White Paper

Introduction to WISA

WISA - Wireless Interface for Sensors and Actuators

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1. Summary

This white paper is an introduction to wireless in the control level of factory automation, the WISA technologies and how they are used in wireless products.

After an introduction, some of the most important basics of wireless communication in factory automation are summarized, followed by more details on the WISA technologies: WISA-COM the tailor made wireless communication solution for factory automation based on IEEE 802.15.1 (physical layer) and WISA-POWER, the unique wireless power supply solution. Adding reliability and low and predictable latency in industrial environments for IEEE 802.15.1 based devices was one of the prime objectives of WISA-COM.

First WISA devices went into industrial production equipment in 2003 and the first series products were available in mid 2004. By now the product portfolio has been expanded to different field devices and several million well monitored node hours have been accumulated in different environments, which prove the excellent performance of the new WISA standard set by ABB for factory automation.

Finally some practical aspects on coexistence, robustness to interference and measurement results are discussed.

2. Overview

Sensors and actuators (SA) are found in large numbers in every production line within every industry (fig. 1). Each and every one of them requires data transmission and power cabling. Not only are these cables costly to engineer and install, they are also one of the most frequent sources of failure in factory automation, where a considerable amount of the sensors and actuators are moving or exposed to harsh environmental conditions. It is here, at the field device level, where problems with wires really exist for the users.

The various field buses which have found their way into most applications since a few years have not changed the situation. The sensors and actuators in factory automation are still typically connected via wires in a star topology to bus concentrators instead of former passive distribution boxes or remote I/O of control systems/ PLCs (see Figure 1). Bus cables have introduced new rules to be followed and are additional error sources.

The Wireless technology in factory automation has the following main advantages: It reduces overall cost thanks to its easy installation, simpler engineering, significantly reduced failures in operation and it eases trouble-shooting at the field device level. Wireless can also increase productivity and ease maintenance by introducing mobility, flexibility and fast control network access for additional devices. To really achieve these claimed advantages of wireless all wires to a critical device should be removed. Therefore there are two fundamental requirements:

- Wireless communication suitable for real time applications
- Wireless power supply.

None of the existing wireless systems/standards satisfies the necessary balance of requirements for the described sensors and actuators as field devices. These are latency vs. data rate (see Figure 2), reliability, power consumption and also node density vs. range. Therefore a customized wireless technology is mandatory to fulfil the requirements. The new wireless technology used is based on IEEE 802.15.1 (physical layer) and is called WISA - Wireless Interface to Sensors and Actuators. WISA basically consists of two main parts:

- Communication (WISA-COM)
- Power supply (WISA-POWER)

Both are generic technologies and not limited to WPS - Wireless Proximity Switches - where ABB has applied them to a first product. The WPS is completely wireless sensor, both for the communication as well as for the power supply.

The WISA product portfolio is growing and has been expanded to devices using up to 32 bits payload and higher power wireless receivers (up to 100mW), showing the scalability of the WISA technologies.

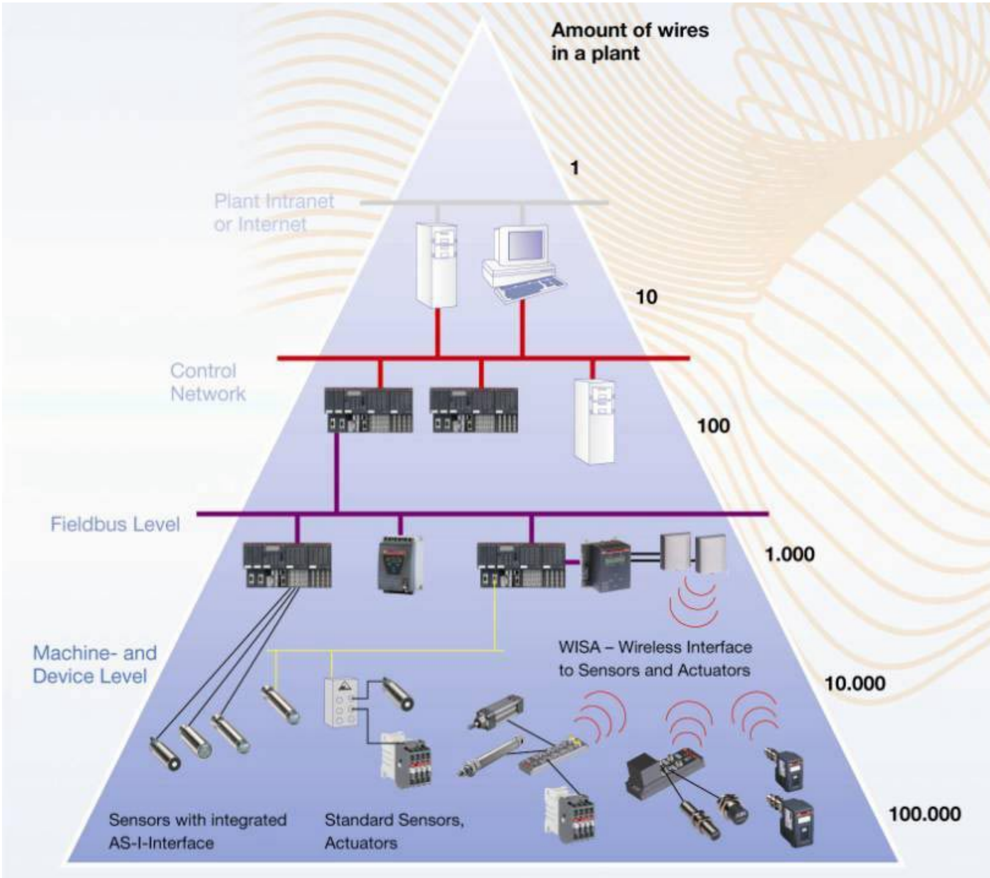

Figure 1: Typical picture of "factory" automation system showing the high node densities in the machine and device level where WISA is advantageously used.

