Design and Implementation of a Real-Time Wireless Sensor/Actuator Communication System

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Abstract

For industrial automation applications using production machines and robotic installations, truly wireless systems offer advantages in terms of cost and flexibility. Requirements on power supply and real time communication for such applications are highly demanding, and cannot be satisfied with today's off-the-shelf systems. A novel factory communication system, called WISA (wireless interface for sensors and actuators), has thus been developed which provides both wireless communication and wireless power supply. The power supply is based on magnetic coupling while real time wireless communication uses a new TDMA protocol combined with frequency hopping. The TDMA protocol uses optimized parameters for reliable and low delay transmission for a high number of active nodes. The frequency hopping sequences are optimized to mitigate effects of multi-path propagation, interference from other systems operating in the 2.4 GHz ISM band, and self-interference. The new design re-uses existing RF transceivers. The paper explains design concepts of the WISA communication system, and describes practical experience gained with its deployment in industrial environments.

1. Introduction

Wireless communication is becoming increasingly important for many industrial automation systems. Sensors and actuators operating over wireless links allow for flexible installation, fully mobile operation, and the circumventing of any cable 'wear and tear' problems. Any wireless communication systems for industrial automation, however, must guarantee high reliability, and low and predictable delay of data transfer. These requirements are mission-critical and may be considerably more stringent than typical requirements for home and office telecommunication applications.

A wireless interface for sensors and actuators (WISA) factory communication system has been designed and implemented. The first application concerns wireless proximity switches used as position sensors in factory automation. The system concept, including its wireless magnetic *powering*, has been described in [1] and [2]. This paper describes the design of the wireless *communication* part of the system in more detail.

Section 2 gives an overview of the wireless communication part and the motivation for its development. Section 3 gives a detailed system design description, covering the cyclic TDMA protocol with retransmission, the selection of frequency hopping sequences and antenna diversity. Section 4 analyses self-interference due to multiple co-located WISA cells (such multi-cell operation may be required for capacity reasons). Section 5 considers interference from other likely sources such as wireless LANs. Finally, section 6 describes an implementation and includes measured performance results.

2. System Requirements and Overview

The wireless communication subsystem transmits messages between the sensors/actuators and the base station. The system must satisfy the demanding requirements of communicating in an industrial environment, including:

- fast response times (generally less than 10-15 ms for real time applications)
- serve a large number (up to 120) of sensors/ actuators located in a cell of several meters radius
- guarantee a high reliability of data transmission even in the unfriendly environment of factories,

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where radio propagation may be affected by many obstacles and where various sources of interfering signals must be expected
- have low power consumption, which is crucial due to the limited capacity of the wireless power supply system.

Currently, the most suitable radio frequency band available for high-bandwidth, low-range wireless communication is the industrial, scientific, and medical (ISM) frequency band at 2.4 GHz. Subject to general radio regulations, systems may operate in this frequency band on a license-free basis. Radio transceivers operating in this band are readily available, e.g. radio modules adhering to the Bluetooth standard. The protocols of existing standardized systems, however, do not satisfy the requirements of low latency, high number of sensors/actuators, and low power consumption. Passive electronic tagging systems, as used for electronic article surveillance, do not have sufficient range, speed, and flexibility. Commercially available wireless systems such as wireless local area networks (IEEE 802.11 WLAN), Bluetooth and ZigBee also do not fulfill all specified requirements. WLANs and Bluetooth are designed for high throughput applications between a small number of terminals, with less stringent latency requirements. ZigBee cannot serve a high number of nodes within the specified cycle time.

Hence a new system tailored to the needs of wireless sensors/actuators was designed, which re-uses as many of the available standard components as possible. The sensor/actuator communication hardware is based on a standard Bluetooth 2.4 GHz radio transceiver in order to benefit from the economies of scale (low cost), component integration (small size) and low power-consumption. For the base station, however, a specialized RF front end had to be developed. To meet the requirements of high transmission reliability, short cycle times, and support of a large number of sensors and actuators, an optimized communication protocol was designed and implemented. It provides collision-free air access by allocating a fixed Time Division Multiple Access (TDMA) time slot to each sensor/actuator. Frequency hopping (FH) is employed to counter both frequency-selective fading and interference effects, and operates in combination with automatic retransmission requests (ARQ).

The parameters of this TDMA/FH scheme are chosen to satisfy the requirements of up to 120 sensors/actuators per base station, each with a response or cycle time of 2 ms. Full use is made of the available radio band of 80 MHz width. The frequency hopping sequences are cell-specific and are chosen to have low cross-correlations. This therefore permits parallel operation of many cells on the same factory floor with low self-interference.

For low power consumption, a sensor communication module can ‘sleep’ until a change in the actual sensor state occurs. When an event takes place, the sensor quickly establishes a radio link using the synchronization signal from the base station before transmitting the message in its assigned TDMA slot. This typically takes 2 ms, with worst-case scenarios of 10-15 ms if the message must be retransmitted several times. For system diagnostic purposes, a sensor/actuator should transmit diagnostics messages about twice per second.

