Guest Editorial Special Section on Wireless Technologies in Factory and Industrial Automation—Part I

WIRELESS technologies are nowadays in widespread use, with cellular telephony and wireless Internet access being two of the major driving forces behind this. Using wireless technologies in industrial and factory automation is also very attractive for many reasons. The wireless way of communicating makes plant setup and modification easier, cheaper, and more flexible. It provides a natural approach towards communication with mobile equipment where wires are in constant danger of breaking. It enables new applications where wireless transmission is the only option, e.g., measurements and control of rotating or highly mobile devices, and provides a novel approach to existing applications, e.g., localization and tracking of goods. Furthermore, tasks like machine diagnosis and maintenance can be greatly simplified by equipping the maintenance personnel with wireless terminals.

In many factory and automation applications, the communication needs are traditionally served by wired fieldbus systems and other industrial communication systems like, for example, sensor/actuator buses [1], [2]. These communication systems have been specifically designed to meet the stringent real-time and reliability requirements found in many industrial applications. Of course, wireless technologies should ideally provide the same type and quality of services to industrial users as the traditional, wired technologies do. However, wireless technologies differ in a number of ways from wired ones. These differences pose significant challenges for the design of network architectures, protocols, and tools for industrial and automation applications [3]–[5].

A first fundamental difference is represented by the error properties of wireless channels as compared to those of the wired ones [6]. Many measurement studies have shown that wireless channels exhibit transient errors (bit errors, packet losses) at often much higher rates than observed on wires or fiber cables [7]. In addition, the error rates are often time-variable. These channel errors result from phenomena like constructive and destructive interference (creating fast fading), attenuation by obstacles (slow fading), path loss, and thermal noise. This has two significant implications for the *design* of industrial networking protocols and applications. First, there is a need for careful choice of physical layer technologies, appropriate medium access control (MAC) protocols, and error control schemes, which are able to combat channel errors in a manner respectful to real-time deadlines (e.g., [8] and [9]). Such a choice should be based on knowledge of propagation conditions and error patterns in industrial sites [10]–[12]. Second, industrial applications involving wireless technologies must be aware of the fact that even the most advanced physical layer, MAC, and error control technologies cannot fully mask out channel errors, and consequently, there is potentially a non-negligible residual error rate. This calls for the design of user applications and application layer protocols capable of taking the presence of transient errors explicitly into account and being reasonably robust against them. It is worth mentioning that standardized, wireless-aware application layer protocols are not yet available (and, actually, standardization activities have not yet been undertaken by the competent bodies, and there is thus some danger of uncontrolled proliferation of proprietary products). When it comes to the *evaluation* of networking and application layer protocols and applications, it is appropriate to leave the *deterministic* view on deadlines behind and adopt *probabilistic* measures, like, for example, the probability to miss a pre-specified deadline or measures like the delay-limited capacity [13]–[15].

Another fundamental difference is that the wireless medium is an "open" medium, i.e., wireless signal propagation is not confined to a cable, but the signals can be received in a whole spatial area. This has a number of important consequences, which of course are not only specific for industrial settings. First, a wireless transmission can be overheard in the whole spatial area, which is an excellent opportunity for an adversary to eavesdrop or to even insert malicious packets. This "openness" of the medium thus creates additional security threats that must be taken into account in the design of protocols (compare [16]). Second, a wireless transmission creates interference to other wireless systems working in the same geographical area and the same frequency band. Vice versa, any wireless (industrial) communication system is susceptible to interference created by other systems, not only from those using the same technology but also from other technologies working in the same frequency band. For example, the license-free 2.4-GHz industrial, scientific, and medical (ISM) band is used by the IEEE 802.11 wireless local area network (WLAN) technology, by IEEE 802.15.1 Bluetooth and by the IEEE 802.15.4 wireless personal area network (PAN) technologies. Consequently, coexistence issues arise. In home or office scenarios, this problem is usually ignored. For instance, all the owners of Wifi WLAN access points in a densely populated urban area simply make some random choice of frequency channel, since there is no practical way to negotiate with neighbors on good ways of spectrum sharing. While being very simple, such a "random" approach is harmful to real-time and reliability properties that are vital in industrial applications. When a certain level of channel quality is needed to achieve requested real-time and reliability levels, proper *network planning* is required, implying decisions about positions of wireless nodes and frequencies

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used, e.g., [17]. Appropriate industrial planning tools tailored to indoor industrial settings are called for.

A third fundamental difference stems from mobility. While in general being a desirable feature, it has the side effect of frequent changes to the topology of the wireless network. Network protocols must then be able to detect such topology changes and to adapt their operations accordingly, e.g., by providing fast handover procedures, by modifying the logical networking structure for MAC schemes based on token-passing, or by modifying routing tables in case of multi-hop networks. This requires flexible, and potentially also more complex protocols.

