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IO-Link Wireless Enhanced Sensors and Actuators for Industry 4.0 Networks

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Abstract:

In the context of the Industry 4.0 initiative Cyber-Physical Production Systems (CPPS) or Cyber Manufacturing Systems (CMS) can be characterized as advanced networked mechatronic production systems interacting with the ambient Industrial Internet of Things (IIoT). In this strongly evolving technological environment appropriate communication technologies and standards play a vital role to let the manifold potential improvements in the production process become true. One of these standards is IO-Link. In 2016 more than 5 million IO-Link nodes have been produced and delivered, still gaining an increasing acceptance for the communication between sensors, actuators and the control level. There is also a steadily increasing demand for more flexibility in automation solutions, which often can be supported by wireless technologies. With the wireless extension for the IO-Link standard, which will be presented in this article, cycle times down to 5 ms could be achieved. The probability that this limit will be exceeded lies at 10^{-9}. Also roaming capabilities, wireless coexistence mechanisms and the possibility to include battery-powered or energy-harvesting sensors with very limited energy resources in the real-time network were implemented. For system planning, setup, operation and maintenance standard engineering tools of IO-Link can be employed so that the backward compatibility with wireline IO-Link solutions can be guaranteed.

Key words: Wireless Industrial Internet of Things (IIoT), Industry 4.0, Wireless Communication, Low-Latency, Sensor/Actuator-Communication, Sensor-2-Cloud, Factory Floor, Cyber-Physical Production System (CPPS).

Introduction

During the last years WirelessHART [1] has become the de-facto standard in process automation (PA), relying on the physical layer of the IEEE standard 802.15.4 and specifying additional transport and applications layers. As the requirements with respect to start-up and latency times, device density, physical dimensions and installation costs are more demanding in factory automation applications, a comparable standard has not been established in this environment up to now. The investigations and developments described in this article are focused on the wireless extension of the IO-Link standard, which has been initiated by the Profibus User Organisation (PNO) and the IO-Link community several years ago [2]. First named "WSAN-FA", it was later renamed to "IO-Link wireless" and further optimized on the technological level. Since the IO-Link standard [3-6] is already well established in the field for sensor/actuator communication, the discussion of the IO-Link standard in the next section is limited to the necessary information to understand the characteristics and properties of the wireless extension.

The classic multi-level communication model of an automation system is shown in Fig. 1, where the target applications for IO-Link communication are on the sensor/actuator level of the automation pyramid.

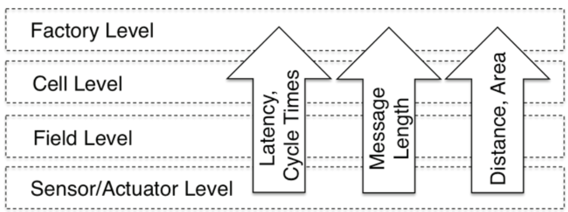

Fig. 1. Classic multi-level organization of an industrial communication system for automation applications.

According to [7] wireless communication requirements in industrial environments can roughly be categorized by the following parameters: system availability, redundancy requirements, safety and security level, electro-

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magnetic compatibility with classical industrial interferers such as induction heaters and switch-mode power supplies, coexistence behavior with already installed wireless systems, type of data traffic, latency times, message lengths and spectrum allocation requirements, number of communicating stations, coverage area, mobility support, handover mechanisms and integration availability. All these requirements have been addressed by IO-Link wireless.

Performance characteristics for wireless sensor/actuator communication systems are usually defined with response times in the order of 10 ms or even lower and with up to 100 sensors and actuators within a production cell extending a few meters [8,9]. For application areas requiring coexistence with already installed wireless systems, e.g. WiFi, radio channel blacklisting has been implemented. Together with the protocol-inherent mechanisms of IO-Link wireless for time- and frequency diversity this provides a reliable and robust wireless technology for real-time communication of the sensors and actuators to the overlaying production process (Fig. 2).

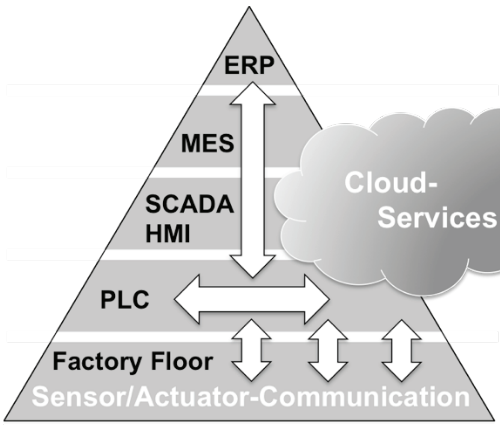

Fig. 2. New standards and technologies enable horizontal and vertical communication systems integration and to break-up the classical automation pyramid [10,11].