3. System Design

The wireless base station (BS) is connected to the automation system’s programmable logic controller (PLC). The radio frequency characteristics of the WISA system are taken from the Bluetooth specification [3]. The raw data rate is 1 Mb/s, modulation uses Gaussian Minimum Shift Keying (GMSK), channel spacing is 1 MHz, and transmission power is 1 mW.

3.1. Medium Access and Retransmission

Medium access uses time division multiple access with frequency division duplex and frequency hopping (TDMA/FDD/FH), as illustrated in Figure 1. The downlink transmission (from the base station) is always active, for the purpose of establishing frame and slot synchronisation by the sensors/actuators (S/A). It enables the S/A to find its own time slot where it is allowed to transmit its uplink message. Uplink transmissions from a S/A occurs only when it has data to send. The frame format allows up to 120 S/As per cell, which are given channel access once per frame. It is possible to support more than 120 S/As by running multiple cells/systems in parallel, with different hopping sequences (see section 4).

The TDMA frame length, $T_{frame,}$ is equal to 2048 µs. A downlink frame is divided into 16 downlink slots of 128 µs. Uplink frames are aligned to downlink frames and there are 32 uplink slots per frame with each slot lasting 64 µs. Each S/A may transmit an uplink burst in, at most, one slot per frame. In order to support up to 120 S/As per cell, each S/A is part of one of four uplink groups $\{UL_1, UL_2, UL_3, UL_4\}$. Two guard slots at the frame boundary are reserved to allow for frequency hopping switching time. Each uplink group uses a separate frequency that is different from the downlink frequency. These five frequencies hop synchronously at each frame boundary.

The slot structure is shown in Figure 2. The downlink double slot format is a compromise between the efficiency of channel usage and synchronisation latency of the downlink. This double slot contains a 24 bit synchronisation preamble, a cell identifier (cell_id), the current double slot number (4 bits), and the data for 8 S/As, all protected by a cyclic redundancy check (CRC). The uplink burst lasts 56 bits, leaving a guard interval for transients of 8 bits (8 µs). The uplink burst carries a

15 bit preamble, cell id, and data from one S/A, protected by a CRC and forward error correction coding. Data fields per S/A contain 8 bits of data, with an additional flag bit to distinguish between data and control information. Control signals may contain diagnostic messages and message acknowledgements.

Frequency hopping is employed in conjunction with automatic retransmission requests (ARQ) to improve transmission performance. A S/A transmits its data packet in its allocated uplink time slot. An acknowledgement is expected in the corresponding downlink slot, which is staggered by 256 μs to allow for TX/RX-turnaround time (acks to uplink packets at the end of the frame are thus expected in the next frame on a different frequency, see Figure 1). If no acknowledgement is received, the S/A will retransmit the data packet in the next frame. With frame-by-frame frequency hopping, the radio channel used for retransmission will largely be independent of the previous transmission, thus increasing the probability of successful transmission. A maximum delay of 15 ms for successful real-time transmission was the design goal. With a given the frame length of 2 ms, a maximum of seven retransmissions is hence permitted. As any retransmission occurs on the uplink slot and frequency allocated to the particular S/A, it will not affect the transmissions from another S/A.

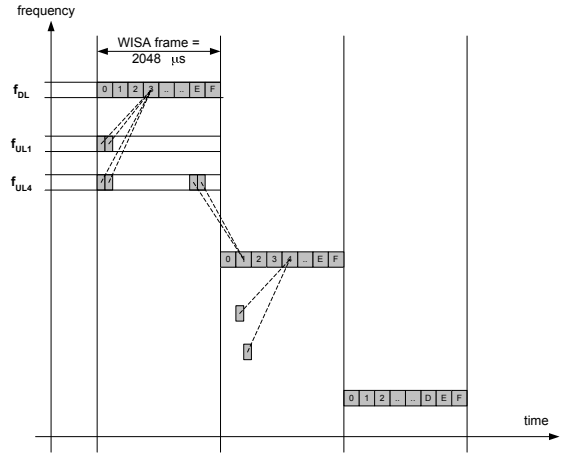


Figure 1. WISA TDMA/FDD/FH pattern. Dotted lines connect downlink/uplink slots allocated to one sensor/actuator. (TX/RX-turnaround time = 2 double slots = 256 μs)).

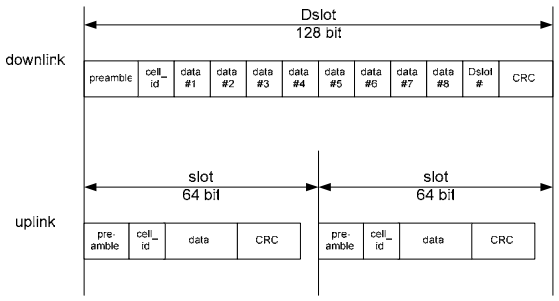


Figure 2. WISA slot format: downlink double slot duration = 128 μs, uplink slot duration = 64 μs.

