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Wireless communications deployment in industry: a review of issues, options and technologies

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Abstract

Present basis of knowledge management is the efficient share of information. The challenges that modern industrial processes have to face are multimedia information gathering and system integration, through large investments and adopting new technologies. Driven by a notable commercial interest, wireless networks like GSM or IEEE 802.11 are now the focus of industrial attention, because they provide numerous benefits, such as low cost, fast deployment and the ability to develop new applications. However, wireless nets must satisfy industrial requisites: scalability, flexibility, high availability, immunity to interference, security and many others that are crucial in hazardous and noisy environments. This paper presents a thorough survey of all this requirements, reviews the existing wireless solutions, and explores possible matching between industry and the current existing wireless standards.

Keywords: Wireless networking technologies and industrial application; Information and communication technology in industry

1. Introduction

Enterprises are as efficient as their processes are. Information [1] is one of the most important assets in the modern enterprise, because it is the basis of knowledge management.

Current challenges are to acquire and manage more information and to integrate and communicate all the entities that conform the production process. To interconnect ‘‘information islands’’, to keep large investments and to adapt to new emerging technologies, enterprises dedicated a considerable amount of their budgets to integrate their communication infrastructure and information systems.

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With the arrival of Internet and new e-business models, companies have to adopt different strategies for doing business and be competitive. For instance, on-line sale or Business-to-Business (B2B) [2], require to integrate Internet operations with data and application from backend systems. Therefore, new technologies must be adopted, adapted and also integrated into legacy systems. During the adoption and integration phases, scalability and inflexibility problems arise, in particular when there is a lack of initial planning. In conclusion, a global view and deep knowledge of the underlying technology are needed to have success.

On the other hand, manufacturing and industrial processes must provide products and services of quality. In short, it has to be competitive. To meet this goal, production process must have some indispensable elements:

(a) *Flexibility*: production must be updated constantly, improving products and services.
(b) *Quality control*: high levels of coordination in acquisition and analysis of data are needed.
(c) *Inventory control*: new strategic trends in business, e.g., JUST-IN-TIME [3], try to decrease fixed capital by reducing or removing products in stock.
(d) *Speed*: if a company cannot deliver on time, it means losing benefits, image and customer fidelity.

These elements, to a great extent, depend on the level of interconnection among: machinery, software (management, monitoring and control), control devices and workers. This information exchange is supported by industrial communication networks. These networks differ from conventional ones because of environmental constraints, mainly: resistance against harsh environment (high temperature, corrosive substances, etc.), real-time application support, noise immunity and fault-tolerance.

As a consequence, manufacturing and industrial processes are the main engine of development and use of industrial communication networks.

In this continuous improvement of an industry (as defined in ISO 9000 [4]), all the effort should not be applied to just one goal; there are a number of tasks that should be at the same level: mobile worker integration into information system, data gathering by means of instrumentation distributed in a plant, installation of a control and logistics management system, implementation of an Enterprise Resource Planning (ERP) or a Customer Relationship Management (CRM) [5,6], etc. There is a need for both quantity and quality information flows which are common to these improvements. Again, communication infrastructure supports these exchanges of data flow.

As an illustrative example, fieldbusses were a revolution in industrial communication since they allow to interconnect several devices through a single wire in order to control and monitor their operation. Namely, simplifying and improving information flows. Wireless technologies are the natural evolution that will allow to collect new information flows (not available at the moment) and, in addition, to improve the existing ones.

At this point, we should question why wireless is interesting in industry. This interest is quantifiable: according to Forrester Research in Cambridge, 15% of industrial companies now have wireless networks in their plants, 6% more than the previous year [7].

Wireless technologies may provide considerable savings in networking cost and a degree of flexibility not known in wired systems. In addition, they can be the solution for specific industrial problems, which are not addressed or easily solved by traditional wired systems. Some of the features that support wireless potential are:

- Lower installation and maintenance costs.
- Solution for physical barrier problems inherent in wiring.
- Comparing to fieldbusses: incompatibility between standards is minimized and transmission bit rate is increased, so that multimedia services become feasible.
- New scenarios, which add value to production process, arise when communication among mobile elements is allowed.

Of course, there are several constraints when using wireless systems that should be carefully taken into consideration. For instance, security issues are one of the major concerns. Also, reliability, coverage area and fault-tolerance are other important issues.

An insufficient knowledge of these issues may discard wireless solutions, probably losing their capabilities and potential. It is worth having at least a general overview of available technologies, issues and options.

Summarizing, productive processes depend more and more on the telecommunication infrastructure. It is a must to have a global overview of technology and to have some specific selection criteria for the network technologies: alternatives, real application cases, cost, etc. In addition, wireless technologies are showing an increasingly significance, due to their enormous potential. This paper provides an overview of wireless systems, problems, and issues regarding their adoption in industry.

The remainder of this paper is organized as follows: related work is discussed in Section 2. An overview of current industrial communication networks is provided in Section 3. This section also includes an enumeration of specific requirements for industrial environments and scenarios of current use of wireless in industry. Section 4 is devoted to technical details of available and emerging wireless systems and important general issues: benefits, cost analysis, security, regulation, etc. Next, a description of emerging and relevant technologies is done, providing technical details and how each technology faces the previously introduced issues. Section 5 deals with potential of wireless systems in industry and shows some application scenarios. Finally, Section 6 concludes the article.