With the introduction of CMS and IIOT in factory automation this highly-structured communication architecture will gradually be modified and improved with highly decentralized networked services [10,11]. In this context IO-Link and IO-Link wireless are seen as enabling technologies for such services, offering full networking capability vertically down to the sensors and actuators on the shop-floor and up to the enterprise resource planning (ERP) tool and horizontally across the various fieldbus platforms on the basis of an already internationally established communication standard.

IO-Link System Description

As indicated in Fig. 3 the open interface standard IO-Link as described in IEC 61131-9 [4] offers a fieldbus-neutral communication between the sensor/actuator-level and the control level. It specifies a serial, half-duplex point-to-point connection for digital communication and energy supply. An IO-Link system typically consists of an IO-Link fieldbus gateway, the IO-Link master, providing some number of master ports, each of which is connected to a single IO-Link device. Devices can be sensors, actuators, RFID-readers, valves, motor starters or simple I/O-modules. Additionally, the standard IO-Link system comprises engineering tools for sensor/actuator configuration and parameter assignment. The following basic data types are defined:

- “Process data” with a length of up to 32 Bytes, which are exchanged with every communication cycle.
- “Value status data" indicating if the process data are valid or not, which are also exchanged cyclically.
- “Parameter and diagnostic data” such as identification information, settings, warnings and errors, which are exchanged on-request.

To give an example: at maximum speed of 230 kBaud it takes 400 µs to exchange two Bytes of process data and one Byte of on-request data between the IO-Link master and the device [4].

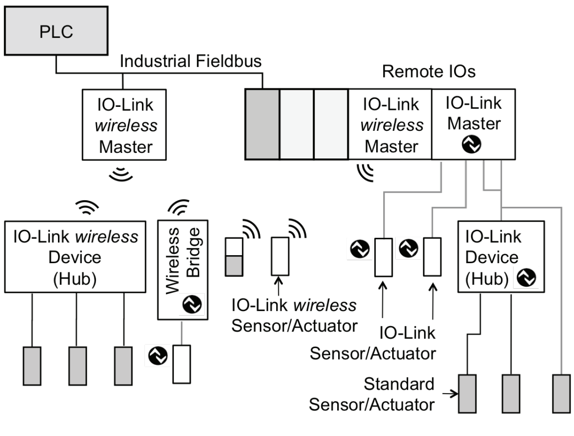

Fig. 3. Example of a system architecture based on IO-Link according to [3].

For system configuration, engineering tools are available that make use of the IODD files, allowing high-level configurability of the IO-Link devices via the IO-Link master. The main tasks are the assignment of the devices to the master ports and address/parameter assignment [6].

For vendor-independent system integration an electronic device description (IODD) file was defined containing communication properties such as the supported baud rate, device ID, manufacturer ID, device specific data and parameters as well as a description of the process data provided by the sensor or actuator.

IO-Link Wireless System Architecture

How the IO-Link wireless system will be embedded in the industrial communication architecture is illustrated in Fig. 4. From a user's perspective there is no difference in the operation of the devices, i.e. sensors and actuators, whether they are connected to the master by wire or wirelessly. Also standard engineering tools for sensor/actuator configuration and parameter assignment can be employed. These can be extended to optimize radio link quality and coexistence behavior. The necessary parameters for wireless communication were added to the standard IODD files. Additionally, conventional IO-Link devices can also be coupled wirelessly to the IO-Link master utilizing a "Wireless IO-Link Bridge" module.

