU without collision in a_j *Advertise* links from j ($P_{i,j}^{H_i,a_j}$) can be obtained as:

$$P_{i,j}^{H_i,a_j} = \begin{cases} P_{i,j}^{H_i} & if \quad a_j \geq 1 \\ 0 & if \quad a_j = 0 \end{cases} \qquad (12)$$

where a_j represents the number of *Advertise* links that device j has during the length of time under evaluation. Similarly to the process followed in the case of the *WirelessHART* standard (WH-ND), the probability of two neighbour devices (i and j) to detect each other's presence at least once in a_i and a_j *Advertise* links can be obtained in the case of LAN-ND as follows:

$$P_{i,j}^{a_i,a_j} = 1 - \left(1 - P_{i,j}^{H_i,a_j}\right)\cdot\left(1 - P_{j,i}^{H_j,a_i}\right) \qquad (13)$$

4. Performance Metrics

Several parameters and metrics are here defined to compare our LAN-ND proposal with the neighbour discovery scheme used in the WirelessHART standard. The duration of a time slot is defined as t_s and the number of slots that comprise a management superframe is defined as N. The duration of a management superframe is then T_N=N·t_s. We consider that each device has in every management superframe one dedicated link to transmit its *Advertise* DLPDU, and one shared link to transmit its *Keep-Alive* DLPDU. *Advertise* DLPDUs are therefore transmitted every T_N seconds or N slots, while *Keep-Alive* DLPDUs are sent, on average, each $\frac{(DLi+1)}{2}$ *Discovery* slots. The number of devices within the network is defined as H, and the number of devices under the radio coverage of device i is defined as H_i.

The first performance metric is the probability that one device can detect another device when one or both of them are mobile devices and they are within each other's coverage range for a limited period of time. This metric is defined as P_{det}. The time that a device is under the radio coverage of the other device is defined as t_{cov}. Based on (6), the probability of detection as a function of t_{cov} can be estimated for the WH-ND protocol as:

$$P_{\det} = L_k \cdot P_{i,j}^{H_i,k} + L_{k+1} \cdot P_{i,j}^{H_i,k+1} \qquad (14)$$

where $P_{i,j}^{H_i,k}$ is the probability that one device i receives at least one *Keep-alive* DLPDU without collision in k *Discovery* links from j, and:

$$k = a_j = \left\lfloor \frac{t_{cov}}{T_N} \right\rfloor \qquad (15)$$

$$L_k = L_{a_j} = 1 - \left(\frac{t_{\text{cov}}}{T_N} - \left\lfloor \frac{t_{\text{cov}}}{T_N} \right\rfloor \right) \quad (16)$$

$$L_{k+1} = L_{a_j+1} = \frac{t_{\text{cov}}}{T_N} - \left\lfloor \frac{t_{\text{cov}}}{T_N} \right\rfloor \quad (17)$$

where L_k represents the probability that device i is under the radio coverage of device j for k *Discovery* links when i is under the radio coverage of j during t_{cov}.

The same probability of detection can be computed for the proposed LAN-ND scheme considering (12):

$$P_{\text{det}} = L_{a_j} \cdot P_{i,j}^{H_i,a_j} + L_{a_j+1} \cdot P_{i,j}^{H_i,a_j+1} \quad (18)$$

with $P_{i,j}^{H_i,a_j}$ represents the probability that one device i receives at least one *Advertise* DLPDU without collision in a_j *Advertise* links from j. L_{a_j} represents the probability that device i is under the radio coverage of device j for a_j *Advertise* links when i is under the radio coverage of j during t_{cov}.

The detection probability is not sufficient to characterize the performance under mobile scenarios since two neighbour devices might detect each other's presence just before leaving their communications range. As a result, a second performance metric is also defined. This metric is the average time required to detect new neighbour devices. This metric, referred to as t_{det}, is equal to the average time elapsed from the time that a device enters the other device's coverage range to the time that the device is detected. This average time can be estimated for the WH-ND protocol as:

$$t_{\text{det}} = \left(\frac{1}{2} + \sum_{k=1}^{\infty} \left(P_{i,j}^{H_i,k} - P_{i,j}^{H_i,k-1} \right) \cdot k \right) \cdot T_N \quad (19)$$

where the factor $\frac{1}{2} \cdot T_N$ corresponds to the average time elapsed from the time that the mobile device enters the coverage range of another device until the time to the first *Discovery* link.

The t_{det} metric can be estimated in the case of the LAN-ND proposal as:

$$t_{\text{det}} = \frac{1}{2} \cdot T_N \quad (20)$$

where $\frac{1}{2} \cdot T_N$ corresponds to the average time elapsed from the time that the mobile device enters the coverage range of another device until the time that this device transmits its first *Advertise* DLPDUs.