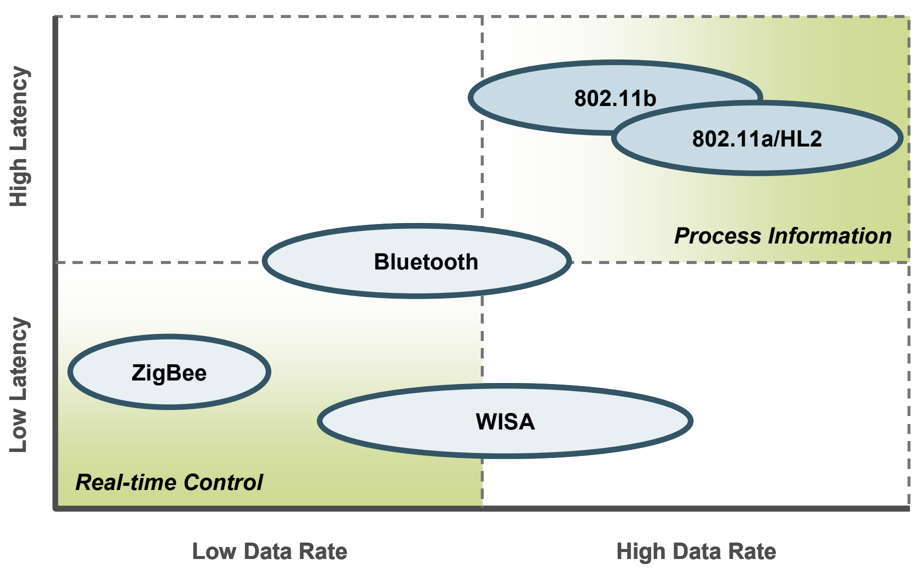

Figure 2: Latency vs. data rate of different communication systems at higher node densities

3. Introduction: WISA - Wireless Interface to Sensors and Actuators

3.1. Wireless Technologies

High-volume production in the consumer and office automation market have made advanced communication solutions available at an astonishingly low cost. The telecommunication industry has facilitated matters by creating *worldwide* standards for wireless links, like 802.11, Bluetooth, GSM, ZigBee, RFID/SRD etc, thus removing the need for region-specific solutions. By operating in the license-free 2.4 GHz Industrial, Scientific and Medical (ISM) radio frequency band there is no need to have the system authorized in individual countries.

The wireless communication system for field device level factory automation, has to be just as reliable as wired devices/SA. As these sensors and actuators are part of closed-loop control systems, strict timing constraints are required. The wireless devices must co-exist with interfering other systems, such as Bluetooth and Wireless Local Area Networks (WLANs), as well as with any self-interference of the possibly hundreds of the same wireless devices in one automation application or ten thousands of such nodes in one factory hall (see fig. 1). None of the existing wireless systems/standards satisfies all the requirements of using wireless in industrial automation devices, especially not when real-time is a requirement. Real-time means that beneath reliability, a constant, defined time behaviour is required under all circumstances.

This is especially true of the field device level, where wires are really a big problem (e.g. to the predominantly used distributed proximity switches in factory automation) and where real-time, reliability, power consumption and node density requirements are the hardest. For example, low power or passive electronic tagging systems (RFID/SRD), as used in department stores, do not have sufficient range and flexibility and WLANs and most short-range wireless links such as Bluetooth do not support large numbers of devices/SA at acceptable and device number independent timing and ultra low energy consumption. ZigBee will support lower power and smaller data packet constraints than Bluetooth, but it has a slower data rate and is also not suitable for real time applications with a larger and possibly varying number of nodes.

Therefore the chosen wireless approach discussed in this paper - WISA - is based on standard low cost hardware using the physical layer of IEEE 802.15.1, enhanced by an access scheme and protocol tailor-made to the task of real-time factory automation at the field device level, which is explained in more detail in the following chapter. Figure 3 provides an example overview and comparison of WISA and other communication systems.

3.2. WISA-COM: Basics

The WISA wireless communication links the sensors and actuators to a so-called input/output module, ("base station"). It satisfies the rigorous demands of an industrial environment, i.e. it has high reliability, fast response time, it serves a large number (hundreds) of sensors and actuators located in a range of several meters radius, and guarantees high data transmission integrity, even where radio propagation may be affected by obstacles and interference.

The sophisticated basestation module designed by ABB ensures that the complexity resides in the input module rather than in the SA. One such module can handle up to 120 devices (sensors). Three base stations can be closely located with acceptable self-interference, (see topology example Figure 8).