2. Related work

Wireless technologies interest is increasing in industrial world. There are a number of new organizations, consortia, conferences and workshops that are specifically focused on industrial wireless. Some examples are: Wireless Industrial Networking Alliance [8], which is a consortium formed recently to promote the use of wireless in industry; in 2003 the Instrumentation, Systems and Automation Society (ISA) [9] organized a Wireless Communications Industrial Technical Conference.

A number of studies on industrial wireless can also be found. However, most of them are related to a specific application of wireless, such as transportation [10], or are studies with little technical description [11]. There are also studies regarding generic issues of wireless applied to business (as in [12]), which are centered on the general economic impact of wireless.

A general overview of issues, which are relevant to wireless adoption in industry can be found in [13], but this is a descriptive overview, with little technical content.

There are also complementary works, as [14], which examines the more general relationship between wireless and information society.

3. Communication systems in industry

The number of processes or activities that ‘‘industry’’ may encompass is probably as large as the number of communication systems developed within this scope. As a consequence, it is an arduous task to provide an overview of the common features of industrial networks. Many of the industrial communication systems have been developed to solve a very specific problem.

A classification of industrial processes may help to clarify the mess of terms related with industrial communications and the nature of these systems. A coarse division of industry would show two types of industrial processes: management or production. A similar classification could be done with communication systems in industry: those designed for management and those for production.

Communication requirements and needs for the former are very similar to those for the office environment: Access to databases, high-data volume exchanges and multimedia capability. Communication networks are commonly based on Ethernet local area networks (LANs) [15] and phone lines interconnected by the public switching infrastructure and Internet, i.e., the common network for the office environment. These networks are usually organized in network segments interconnected by switches and routers. Large organizations may use high speed and high performance switches.

On the other hand, production usually imposes quite different constraints, which result in highly specialized networks. These environments are typically high-structured and location of elements does not frequently change. Industrial networks for production (see Fig. 1) are arranged into hierarchical

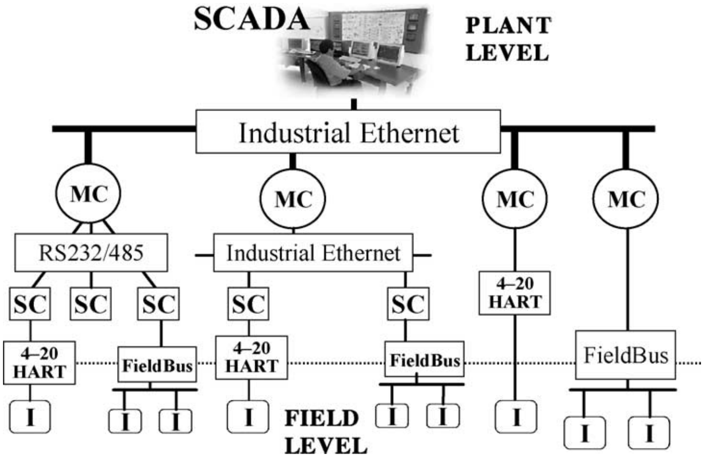

Fig. 1. Network deployment in an industrial plant.

levels (plant, area, cell and field level), depending on the complexity of the overall production process. Plant level is on top, where information from lower levels is collected and the entire automation system is commanded by means of a Supervisory Control And Data Acquisition system (SCADA) [16]. A plant is divided into areas, which are made up of cell groups. Field level is the lowest one and includes the instrumentation: sensors and actuators.

In short, we have highly distributed architectures in which hierarchical control modules, mainly Programmable Logic Controllers (PLC), are interconnected by communication networks to provide both low-level control functionality and data acquisition from the instrumentation (I). Therefore, reliability and performance of the automation system greatly depend on its underlying telecommunication network. Note, in Fig. 1, that the controllers could be master controllers (MC) and slave controllers (SC).

The hierarchical network, that forms the SCADA system and the controllers (MC and SC), is typically made of industrial Ethernet and point-to-point connections complying RS232 and RS485 standards.

The differences between common data networks and industrial networks arise at the lower levels. This is so because at cell and field level the requirements notably change: real-time services, system availability, and fault-tolerance become crucial. Changes are not only functional but also physical: high electromagnetic interference, high temperature, corrosive substances, etc. There is also a large number of small devices (instrumentation) working together. The network must guarantee requirements, such as throughput and mean transmission delay.

However, the upper levels have little difference with respect to the systems used for management processes or office environments. Therefore, down the hierarchy up to cell and field levels, the communication infrastructure is practically the same for both management and production.

3.1. Field level

This level sets up the real difference between common office networks and industrial networks. The production process imposes their own specific constraints, requirements and specifications for the communication system at this level. The system is closely related to the actual process under consideration. As a result, there is a huge diversity in systems.

In general, the instrumentation can be divided into sensors (data and signal alarms on temperature, pressure, etc.) and actuators (valves on–off, regulated valves, speed regulators, etc.). Instrumentation has an electronic interface to be connected to a controller. Depending on its electronic interface, the following coarse division can be established:

- Instrumentation with interface 4–20 mA.

- Instrumentation with interface 4–20 mA and HART protocol.
- Instrumentation with a fieldbus interface.

The 4–20 mA consists of a point-to-point connection between the device and the controller through a twisted pair cable. Information is encoded in the amplitude of the analogue signal. The HART protocol [17] uses modulated signal to superimpose digital information on the conventional 4–20 mA analogue signal. Maintained by an independent organization, the HART Communication Foundation, the HART protocol is an industrial standard developed to define the communications protocol between intelligent field devices to calibrate and control them.