3.2. Frequency Hopping

Frequency Hopping is employed to counter two causes of transmission impairments. First of all, reflections and obstacles in the multiple radio propagation paths between transmitter and receiver antennas result in frequency-selective fading and shadowing. Figure 3 shows the measured frequency-depending attenuation in the 2.4 GHz ISM band. It can be seen that the coherence bandwidth of the signal may be some tens of MHz (corresponding to propagation path length differences of 30 m). Wideband frequency hopping will thus improve transmission performance. Secondly, the variety of commercial electronic devices available that operate in this band, such as microwave ovens, RF tagging systems and IEEE 802.11 wireless LAN systems, represents a likely cause of radio interference affecting the intended transmission link. Most of these systems transmit on fixed frequencies and hence frequency hopping helps to evade some of this radio interference.

The GSM [3] and Bluetooth [2] systems are the best-known wireless communication standards using TDMA and FH. In these systems, the frequency hopping sequences are determined in a pseudo-random manner. The chosen FH sequences do not control frequency separation between consecutive hops. Hence, consecutive transmissions will often have similar high packet error probability, so that ARQ schemes will result in an increased communication delay. It is therefore of interest to employ FH sequences with the property that consecutive hops are widely separated in frequency. Specifically, within an ARQ window of seven frames, no frequency should be visited twice. A direct method is to screen sets of pseudo random FH sequences for these desired properties and to retain only the best subset [4]. A new method is presented below in which the desired property is guaranteed by construction.

The available frequency band of 80 MHz is partitioned in $n_B = 7$ disjoint sub-bands, each containing $n_I = 11$ hop frequencies at a given channel spacing of B_H

=1 MHz. The sub-band bandwidth of B_S = 11 MHz is equal to or larger than the typical bandwidth of the fading or the interference (e.g. from WLANs, see Section 5.1), and the seven sub-bands together cover the available band. A 7-ary integer sequence, W, is used to select the sub-band on each hop, i.e., once per frame. A separate 11-ary integer sequence, X, then determines the frequency index within the sub-band. The actual transmission frequency is calculated by the mapping of:

$$f = f_0 + W \cdot B_S + X \cdot B_H =$$
$$= 2403 \text{ MHz} + W \cdot 11 \text{ MHz} + X \cdot 1 \text{ MHz},$$

where f_0 = 2403 MHz is the lowest frequency used. Since W changes every hop, this FH generation method produces an FH sequence, f, such that consecutive hops are separated by at least 11 MHz, as desired.

For multi-cell operation, i.e. where base station coverage areas overlap and where all cells may use the entire ISM frequency band, an additional criterion of low cross-correlation of hopping sequences, pertaining to different cells, becomes relevant to reduce inter-cell interference. Construction of sets of q-ary periodic sequences with low (Hamming) cross-correlation is described in [5]. For q of the form $q = p^N$, where p is a prime number and N an integer, several construction methods based on operation in GF(p^N), yield sets of q-ary integer sequences with, at most, one coincidence between any cyclic shifts of any pair of sequences in the set. There are typically q or q–1 different sequences in the resulting sets and their period is also q or q–1. This construction is applied twice, separately for the outer and inner sequences W and X: First, the set of six (n_B=7-ary) sequences $\{W_0(j),..W_5(j)\}$ is determined using construction 2 of [5] with GF(7). Secondly, the set of ten (n_I=11-ary) sequences $\{X_0(i),..X_9(i)\}$ is determined again using [5] with GF(11). These constructions result in the following simple relationships:

$$W_0(j) = j, \qquad j = 0 \,..\, 6$$
$$W_K(j) = (W_0(j) \cdot (K+1)) \bmod 7, \text{ for } K = 0 \text{ to } 5$$

$$X_0(i) = i, i = 0 \,..\, 10$$
$$X_I(i) = (X_0(i) \cdot (I+1)) \bmod 11, \text{ for } I = 0 \text{ to } 9.$$

The combination of W and X produces 6·10 = 60 different frequency sequences. A cell is identified by its cell_id, written as cell_id = 10·K+I, so that the unique index pair (K,I) uniquely select the sequences $W_K(j)$ and $X_I(i)$. The sequences W and X have periods of 7 and 11, respectively. In order to select the numbers $W_K(j)$ and $X_I(i)$ for a given frame number, FN, a suitable mapping is

$$j = FN \bmod 7$$
$$i = FN \bmod 11.$$

The resulting hopping sequences, f, then have a period of 7·11 = 77 frames. Each hopping frequency is visited exactly once per period. A sensor/actuator can take advantage of this last property when acquiring synchronization: once a downlink frame has been detected on a certain frequency (giving j and i in the above mapping), the frame number FN and hence the continuation of the FH sequence for the given cell_id can be calculated by inverting the above mapping using the Chinese Remainder Theorem.

