Impact of Mobility on the Management and Performance of WirelessHART Industrial Communications

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Abstract

Wireless communication technologies will represent an essential technological component of the Factories of the Future in order to facilitate the real-time monitoring of the industrial processes, as well as the working conditions and the workers' health and safety. To this aim, wireless sensor networking technologies are being evolved to overcome the industrial challenging propagation environments and guarantee the strict QoS requirements characterizing industrial applications. However, a major future demand for wireless industrial systems could be the capability to support mobility. In this context, this paper analyzes the impact of mobility on the performance of industrial wireless communication systems based on a centralized management like the WirelessHART standard.

1. Introduction

The new Factory of the Future model emphasizes the workers' importance to improve productivity and competitiveness, and places their health and safety at the center of the agenda. In this context, the FASyS (Absolutely Safe and Healthy Factory) project [1] is working to develop technologies for monitoring the working environment and its conditions, and also the workers' health and safety. This monitoring process will be facilitated by FASyS's heterogeneous wireless communication platform for short, medium and long range communications. FASyS's short range communications will be enabled through the deployment of low cost Wireless Sensor Networks (WSN), which allow continuously monitoring on-site the working conditions and workers' health and safety. However, specific communications and networking protocols are necessary to maintain adequate Quality of Service (QoS) levels under adverse propagation environments such as those experienced in factories with multiple obstructing elements [2]. The provision of adequate industrial WSN QoS levels is further challenged under mobile conditions (e.g. when a WSN mote is carried by a worker or industrial vehicle). The impact of mobility in WSN is reviewed in [3] where several relevant contributions are analyzed. However, most of these contributions focus on decentralized mobility management and do not consider mechanisms to guarantee end-to-end QoS levels. Recent contributions have started investigating the design of new protocols to improve mobility in industrial wireless systems. For example, the study reported in [4] defines a pre-dimensioned virtual tree topology with hierarchal addresses. However, the proposed schemes are based on reserving resources for potential mobile nodes, which can be inefficient in highly dynamic networks. WirelessHART (WH) [5] has been developed to operate under challenging environments, and to provide high levels of reliability and robustness using a centralized management approach. Although such approach can help sustain high and reliable QoS levels, it might present certain inefficiencies in case of highly dynamic mobile networks. As a result, this paper presents the first study on the impact of mobility on the performance of wireless industrial communications based on the WH standard.

2. WirelessHART

The WH communications standard is based on IEEE 802.15.4 operating in the 2.4GHz band. WH adds on top of IEEE 802.15.4 a TDMA medium access mechanism for improved transmission robustness. WH divides the time into slots, each with a duration of t_s=10ms. The slots are organized into superframes that are periodically repeated. The management superframe should contain N=6400 slots and has a total duration of $T_N=N\cdot t_s$=64s. The WH Network Manager (NM) is responsible for allocating data and management slots to network nodes.

The NM is also in charge of handling the joining process to the network of a new node (the process summarized in Figure 1 omits for simplicity the security management message exchange). A new node that wants to join to the network must first be in reception mode to receive an *Advertise* message from another network node. This message transmits information on how and in which slot the new node has to request joining to the network. Then, the node that requires joining to the network sends a *Join Request* in the *Join* slot specified by the *Advertise*. The node that receives the *Join Request* forwards it to the next node in the route to the NM. If the new node is accepted into the network, the NM sends to the new node information and the scheduling of its time slots. This new schedule may also involve the allocation or reallocation of slots to other nodes to establish new data and management communication routes. One receipt of the schedule, the new node completes the joining process and can start its transmission.

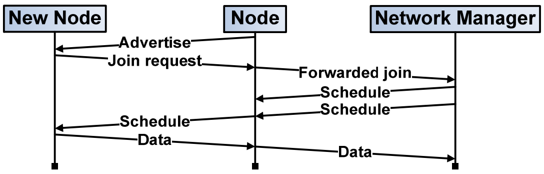


Figure 1. Join sequence.

3. Performance Metrics

The objective of this study is to analyze the impact of mobility on the management and performance of WH industrial communications. To this aim, several parameters and metrics are next defined. The developed metrics are particularized for scenarios with a single mobile node and a single channel frequency, and could be extended to more complex cases that include a higher number of scenarios.