Finally, the instrument can have an interface to a commercial fieldbus system although instrumentation with an industrial Ethernet or RS232/RS485 interface can be also found.

In this case, the variety of interconnected devices requires the adoption of a communication standard. This need led to a struggle between industry consortia to set their own proprietary fieldbusses as standard. This situation has produced a lot of confusion regarding current fieldbus availability and features.

At present, a wide range of fieldbusses [18] can be found. For instance: DeviceNet, Profibus, AS-I, SDS, Interbus, CANopen or Foundation. Since 1996, there is also a European standard, EN50170, which is based on three previous technologies: Profibus, WorldFIP and P-Net. Despite this diversity, some similar features can be found.

All mentioned busses offer transmission rates ranging between 125 Kbps and 1 Mbps (Profibus can reach 12 Mbps).

- Distances between 100 and 500 m, without repeaters.
- They use proprietary protocols with real-time features.
- Limited message size, mostly 8 data bytes per node and message (again, except for Profibus).
- Most of them are based on RS485 interface and Controller Area Network (CAN) technology.

Trends in fieldbusses development are the search for compatibility with TCP/IP and open specifications to make easier the integration with upper levels.

3.2. Industrial environment requirements

As it was previously mentioned, the requirements that an industrial communication system must fulfill differ according to the level in the general structure. At upper levels, the requirements are very similar to those arisen in office environments. Indeed, the top level is the boundary between office area and production area. At this point, there will be used office solutions, whose multimedia capabilities have a positive impact on production management. When descending the structure, other functions (as real-time services, system availability and fault-tolerance) become crucial. At the field level, the most restrictive requirements appear. In general, a communication system at this level has to satisfy:

- Instrumentation with interface 4–20 mA.
- Resistance to electromagnetic interference.
- Resistance to aggressive media, such as high temperature and corrosive substances.
- Low latency.
- Real-time services support.
- High availability.
- Fault-tolerance.

In addition, there are several problems that affect specifically wired systems: physical barriers, difficulty in constructing additional infrastructure associated to wired solutions, rotary elements in machinery, productive processes continuously moving, as well as long distances between elements. These requirements not only increase wiring costs but also mean inflexibility when reconfiguring productive processes.

Summarizing, the requirements imposed come from both the physical characteristics and the applications that are used within the industrial framework.

3.3. Wireless in industry

Wireless communication has been long used in industry. The use of walkie–talkies is an obvious example. However, its use has been limited to solve very specific problems and rarely as the main communication infrastructure. There are a number of examples of wireless used in industrial activities that can give us an idea of the role they have played so far.

Traditionally, it has been used to provide voice services in those environments where it was the only feasible choice, e.g., farm, forestry, mines, oil exploitation. These systems have evolved to more sophisticated *trunking* (see Section 4.7.4) systems, which can eventually provide data transmission services as well, becoming a more general communication infrastructure.

Point-to-point radio-links are still a common solution in rural areas. This market is dominated by expensive proprietary solutions.

Also satellite communications have been long used to reach isolated and remote facilities. Mining and oil companies have been their traditional users. More recently, Global Positioning System (GPS) is widely employed by a number of companies. Distribution companies use it to track their freighter fleets.

A closer example is the utilization of Radio Frequency Identification (RFID) [19], also called RF Tags. These systems are used worldwide for stock management, in stores, in airports to automate luggage transportation, or as an anti-theft system.

In general, the aim of the system is not to support the whole communication infrastructure but to provide or support a particular application or service. However, emerging wireless technologies have an increasing potential either as a solution to many current industrial problems or even as a way of complementing or becoming the general communication system, as next sections will try to show.

4. Wireless technology survey

Computer science and telecommunications are observing the exponential growth of wireless market, which has recently experienced a notable advance. Wireless technologies will probably become a new paradigm in industrial development, since they are now in commercial areas. Wireless offers low-cost networking and the possibility of new applications. In this section, we will try to demonstrate this assessment by having a closer look at the characteristics common to almost all wireless technologies. Also, we will focus on requirements for industrial networks, such as reliability or security. Finally, a brief analysis of the most relevant networking standards is offered.

4.1. General overview

Two decades ago, wireless commercial market was scarce, and it was ruled by proprietary solutions. Such situation is a clear analogy with current networking industrial market (as shown in Sections 1 and 3). Fig. 2 shows a schematic view of the evolution that made the change possible. First, new technologies in signal processing and radio field, plus standardized protocol design with OSI-like [20] models shifted the situation to the development of open solutions and standards. Then, wireless market started to grow in a continuous symbiosis with the needs of the users: new applications and best features, which led to the massive wireless presence in nowadays society.

Several standards were, or are being developed: IEEE 802.11, DECT, GSM, etc. Each of them has its own pros and cons. Selecting the right wireless solution for a given problem is sometimes a complex task that depends on many factors, namely:

- capacity,
- range,
- noise immunity,
- noise emission,
- security,
- setup and running cost,
- power consumption,
- free versus licensed operation,
- regulations,
- compatibility with hazardous environments,
- fault-tolerance,
- technological availability,

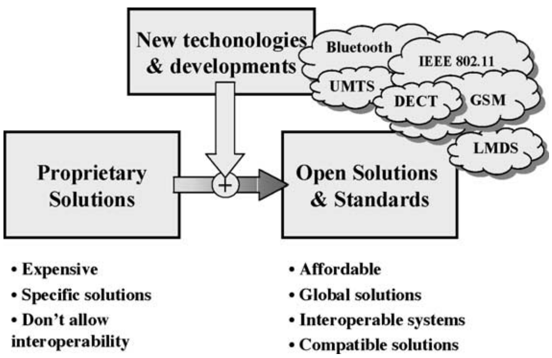

Fig. 2. Evolution from proprietary solutions.

