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Neighbor discovery for industrial wireless sensor networks with mobile nodes

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ABSTRACT

Industrial wireless sensor networks can facilitate the deployment of a wide range of novel industrial applications, including mobile applications that connect mobile robots, vehicles, goods and workers to industrial networks. Current industrial wireless sensor standards have been mainly designed for static deployments, and their performance significantly degrades when introducing mobile devices. One of the major reasons for such degradation is the neighbor discovery process. This paper presents and evaluates two novel neighbor discovery protocols that improve the capability of mobile devices to remain connected to the industrial wireless sensor networks as they move. The proposed protocols exploit topology information and the nature of devices (static or mobile) to reliably and rapidly discover neighbor devices. This is achieved in some cases at the expense of increasing the number of radio resources utilized and the energy consumed in the discovery process. The proposed solutions have been designed and evaluated considering the WirelessHART standard given its widespread industrial adoption. However, they can also be adapted for the ISA100.11a and IEEE 802.15.4e standards.

1. Introduction

Industrial Wireless Sensor Networks (IWSNs) can help reduce the cost and time needed for the installation and maintenance of cables and machinery, enhance the flexibility and reconfigurability of a factory, and facilitate the introduction of healthcare solutions [1,2]. Current IWSNs mainly focus on static deployments and devices, but there is a growing interest in utilizing IWSNs for connecting mobile subsystems or devices. For example, NAMUR (User Association of Automation Technology in Process Industries) has established a "Mobile Automation" working group (WG 4.15) to study fields of application for wireless technologies and mobile applications in process automation.

Current IWSN standards include WirelessHART [3], ISA100.11a [4] and IEEE 802.15.4e [5] for industrial automation and control applications. Despite their differences, both standards share some fundamental wireless technologies and mechanisms [6], e.g. a centralized network management to provide the reliability and latency levels required by industrial applications. IWSNs still face significant challenges to ubiquitously guarantee the reliability and latency requirements of industrial applications, in particular when considering mobile nodes (robots, vehicles, goods, people, etc.). In fact, the mechanisms defined in WirelessHART for joining, discovering, scheduling or routing are currently not optimized for scenarios where mobile devices would require permanent network connectivity. So, even if WirelessHART considers the use of handheld devices, these handheld devices can only communicate with the attached device and cannot maintain network connectivity as they move. In this context, studies such as [7,8] have highlighted the need to design new mechanisms that reduce the time required to discover neighbor devices and the time to reconfigure the network before mobile nodes can be integrated in existing WirelessHART networks. Mobility management mechanisms are also necessary for mobile devices to remain connected to the network [9]. Such connectivity is also significantly influenced by the Neighbor Discovery Protocols (NDP) [10]. Devices utilize the NDPs to discover their one-hop neighbors. Adequate NDPs are necessary to reduce the probability of mobile devices to lose network connectivity and minimize the time to discover neighbors in case the connectivity is temporarily lost. It is important to highlight that the discovery process can only be executed by devices that have previously joined the network. As a result, the NDPs are independent of the process followed by devices to join the network.

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NDPs can be classified as probabilistic or deterministic [11]. Deterministic NDP schemes ensure a bounded discovery time. This is generally done by transmitting discovery packets on dedicated radio resources in order to avoid packet collisions. On the other hand, probabilistic NDP schemes are simpler to implement and require fewer radio resources and lower energy consumption for the discovery process. The NDP scheme included in WirelessHART is probabilistic, and cannot hence guarantee strict upper bounds on the discovery latency. This might not be critical when nodes are static and maintain the same neighbors for long periods of time. However, the capacity to rapidly detect neighbors is critical when considering mobile devices. In this context, this paper proposes two novel NDP schemes that improve the neighbor discovery process under the presence of mobile nodes in IWSNs. The first proposal is a deterministic NDP scheme that exploits information about the network topology that is exchanged among devices. The second proposal combines the advantages of deterministic and probabilistic NDP policies. It does so by applying probabilistic policies for static devices, and deterministic ones for mobile devices. This approach helps reducing the discovery overhead while providing the necessary capacity for mobile nodes to detect neighbors. This study is conducted under the framework of the WirelessHART industrial standard, and the proposed NDP schemes do not affect other existing WirelessHART mechanisms such as the process followed by devices to join the network or the routing [3]. The obtained results demonstrate that the proposed schemes significantly improve the capacity of mobile devices to discover neighbors and the time needed to detect them compared to the existing WirelessHART NDP solution. These benefits are achieved, for some of the proposed NDP protocols, at the expense of increasing the number of radio resources utilized and the energy consumed in the discovery process compared to the current WirelessHART NDP process.