Although similar to a WLAN access point in many respects, the ABB design has several features that clearly set it apart:

- Simultaneous transmission and reception of radio signals; i.e. full-duplex operation.
- Simultaneous reception of strong and weak signals. The difference in power between a strong signal and a weak one may be as much as a million to one.
- Interference suppression. Reception of a very weak sensor signal is possible even though a large interfering signal may exist at some adjacent frequency.
- Transmit and receive antennas at the input module are swapped every 2 ms to provide a diversity of radio propagation paths against fading and shadowing effects.
- Deterministic frequency hopping to combat broad band interferers
- Efficient frequency use: Only changes are transmitted combined with discrete presence/status monitoring of the devices (at ~ 500ms intervals).
- Five simultaneous communication channels for free access and immediate acknowledgement of 120 devices

The devices communication hardware is based on an IEEE802.15.1 compatible standard transceiver (radio) in order to benefit from economies of scale, component integration (small size) and low power consumption.

The integrated radio antenna in the devices has been carefully designed. Its radiation characteristic is nearly omni-directional in order to achieve uniform transmission performance irrespective of the devices orientation.

The communication protocol provides sensors with collision-free air access by allocating each sensor a specific time slot and frequency for its transmission. The content of the WISA protocol is chosen to meet the requirements of large numbers of sensors, it ensures a short response time and makes full use of the available radio bandwidth. A frequency-hopping scheme, combined with error detection and automatic message retransmission in case of transmission errors, ensures that the messages from the sensors are reliably delivered, even in the presence of interfering systems such as Bluetooth, WLANs, microwave ovens and electronic tagging systems.

To reduce the power consumption, the sensors communication module hibernates until a change in the sensor state occurs. When an event takes place at the sensor, the sensor quickly establishes the radio link by means of a pilot signal from the input module, before transmitting the message. Typically this air interface handling takes 5 ms, with worst-case scenarios of up to 20 ms if the message must be re-transmitted several times. This also helps for coexistence with other systems as the frequency use is always minimised. The design target was a Telegram Error Rate TER of less than 10^{-9}, which is comparable to a wired or field-bus connection in industrial operation.

Compared to standard Bluetooth, the WISA In-Output module (Basestation) has practically in total a five fold data rate, (see fig. 3).

Requirement	WISA	802.11	Bluetooth	ZigBee
Global Standard Build on a standard to shorten time-to-market and minimize in-house development	+	++	++	+
License Free Operating Band Avoid license costs and administration	++	++	++	+
Operating Frequency Operate above 1 GHz to sustain frequency noise introduced by welding equipment	++	++	++	++
Industrial Strength Proven in typical industrial environments (performance as well as reliability)	++	++	++	+
Communication Bandwidth Medium bandwidth requirements	++	++	++	+
Communication Latency Low and deterministic communication delays	++	--	-	-
Node Density Serve a large number of sensor/actuators located in a cell	++	--	-	++
Power Consumption Low power consumption to enable wireless power supply systems	++	--	-	++

Figure 3: Functionality comparison of different communication systems (++: well suited; +: partly suited; -: bad ; --: unsuited)

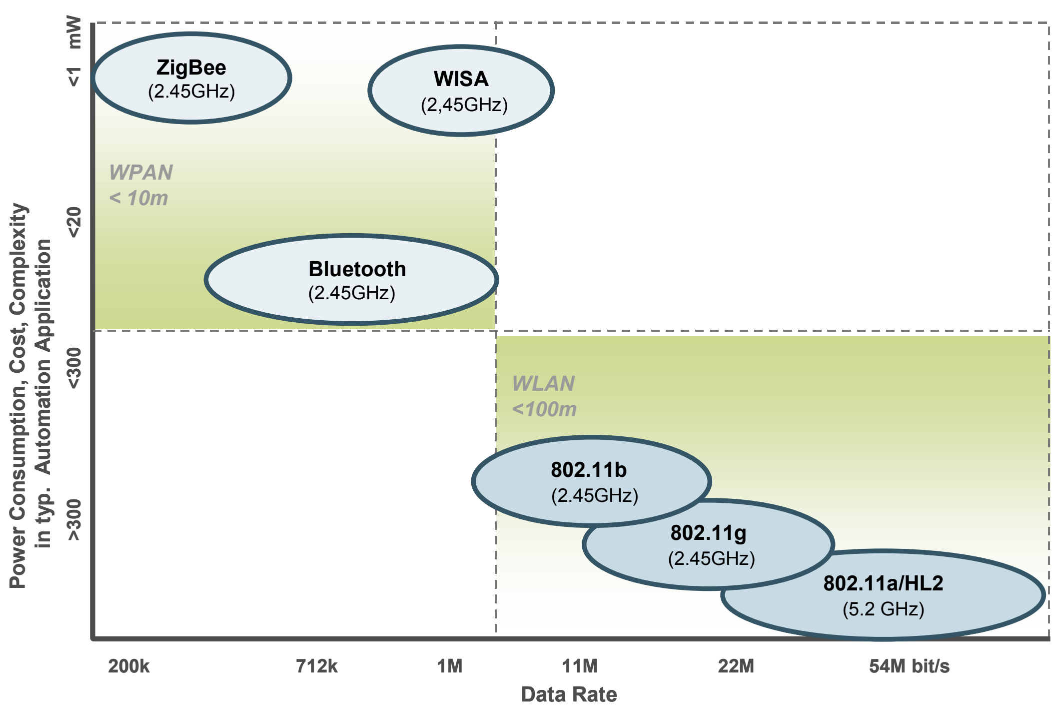

Figure 4: Power consumption and cost vs. data rate of different wireless systems

3.3. WISA-POWER: Basics

In order to provide a real benefit to the user, also a “wireless power supply” has to be provided for the critical field devices. Batteries/energy storage are normally not an option in industrial factory automation with its tens of thousands of nodes and often 24h/day operation, even the WISA power consumption is not low enough. Alternative ways of energy scavenging from the environment of the application are not reliable, when considering the widely varying applications. An analysis of theoretically usable approaches (see Figure 5), when looking at the varying applications in industrial automation, clearly leads to providing power in a continuous, reliable manner via electromagnetic coupling [4]. Magnetic fields (~120 kHz) can be set up in a limited volume, fitting well with typical manufacturing applications, modular lines or stand-alone machines for reasonable expenditure.

