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

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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_s_ 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:

$$DL_i = \left\lfloor \frac{\text{Discovery time}}{T_N} \right\rfloor$$  \hspace{1cm} (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:

$$\overline{DLN_i} = \frac{DL_i + 1}{2}$$  \hspace{1cm} (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 $\overline{DLN_i}$:

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

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

$$R_i = 1 - P_i = \frac{DL_i - 1}{DL_i + 1}$$  \hspace{1cm} (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:

$$P_{i,j}^{H_i} = P_i \cdot R_i \cdot \prod_{h \neq j}^H R_h$$  \hspace{1cm} (5)

where $\prod_{h \neq j}^H R_h$ 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 $DL_i$ 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:

$$P_{i,j}^{H_i,k} = 1 - \left(1 - P_{i,j}^{H_i}\right)^k$$  \hspace{1cm} (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:

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

where $P_{i,j}^{H_i}$ and $P_{i,j}^{H_j}$ 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:

$$P_{i,j}^k = 1 - \left(1 - P_{i,j}\right)^k$$  \hspace{1cm} (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.](image)

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:

$$P_i = 1$$  \hspace{1cm} (9)

If all Advertise links are programmed adequately, all devices, except the one transmitting the Advertise DLPU, are in reception mode when a device transmits its Advertise DLPU. 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:

$$R_i = 1$$  \hspace{1cm} (10)

In LAN-ND, the probability that a device $i$ receives an Advertise DLPU 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:\footnote{Assuming the same radio transmission conditions as in Section 2.2.}

$$P_{ij}^H = P_j \cdot R_i = 1$$  \hspace{1cm} (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 DLPU without collision in $a_i$ Advertise links from $j$ ($P_{ij}^{H,a_i}$) can be obtained as:

$$P_{ij}^{H,a_i} = \begin{cases} 
P_{ij}^H & \text{if } a_j \geq 1 \\
0 & \text{if } a_j = 0
\end{cases}$$  \hspace{1cm} (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:

$$P_{ij}^{a_i,a_j} = 1 - \left(1 - P_{ij}^{H,a_i}\right) \cdot \left(1 - P_{ij}^{H,a_j}\right)$$  \hspace{1cm} (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 $T_s = N \cdot t_s$. We consider that each device has in every management superframe one dedicated link to transmit its Advertise DLPU, and one shared link to transmit its Keep-Alive DLPU. Advertise DLPDUs are therefore transmitted every $T_k$ seconds or $N$ slots, while Keep-Alive DLPDUs are sent, on average, each $\frac{1}{2}(Di + 1)$ 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:

$$P_{det} = L_a \cdot P_{ij}^{H,a_i} + L_{j+1} \cdot P_{ij}^{H,a_i}$$  \hspace{1cm} (14)

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

$$k = a_j = \left\lfloor \frac{T_{cov}}{T_k} \right\rfloor$$  \hspace{1cm} (15)
where $L_i$ 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):

$$P_{det} = L_{a_j} \cdot P_{i_j}^{R_i,j} + L_{a_j+1} \cdot P_{i_j}^{R_{i+1,j}} + P_{i_j}^{R_{i+1,j}}$$

with $P_{i,j}^{R_{i,j}}$ 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:

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

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:

$$t_{det} = \frac{1}{2} \cdot T_N$$

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 lose 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.](image)

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.

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 \( P_{d_{ij}} \) 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 \( t_{cov} \).

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 DLPDUs 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

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Topology 1 (( H_i = 4 ))</th>
<th>Topology 2 (( H_i = 5 ))</th>
<th>Topology 3 (( H_i = 7 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH</td>
<td>11.685 ( T_N )</td>
<td>14.318 ( T_N )</td>
<td>19.088 ( T_N )</td>
</tr>
<tr>
<td>LAN</td>
<td>0.500 ( T_N )</td>
<td>0.500 ( T_N )</td>
<td>0.500 ( T_N )</td>
</tr>
</tbody>
</table>

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 \( t_{det,90} \), \( t_{det,95} \) 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

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Metric</th>
<th>Topology 1</th>
<th>Topology 2</th>
<th>Topology 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>($H_i=4$)</td>
<td>($H_i=5$)</td>
<td>($H_i=7$)</td>
</tr>
<tr>
<td>WH</td>
<td>$\Delta t_{\text{det,50}}$</td>
<td>8,122 $T_N$</td>
<td>10,004 $T_N$</td>
<td>13,786 $T_N$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{\text{det,90}}$</td>
<td>26,949 $T_N$</td>
<td>33,213 $T_N$</td>
<td>45,753 $T_N$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{\text{det,99}}$</td>
<td>53,896 $T_N$</td>
<td>66,431 $T_N$</td>
<td>91,521 $T_N$</td>
</tr>
<tr>
<td>LAN</td>
<td>$\Delta t_{\text{det,50}}$</td>
<td>0,500 $T_N$</td>
<td>0,500 $T_N$</td>
<td>0,500 $T_N$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{\text{det,90}}$</td>
<td>0,900 $T_N$</td>
<td>0,900 $T_N$</td>
<td>0,900 $T_N$</td>
</tr>
<tr>
<td></td>
<td>$\Delta t_{\text{det,99}}$</td>
<td>0,990 $T_N$</td>
<td>0,990 $T_N$</td>
<td>0,990 $T_N$</td>
</tr>
</tbody>
</table>

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 ($\text{Psucc}$) 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 $\text{Psucc}$. This value is equal to 10 for the scenario represented in Figure 3. In the case of LAN-ND, assigning $\text{Advertise}$ links to devices in consecutive time slots or randomly results in different values of $\text{Psucc}$. Figure 6 illustrates the $\text{Psucc}$ 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 $\text{Psucc}$ performance is depicted for WH-ND when $DL_i=10$. The depicted LAN-ND performance corresponds that obtained when $\text{Advertise}$ 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 $\text{Psucc}$ increases when $\text{Advertise}$ links are assigned to devices randomly (LAN-ND-Rand). Figure 7 and Figure 8 illustrate the $\text{Psucc}$ 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 $\text{Psucc}$ as a result of increasing the number of $\text{Keep-alive DLPDU}$ and $\text{Advertise DLPDU}$ 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.
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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