The paper is organized as follows. Section 2 reviews the state of the art on neighbor discovery protocols in IWSNs. Section 3 describes the WirelessHART standard and its NDP scheme. Section 4 describes the proposed NDP schemes, and Section 5 defines the metrics utilized to evaluate their performance. Section 6 presents analytical performance models for the NDP schemes under evaluation, and Section 7 compares their performance through simulations. The main contributions and conclusions of this study are summarized in Section 8.

2. State of the art

Managing the mobility of nodes usually requires handover mechanisms that implement three different phases: information gathering, decision and execution. The information gathering phase is responsible for monitoring and collecting all context information. Based on the collected information, a handover decision would then be taken, including the selection of the new connecting node. Executing a handover can require, for example, changing the assigned frequency channel or time slot. NDP schemes are part of the information gathering phase, and are the focus of this study.

The study in [12] presents an excellent review of existing NDP schemes in wireless networks. All NDPs generally fall into two categories: probabilistic or deterministic [11]. In deterministic NDPs, nodes transmit discovery packets following a predefined schedule that guarantees a bounded discovery time [13]. Probabilistic NDPs cannot provide such guarantee since nodes transmit their discovery packets at randomly chosen times and packet collisions can be produced. On the other hand, probabilistic NDPs are simpler to implement and utilize fewer radio resources and lower energy consumption for the discovery process. The WirelessHART NDP scheme and the birthday protocol [14] are examples of probabilistic NDPs implemented over Time Division Multiple Access (TDMA). With the birthday protocol [14], nodes can choose for each time slot dedicated to the discovery process whether they are in transmission, reception or sleep mode following predefined probabilities. WirelessHART does not employ the sleep mode, and each device goes into transmission mode after a random waiting time. To discover neighbors, WirelessHART requires devices to be in reception mode in all discovery slots in which they are not transmitting.

The time necessary to discover neighbors can be arbitrarily long in the case of probabilistic NDPs. Probabilistic NDPs might hence not be suitable for mobile networks that require a strict upper bound on discovery latency [15]. Deterministic NDP schemes are hence usually utilized by mobile devices for neighbor discovery [15]. For example, cellular systems use deterministic schemes to identify the base station to which a node should connect. Cellular networks periodically inform mobile terminals about the neighboring cells, and the mobiles perform radio measurements to identify whether they should change their serving base station [16]. Several deterministic NDPs explicitly or implicitly use brute force techniques to ensure the detection of neighbors before a given deadline [17]. In this case, nodes try to remain in reception mode as long as possible if they do not have any other packet to transmit. NDP schemes that use brute force are not very energy efficient. To reduce energy consumption, schemes such as those presented in [18,19,20] limit the number of time slots under which a node is in reception mode to those where it is known that neighbor nodes can transmit discovery packets. In this case, the challenge is how to identify and inform each node about the time slots in which it has to be in reception mode to detect neighbors. The NDP scheme proposed in [18] predicts future contacts statistically using network science in order to reduce the energy consumption. The NDP scheme proposed in [19] uses reinforcement learning techniques to dynamically identify the time slots under which a node should be in reception mode. For improving the learning process, and to account for pattern variations, the NDP scheme in [19] also allows nodes to monitor other time slots.

Neighbor discovery is particularly challenging when devices can operate over multiple channels like it is the case of WirelessHART. Multi-channel neighbor discovery policies are also necessary when applying deterministic NDP schemes to standards that allow for the simultaneous use of several channels. The multi-channel NDP proposed in [21] operates with heterogeneous duty cycles and without clock synchronization. Another example is the McDisc proposal [22] that utilizes multiple available channels to establish a multi-channel neighbor discovery schedule that reduces energy consumption and increases the discovery reliability. A different approach is considered in [20] where a central entity informs each node about the time slots under which it should be in reception mode to detect neighbors. The work proposed in [20] is the first study that considered the neighbor discovery challenge in WirelessHART networks that include mobile devices. Other relevant NDP schemes have been reported in [10,13,17] However, they cannot be directly applied in WirelessHART since Sun et al. [10] considers full-duplex technology, Vasudevan et al. [13] divides each slot into two subslots, and Kandhalu, et al. [17] assumes that if two devices are awake during the same slots they can mutually discover each other.

3. WirelessHART

WirelessHART defines a centralized network architecture. It is based on the IEEE 802.15.4 physical layer and operates in the 2.4 GHz ISM band. Although 16 channels are available in this band, only channels 11–25 can be used by WirelessHART devices. On top of the IEEE 802.15.4 physical layer, WirelessHART adds a TDMA scheme combined with Frequency Hopping for improved robustness and capacity. A communications link is therefore defined