- commercial availability,
- Quality of Service (QoS), etc.

4.2. Common benefits of wireless networks

Some of their noteworthy benefits are:

(a) Allows mobility, either to physical users or to machinery components. For example:
  - Warehouse employees can use wireless equipment (such as a PDAs) to move around while making inventory, with products statistics being displayed in real-time in the central computer.
  - In machinery, rotating parts can be communicated seamlessly.

(b) Application layer software developed for wired networks can be directly used in wireless environments thanks to the layered design.

(c) Native support for multicast and broadcast communications, allowing services, such as:
  - Multimedia broadcast.
  - Fast management information delivery, from a master to several devices.

(d) Easy installation, with associated savings in cost and time. Such savings often compensate for additional technology expense. For example, in the Indonesian telephonic system, a satellite launch was preferred over dropping thousands of wires among the 13,667 islands of the archipelago [20]. It is not wire price, but installation cost what makes the big difference between wired and wireless solutions, despite significant satellite design and launch costs.

Other situations where an easy installation is an advantage are:

- Need of fast deployment, for example in catastrophic zones.
- Temporary networking, like business meetings.
- Places where wired installations are forbidden, like historical buildings.

To quantify this benefit, we have developed a simple expression for the total network installation cost (no operation and maintenance costs are considered):

$$\text{Global cost (GC)} = \text{installation cost (IC)} + \text{hardware cost (HwC)} + \text{network planning cost (NPC)}.$$

$$\mathrm{GC} = \mathrm{IC} + \mathrm{HwC} + \mathrm{NPC} \tag{1}$$

If N denotes the total number of "stations", then: IC = $N \times$ number of workers (W) $\times$ total installation time (T) $\times$ hourly cost of one worker job (HC).

Obviously, $W \times T$ can be considered as constant. If we name it WT, then:

$$\mathrm{IC} = N \times WT \times \mathrm{HC} \tag{2}$$

Note that WT can be calculated as "the time spent by a single worker to install a single station".

Hardware costs (HwC) include the prices of all network interfaces, wires, switches, hubs, access points, etc. Let *station cost* (SC) be the average hardware cost per station, then:

$$\mathrm{HwC} = N \times \mathrm{SC} \tag{3}$$

Finally, network planning cost encloses those concepts related to the design and further verification of the network. For wireless networks, verification phase is generally more difficult (and expensive) than for wired ones, since coverage maps of the area to assure good reception are needed. NPC increases as a function of N, but not in a linear fashion (i.e., price of planning a 40 stations network is similar to price of planning a 41 stations network, but smaller than for a 100 stations network). Thus, if for a given number of stations N_0, the planning and verification price NPC_0 is known, we can estimate NPC function cost within an interval of N_0 using some slowly increasing expression. We *heuristically* selected a logarithmic formula to characterize this function:

$$\mathrm{NPC}(N) \approx \mathrm{NPC}_0 \times \frac{\log(N)}{\log(N_0)} \tag{4}$$

Factor $\log(N_0)$ is introduced to define NPC coherently:

$$\mathrm{NPC}(N_0) = \mathrm{NPC}_0 \times \frac{\log(N_0)}{\log(N_0)} = \mathrm{NPC}(N_0) \tag{5}$$

Also, this heuristics has the desirable property of overestimate cost for NPC if $N < N_0$, which seems reasonable in order to establish a comparison. Therefore, GC is finally expressed by (6).

$$\mathrm{GC}(N) = N(WT \times \mathrm{HC} + \mathrm{SC}) + \mathrm{NPC}_0 \frac{\log(N)}{\log(N_0)} \tag{6}$$

For the sake of clarity, in Fig. 3 we represent the "wired/wireless cost ratio" versus the "number of stations" for a family of input parameters, which are