Finally, for uplink and downlink transmission, different frequencies must be used for any given frame in FDD fashion. Uplink and downlinks may use the entire ISM band, but should maintain wide frequency separation at any given time, since high duplex spacing is desirable for RF implementation. This is achieved by defining

$$f^{DL}(FN) = f_0 + W_K(j) \cdot B_S + X_I(i) \cdot B_H$$

for the downlink, and

$$f^{UL1}(FN) = f_0 + ((W_K(j)+3) \bmod 7) \cdot B_S + X_I(i) \cdot B_H$$
$$f^{UL2}(FN) = f_0 + ((W_K(j)+3) \bmod 7) \cdot B_S + (X_I(i)+3)) \bmod 11) \cdot B_H$$
$$f^{UL3}(FN) = f_0 + ((W_K(j)+3) \bmod 7) \cdot B_S + ((X_I(i)+6)) \bmod 11) \cdot B_H$$
$$f^{UL4}(FN) = f_0 + ((W_K(j)+3) \bmod 7) \cdot B_S + ((X_I(i)+9)) \bmod 11) \cdot B_H$$

for the four uplinks. An example of the five FH sequences for a given cell_id is shown in Figure 4.

In summary, the constructed frequency hopping sequences have a number of desirable properties:

- Consecutive frames are in different sub bands, i.e. spaced at least 11 MHz.
- The (duplex-) spacing between downlink and uplink frequencies is three sub-bands, i.e. at least 22 MHz.
- The four concurrent uplinks are in the same sub band and hop with a fixed spacing of 3 MHz apart.

This simplifies the design of the base station RF receiver considerably. The sequences W and X are, by construction, one-coincident, i.e. their maximum cyclic Hamming correlation is only one [5]. The cross-correlation of the combined sequence, relevant for inter-cell interference, should also be low. This is studied in section 4 below.

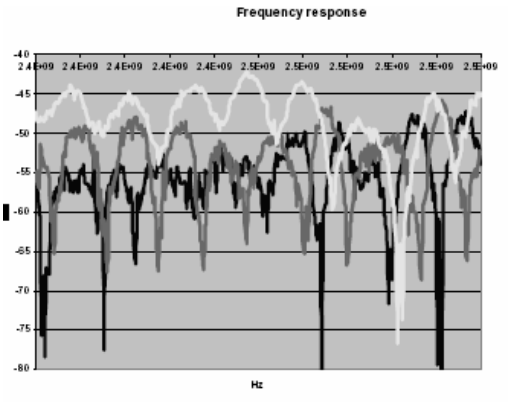


Figure 3. Frequency selective fading in the 2.4 GHz ISM band: frequency-dependent attenuation from a sensor/actuator to 3 BS antennas in a test installation. Grey and light grey: pair of base station antennas, separated by 37 cm. black: 3rd BS antenna, line of sight path obstructed by robot arm.

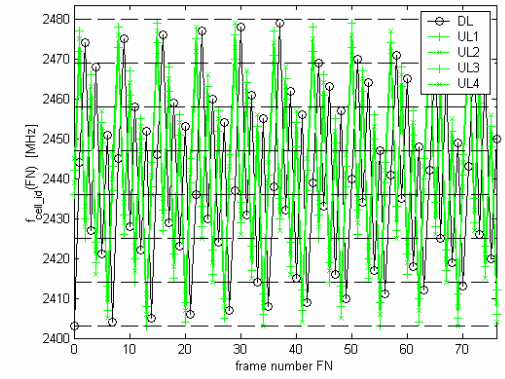


Figure 4. FH sequences for cell_id = 27.

3.3. Antenna Diversity and Switching

As an additional and optional measure for improving transmission, multiple antennas may be used. Antennas with sufficient separation reduce the effects of multi-path fading and shadowing. Figure 3 illustrates the measured effect of frequency selective fading due to destructive interference by multi-path propagation. At any given frequency, the level of the received signal is typically sufficient at a minimum of one receiving antenna provided they are separated by more than half a wavelength λ. This effect is exploited by antenna diversity reception. With λ = 12.5 cm, only the BS, for practical reasons, may be fitted with multiple antennas. With antenna diversity, one BS antenna transmits during one TDMA frame, while the remaining antennas are put into receiving mode. The simplest way is to switch transmit and receive antennas once per frame in a round robin sequence. The BS receiver combines the signals from the receiving antennas in an appropriate manner. The simplest is by selecting the signal with the highest level. With frequency hopping, antenna switching is done together with frequency switching at the frame boundary, i.e. every 2 ms. Guard slots are reserved at the frame boundary to allow for switching transients.

4. Multi-cell Operation

Several WISA cells may operate on the same factory floor. The system is designed such that each cell may use the entire 2.4 GHz ISM band of 80 MHz, without any need for inter-cell coordination such as frequency planning or synchronisation, except of course for the requirement of using different frequency hopping sequences (different cell_ids).