Concept	**Energy Scavenging**	**Energy Storage**	**Energy Distribution**
Technologies ++ = Commercial availability / Industrial suitability	++ Photovoltaic + Temperature gradient - Human power - Wind / air flow -- Pressure variations - Vibrations	++ Batteries + Micro-batteries - Micro-fuel cells ++ Ultra-capacitors - Micro-heat engines -- Radioactive power sources	**++ Electromagnetic coupling** + RF radiation - Wired power grid - Acoustic waves - Optical
Power Levels	10 µ – 15 m W/cm3	50 – 3 500 Ws/cm³	µW – kW (m – mm)
Deficiencies	Reliability	Maintenance	Electric field radiation Power level vs. range
Industrial Applications	**N/A**	**Portable/mobile user interface**	**Cell automation power supply**

Figure 5: Energy sources - overview of power supply to wireless devices

The so-called **WISA-POWER** system operates with such magnetic fields, similar to RFID and anti-theft devices, and provides power in a similar fashion to a transformer, but without a core and with a huge air-gap. Typically “primary” power loops are installed around the application. These are fed by power supplies that set up an alternating current in the loops, producing a magnetic field throughout the application/machine. Wireless devices within the machine/application have small “secondary” coils that pick up the energy from the magnetic field and convert it to electric power. Although people will often not be working continuously in the machine/application, the typical field strength lies below all international occupational regulations and recommendations [3], allowing continuous unlimited work in such systems. The power losses in the loops due to skin and eddy-current effects are dependent on their environment, but typically surprisingly small (~15W/m³). The primary power supply WPU is able to cope automatically with the environment and its changes. To be orientation-independent an omni-directional receiver is used. As a unidirectional primary field could be shielded by metal objects, a rotating field has to be used in some applications.

A typical power value achieved under worst-case conditions (e.g. partly shielding) on the receiver sides in the WPS, is ~10mW and above 100mW under same circumstances for the WSP Sensor Pad. Higher power levels can be provided, e.g. for industrial actuators (e.g. pneumatic valves, the most widespread actuator in factory automation) with a different sized secondary side. The primary power supply system is able to serve typical applications up to 6x6x3 m in size. Several of these power cells can be operated in a factory hall. Also more simple power loop configurations can be used if the movement/location of the receiving devices is better known e.g. rotating or linear moving applications like conveyor belts [6].

3.4. WISA Product Platform and Devices

WISA supports a growing range of products for the machine and device level (see fig. 6):

- The Wireless Proximity Switch (WPS) consist of a low power sensor head (WSIN/WSIF) and a communication module called WSIX (Wireless Sensor Interface for proximity switches). The wireless proximity switches, in contrast to conventional proximity switches, do not require any cable connection between sensor and machine control system due to using both WISA technologies.
- The Wireless Sensor Pad (WSP) is a WISA communication module shaped as a sensor distribution box. It allows several low power sensors heads to be connected to one communication module. It also uses both WISA technologies and therefore does not require any cable connection between sensors and machine control and enables the use of reed or other mechanical switches.
- The Wireless Input/Output Pad (WIOP) is a sensor actor distribution box which communicates via WISA-COM, but is supplied with 24V conventional power supply in order to enable the connection of outputs/actuators (which are typically more centralized) and other third party sensors/inputs to a WISA system.

Figure 6: WISA overview and devices: Infrastructure on right side, sensor/ actuator interfaces (field devices) on left side. The devices can be used together or in parts (e.g. WIOP+WDIO ; WPU/WPC with user secondary side energy receiver):

These wireless devices communicate via WISA-COM radio communication to an Wireless Devices I/O module (WDIO). The WDIO receives the WISA-COM signals via a pair of antennas and connects to a control system/PLC via a choice of field busses via the ABB FieldBusPlug FBP. Up to three WDIO can be operated in one cell without noticeable performance change, which would support up to 360 wireless proximity switches or 39 pads (up to 624 IO points). A continuous function messaging of each wireless device ensures an immediate detection of communication failures.

The electromagnetic field used for the power transfer is typically produced by two pairs of primary loops to supply a volume. The Primary loop cable WPC is connected to the Wireless Power Units (WPU) which control the 120kHz current to a constant value. Also other more simple configurations are possible e.g. spot and line configurations for rotating or linear moving equipment.

Figure 7 gives an example of a WISA installation in a typical robot type manufacturing application.

The magnetic field power supply consists of power supply devices and primary loops, which envelope the application. The wireless devices receive power from the magnetic field (WISA-POWER) and communicate to the Input Module via WISA-COM. They can be equipped with different sensor heads (WISA-sensor).