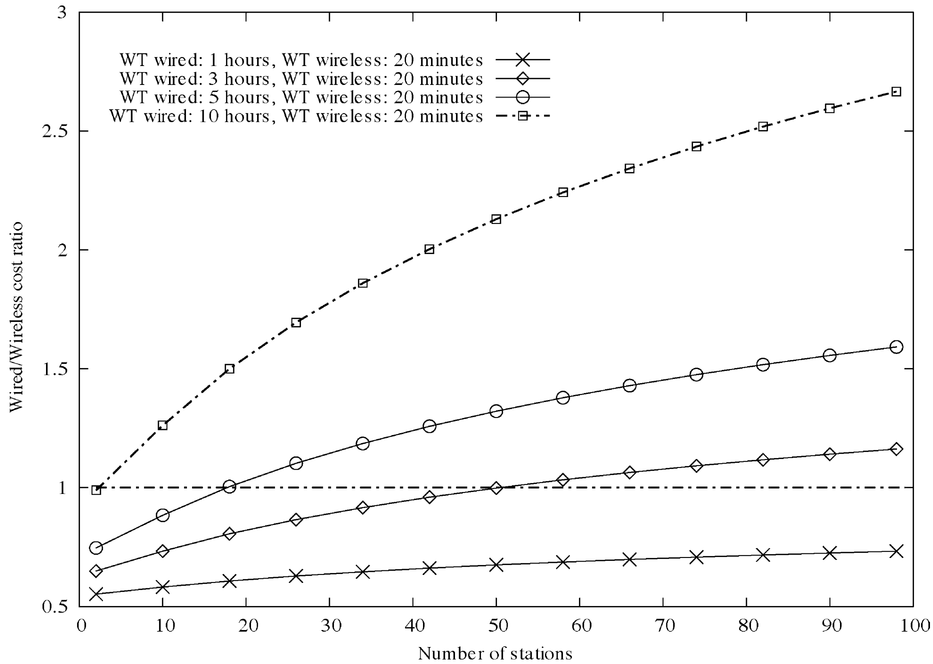

Fig. 3. Comparative for the net setup cost.

selected based on average market prices. Ratio values greater than 1 mean that wireless is a cost-effective solution; whereas, values less than 1 mean that wired installation is cheaper.

The following input parameters are employed:

- HC = 40 €
- WT_{wired} = 20 min
- WT_{wireless} = (1 h, 3 h, 5 h, and 10 h)
- SC_{wired} = 50 €
- SC_{wireless} = 80 €
- N_0 = 100 stations
- $NPC_{0\ \text{wired}}$ = 1000 €
- $NPC_{0\ \text{wireless}}$ = 2000 €

Summing up,

- *WT* is the key factor to select a wired or a wireless solution. Wireless is a better option as *WT* increases for a wired installation: ratio grows as wired installation process becomes slower (for example, when building modifications are necessary) and is less if wired installation is fast.
- Ratio increases as it does the number of stations (*N*), or the hourly cost rises.
- Ratio decreases as it does the wireless network planning cost (NC), or the station cost (SEC).

This cost computation includes only network setup. Running cost should also be taken into account. However, it is difficult to estimate it because it depends on quite unpredictable factors; for instance, a change on the arrangement of machinery may create a coverage fading. It is not clear whether this case offers higher savings than a wired installation. However, there are some cases that clearly offer long-term benefits: when moving a facility, such a lab, previous wired infrastructure cannot be carried; it must be removed and reinstalled with its associated costs. Nevertheless, wireless is not affected by this issue.

4.3. Problems and disadvantages

Disappointedly, wireless systems also have several restrictions and drawbacks, and it is necessary to know and characterize them. Among these problems we have:

- More expensive station technology.

- Power consumption, that is specially relevant to mobile users.
- Incompatibility among standards that use the same unlicensed frequency bands. For example, IEEE 802.11b uses the 2.4 GHz ISM band. Bluetooth uses the same spectrum, and when transmitting it jams nearby 802.11b stations [21].
- Less capacity than their wired equivalents. For example, IEEE 802.11 g has a maximum transmission capacity of 54 Mbps, versus the 100 Mbps of Fast Ethernet.
- Security issues (see Section 4.5).
- To guarantee coverage in any situation and location is complicated.
- Problems in the co-existence of wired and wireless technologies (see Section 5).
- Hidden nodes problem [22].
- Radio communication issues (see Section 4.6), such as, noise or interference.
- Health issues (see Section 4.4.3).

4.4. Regulation issues

If we plan to use a particular wireless technology, we have to contemplate three general types of regulations, and to check if our choice verifies them.

4.4.1. Spectrum regulation issues

Equipment transmissions must be regulated to efficiently share the finite available frequency spectrum and avoid interference between them. Main regulatory organizations [23] are the International Telecommunications Union (ITU) [24], the U.S. Federal Communications Commission (FCC) [25], the European Telecommunications Standards Institute (ETSI) [26] and the Japan Association of Radio Industries and Business [27]. Additionally, international normative may be superseded by national regulations. Recommendations and rules apply to:

- Maximum transmitted power, constraining the range of a particular technology.
- Maximum permitted Electro-magnetic fields (EMF) and noise emissions.
- Frequency band.

Regulatory bodies distinguish between licensed (permission must be granted by a regulatory body) bands and unlicensed (free) bands. A particularly interesting unlicensed band is the ''Industrial, Scientific and Medical'' (ISM) defined by the ITU and used in most countries with minimum differences (Table 1).

Table 1
Frequency allocation in the ISM bands

Frequency band	Center frequency
6765–6795 kHz	6780 kHz
13,553–13,567 kHz	13,560 kHz
26,957–27,283 kHz	27,120 kHz
40.66–40.70 MHz	40.68 MHz
433.05–433.79 MHz	433.92 MHz
902–928 MHz	915 MHz
2400–2500 MHz	2450 MHz
5725–5875 MHz	5800 MHz
24–24.25 GHz	24.125 GHz
61–61.5 GHz	61.25 GHz
122–123 GHz	122.5 GHz
244–246 GHz	245 GHz

ISM bands are not constrained to any technology, then any system may share the same range of frequencies. Many wireless networks, like Bluetooth and IEEE 802.11, operate at this spectral band since it is free. However maximum power emission is limited by law (in Europe, lesser than 100 mW for spread spectrum equipment [28]).

4.4.2. Industrial and security regulation issues

Special restrictions apply to industrial areas. There is a classification of hazardous areas depending on the risk of accident, explosive atmospheres and environmental dangerousness. Only special instrumentation, devices and machinery with demanding security levels are permitted (intrinsically safe equipment) [29,30].