The minimum distance to ensure self-interference-free operation is the same as that for Bluetooth, as the S/As use the same RF front-ends as Bluetooth. According to the calculations in section 5, a nominal WISA cell radius of 5 m requires a minimum distance from neighbouring WISA cells of 16 m for interference free operation. Where cells operate in closer proximity, the interference depends on the correlation properties of the frequency hopping sequences and the cell traffic load.

Cross-correlation between two scalar q-ary sequences, $f_i(n)$ and $f_j(n)$, of length p has been studied in [4], using the Hamming cross-correlation

$$v_{ij}(\tau) = v\left(f_i(n), f_j(n-\tau)\right) = \#\left(f_i(n) = f_j(n-\tau)\right)$$

where #(X) is defined as the 'number of frames where the condition X holds within the length p'. For p-periodic usage of FH sequences, the *cyclic* Hamming cross-correlation is relevant, and is defined as above with (n-τ) taken modulo p [5]. In addition, if cells are not synchronised, the cross-correlation must be considered for all frame clock offsets τ. This definition counts the number of frames of the wanted cell, i, that have been hit due to co-channel (same frequency) interference from an interfering cell j. In general there are a number of interference effects to be included:

- Co-channel interference from same frequency transmissions becomes relevant if the C/I ratio is below 14 dB [3]. This has been used above to calculate distance effects.
- Adjacent channel interference with $|f_i(n) - f_j(n)| = 1$ MHz is relevant if the adjacent channel interference C/I ratio is below –20 dB. This condition may well be true for co-located base stations installed to increase the number of S/As supported at a given cell. (With co-located base stations, RF issues such

as blocking and inter-modulation may also become relevant.)

- Multiple interference from any of the five links (DL, UL_1,UL_2,UL_3,UL_4) of an interfering cell within range. By construction, these links from a given interfering cell are synchronous and never use the same frequency; hence they will hit the wanted link at different frames. While downlink transmissions are continuously active (p_{DL} = 1), the uplink load may be far lower: With a frame rate of 488 frames/sec, and assuming a maximum uplink rate of 5 transmissions / second per S/A, a given uplink slot number in a frame is only used with a probability of p_{UL} = 1.02%, thus decreasing the probability of interference from an uplink transmission.
- Multiple interference from the links of more than one adjacent cell. Links from different cells are mutually asynchronous, causing hits to the wanted link to occur at different times.

In Figure 5 the frequency difference between the five hopping links of a given cell has been plotted along with the five links of an interfering cell, with some given clock offset. Co-channel interference occurs if the difference is 0, while a difference of 1 MHz causes adjacent channel interference.

To evaluate the performance of the retransmission protocol in the presence of inter-cell interference, the time domain behaviour of the interference must be considered. For example, Figure 5 shows that in a retransmission window of seven frames, there are two downlink frames hit by the downlink of the interfering cell, and in the remaining five frames the uplink may be hit by an interfering uplink. To assess these effects, a generalized cross-correlation was defined as

$$v(\tau) = v\left(\underline{f}_i(n), \underline{f}_j(n-\tau)\right) =$$

$$= p_{DL} \cdot \#\left(\left|f_i^{DL}(n) - f_j^{DL}(n-\tau)\right| \le d\right) + p_{UL} \sum_{UL=1}^{4} \#\left(\left|f_i^{DL}(n) - f_j^{UL}(n-\tau)\right| \le d\right)$$

and its properties were analyzed. The results confirm that even in the worst case, the retransmission protocol ensures that messages can be reliably transmitted.

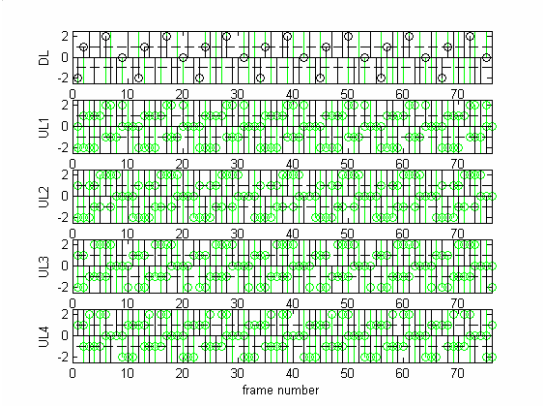


Figure 5. Interference: wanted FH sequence $\underline{f}_{27}(n)$, interfering sequence $\underline{f}_{24}(n-\tau)$, clock offset τ = 7 frames. Traces show frequency separation of the wanted link to links from interfering cell. black: interference from downlink. grey: interference from an uplink.