A third performance metric is proposed to evaluate the probability P_{succ}, that mobile devices remain connected to the network while they move around the network's coverage area. It is important noting that a mobile device does not require detecting all its neighbour devices to maintain the connection to the network. Such connection can be maintained if the mobile device is always connected to at least one neighbour device that is connected to the network. P_{succ} is obtained as the ratio between the number of occasions in which the mobile device does not loose connectivity and the number of conducted simulations for a particular scenario (Figure 3 explained in the next section).

5. Performance Evaluation

The performance of the WirelessHART neighbour discovery scheme is compared against the LAN-ND proposal under different scenarios. The conducted evaluations consider that the *Network Manager* schedules transmissions so that two devices do not transmit their *Advertise* DLPDUs in links characterized by the same time slot and equal or different frequency channels. In this context, the *Network Manager* can assign *Advertise* links for devices in consecutive time slots. The *Network Manager* could also assign the *Advertise* links randomly. In both cases, we consider that all devices can listen to the *Advertise* links of all network devices. In our study, we also consider that the transmission between two devices is correct if they are within each other's transmission range.

5.1. Evaluation Scenarios

The performance evaluation has been conducted in three generic network topologies represented in Figure 2. All the depicted nodes represent fixed devices. For all the topologies, the distance between two fixed devices that have direct connectivity is fixed and equal to the communications range (R). The deployments represented in Figure 2 result in that each device has three, four and six neighbour devices for topologies 1, 2 and 3, respectively. The performance is evaluated considering a mobile device that moves around the topologies shown in Figure 2, where the grey nodes represent fixed devices. The mobile device is considered to be t_{cov} seconds within the coverage range of fixed devices.

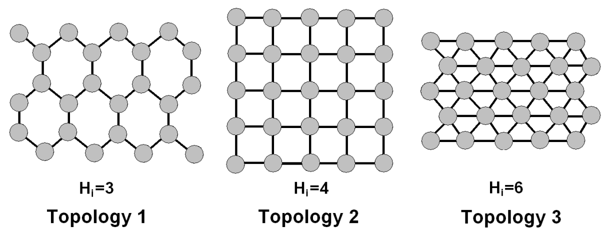

Figure 2. Generic network topologies.

The performance evaluation has also been conducted for a scenario representing a corridor in a factory (Figure 3). The grey dots correspond to fixed devices, and the red one to a mobile device. The mobile device is initially placed at the start of the corridor (position Z in Figure 3), and moves along the centre of the corridor with constant speed (v). This scenario has been specifically selected to evaluate P_{succ} and analyse whether a mobile device can reach the end of the corridor without losing network connectivity. The scenario represented in Figure 3 considers nine devices deployed in a corridor that is 100 meters long and 15 meters wide. Four devices are deployed at one side of the corridor and five devices on the other side. Devices in the same side of the corridor are separated by 25 meters. The scenario represented in Figure 3 considers a communications range of 25 meters.

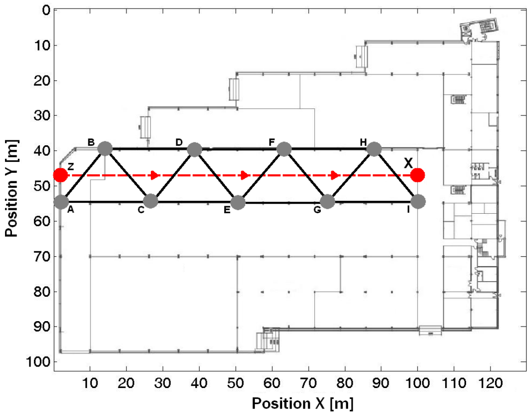

Figure 3. Deployment along a factory's corridor.

5.2. Results

The performance evaluation is first conducted for the three topologies shown in Figure 2 when a mobile device enters into the coverage range of the deployed network. The results have been obtained for the superframe duration recommended by the WirelessHART standard, i.e. T_N=64 seconds. When evaluating the WirelessHART standard (WH-ND scheme), DL_i has been set to the values maximizing the $P_{i,j}^{H_i}$ probability when considering the presence of the mobile device. The values of DL_i are obtained from Figure 1, and are equal to 9 for topology 1 (H_i=4), 11 for topology 2 (H_i=5) and 13 for topology 3 (H_i=7). Figure 4 represents the neighbour detection probability as a function of t_{cov} when a mobile device moves around the topologies represented in Figure 2. WH-ND T1, WH-ND T2 and WH-ND T3 represent the performance reached by the WirelessHART standard neighbour discover scheme (WH-ND) under topologies one, two and three, respectively. First, it is important noting that the LAN-ND performance does not depend on the network topology. On the other hand, the WH-ND performance does depend on the topology. In particular, the obtained results show that the larger the number of neighbour devices, the lower the neighbour detection probability in the presence of mobile devices. The depicted results show that the LAN-ND proposal significantly improves the neighbour detection probability in the case of mobile devices, especially for values of t_{cov} that are close to T_N. The results depicted in Figure 5 for T_N=8 seconds show that similar trends are observed for different superframe sizes in terms of the performance difference between LAN-ND and WH-ND. However, as expected, reducing the superframe size increases the neighbours' detection probability for both schemes when considering the same value of t_{cov}.