In Europe, the Atmosphere Explosive directive (ATEX) [31] rules the intrinsic safety for electronics. According to this directive, wireless devices have to be certified by the CEN/CENELEC [32,33]. USA equivalent is FCC part 15, for radio frequency devices, and part 18, for industrial, scientific and medical equipment [34]. As an example, in [35] there is a summary of regulations and standards applied to a wide-used distributed control system in industry.

4.4.3. Radio frequency safety regulation issues

Besides, a specific technology also has to obey severe rules about impact of radiation in human health

[36,37]. Therefore, the electromagnetic emissions must be limited: see [38,34].

4.5. Security issues

There is a great concern about wireless implication on security. Wireless is often seen as a threat to communication security due to the broadcast media, which has made eavesdropping and jamming easier. However, we think it is a biased approach to look at security only at this level, i.e., at data link level. It is true that wireless transmission is easier to eavesdrop than wired transmission, but security must be globally treated.

A company must have a global security policy, which includes issues such as stored data protection, resource control access, the appropriate behavior of the employees and, of course, data transmission protection [39,40]. From this point of view, we think that data transmission security should be implemented at network layer because it provides a solution that does not depend on the different company subnetwork technologies. Therefore, either an Ethernet segment or an ISDN link or a wireless link can be secured by using the same security scheme at the network layer. Transmission channel can be secured (at network and upper levels) using strong security methods like IPsec [41] (network layer), SSL [42,43] (transport layer), Kerberos [44] (application layer) and others.

It may be argued that in industrial communication there are a number of transmissions that do not reach network layer. For instance, data sent from a sensor to a PLC (which do not go through network layer) might be eavesdropped if a wireless link is used. Those cases are also covered since most wireless standards use lightweight protocols (like IEEE 802.11 WEP: Wired Equivalent Privacy) to make ‘‘wireless transmission channel as secure as wired’’. It has been proved that this weak protection can be broken [45] with some effort. But, cannot wired transmission also be broken with some effort if data are not further protected by cryptographic means at this level?

4.6. Radio emissions issues

4.6.1. Noise and media effects on communications

Problems like noise, interference, multipath delay and fading effects [46] are specially important in industrial environments, because there are lots of impulsive noise sources, lots of interfering devices, and usual machinery distribution is prone to multipath effects.

Multipath delay is caused by signal reflections in obstacles. Thus, any station receives the original signal plus several echoes of the signal. These echoes may cancel the signal and become mere noise at reception. Thus, the more multipath delay we have the less Signal-to-Noise Ratio (SNR) we get. This phenomenon is especially dangerous for frequencies above 1 GHz ($\lambda = 1/3$ m), where fast fading appears. Fast fading produces quick and large changes in SNR ratio if the receptor moves a distance comparable to signal wavelength.

Transmission techniques try to avoid these handicaps by means of:

- Error detection with CRC, and error recuperation with FEC techniques [47].
- Adaptive equalizers and other pre-demodulation signal processing methods [48].
- Antenna diversity [49].
- Block interleaving to keep away from burst errors and other pre-modulation processes [48].
- Robust digital modulations, such as the Orthogonal Frequency Division Multiplexing (OFDM) [48] used by IEEE 802.11 and HIPERLAN.
- Robust digital multiple access procedures such as spreading spectrum, or hopping sequence [48]. For example, IEEE 802.11 uses Barker spreading codes, a special code that avoids fading [28].
- Fast fading can be minimized using a continuous feedback between stations. For example, a UMTS mobile (UE) sends the calculated SNR ratio to base station (B-node) each few milliseconds. Then B-node calculates the effect of fading and commands UE to keep, reduce or increase its power transmission while B-node proceeds accordingly.

Despite all these corrective measures, channel Bit Error Rate (BER) is usually two orders of magnitude higher than it is in a wired system.

4.6.2. Environmental impact

On the other hand, environmental impact produced by network interfaces could be an important issue. For example, GSM mobiles are forbidden in hospitals and airplanes because they can disturb electronic equipments.

To some extent, this effect cannot be completely avoided. To minimize it, manufacturers must follow regulations about maximum permitted EMF and noise emissions (see Section 4.4). Additionally, machinery and equipment must be properly isolated.

Another alternative to reduce interference from wireless network to other devices is limiting power transmission in stations. But, this approach has two problems: first, SNR ratio in receptors will be reduced, which may lead to smaller data rates as well as to the fact that real-time service may become useless. Second, network range will be reduced. Thus, far away devices may not reach other stations.

Additionally, firms are encouraged to execute network setup by using qualified components and installers services that are in charge to carrying out all type of environmental impact tests to assure compatibility.

4.6.3. Health issues

In the last years, forceful discussions about health issues have started. The aim of the discussions is to find an answer to base station transmitter/antennas for cellular phones, mobile phones, and other types of portable transceivers whether are or are not a risk to human health. It is still an open question. Several studies are in progress (see [37]), like the United Nations International EMF Project [50]. Its mission is ‘‘pooling resources and knowledge concerning health effects of exposure to EMF’’.

4.7. Networks Taxonomy and Technological description

First, some criteria must be chosen to classify networks. In literature, several interdependent parameters are used. Some of them were described in the beginning of this section: cost, range, capacity, etc. (See [22]).