5. Interference Issues

Use of the 2.4 GHz ISM band requires the appropriate design to enable it to properly co-exist with other systems operating in the same band. Even with frequency hopping, interference will cause some performance degradation. In order to illustrate distance-dependent interference effects, the following attenuation model for the path loss (PL) in [dB] is often used for Bluetooth-type applications (see e.g. [7]):

$$PL = \begin{cases} 20\log_{10}(4\pi d/\lambda), & d \le d_1 = 8m \\ 58.1 + 33\log_{10}(d/d_1), & d > d_1 = 8m \end{cases}$$

where d is the distance between transmitter and receiver. In the near field of the transmitting antenna, this attenuation is proportional to d^2. For larger distances this empirical formula for the average effect of multipath fading stipulates an attenuation proportional to $d^{3.3}$. This describes the distance-dependent average signal power. In addition, the signal may be further attenuated by *shadowing* due to large objects such as parts of machines or robot structures. The detailed effects of shadowing depend on the particular environment, hence the distance values derived below should be considered only as indicative values.

5.1. Interference from IEEE802.11b

IEEE 802.11b WLAN systems employ Direct Sequence Spread Spectrum modulation with a symbol rate of 11 MHz, occupying a fixed channel of 22 MHz

bandwidth. The protocol uses carrier sense multiple access/collision avoidance (CSMA/CA).

Consider a WISA cell operating with a nominal radius of 5 m. Factory staff working in the vicinity use a lap-top computer to upload a large document from an 802.11b base station. The minimum distance needed to ensure safe operation is estimated as follows: The WISA transmission power is 0 dBm. Using the path loss formula from above, this results in a reception level, at the WISA base station at a distance of 5 m, of C = –54 dBm. WISA/Bluetooth receivers require a co-channel C/I ratio of > 14 dB for sufficient reception performance. Hence, the interferer level should be I < –54dBm – 14dB = –68dBm. The 802.11b transmitter power may be up to 100 mW, equivalent to 6.5dBm per WISA/Bluetooth receiver bandwidth of 1 MHz. The required path loss to ensure safe operation is therefore 6.5dBm –(-68dBm) = 74.5 dB. Again using the path loss formula, this translates into a minimum distance requirement for an 802.11b transmitter from the BS base station of 25 m. Conversely, an 802.11b transmitter within a 25 m radius of a WISA cell using the same frequency band will cause interference. (Adjacent channel interference and out-of-band RF blocking and inter-modulation are second-order effects not further considered here.)

Given that there is an 802.11b transmitter within a distance of 25 m, interference may occur. A WISA packet is lost with certain probability if WISA and 802.11b transmissions overlap both in time and in frequency. 802.11 systems transmit over a bandwidth of 22 MHz. Under the assumed scenario of file transfer, the transmitter will nearly always be transmitting. Assume that the hop frequency for a WISA transmission node is uniformly chosen over the 79 available frequencies (1 MHz carriers) in the ISM band. A band of 22 MHz is continuously occupied by the 802.11b system. The FH sequences, constructed as described in section 3, ensure that only 2 out of 7 consecutive packets will be lost. In combination with the ARQ scheme, this ensures reliable message transmission.

5.2. Interference from Bluetooth

Bluetooth uses frequency hopping on a per slot basis. 79 channels are selected in the ISM-band, each channel covering 1 MHz. The minimum slot length is 625 μs, which gives a hop-rate of 1600 hops/s.

Assume a factory worker is using a Bluetooth phone headset in the vicinity of the WISA cell. The typical Bluetooth transmitter power is 0 dBm and the required path loss to ensure C/I > 14 dB is therefore 68 dB, which corresponds to a minimum distance requirement of 16 m. A Bluetooth link operating within 16 m of the WISA base station will therefore cause noticeable interference.

6. Implementation

Figure 6 shows a WISA base station. One BS supports up to 120 wireless sensors/actuators with a cycle time of 2 ms and is controlled by a small microcontroller. Time-critical control of the RF transceiver and baseband signal processing are delegated to an FPGA. The base station maps the wireless links (slots) to the addresses of the fieldbus connecting it to the automation controller. Diagnostics and configuration features are fully supported.

Due to the communication protocol requirements, a standard RF front-end could not be used for the base station implementation. The requirements differ significantly from those found in e.g. WLANs and Bluetooth in that the BS must operate in full duplex mode. To allow reception of weak uplink signals in the presence of the continuous downlink, very high isolation between transmission and reception paths must be ensured. The BS must simultaneously receive signals from sensors/actuators with a dynamic range of more than 60 dB. High suppression of out-of-band interference is required to protect against blocking from external systems. The placement of the base station antennas is crucial for coverage. The BS provides two connectors for the transmit and receive antennas, which are framewise cyclically switched. In order to boost the effect of antenna diversity in a multipath environment, one antenna uses left circular polarization, while the other uses right circular polarization.