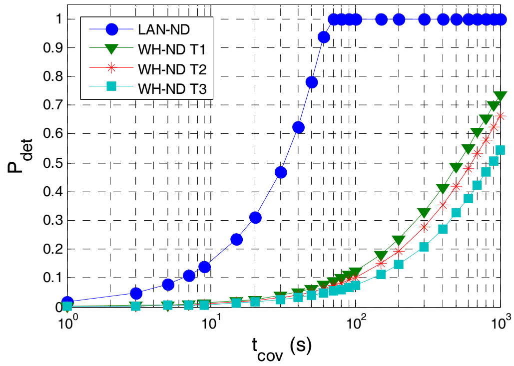

Figure 4.- Neighbour detection probability vs. t_{cov}, T_N=64 seconds.

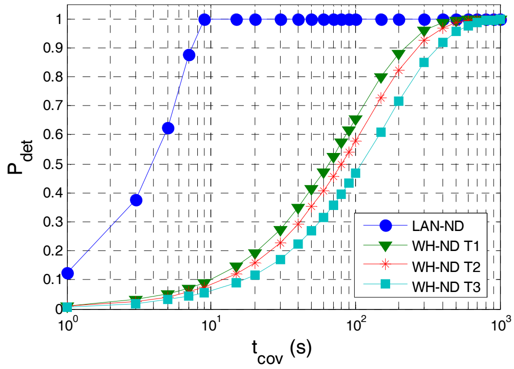

Figure 5.- Neighbour detection probability vs. t_{cov}, T_N=8 seconds.

Table 1 presents the average time required to detect a new neighbour device as a function of T_N. The results are presented for both protocols and for the generic topologies shown in Figure 2. The obtained results show that in the case of WH-ND, the larger the number of neighbour devices (H_i), the higher the average time required to detect a new neighbour device (t_{det}). This is due to the fact that for larger number of neighbour devices, more *Discovery* links are needed to receive a *Keep-alive* DLPDU without collision, and therefore to detect neighbour devices. However, the LAN-ND scheme significantly reduces the average time required to detect a new neighbour device, which is particularly relevant for mobile devices. In addition, the performance is again shown to be independent of the network topology.

Table 1. Average time t_{det} required to detect a new neighbour device

Protocol	Topology 1 (H_i=4)	Topology 2 (H_i=5)	Topology 3 (H_i=7)
WH	11,685·T_N	14,318·T_N	19,088·T_N
LAN	0,500·T_N	0,500·T_N	0,500·T_N

Table 2 presents the average time required to detect a new neighbour device with a certain Quality of Service, or probability of success, as function of T_N. In particular, the metrics t_{det_50}, t_{det_90} and t_{det_99} are defined as the average time from the time at each a new device enters into the coverage range of another device and the time at which the new device is detected with a 50%, 90% and 99% probability respectively. When Quality of Service is an important factor, it is not sufficient to evaluate the average time required to detect a new device. The obtained results show an exponential dependence of the reported WH-ND results with the probability of success. Such dependence is only linear in the case of LAN-ND. The depicted results show that under the presence of mobile devices, WH-ND requires 30, 37 and 51 times more compared to LAN-ND to detect one neighbour device with a probability of success of 90% for topologies 1, 2 and 3, respectively. These values are again significantly increased if the required probability of success is equal to 99% (54, 67 and 92 times more for topologies 1, 2 and 3, respectively). The obtained results also show that, under the presence of mobile devices, LAN-ND can detect neighbour devices with a probability of success of 99% in less than one superframe duration for the three simulated topologies.