Non-broadcasting networks can be also divided according to their ‘‘historical evolution in market areas and application scope’’, resulting in the following groups:

- Cellular telephony systems.
- Local loop substitutes.
- Trunking systems.
- Indoor wireless communications.
- Wireless LANS.
- Wireless PANS.

Fig. 4 shows the timeline progress of the most important systems explained in the next sections. The

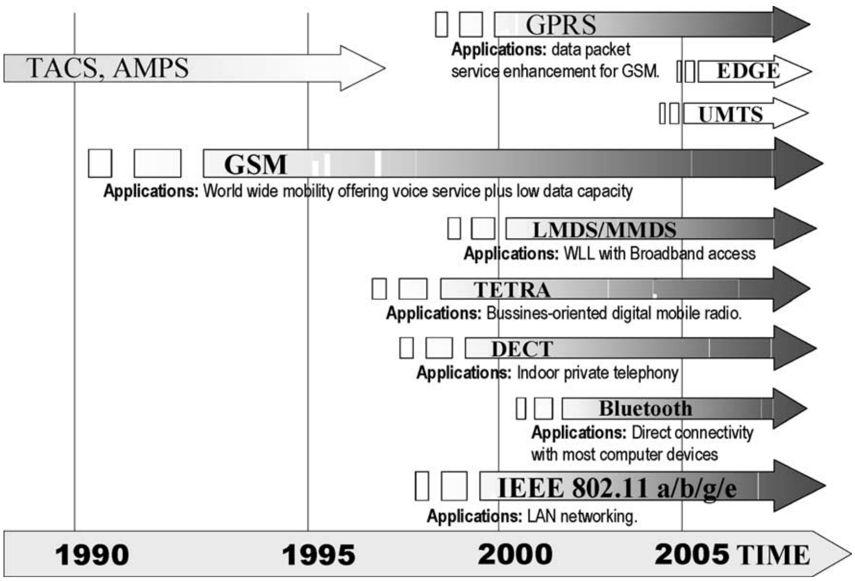

Fig. 4. Commercial service timeline.

beginning of the commercial service is shown, including a brief explanation of the scope of each technology. Future systems, which are indented to be in service in successive years, are also illustrated: EDGE and UMTS.

4.7.1. Historical preview

Modern-age wireless communications begun in the mid-19th century with Maxwell's electromagnetic theory, followed by Hertz's 1880s experiments that demonstrated EMF existence. It was not until 1895 that first commercial services appeared with Marconi's wireless telegraphy (an example of efficient low-cost large-range system versus wired telegraphy or telephony).

During the first decades of 20th century works continued in both theoretical and practical tools (for example, Armstrong's FM or Fersenden's Radio). That led to the development of new commercial services, like voice broadcasting and the like. Finally, in the 1980s (just 100 years after Hertz's experiments) the first cellular systems were developed.

4.7.2. Cellular telephony systems

After an early (and unsuccessful) attempt in Japan to create a cellular network, the first commercial systems were put into service in the west coast of USA in 1983. This system used analog technology, that is, voice and signaling are transmitted over an analog bearer. In this early system, whenever a user crossed the cell boundary with an ongoing call, it was lost since it did not implement communications hand-off yet [51].

Cellular systems use space multiplexing (Space Division Multiple Access, SDMA), i.e., different portions of space (''cells'') use different spectral bands, and the same spectrum bands are re-used in different (non-neighbor) cells. To avoid interferences, reuse of frequencies must be done as far as possible.

First generation of analog cellular systems proliferated during the following years, but a set of problems appeared:

- It was not easy to offer new services (such as data transmission) due to the lack of signaling possibilities.
- Many different non-interoperable standards were in use, like Advanced Mobile Phone Service (AMPS), Total Access Communications Systems (TACS), Nordic Telephone System (NMT), etc.
- Spectrum bands were saturated, so it was necessary to develop new modulation techniques, which use spectrum better, and the allocation of new frequency bands.

Later, second generation systems (2G) appeared. This generation is characterized by using digital communication networks, such as GSM, or hybrid IS-95 (analog/digital) equipments. Third Generation Systems (3G), such as UMTS, are intended to start service in the coming years.

4.7.2.1. GSM. Global System for Mobile Communications (GSM) is a worldwide mobile telephony system. Nowadays, there are GSM networks in operation in over 160 countries, with more than 400 million users, and more than 1000 million users are expected for 2006.

GSM started in 1982, when the *Conférence Européenne des Administrations des Postes et des Télécommnunications* (CEPT) created the *Groupe Spéciale Mobile* (original meaning of GSM) workgroup with the aim of creating a set of standards for the future pan-European cellular network.

One of the keys of GSM success is its evolutionary design. At first, a subset with reduced attributes was developed (*GSM Phase 1*). Specifications were designed to be backwards compatible, with services and functions that began later. Subsequently, GSM Phase 2 and GSM Phase 2+ appeared, each one enhancing the previous ones.

GSM specifications are available in natural language in the ETSI Website [52], but are complex for beginners. For an introductory text to GSM, see [51,53].

It is extensively used all over Europe and the Commonwealth countries and its coverage can be considered almost global. Its associated infrastructure is extremely expensive and it is only deployed by big telcos.

GSM uses both Frequency-Division Multiple Access (FDMA) and Time-Division Multiple Access (TDMA), i.e., full GSM spectrum is multiplexed in frequency bands. These frequency bands are further subdivided in to time-shared channels, where users synchronously access their time-slots. GSM allows voice service and data transmission service at 9.6 Kbps, 4.8 Kbps and 2.4 Kbps. Billing is time-based and fees are steadily moving closer to landline phones.