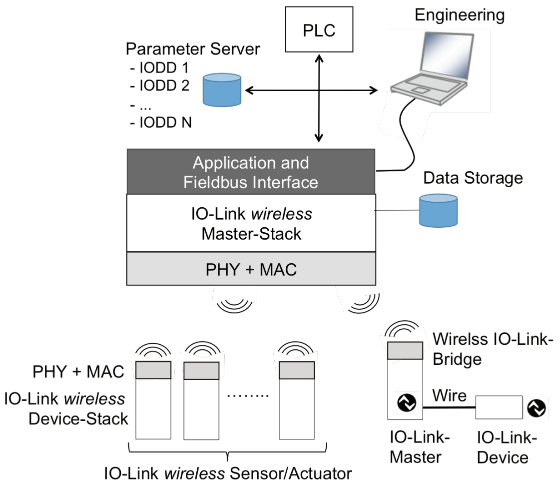

Fig. 4. IO-Link Wireless System Architecture

IO-Link Wireless Physical Layer and MAC

It has been found that the physical layer of Bluetooth Low-Energy devices optimally fits to the requirements for an efficient wireless data exchange. To comply with regulatory standards the maximum RF transmission power is smaller than 10 mW. The 2.45 GHz ISM-band has been chosen due to multiple reasons: global availability, the availability of low-power RF-transceivers and the capability to support the communication load of several dozens of wirelessly connected sensors and actuators due to an allocated bandwidth of 80 MHz.

To guarantee a highly reliable and well-defined temporal behavior of cyclic data transfer in the presence of channel fading effects a combination of a frequency- and time division media access scheme (F/TDMA) has been employed. Downlink (DL) massages from the IO-Link master to the devices and uplink (UL) messages from the devices to the master are exchanged in a half-duplex mode in a defined timeframe, as is shown in Fig. 5. Initially, a cycle-time of 10 ms was specified, but this could later be optimized to 5 ms. In Fig. 5 one RF cycle with a duration of 5 ms is shown, allowing two retransmits of cyclic data within three sub-cycles, each having a duration of approximately 1.6 ms. With a length of 416 µs for the downlink-telegram and a length of 200 µs for an uplink-telegram four timeslots for uplink-communication can be provided. The organization interval (Fig. 5) is the time which is needed for frequency change and/or RX/TX-switching of the RF-transceivers. For the realization of the IO-Link wireless master a modular architecture has been defined [9,12] that allows to realize masters equipped with up to five radio transceivers, each serving several wireless IO-Link devices on the same frequency of operation, i.e. the same "frequency track". A single-track master with one RF-transceiver can handle up to eight wireless devices. Multi-track masters with five transceivers thus can accomodate 40 wirelessly connected sensors and actuators.

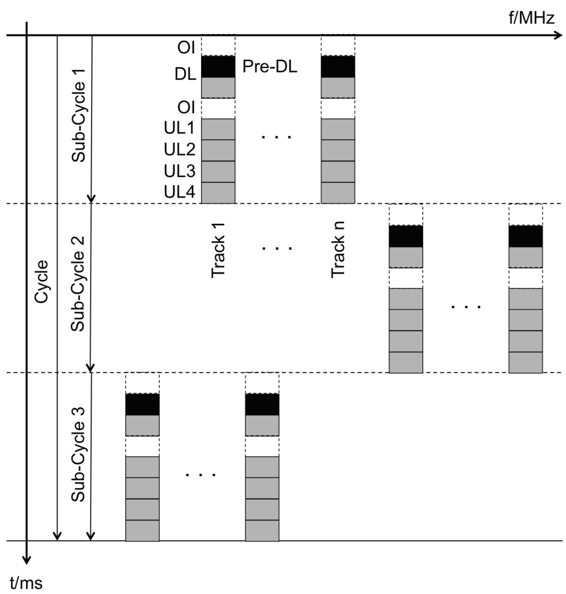

Fig. 5. IO-Link Wireless Medium Access. OI=Organization Interval, DL=Downlink, UL=Uplink.

Suitable frequency-hopping algorithms have been developed to mitigate channel fading, to improve coexistence behavior and to allow roaming of devices between masters. The frequency-distance between two frequency-hops is adjusted in a way that the typical coherence bandwidth of an industrial radio channel is always exceeded [13,14].

Several concepts have been defined to reduce energy consumption to allow also devices with very limited energy resources to be integrated into the wireless communication system, such as long-term operable battery-powered devices. One example for energy optimization concepts is that the downlink sequence DL has been subdivided in a pre-downlink telegram (Pre-DL) and an extended part, as is indicated in Fig. 5. This will significantly reduce the RF-receiver up-time and thus the energy consumption. The idea behind is as follows: If, e.g. an energy-autonomous sensor has just sent an RF telegram, this sensor expects only a short acknowledgement (ACK)-signal from the master in the next downlink protocol. All the ACK-signals for energy-limited sensors are positioned in the Pre-DL so that they only have to listen for the master response over a very short time interval and can than go back into sleep-mode, immediately.

