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WIRELESS FIELDBUSSES – A SURVEY OF ISSUES AND SOLUTIONS

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Abstract: Connecting sensors and actuators by wireless links is the next step in fieldbus technology. We present here the problems that need to be solved and some proposals in the industrial domain. It appears that there is no straightforward solution to the problem. Possible wireless LAN solutions are described and checked for suitability. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Networking in the factory floor is now very common. Solutions exist for different levels, sensory, cell or plant. In this paper, we concentrate on the sensory level where sensors and actuators are linked to the first level of automation by networks usually called fieldbusses (Pleinevaux, 1988). Their use is not restricted to factories. They can also be found in process plants, car automation or building automation.

Since the first solutions were designed in the early 80s, a number of proposals have flourished and the field is well established both in terms of research and industrial use. Most solutions use wired transmission (twisted pairs, coaxial cables, optical fibers).

Using wireless transmission at the factory floor is very attracting. It has been used for years to link mobile robots or automated guided vehicles to control and supervision computers.

At the fieldbus level, a number of solutions have been proposed. Esprit Project OLCHFA (Roberts, 1993) designed a full wireless network based on the FIP protocol (CENELEC, 1996). LON (EIA, 1998) offers some wireless transceivers that can be used to built a mixed wired / wireless network. The same applies to the IEC fieldbus (IEC, 2000). More recently, a wireless link between two Interbus nodes has been described (Peter, 1999).

In this paper, we look at the issues raised when cables are replaced by wireless, radio or infrared, transmission. We will show that replacement cannot be done without modifications and look at different proposals in the industrial domain. The suitability of solutions defined for the SOHO (Small Office and Home) market.

The paper is organized as follows. Section 2 outlines the fieldbus requirements. Section 3 presents the various particularities of wireless transmission that may have an impact on the solutions. Section 4 explains the implications of these characteristics on existing fieldbus protocols. Sections 5 and 6 presents the main proposed solutions in the industrial and SOHO contexts respectively. The conclusion puts the problems into perspective.

2. CONTEXT

The objective of this section is to quickly review the main requirements on fieldbusses. The interested reader is referred to existing literature for details (ISO 1994).

2.1 Fieldbus requirements

The properties that have the strongest impact are:

- handle periodic traffic with different period durations. In many fieldbus solutions, this requirement is translated into some cyclic traffic. The real need it to be able to transport the information well before the end of the period at which the data has been sampled;
- handle sporadic traffic with bounded latency;
- allow for quasi simultaneous sampling of a number of inputs;
- provide indication for temporal consistency. The fact is that control or acquisition systems expect that different sensed values correspond to the sampling instants that should be within a few percents of the sampling period. The network should hence provide ways to know if a set of values exhibit this property, named temporal

consistency. Sometimes the age (time elapsed since sampling) of a data, also called absolute temporal consistency (Kopetz, 1988), is also important to its users;

- for sporadic traffic, provide ways to know the order in which events have occurred. An application will take different decisions depending on the order in which events have occurred. As the events are potentially detected on different nodes of the network, there should be a way to find out the order;
- transfer data from one node to another or one node to a number of others;
- rugged solutions in terms in resistance to interference, vibrations, etc;
- low cost solution. The cost picture includes the devices (nodes, connectors, cables, hubs, switches) as well the planning, installation, commissioning and maintenance expenses.

Although these are not the only requirements, they are the main ones that make fieldbusses different from other networks.

2.2 Addition of wireless nodes

There are at least two ways in which wireless transmission can be used at the fieldbus level:

- All nodes use wireless transmission. This is what we may call a “pure wireless fieldbus”.
- Only a few nodes are without wires. This approach is often selected for cost and performance reasons when a number of nodes can be easily connected through wires. We shall call this case a “mixed wireless fieldbus”.

3. WIRELESS TRANSMISSION PROPERTIES

Wireless transmissions come in two flavours, radio and light based systems. They both exhibit characteristics that make them very different from cable based transmission.