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, and their duration as $T_N=N \cdot t_s$. The number of slots used in one superframe for management functions is defined as M, so that the free slots in the management superframe (N-M) may be used for data transmission and reception. Furthermore, the time that a mobile node is under network coverage is defined as t_e, and depends on the network topology, the radio coverage, and the node's trajectory and speed. Finally, the number of hops between the data source node and the data destination node is defined as N_h.

The experienced end-user QoS will strongly depend on the slots that a user can be assigned for transmitting data. As a result, an important performance metric is the channel utilization that can be used by a node to transmit data (*Data_Ch_Usage*), and is defined as the ratio between the maximum number of slots that the NM can assign to a node for transmitting data messages and the total number of slots of a superframe. This metric allows analyzing the impact of mobility independently of different factors such as the instantaneous transmission rate and messages sizes. To increase the communications reliability, WH does not allow instantaneously reusing one slot of a given frequency channel for more than one data transmission. As a result, if there are N_h hops between sender and receiver and the number of slots available for data transmission is N-M, the maximum number of slots that can be assigned to a node for data transmissions is $(N\text{-}M)/N_h$. *Data_Ch_Usage* can be defined for a static node connected to the network as:

$$Data\_Ch\_Usage = \frac{N-M}{N \cdot N_h} \quad (1)$$

If a node is mobile, it may loose the radio connectivity with the node that it uses to connect with the rest of the network. If the mobile node cannot find a new node to maintain network connection before losing its connectivity, it will have to initiate a *Rejoin* process. During this process, the mobile node does not have slots assigned for communication, thereby degrading its end-user QoS. The duration of the *Rejoin* process is equal to the access time (t_a), which can be defined as the time elapsed from the moment that a node (under network coverage) turns its radio to reception mode to receive an *Advertise*, to the moment it finishes its join process and can begin transmitting data. During the trajectory of a mobile node, multiple *Rejoin* processes may take place.

Additionally, if the mobile node can find a new node to maintain network connection before losing connectivity with its current attaching node, we assume that a *Handover* can be performed (although it is not currently defined in the WH standard). For a successful *Handover*, it is necessary that the NM configures and assigns the new slot allocations before the mobile node loses connectivity with its current attaching node. If a *Handover* is successfully performed, the mobile node does not need to stop transmitting data during its trajectory. In these cases, equation (2) defines how mobility with *Rejoin* (multiple accesses) or with Handover (only one access) processes impacts the *Data_Ch_Usage* parameter.

$$Data\_Ch\_Usage = \left(\frac{N-M}{N \cdot N_h}\right) \cdot \left(\frac{t_e - \sum t_a}{t_e}\right) \quad (2)$$

The access time can be computed as the sum of a variable and a fixed time of period. The variable time corresponds to the time that a node needs to wait until it receives an *Advertise* message. This time can be defined as a random variable with uniform probability distribution between zero (the node goes into reception mode during the slot just before an *Advertise* transmission) and T_N-t_s (the node goes into reception mode during the slot just after an *Advertise* transmission). On the other hand, the time elapsed from the reception of an *Advertise* until the NM assigns data slots is fixed for a given network topology and deployment. It is important to note that this study considers contiguous management slots within a superframe and management slots organized following the order of messages used in the join process. As a result, the fixed time period within the access time is minimized, and is approximately equal to the time spent in management functions within a superframe ($T_M=M \cdot t_s$). The total access time can therefore be represented as a random variable with a uniform probability distribution between a minimum ($t_a=T_M$) and maximum ($t_a=T_M+T_N-t_s$) values. The average access time ($\overline{t_a}$) can then be computed as:

$$\overline{t_a} = \frac{T_N + 2 \cdot T_M - t_s}{2} \quad (3)$$

4. Impact of Mobility

To evaluate the impact of mobility on the performance of wireless industrial communications with centralized management, this study considers the three network topologies depicted in Figure 2. For all topologies, the distance between two nodes with connectivity is fixed and equal to the communications range (*R*). The first topology will allow evaluating the impact of mobility in a simple and realistic topology trying to minimize the number of hops between nodes. The second topology is proposed to evaluate how an increasing number of fixed nodes influences the impact of mobility. The third topology is proposed to evaluate the influence of the number of hops between the fixed nodes and the NM. An example of the resulting superframe assignation for the first network topology is illustrated in Figure 3. As previously mentioned, management slot are placed consecutively and within the order used in the join process. The discovery slot is used to detect new neighboring nodes. The rest of management slots are used for the joining process illustrated in Figure 1.