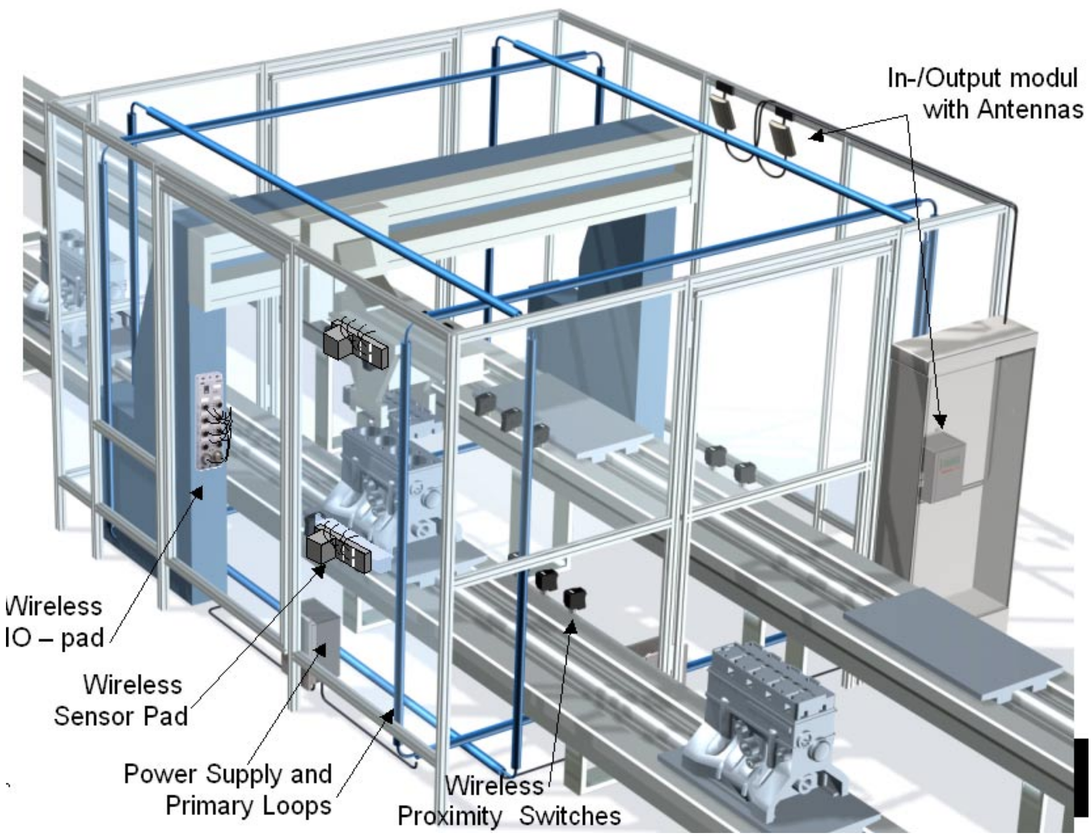

Figure 7: WISA devices installed in a typical robot type production - cell (27 m³)

4. WISA-COM: Technical Information

Network Topology: The requirement of wireless real-time communication combined with a need for a high number and high density of devices, makes efficient use of the available bandwidth very important. This calls for a cellular network topology with re-use of frequencies. A number of input modules/ base stations can be distributed in the plant, with short-range communication to local sensors/actuators. As for cellular telephony networks in larger geographical areas, the same bandwidth can be re-used in cells that are separated by a sufficiently large distance (the limited range of the radio is a bonus not a restriction!). The input modules/ base stations are connected to the control network via any field bus (ABB FieldBusPlug concept used) and communicate with the local wireless devices. In typical applications where target devices are sensors/ actuators that need only limited mobility, there is no need for roaming. This means that there is typically a one-to-one connection between one wireless WISA device and a base station (star topology). This simplifies the communication protocol, since a network layer is not required. More than one (up to three) input modules/base stations can coexist within an application with acceptable self interference (see topology example Figure 8).

Communication Environment: The main threats to reliable communication are interference from other wireless communication devices (same or other systems), microwave ovens/heaters and frequency selective fading. It is necessary to design the system such that it can co-exist with systems such as Bluetooth and IEEE802.11b, which also operate in the 2.4GHz band. Systems must also cope with the frequency-selective fading caused by multi-path propagation of the radio waves and resulting destructive combination – several quite broad frequency areas with the ISM can be faded at the same time. Two diversity techniques are commonly applied in wireless communication systems in order to combat frequency selective fading. These are antenna diversity techniques and spread spectrum technology (e.g. frequency hopping). Antenna diversity techniques alone do not offer protection in terms of interfering systems.

Physical Layer and Medium Access Control (MAC): WISA is based on IEEE 802.15.1 (physical layer). In a system that needs to achieve the delivery of messages with a very high probability of success and high number of devices, the medium access – the sharing of the communication medium - is important. The techniques widely applied are Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA). The TDMA technique is most suitable for low-cost and low-power communication with critical timing. In combination with Frequency Hopping (FH) this can provide reliable communication with the possibility of low-cost and low-power implementation. The medium access in WISA is therefore time division multiple access with frequency division duplex and frequency hopping (TDMA/FDD/FH). The WISA frequency hopping scheme guarantees that the frequencies used in successive frames are widely spread, providing robust communication in the presence of wideband interference or faded channels.