3.1 Main radio transmission properties

The properties that have the strongest impact are:

- Compared to cables, radio transmissions suffer from bit error rates (BER) that are some orders of magnitude higher. BER of 10^{-3} to 10^{-4} are usual whereas in cables one may expect BER ranging from 10^{-7} to 10^{-9}. Error detection schemes should hence be enhanced accordingly. This is especially a concern for token based systems because the token recovery takes quite a long time compared to the temporal constraints.
- The signalling rate is most of the time limited to a few tenth of kilobits per second and seldom exceeds 10 Mbit/s.
- Spatial reuse is low as spectrum is limited. This means that coexistence of several systems in the same area should be either planned (code or frequency allocation) or the medium access control should be designed in a way that takes care of the interference between systems.
- Radio transmission can be easily jammed by perturbating systems. This is especially true in the ISM (instrument, scientific and medical) bands. For instance, in the 2.4 GHz band, high power medical devices are allowed. They may completely suppress all communications for long periods of time.
- Transmission distances are smaller. Typical range are a few tenth of meters indoor and up to 300m outdoor. Furthermore, obstacles may further limit this distance.
- Higher cost. Due to its intrinsic complexity, radio transmission is more expensive than cable transmission. However, this cost may be offset by lower installation costs.
- Collisions cannot be detected while emitting. The power of remote emitters is much lower than the power of the transmitter emission that masks the others.
- A transceiver needs a longer time (up to a few milliseconds) to switch from emission to reception and vice versa. This has to be taken into account when designing the protocol. In particular, protocols that require immediate answers to incoming requests cannot be used.
- Radio transmissions suffer from frequency selective multipath fading. Waves may follow different paths that interfere destructively at the receiver site. This effect can be avoided by using spectrum spreading techniques.
- The radio bands cannot be used freely. There are a number of “free” bands, most of them ISM, but their use is governed by a number of rules. For instance, some bands are not allowed to be used 100% of the time. Duty cycles as low as 0.1% can be found. Finally, the number of bands that are available world wide is very restricted. The 2.4 GHz ISM is among this few.
- While taping a cable requires physical access to the installation, spying radio communication can be done easily. If required, special measures should be added to ensure confidentiality.
- Radio communication suffers from the so-called “hidden terminal” effect. A node A may well listen to nodes B and C while node C cannot ear node B. This means that, if no special policy is implemented, node C emissions will interfere with node B emissions at the location of A because it has no mean to know that node B is transmitting at the same time.
- When is wired transmission is used, power can be transported in the same cable. With wireless, nodes may have to operate on batteries. This calls for special battery conserving transmission techniques.

3.2 Main light transmission properties

We will here restrict the discussion to infra red transmission as it is the most commonly used. Its special properties are:

- Transmission operates only in line of sight. An emitter and a receiver should have direct visibility. This constraint is often relaxed by using satellite like techniques. A special device that acts as a repeater is located in a place where it “sees” all the other devices. This location is often of the ceiling of the room, thus named satellite.

- Sources of heat (sun, machines, heaters, etc.) interfere with transmission.
- High power light sources may damage the eyes of users. This is particularly true for cleaning personal with satellites in factory floors.
- Spectrum reuse is limited as all systems share the same wavelength.

4. IMPLICATIONS ON WIRED SOLUTIONS

One of the first ideas when going to wireless is just to substitute the cable transceiver by a wireless, radio or light, transceiver. Except in special cases, this cannot be done so easily as explained below.

4.1 Medium access control

Fieldbus medium access controls are diverse:

- In the master-slave case (for instance AS-Interface (AS-International Association, 1998)), a central station called master polls all other stations (slaves). A slave is not allowed to transmit unless explicitly requested by the master. Most solutions detect errors (frame loss or absent slave) using timeouts. In order to guarantee short response times, there is a bound in the time left to a slave to answer a master request. With a wireless transceiver, there is an additional delay introduced by the switching time from reception to emission and vice versa. The timeout should hence be extended accordingly thus reducing the performances.
- The central bus arbiter (BA) technique used in FIP exhibits the same problem. To handle cyclic traffic, FIP relies on broadcast. The BA broadcasts the identifier of a variable. The producer of the variable responds by sending the value and the consumers just capture it. In wireless systems, not all nodes may be visible from others as with cables. Additionally, failure of a BA is detected by the absence of traffic during a given period. With wireless transmission, this may occur as a result of fading and interference.
- In token based systems such as Profibus (CENELEC, 1996a), problems come from the hidden node effect that may preclude token passing as well as the longer delay in responses due to the transceiver switching time.
- PNET (CENELEC, 1996b) uses a virtual token passing technique. If the bus is idle for more than a given duration, the access counter is incremented. The station that has the resulting value as node address holds the token. Problems are here similar to those encountered in FIP, reliable detection of silence and additional time due to the transceiver switching delay.
- Some sort of CSMA is used in CAN (ISO, 1992) and LON. Carrier sensing is possible, and used (see 802.11), with wireless transmission but not very reliable as the signal power coming from a remote node may be weaker than the signal from a station in proximity but using another band. Collision detection is nearly impossible (except by using timeouts as in LON) and deterministic collision resolution as in CAN cannot be implemented. Note that some application layers of CAN exploit the broadcast nature of the medium and will suffer from the effects mentioned above.
- In preconfigured TDMA schemes as used by TTP (Kopetz et., 1994) or SERCOS (CENELEC, 1998a), each station knows when it has to transmit. In most of the cases, additional gap time should be left between transmissions to cope with the transceiver longer switching times.

4.2 Error recovery

There different schemes are used to recover from errors:

- When an error is detected, an immediate retransmission takes place. With wireless transmission, this will occur more often and thus reduce the performances. Furthermore, as the number of retransmissions is limited, there will be an impact on higher layers.
- In case of error, there is no immediate retransmission. Recovery is based on the fact that transmission is cyclic (Interbus (CENELEC, 1998), FIP, TTP, SERCOS) and the likelihood that no error will occur during the next cycle. In the meantime, the consuming application just keeps the previously transferred value. With higher frame error rate, there is high probability of error in the next cycles and no fresh value will be available to the application.

Forward Error Correction (FEC) codes might be used to lower the frame error rate and bring it to an acceptable level. With such an approach, a simple "repeater" approach can be built (Morel, 1996).

5. PROPOSALS IN THE INDUSTRIAL DOMAIN

There exist a number of proposals to interconnect field devices without wires. As described in (Decotignie et al., 2001), the approaches differ in the way devices are interconnected:

- In the simplest case, all devices belong to a single wireless cell and no connection is made to wired segments.
- In the repeater approach, a wired segment and a wireless cell are linked together by a repeater that converts signals bit by bit, or character by character, from one medium to the other (Morel 1996, Morel et al., 1996a).
- In the bridge approach, a different medium access control is used on the wire segment and on the wireless cell (Cavalieri et al., 1998).
- In the gateway approach, a special device, the gateway, allows to "see" the set of wireless

devices as if they were connected to the wired segment (Morel et al., 1995)

5.1 OLCHFA (Roberts, 1993)

OLCHFA (Open Low-Cost Time-Critical Wireless Fieldbus Architecture) is an EU funded project that ended in 1995. The aim has been to provide a fieldbus system which is able to operate transparently over either a wired or wireless medium by providing flexibility depending on the particular application. The microwave wireless system uses spread-spectrum techniques to achieve the required resiliency. Although the OLCHFA architecture is designed using FIP components, the messaging service has been extended to accommodate true time-critical support and access to a synchronized time reference.

5.2 LON (EIA-709.1, 1998)

LON is a network initially designed for building automation. It operates at 1.25 Mbit/s on twisted pairs and reduced speeds on other media including radio links (19.2 Kbit/s). Segments using different media can be combined using repeaters. The medium access control is a variant of CSMA with collision detection and adaptive persistence. As collisions cannot be detected on radio links, error recovery is done using timeouts at the transport layer. Temporal constraints should hence be relayed on traffic send to or received from nodes connected through radio links. On of the may strength of LON lies in its ease of programming and use.