Table 2. Average time required to detect a new device with a certain probability of success

Protocol	Metric	Topology 1 (H_i=4)	Topology 2 (H_i=5)	Topology 3 (H_i=7)
WH	t_{det_50}	8,122·T_N	10,004·T_N	13,786·T_N
	t_{det_90}	26,949·T_N	33,213·T_N	45,753·T_N
	t_{det_99}	53,896·T_N	66,431·T_N	91,521·T_N
LAN	t_{det_50}	0,500·T_N	0,500·T_N	0,500·T_N
	t_{det_90}	0,900·T_N	0,900·T_N	0,900·T_N
	t_{det_99}	0,990·T_N	0,990·T_N	0,990·T_N

As previously discussed, a mobile device can maintain the connection with a network without necessarily detecting and being connected to all neighbour devices. In this context, it is of interest evaluating the probability (P_{succ}) that a mobile device remains connected to the network as moving around the network coverage area. This probability is analysed for the scenario depicted in Figure 3. The WH-ND scheme is configured with the DL_i value that maximizes P_{succ}. This value is equal to 10 for the scenario represented in Figure 3. In the case of LAN-ND, assigning *Advertise* links to devices in consecutive time slots or randomly results in different values of P_{succ}. Figure 6 illustrates the P_{succ} performance as a function of the speed of the mobile device when the superframe duration is set to the duration recommended by WirelessHART (T_N=64 seconds). The P_{succ} performance is depicted for WH-ND when DL_i=10. The depicted LAN-ND performance corresponds that obtained when *Advertise* links are assigned to devices in consecutive time slots (LAN-ND) or randomly (LAN-ND-Rand). The obtained results show that even under low mobility conditions (low speed values), the WH-ND protocol results in a low probability for the mobile device to successfully maintaining the network connectivity as it moves along the corridor represented in Figure 3. Figure 6 also shows that P_{succ} increases when *Advertise* links are assigned to devices randomly (LAN-ND-Rand). Figure 7 and Figure 8 illustrate the P_{succ} performance when the superframe duration is equal to 16 and 8 seconds, respectively. The obtained results show that the smaller the superframe duration, the higher the P_{succ} as a result of increasing the number of *Keep-alive* DLPDU and *Advertise* DLPDU sent and received. The obtained results demonstrate that our LAN-ND proposal allows the mobile device to move along the corridor without loosing network connectivity even for speeds than 3 m/s when T_N is equal to 8 seconds. The network connectivity is also guaranteed by LAN-ND for speeds below 2.2 m/s when T_N is equal to 16 seconds. The performance degrades when T_N is equal to 64 seconds since the speed limit for maintaining network connectivity decreases to 0.4 m/s. In any case, it is important noting that LAN-ND always outperforms WH-ND since the speed limits for guaranteeing the network connectivity of mobile devices is always smaller than those achieved by LAN-ND.

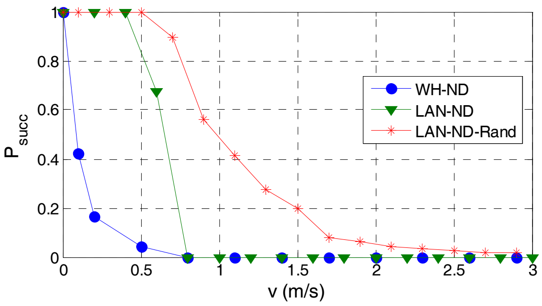

Figure 6.- P_{succ} versus the speed of the mobile device when T_N=64 seconds.

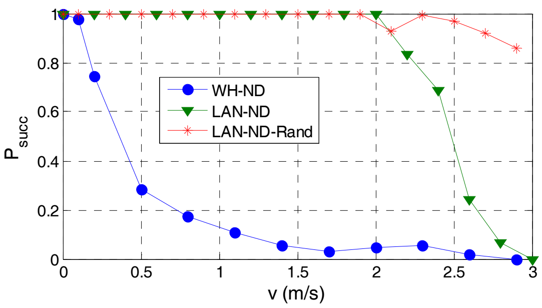

Figure 7.- P_{succ} versus the speed of the mobile device when T_N=16 seconds.

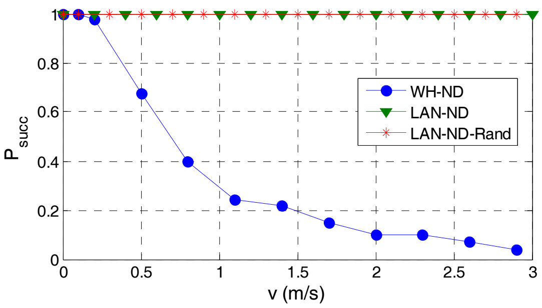

Figure 8.- P_{succ} versus the speed of the mobile device when T_N=8 seconds.

6. Conclusions

This paper has proposed and evaluated a new neighbour discovery protocol (LAN-ND) that improves the network connectivity of mobile devices in industrial wireless networks with a centralized management. The proposal has been compared to the WirelessHART neighbour discovery scheme that is shown to be inefficient in the case of mobile devices. The obtained results have demonstrated that the LAN-ND proposal increases the probability of mobile devices to maintain network connectivity, and reduces the average time needed to detect new neighbour devices.

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