The downlink transmission (from the base station) is always active, for the purpose of establishing frame and slot synchronization for the devices, but also to send acknowledgements and data. It enables the device to quickly find its own time slot, where it is allowed to transmit its uplink message. In order to save power, uplink transmissions from a sensor only occur when it has data to send. In both directions user data bits are exchanged (data or control) dependent on the profile used.

General WISA Principles and Features: A simple transmission control protocol is applied where telegrams received by the base station are acknowledged. In case of a missing acknowledgement, the device will re-transmit the telegram (automatic repeat request ARQ). The short frames allow for several re-transmissions within the permissible delay window, and provide a sufficiently high reliability also with heavy disturbance.

With frame-by-frame frequency hopping and antenna switching at the input module (base station), the radio channel used for re-transmission will largely be independent of the previous transmission, thus noticeably increasing the probability of successful transmission. As any re-transmission occurs on the uplink slot and frequency allocated to the particular SA, it will not affect the transmissions of any other SA.

A special requirement for an energy-autonomous system, e.g. a sensor, is the extreme low-power requirement for communication. This is a challenge when combined with the real-time requirement. The use of the sensors and actuators radio needs to be minimized by exploiting the possibility of a more complex base station design. A minimized radio use also minimizes interference to other users. The system has a continuous downlink, offering synchronization information to sensors. When a device (e.g. sensor) wakes up, it can immediately find synchronization, which means less use of the receiver. Figure 9 summarizes some important requirements of wireless field device automation and compares WISA and a Bluetooth implementation by typical data.

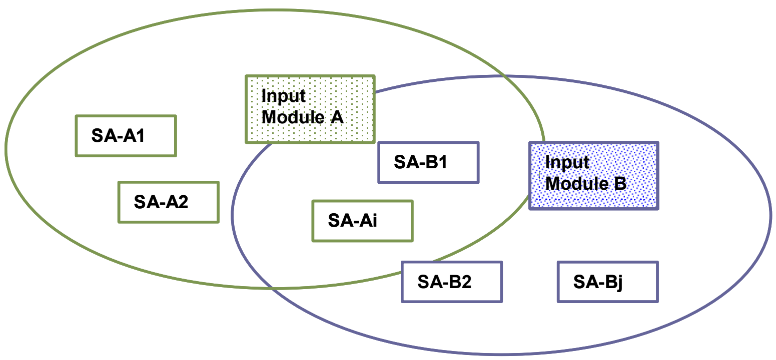

Figure 8: Topology of WISA

Requirement	WISA	Bluetooth*
Operating Frequency	2.4 GHz	2.4 GHz
Communication Bandwidth Raw bit rate	1 Mbps (DL) 4x1 Mbps (UL)	1 Mbps (DL/UL)
Communication Latency Nominal typical Worst-case (heavy disturbance -> retransmitts; max. No. of act. slaves)	2 ms < 5 ms 20 ms	5 ms 18 ms > 100ms
Node Density Number of active slaves per master Number of parked slaves per master	≤ 120 -	7 (256 **)
Power Consumption Active Sleep mode	200 mW 0.1 mW	300 mW 4 mW

* Infineon Flinkstone; ** 1-3s wake up time!

Figure 9: WISA vs. Bluetooth

WISA Profiles: Different profiles are used for the integration of different devices. The generic WISA technology can be easily adapted to new applications. The definition of the pay-load in each packet can be redefined to cater for different applications having their own profile. Currently there are different profiles defined for the system, one for the wireless proximity switches and one with 32 bit for digital I/O or analogue values. The different profiles can coexist and can be handled by the same input/output module.

5. *WISA-COM: Reliability/EMC, Coexistence and System Performance*

The WISA system has not been optimised for pure data throughput but rather for highest reliability, minimum latency with many nodes and low power consumption in an industrial environment. Reliability is the most important requirement for the users, therefore WISA uses a number of measures to increase reliability.

There are generally three possibilities to interfere with wireless communication in industry:

1.) Interference/disturbance by industrial processes

2.) Other users of the same frequency (Coexistence)

3.) Environmental influence (e.g. multipath effects, moving devices)

1.) After extensive measurements it can be stated that typical industrial processes or devices have no harmonics above approximately 1,5 GHz. As an example arc welding and foil welding has been identified to emit broadband noise up to this frequency, but not higher. Then the main possible interference source are processes using the 2,4GHz ISM band (Microwave ovens/processes like drying) themselves. Therefore frequency planning has to be done - use should be coordinated and a certain distance has to be kept depending on the power levels.