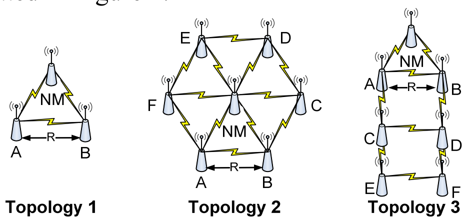


Figure 2. Network topologies.

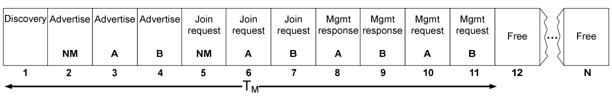


Figure 3. Management superframe example.

4.1. Evaluation Scenarios

To analyse the impact of mobility, four different evaluation scenarios are considered (S_1, S_2, S_3 and S_4). The first three scenarios (S_1, S_2 and S_3) consider topologies 1, 2 and 3, respectively, in which a new static node Z is added with connectivity only to node A or a new mobile node Z enters the network with a rectilinear trajectory and constant speed. In these scenarios the mobile node Z accesses the network via node A, and only stays a certain time t_e under A or B coverage. The fourth scenario considers the third topology where a new static node Z is placed with connectivity only to node E or a new mobile node Z accesses the network via node E, and stays a certain time t_e under E or F coverage. As an example, Figure 4 illustrates the scenario S_1 with the mobile node conducting a *Rejoin* process as it looses its connectivity with node A. The figure also shows the two periods (t_a) during which Z stops its data transmissions to request network access.

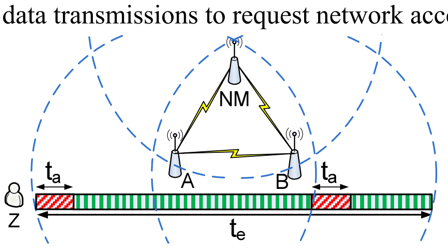


Figure 4. S_1: mobile node Z with *Rejoin*.

4.2. Results

The results shown in this section refer to the performance experienced by the (static or mobile) node Z. It is important noting that the depicted *Data_Ch_Usage* performance corresponds to the average *Data_Ch_Usage*, computed considering all possible moments in which node Z accesses the network coverage. The maximum performance achievable under S_1, S_2 and S_3 is 0.5. This is due to the fact that data packets transmitted by Z to NM need to be forwarded by an intermediate node. Figure 5 represents the performance obtained under S_1 considering the node Z is static or mobile. The results have been obtained considering the WH superframe duration of 64 seconds. Following equation (1), *Data_Ch_Usage* is constant and independent of t_e in the case of static nodes. On the other hand, *Data_Ch_Usage* increases with t_e in the case of mobile nodes. The results obtained also show that the time spent to re-gain access to the network in case a mobile node needs to conduct a *Rejoin* process results in a lower *Data_Ch_Usage* performance compared to the case in which the mobile node can conduct a *Handover*. Overall, these results clearly illustrate the potential negative effect of mobility on WH, in particular, when the time that the mobile node is under coverage is small.

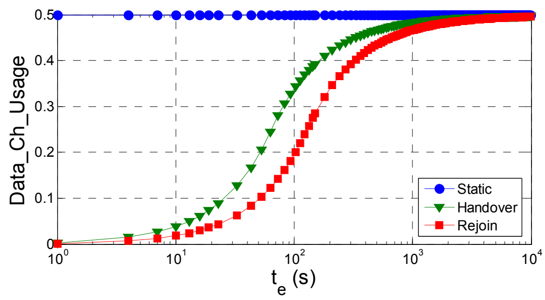


Figure 5. S_1 *Data_Ch_Usage* performance as a function of t_e.

Figure 6 illustrates the *Data_Ch_Usage* performance for different values of the superframe duration T_N (scenario S_1 when mobile node Z conducting *Rejoins*). The obtained results show that under low mobility conditions (high t_e values), the larger the duration of the superframe, the higher the *Data_Ch_Usage* performance. This is because for large superframes, fewer slots are dedicated to management functions, and more slots can therefore be available for data transmissions. However, under high mobility conditions (low t_e values), higher *Data_Ch_Usage* performance is observed with shorter durations of the superframe. This is due to the fact that under high mobility conditions, the mobile node needs to more frequently conduct a *Rejoin* process. In this case, shorter durations of the superframe increase the number of management slots, and therefore reduces the time necessary to re-gain network access and start data transmissions. Similar trends to that observed in the case of mobile nodes performing *Rejoin* processes have been observed when *Handover* processes are considered. The obtained results highlight the potential benefits that could be gained from a dynamic adaptation of the superframe duration as a function of t_e.