The RF system architecture and the system parameters have been adjusted such that a maximum packet error rate of 10^{-3} per sub-cycle can be achieved. Thus, with two possible retransmits the probability that the maximum latency time of 5 ms for cyclic data-transfer is exceed is as low as 10^{-9}. This value is comparable with wired communication solutions. Assuming a packet error rate below 0.1% the acyclic data transfer can be interwoven with the transfer of cyclic data. This is depicted in Fig. 6, showing the normal mode of operation. Within one RF-cycle master and device only require one single sub-cycle for data exhange and ACK. Thus, the other two sub-cycles can be used for the transmission of acyclic data.

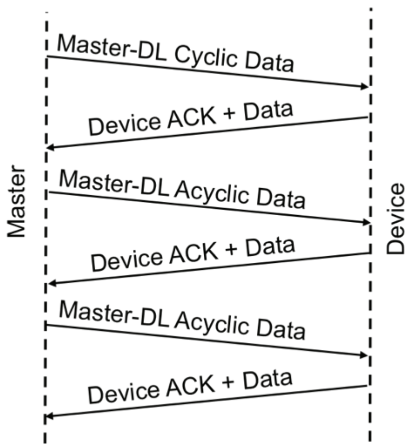

Fig. 6. Cyclic and acyclic data transfer interwoven in one RF cycle.

The worst case is shown in Fig. 7, where the ACK-signal from the device is missed by the master. In this case the master starts a retry, which is also not acknowledged by the sensor generating a second retry.

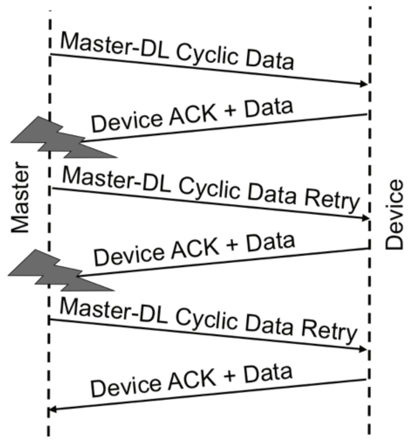

Fig. 7. Worst-case scenario: double-error occurring in cyclic data exchange.

Acyclic data exchange is not real-time critical. If there should be an error during acyclic data transfer, as is shown in (Fig. 8), data transmission will be repeated until the information will be acknowledged.

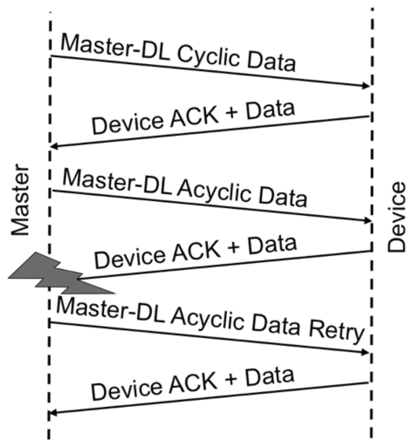

Fig. 8. Error occurring in acyclic data exchange.

IO-Link Wireless Coexistence Mechanisms

For an improved coexistence behavior two mechanisms were implemented, frequency hopping and blacklisting, which allows to operate the wireless sensor/actuator network with low packet-error rates even in industrial plants where three WiFi-band are allocated in the 2.45 GHz band, as is shown in Fig. 9. It was also investigated how the WiFi-systems are affected by the IO-Link wireless system [14]. With the help of a wired measurement setup no significant decrease of the performance of the WiFi-system could be detected in the presence of an IO-Link wireless system.

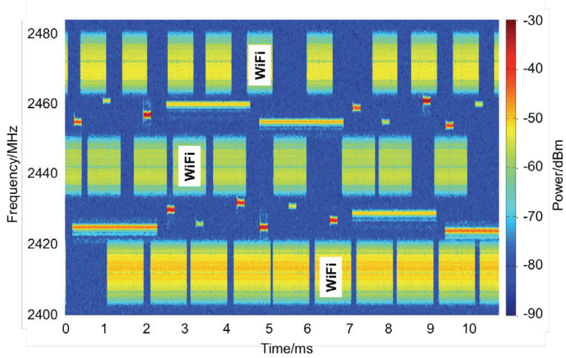

Fig. 9. Spectrogram of the RF traffic in the 2.45 GHz band. The IO-Link wireless network operates between the three WiFi-systems.

Conclusion

In this article a wireless extension the IO-Link standard has been presented. The proposed concepts and mechanism are paving the way towards a reliable and robust wireless sensor/actuator communication on the shop-floor. This wireless system sustainably supports the ideas of future decentralized networked services with vendor-independent components coming along with the ongoing development towards the industrial internet of things.

Acknowledgement

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