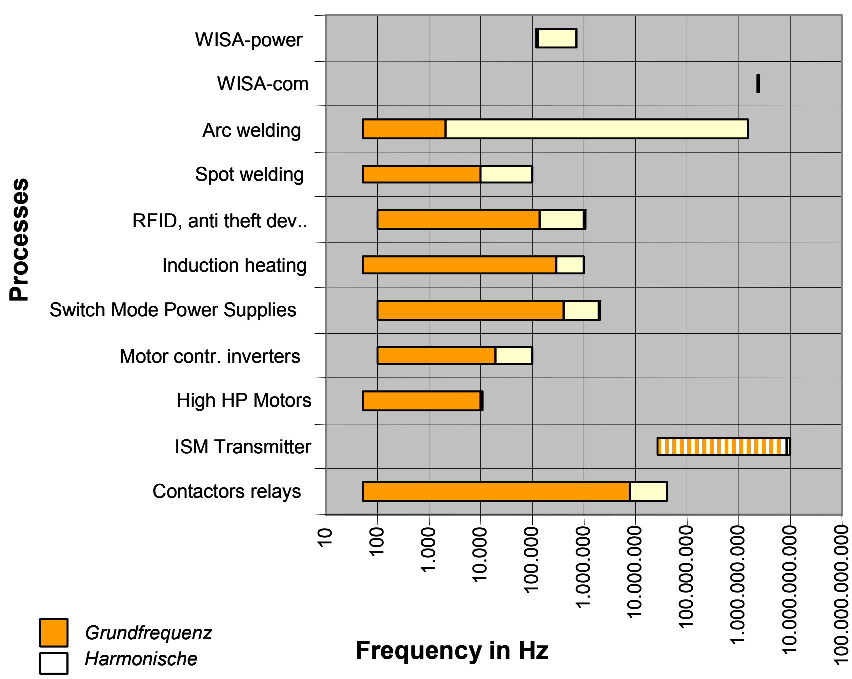

Figure 10: Frequency areas of different processes or devices in industry

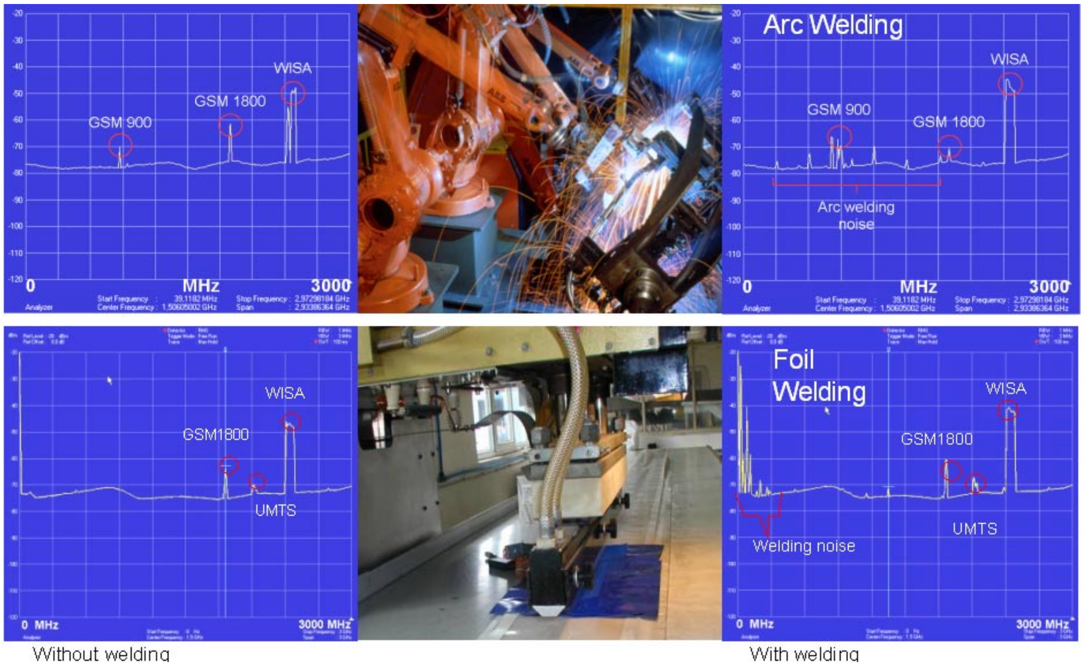

Figure 11: Example effects of arc- and foil-welding in the frequency band 0-3GHz [5]

2.) As other users in the 2,4GHz band also may use the same frequency an influence cannot be avoided in general, depending on power levels and distance. Broadband users as WLAN and some video systems reduce available bandwidth for other systems considerably and therefore frequency planning has to be done (like electrical and other installations in a factory also have to be planned and documented). WISA has exceptional good properties for coexistence as it not only uses an optimized frequency hopping but also shortest telegrams and transmits only changes to reduce frequency usage as much as possible.

3.) Reflections from e.g. metallic objects lead to multipath effects like fading which can change fast with time due to moving objects. This necessitates that frequency hopping and antenna diversity are used, several broad band fadings at the same time can be measured in industrial environments like machines making random hopping systems critical.

Coexistence example:

The effect on the WPS retransmission statistics was studied, which result in varying delays, this time caused by 802.11 interference. The WPS system and the WLAN access point are placed at different distances of X meters apart, see Figure 12, (X = 1, 4, 7.5 m). The minimum delay from the sensors and actuators to the RF-part output at the basestation is 3.5-5,5 ms, an initial variation comes from matching the 2ms frame cycles of WISA. With an interfering WLAN still most of the telegrams come through with only ~5 ms latency, nevertheless a few arrive later.

The WLAN Access Point (AP) and the PC with a 3Com network card are about 4 m apart to prevent power reduction. The AP is set to use 54 Mbps, channel 5 and no encryption. The laptop runs the GuildFtpd ftp server, which has the possibility of limiting the download speed. This feature was used to limit the speed (125KB/s, termed “throttled” in Figure 12).

Similarly to the effect of WLAN interference on WISA, the interference from WISA on WLAN has been investigated. Transferring a 1.5GB file forms the reference for the WLAN system and timing this transfer gives a measure of the transfer rate of the WLAN.