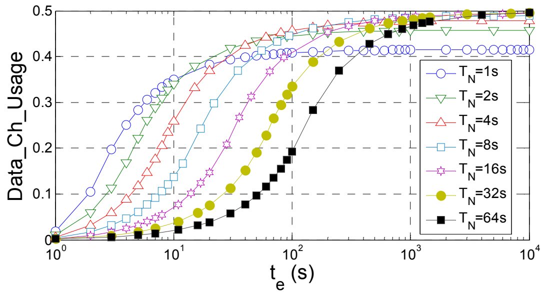
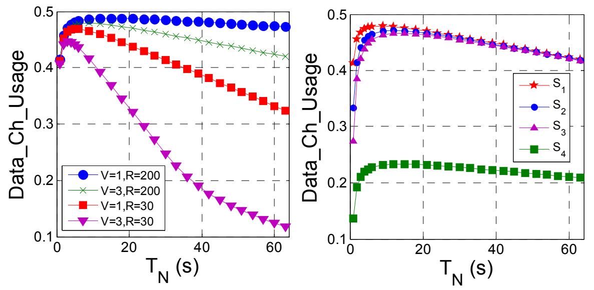


Figure 6. *Data_Ch_Usage* performance as a function of t_e under S_1 (*Rejoins*).

The time that the node is under network coverage is related to the node's speed (*V*) and the communications range of each node in the network (*R*). In this context, Figure 7a shows for different values of these two parameters[1], the *Data_Ch_Usage* performance achievable under S_1 when the mobility of node Z results in a *Handover*. The obtained results show that each configuration of mobile speed and communications range considered results in different superframe duration in order to maximize *Data_Ch_Usage*. It is important noting that under all considered combinations, the superframe durations maximizing *Data_Ch_Usage* are significantly lower than the 64 seconds recommended in the WH standard, further emphasizing that some relevant WH operational parameters (e.g. T_N) are not optimized for mobility scenarios.



(a) Scenario S_1 (b) V=3m/s, R=200m

Figure 7. *Data_Ch_Usage* performance as a function of T_N (*Handovers*).

All previous results were obtained under the first scenario. Figure 7b depicts the dependence of the *Data_Ch_Usage* performance on the superframe duration for the four different scenarios in the case of mobile node Z being capable to perform *Handovers*. The results show that increasing the number of fixed nodes in the network topology (from S_1 to S_2 and S_3) reduces the data transmission capability only for low T_N values, because the number of management slots needed is increased. Furthermore, the results clearly show that an increase in number of hops between source and destination nodes (S_4) significantly reduces the *Data_Ch_Usage* performance, due to the need of forwarding packets from the source node to the NM. As a result, a mobile node's data transmission capability is variable, and strongly dependent on the topology and the fixed node through which it connects to the network.

5. Conclusions

Industrial wireless communications are expected to have an important role in improving industrial productivity, as well as the worker's health and safety. To this aim, it is important that industrial wireless systems are capable to maintain high QoS levels under challenging propagation and mobility conditions. In this context, this paper has conducted the first study in analyzing the impact of mobility on the performance of industrial wireless communications systems based on a centralized management as in the case of the WH standard. The study has analyzed different network topologies, and has investigated important operational parameters as well as multi-hop communication scenarios. To establish performance bounds, the study has considered two relevant mobility scenarios: one in which mobile nodes are capable to conduct *handovers* as they move across the network, and another one in which they need to conduct a *rejoin* process each time they leave the communications range of the fixed node to which they are attached. The obtained results show that the existing management mechanisms are not suitable to efficiently handling mobility of network nodes, and can significantly degrade the data transmission capability even under relatively simple network topologies. In addition, industrial wireless communication standards supporting nodes' mobility could also benefit from the dynamic management of superframes.

Acknowledgements

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[1] The selected communications range represent realistic ranges achievable under line of sight propagation conditions (R=200m), and non light of sight propagation conditions (R=30m). The selected speeds represent a moving pedestrian (V=1m/s) and small vehicles moving in indoor industrial environments (V=3m/s).