Besides these issues, a number of other, more practical, problems have to be resolved. Given that industrial users will be reluctant to simply throw out their functioning wired fieldbus installations in favor of wireless ones, wireless stations should be *integrated* with wired fieldbuses to create *hybrid wired/wireless fieldbus systems* [18], preferably without requiring changes to the protocols of already existing wired stations. The coupling devices transferring packets between wired and wireless parts of the network introduce additional forwarding delay [19], which depends on their precise type of operation (cut-through forwarding versus store-and-forward). This additional delay needs to be considered in the configuration and operation of protocols, e.g., [20] and [21]. The precise implementation of hybrid systems of course depends on the specific wired fieldbus systems and wireless technologies considered. As an example of a hybrid system, in [22], a wireless extension of Profibus DP [23], implemented using the Bluetooth technology [24], is described.

Among the available radio systems, in particular, WLAN technologies like the IEEE 802.11 family of standards [25], [26] and the upcoming technology of wireless sensor networks (WSN) [27]–[29] have moved into the focus of researchers and practitioners interest in factory-level wireless industrial communications. When wireless sensor networks have been chosen as underlying wireless technology, energy conservation is an additional aspect of paramount importance [30], [29] or, alternatively, the (wireless) supply of energy to wireless devices [31], [32] as well as electromagnetic compatibility.

This special section on "Wireless Technologies in Factory and Industrial Automation" of course cannot cover all these issues in a comprehensive manner. In response to the call for papers, we received in total 20 submissions. The section is split over two issues of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS. In the present issue, three papers are presented; further papers will appear in the August issue of these transactions.

In the paper "Channel Characterization and Link Quality Assessment of the IEEE 802.15.4-Compliant Radio for Factory Environments" by L. Tang *et al.*, the authors present the results of a wireless channel measurement study carried out with commercial radio equipment compliant to the IEEE 802.15.4 standard [27]. The results give insights into the relationship between the propagation conditions found in factory environments and the packet error characteristics of wireless links. This kind of information is very useful for proper planning of industrial wireless networks based on sensor radios, as well as for the design of protocols. The measurement approach captures both spatial variation (from measuring on a fine grid in a machine shop) as well as temporal variation (from 24-h measurements at fixed positions). It is shown that spatial variation in channel quality corresponds to the presence or absence of a line-of-sight (LOS) path and the presence or absence of metallic clutter in the vicinity of transmitting or receiving stations. A further important contribution is an assessment of the relationship between certain per-packet quality values delivered by the wireless transceiver when receiving a packet [like the received signal strength indicator (RSSI)] and the observed packet error rate (PER). It is shown that the link quality indication (LQI) value has a high correlation to the PER and therefore allows to predict the PER. This kind of information can, for example, exploited by protocols to adapt their operations.

The paper "Modular Wireless Real-Time Sensor/Actuator Network for Factory Automation Applications" by H. J. Koerber *et al.* is concerned with a wireless sensor/actuator network for employment at the low levels of factory automation systems. The paper represents a very comprehensive work, since it faces several aspects of wireless industrial communications. Indeed, after an analysis of the user requirements, it presents a set of measurements aimed at providing the characterization of the physical channel. Then, the network design is introduced, along with an exhaustive discussion on the choice of the radio technology and components. The proposed network has been conceived in order to provide performance similar to those of the most popular (wired) sensor/actuator buses, like, for example, AS—interface [33] and Seriplex [34]. In such a direction, the paper reports some experimental results, obtained from a set of tests carried out on a prototype implementation of the network, which demonstrate the effectiveness of the design. Finally, some interesting considerations on energy consumption aspects are given.

The paper "WiDom: A Dominance Protocol for Wireless Medium Access," by N. Pereira *et al.*, deals with the problem of scheduling real-time transmissions in a wireless industrial network. In the paper, the authors present a novel mechanism, called WiDom, which is based on the adaptation to the peculiarities of the wireless medium to the dominance protocol used in the CAN bus. The proposed mechanism is relevant in that it has the potential to overcome some of the limitations incurred by current deployment of wireless technologies in industrial environments, usually built using COTS devices based on general-purpose standards. The paper comprises a detailed description of the proposed protocol, together with an experimental evaluation thereof, carried out using embedded computer platforms. Concluding remarks cover a number of issues, such as the possible integration of power management in the proposed scheme and the applicability limitations determined by wireless channel impairments.

Preparing such a special section requires the help of a lot of people. First, we thank all the authors for their contributions and their prompt cooperation in the later steps of the publication process. The reviewers did an excellent job in providing the authors with comprehensive and useful reviews. We thank all of them. We also would like to thank the editors of these

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