The interference effect of the WISA system on the WLAN is shown in the table below where the transmission is not deliberately throttled, the effect there can be minimized by a distance of e.g. 7m.

Table 1: WPS effect on WLAN throughput

Distance X between WPS and WLAN	Effective data rate KB/s
Reference	3129
7.5	2825
4 m	2250
1 m	860

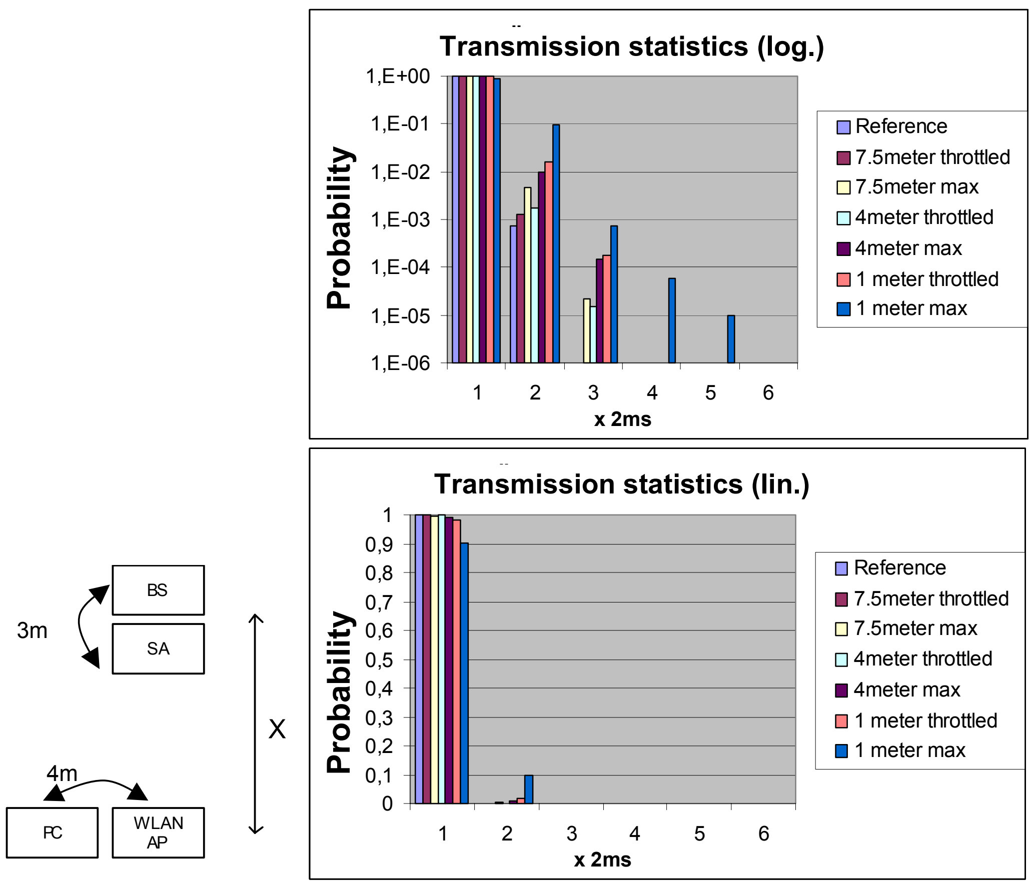

Figure 12: **WLAN effect in varying dist. X on WISA transmission statistics: Example from sensor to base station. (~2ms per transmission attempt)**
For a few worst case events up to five transmission attempts are needed if the WLAN is directly in the WISA application (1meter max.): The typical timing value is not affected.

6. Glossary

ARQ	Automatic repeat requests
BER	Bit Error Rate
Bluetooth	short range communication standardized according to Bluetooth Special Interest Group, adopted by IEEE 802.15.4
CDMA	Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FHSS	Frequency Hopping Spread Spectrum
MAC	Medium Access Control
SA	Sensor or actuator
TDMA	Time Division Multiple Access
WISA	Wireless interface to Sensors and Actuators, based on physical layer of IEEE 802.15.1
WLAN	Wireless Local Area Network, used for communication, standardized according to IEEE 802.11
WPAN	Wireless Personal Area Network, used for communication standardized according to IEEE 802.15
WPS	Wireless Proximity Switch
ZigBee	low power, short data packets, short range communication (based on IEEE 802.15.4)

7. WISA and WPS System Parameters

Maximum number of nodes to one base station/Cell ID	120
Maximum number of base stations in one cell (same performance)	3
Minimum distance between non-interfering cells (different Cell ID)	10 m
Max. number of base stations in interfering distance of 10m (degr. performance)	6
Maximum number of cell ID´s	59
Maximum distance between SA and input module antenna	5 m
Typical latency from WISA air interface	5 ms
Typical latency SA event (e.g. WPS sensing) to field bus availability of signal	17 ms
Maximum latency from WISA air interface	20 ms
Maximum latency from SA event (e.g. WPS sensing) to field bus availability	< 34 ms
Probability of losing events (maximum latency > 34ms)	< 10-9
Maximum average event/transmission rate WPS (@worst case power condition)	5 per second
Maximum peak event rate WPS (max. 5 within a second for WPS, see above)	20 per second
Number of frequencies used	77 + 2
Minimum distance to non-interfering WLAN/Bluetooth	25/16 m
Maximum number of WLANS within interfering distance	1
Maximum output RF power	1 mW

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