5.3 R-Fieldbus (Haehniche., 2000, Alves. 2001)

“R-Fieldbus: High Performance wireless fieldbus in industrial related multimedia environment” is an on-going European Union funded project. It aims at developing "an integrated, high performance Wireless Fieldbus Network, that is an industrial radio local area network". It is based on Profibus and adds support for multimedia services. Wireless nodes are linked to a wired segment using base stations. There might be more than a single base station connected to the same wired segment to provide extended coverage on the radio side. Each base station acts as a bridging device. Frames received from the wired segment as transmitted on the wireless cell and vice versa. The wireless cell can be seen as an extension of the wired segment and the same medium access control mechanism is used. Radio transmission is Direct Sequence Spread Spectrum in the 2.4 GHz band (same as 802..11 but the 802.11 Medium Access Control is not used). Different cells seem to use different channels.

5.4 Morel

Morel et al. have studied several solutions to integrate wireless nodes to a FIP fieldbus. The first solution is a simple repeater that converts from cable to radio and vice-versa (Morel et al., 1996a). The various ways to handle FIP constraints are discussed. The second solution (Morel, 1996) is what they called a "word repeater" approach in which they use all frames coming from the wired segment are repeated byte by byte with additional forward error correcting code in order to increase to reduce the bit error rate on the wireless side. They used Golay codes (Proakis, 1983).
Finally, the gateway approach (Morel et al. , 1995) seems to be the best solution to overcome the limitations due to the wireless transceiver switching time.

5.5 Others

The Fieldbus international standard has defined a radio physical layer (IEC 61158-2, 2000-08) that can be used in place of wireline transceivers. In addition, there are a few individual products available that use some sort of wireless link. However, none of these products is a standard.

6. GENERAL PURPOSE WIRELESS LANs

In the office environment, a number of proposals to interconnect computers together or with peripherals are available.

6.1 IEEE 802.11(ISO/IEC, 1999),

IEEE 802.11 is an ISO/IEC international standard (ISO/IEC 8802-11) originally defined by the IEEE. It is a wireless LAN for use in the SOHO (Small Office and Home) environment although experiments have been made for transmission up to 30 Km. The standard only defines the physical and medium access control layers. The former comes in three versions: a basic version with a raw bit rate of 1 and 2Mbit/s, a extended version (802.11b) at 11 Mbit/s and a high speed version (802.11a) at bit rates up to 54 Mbit/s. The first two operates in the 2.4 GHz band while the latter uses the 5 GHz ISM band.
The basic version of the standard specifies Infrared transmission as well frequency-hopping and direct sequence spectrum (DSSS) techniques on radio channels. The extended version only uses the DSSS technique. The high speed version physical layer uses orthogonal frequency division multiplexing (OFDM) on 52 subcarriers modulated with binary or quadrature phase shift keying (BPSK / QPSK), 16-QAM (Quadrature Amplitude Modulation) and 64 QAM.
CSMA with collision avoidance is used as a medium access control. Collisions are partially avoided by sending reservation frames (RTS) that are acknowledged by the receiver using a CTS frame. Both frames include the reservation duration. When receiving one or both of these frames, all other stations refrain from requesting any traffic. This mode of operation corresponds to the DCF (Distributed Coordination Function). In this mode, there is no temporal guarantee. When guarantees are required, the PCF (Point Coordination Function) can be used. A special node, the point coordinator, is used to create a cycle in the traffic. This cycle is split in two parts. In the first part, there is no contention

and medium access control is managed by the point coordinator. In the second part, all nodes can compete as in the previous mode.
The standard also defines encryption to protect the transmissions.
IEEE 802.11 is widely available in its 11 Mbit/s DSSS version. Using PCF, it can be used as a wireless fieldbus with strict temporal constraints. Its main drawback is to operate in a licence free band where sources of interference abound.