In contrast to the BS, the WISA node may re-use existing RF transceiver hardware for Bluetooth. The TDMA and FH parameters chosen in the new design are well within the capabilities of modern Bluetooth RF modules. A WISA sensor module is shown in Figure 7. It includes the actual sensing element (in this implementation a proximity switch [1]), the power receiving coil, a Bluetooth transceiver, and a small 8-bit microcontroller that handles the WISA protocol. Control of the Bluetooth transceiver and baseband signal processing is performed by an FPGA. In order to conserve energy, the proximity sensor is operated in a pulsed rather than in a continuous manner. Power consumption in sleep mode is about 1 mA at 3 V, and 45 mA during transmission/reception. The communication antenna on the module should have omni-directional radiation characteristics in order to achieve uniform transmission performance irrespective of the orientation of the sensor/actuator with respect to the base station antennas.



Figure 6. WISA base station. Top: antenna connectors. Left: fieldbus connector to controller.

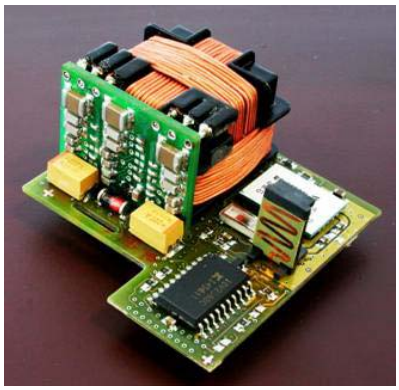


Figure 7. Open WISA sensor module (early prototype). Top: receiver coil for wireless power supply. Bottom: communication transceiver, controller, antenna.

6.1. Performance Results

The RF performance of the WISA system is determined by the transceiver hardware and hence satisfies Bluetooth specifications. In particular, receiver sensitivity is typically better than -90 dBm. As discussed in section 5, normal operation is at relatively short distances, with reception signal levels of about -50 dBm, well above the sensitivity level of the hardware. Hence performance is, in practice, not limited by distance or fading effects, but mainly by external radio interference.

Performance evaluations were done by measuring the message delays. An initial message delay is caused by the TDM/TDMA framing before a message can be transmitted. Any loss of message in the uplink (sensor status message) or in the downlink (BS acknowledgement) causes a retransmission in the next frame, resulting in an additional delay of 2 ms. Retransmission statistics for uplink messages were obtained at the BS by reading the retransmission counter in the data field of received uplink messages. The measurement setup consisted of 60 WISA nodes set to transmit at a rate of 2 messages per second over distances of about 70 cm to the WISA base station. In the interference-free case, one in about 1000 uplink messages required a retransmission (marked as 'reference' in Figure 8), but no second retransmissions were necessary.

The effect on the WISA transmissions due to interference from other WISA base stations was also measured in a realistic scenario. The antennas of the interfering base stations are set to point towards the WISA system under test, thus simulating multi-cell operation. As shown in Figure 8, WISA retransmissions are all within the delay limit also in this case. This confirms the robustness of the design.

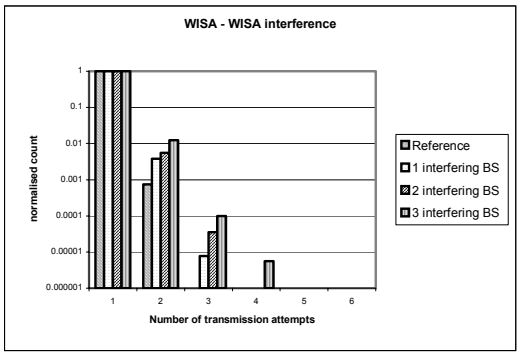


Figure 8. WISA / WISA interference. Measured retransmission statistics for WISA uplink messages under interference from other WISA base station.

6.2. Industrial Electromagnetic Interference

Investigation of a number of potential industrial sources of interference showed that no interference is to be expected in the 2.4 GHz band from spot welding equipment or frequency converters. A spot welding gun used in induction welding operates at up to 20 kA and generates very high electromagnetic field strengths. However, the majority of the frequency noise introduced by welding equipment fades out above 1 GHz and therefore has a minimal impact on WISA, which operates in the 2.4 GHz band. The only measurable interference with high frequencies (up to 1800 MHz) was identified as being generated by arc welding (see Figure 9). WISA wireless proximity switches have been

tested in both spot welding and arc welding installations, were the sensors have been positioned only a few centimeters away from the welding gun. The design of WISA has proved to be very robust, even in these most demanding environments. The tests showed no measurable impact on the communication performance.