6.2 Bluetooth

Bluetooth is an industry standard for short range radio in an office and home environment. It uses the 2.4GHz ISM license free band available worldwide (although with some restriction in some countries). Bluetooth networks are composed of piconets. Interconnected piconets in the same geographical area form a scatternet. A piconet has a single master and up to 7 active slaves. Many more slaves may be synchronised with the piconet traffic but not participate actively (park mode). Bluetooth operates in the 10 meter range with future extensions to longer distances. It uses a frequency hopping spread spectrum technique on 79 carrier frequencies. Each hopping sequence lasts approximately 24 hours. The raw bit rate is 1Mbit/s. Traffic is master slave with the piconet master polling a single slave in one hop. The slave has to answer in the next hop. This transaction is repeated in case of error. The order in which slaves are polled is not defined by the protocol but depends on the pending traffic. Besides this sporadic traffic, bluetooth support real-time isochronous traffic. Each isochronous connection uses one third of the available bandwidth and up to 3 isochronous connections can be established. A node can participate in more than a single piconet but cannot be the master on both as the hopping sequence and its phase are defined by the master identity and clock phase.
Bluetooth offers authentication and ciphering to protect the communication. It also includes a service discovery protocol that allows to find a node with a given capability. Higher layers are based on a serial link emulation (RFComm) and the PPP/IP/TCP-UDP suite as well as the object exchange protocol OBEX. Besides the isochronous traffic which cannot be used between more that 3 devices, Bluetooth does not offer temporal guarantees. The limitation in the number of devices can be overcome by regularly swapping nodes from active to park mode and vice versa. The fact that traffic is master slave is certainly a problem for fieldbus applications. Bluetooth strength lies in its robustness and absence of preconfiguration as well as the planned low cost. Despite its robustness (Shorey, 2000), as for 802.11, the use of a licence free band and the limited distance of operation may preclude its use in industrial environment unless other sources are eliminated.

6.3 DECT (Muchaxo et al., 1999),

DECT (Digital Enhanced Cordless Telephone) is an ETSI (European Telecommunications Standards Institute) that defines an in-door wireless extension to ISDN. It operates in a reserved band in more than 100 countries. DECT uses 10 frequency channels. On each channel, cycles of 10 ms duration are repeated. Each cycle contains 24 time slots. A single connection uses 2 slots, one for the uplink and one for the downlink. Up to 120 connections may be established from a single base station. The information is sent at 1Mbit/s which means that each slot can accommodate 320 bits for a voice channel or 256 bits for a data channel. For a data connection, up to 23 slots can be used in one direction if asymmetric traffic is necessary.
Multiple cells (multiple base stations) can coexist without configuration. The 120 channels need however to be shared among the cells.
Through the static assignment of a channel, traffic can be guaranteed. Furthermore, the use of a protected band makes DECT immune to other sources of perturbation.

6.4 IrDA AIr (Gfeller, 2000)

AIr (Advanced Infrared) is an industry standard defined by the Infrared Data Association (IrDA).It uses infrared light with a 4-slot pulse position modulation at 4 and 16 Mbit/s. Its range can cover a complete room. Contrary to other IrDA standards, AIr allows multipoint operations. The medium access is similar to the 802.11 DCF scheme. As a consequence, AIr does not offer guaranteed traffic. The direct visibility constraint may be easily overcome by using a satellite repeater approach as mentioned above (§)3.2). AIr is a good alternative to Bluetooth. Its use in an industrial environment may be questioned because sources of heat may perturbate it.

6.5 Others

There are a few other proposals:

- Hiperlan 2 (Khun-Jush J., 2000) is an ETSI defined radio LAN targeted at multimedia home applications. Its characteristics are similar to the high speed version of IEEE 802.11 to such an extend that IEEE and ETSI are studying ways to converge to a single solution.
- HomeRF (Lansford, J., 2000) is an industry initiative that defines a radio LAN for voice and data transmission in the 2.4GHz ISM band.
- There are a number of projects such as WINS (Potttie, 2000), WIND (Heizelman et al. 1999) or Wisenet (El-Hoiydi, 2002) dedicated to what are called wireless sensor networks. The aim is to develop radio based ad-hoc self organising networks of sensors and actuators.

8. CONCLUSION

In this paper, we have presented the issues that arise when building a wireless fieldbus. Proposals in the industrial domain and solutions in the SOHO environment were described. At this point, we lack a solution that covers all requirements especially because existing wired solutions cannot be readily expanded. Some SOHO solutions such as 802.11 can be used in conjunction with existing wired fieldbusses. One of the problems is that most radio based solutions use ISM bands that can be used freely by other incompatible solutions. It is hence difficult to offer the required reliability and temporal guarantees unless the environment can be protected. This calls for solutions using protected bands.

With the explosion of projects in the area of wireless sensor networks, we may see good solutions in the near future.

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