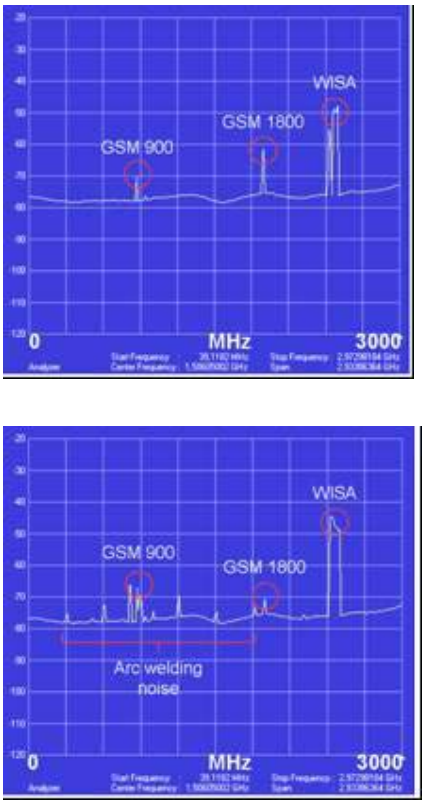


Figure 9. Measured spectra. Upper picture without active welding present, lower picture measured during arc welding. Arc welding noise is at 300-1800 MHz, while the 2.4 GHz band is not affected.

6.3. Interference from other Communication Systems

A number of measurements and tests have been conducted to quantify the effect of interference from other communication systems in the 2.4 GHz band. Two interference scenarios were considered. In the first scenario, interference was caused by a WLAN system consisting of a laptop PC with a IEEE 802.11g WLAN communication card and a corresponding access point (AP). The PC transmits at the maximum rate of 54 Mb/s on channel 5 (2432 MHz) towards the AP, with a transmission power of 100 mW. Measurements were repeated at several distances (d = 7.5 m, 4 m, and 1 m) between the WLAN AP and the WISA BS, and were taken over about 100000 WISA messages each. Figure 10 shows the increased number of WISA retransmissions due to the WLAN interference. The total delay of the WISA uplink transmissions is well within the design goal of 15 ms, even in the unlikely case where the interfering WLAN transmitter is only 1 m away. Conversely, the interference of the 60 transmitting WISA nodes on the WLAN system was also measured. The effective data rate of the WLAN was reduced from 3.1 MB/s in the interference-free case to 2.8 MB/s, 2.25 MB/s, and 0.86 MB/s respectively for distances d = 7.5 m, 4 m, and 1 m, of the interfering WISA system.

In the second scenario, the effect of interference from a Bluetooth link was measured. A Bluetooth-equipped laptop continuously transmits towards a Bluetooth AP with a transmission power of 1 mW. The Bluetooth interferer is spaced 1 m away from the WISA system. Figure 11 shows that the effect of Bluetooth interference on WISA retransmissions is much smaller than the effect of WLAN interference. In the converse direction, the Bluetooth data rate was reduced from 29.2 kB/s to 25.6 kB/s by the interference from WISA.

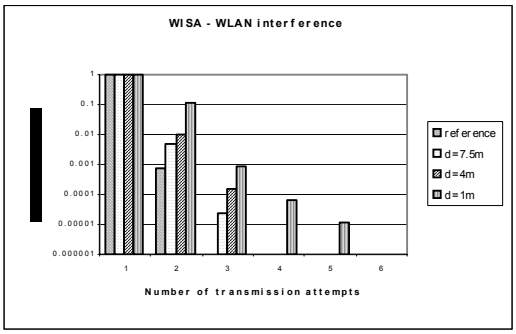


Figure 10. WISA / WLAN interference. Measured retransmission statistics for WISA uplink messages under interference from WLAN.

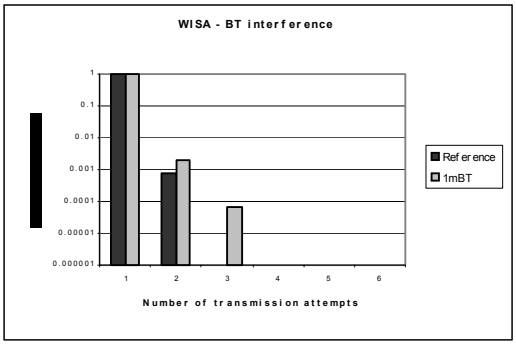


Figure 11. WISA / Bluetooth interference. Measured retransmission statistics for WISA uplink messages under interference from Bluetooth.

7. Conclusions

A frequency hopping wireless system for sensor/actuator communication for real-time factory automation has been presented. It reuses Bluetooth radio transceivers, but adds an optimized TDMA protocol to support a high number (120) of sensors/actuators as well as short cycle times (2 ms). It is important to note that these parameters differ by orders of magnitude from the design goals of existing short-range wireless systems such as Bluetooth or ZigBee. The frequency hopping sequences are constructed to guarantee more than adequate separation between consecutive hops and low correlation (low interference) in the case of multi-cell operation. In combination with an appropriate ARQ scheme, this provides reliable and low delay data transmission. All cells can use the entire available ISM frequency band of 80 MHz at 2.4 GHz, without any requirement for frequency planning.

The effect of interference from other systems likely to operate in the same frequency band has been analyzed, and WISA is designed to withstand such interference.

The system has been implemented and its performance in real factory environments has been tested and verified. Products based on it are now commercially available [2].

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