In GSM, security is provided using the ciphering A5 family protocols [51]. ATEX terminals are available in different companies like PACSCOM [54]. Low rate real-time services can also be provided through its data circuit mode. Spectrum bands are exclusively licensed to operators and EMF compatibility has to be assured.

4.7.2.2. GPRS and EDGE. GSM is a circuit switched technology, based on TDMA multiplexing. It works well for voice-data services because voice-data are transmitted synchronously. Unfortunately, such scheme is not adequate for data transmissions: channels are exclusively assigned to a single user, even though it does not have data to send. This leads to inefficient channel utilization and low data rates.

To solve this problem, General Packet Radio System (GPRS) was developed. In the near future, the new Enhanced Data Rates for GSM Evolution (EDGE) system will improve data capacity even more. For this purpose, it will use new digital modulation techniques. GPRS is a packet switched system that uses free GSM carriers for data transmission. It allows GPRS stations to reach up to 170 Kbps. EDGE will support up to 384 Kbps.

Unlike GSM, GPRS users are charged depending on the amount of data transmitted. At the moment, prices are not competitive compared to wired alternatives.

As a GSM enhancement, GPRS and EDGE terminals provide the same industrial potentials, and their packet mode opens ways to new services.

4.7.2.3. UMTS. The first steps towards UMTS and other 3G systems are found in 1985, when the International Telecommunications Union (ITU) announced its initiative for a Future Public Land Mobile Telecommunications System (FPLMTS). In the ITU 1992 World Administrative Radio Conference (WARC) frequencies in the 2 GHz band where identified for 3G systems. Then, the term International Mobile Communications 2000 (IMT-2000) was adopted for these systems. This name refers both to the expected date of release, and to the frequency they use. The main ITU goal was to create a broadband solution for worldwide coverage, with support for multimedia services. Finally, two of the proposals that were presented for IMT-2000 systems succeeded:

- ETSI UMTS Terrestrial Radio Access Networks (UTRAN)
- CDMA2000, developed by CdmaONE.

In January 1998, ETSI selected Wideband Code Multiple Access (WCDMA) [48] as the air interface for UTRAN. It has two modes of operation: Frequency Division Duplex (FDD) for paired spectrum bands, and Time Division Duplex (TDD) for unpaired bands.

ETSI continued UTRAN standardization until it transferred this work to the international 3rd Generation Partnership Project (3GPP) [55], in the beginning of 1999. UTRAN specifications can be consulted on the ETSI Website [52]. For an introductory reference, see [49].

UMTS is an evolution of GSM architecture over WCDMA, a technique that does not divide spectrum bands in time-slots, but in code-slots. Each user is assigned to an exclusive code (called "spread sequence"), which is used to modulate its data. Since codes are orthogonal, receptors are able to demultiplex single user signals by processing signal again with the same transmission code.

One of the claims of UMTS telcos is that it can reach up to 2 Mbps of capacity. Actually, this is very difficult, since a single mobile must acquire most of "spread sequences" in a cell, with the subsequent limitation of the amount of mobiles in the cell (because total number of codes is restricted).

Being realistic, we can state that the great achievement of UMTS is the increase in the users/bandwidth ratio and a high capacity packet data transmissions, with support for QoS services.

At the moment, the infrastructure is being deployed and tested around Europe, but it is not available to consumers yet.

Summing up, UMTS will offer higher over-the-air security for industrial environments, with provision for QoS data services and multimedia. Therefore, real-time applications become possible. Operation through licensed bands will ensure EMF compatibility with environment. It is likely that ATEX devices will also appear in the market.

4.7.2.4. Industrial applications of cellular networks.

- Alarm systems through short messages: This type of application uses network short message service (SMS). Since alarms are unusual events, service price is affordable. And since there exists global coverage, designed solutions are universal and reach isolated places. They are typically used in surveillance [56].
- Tracking systems, such as fleets monitoring and management, typically using GPS (see Section 4.8.2) [57].
- Pay systems, like Ericsson e-pay solution [58].
- Remote control systems, like irrigation systems [59].
- Telemetry [60].

4.7.3. Local loop substitutes

Local loop deregulation started in 1984 when, by a judicial sentence, Bell was split in order to encourage free competition. Since the late nineties companies are free to compete for the local telephony market in Europe, USA and other countries. However, the enormous investment needed to deploy the network constitutes a barrier to the newcomers.

An available solution comes from wireless systems since they minimize initial investment. The Wireless Local Loop (WLL) business is aimed at non-mobile users who demand broadband Internet access.

4.7.3.1. LMDS and MMDS. Local Multipoint Distribution Service (LMDS) [61] is a broadband access used for voice, data and video-on-demand services. Multichannel Multipoint Distribution Service (MMDS) [61] is considered to be a complementary technology to Digital Subscriber Line (DSL).

IEEE proposed an LMDS standard: IEEE 802.16. Additionally, several LMDS proprietary solutions are being deployed, such as Alcatel DAVIC physical layer specification [62] and Motorola and Nortel Networks DOCSIS [63].

MMDS operates on the 2.5–2.7 GHz range, under licensed bands, providing rates of 1–2 Mbps and covering areas in the order of 30 km.

LMDS achieves up to 500 Mbps in the aggregated uplink, i.e., shared between all users. It operates at frequencies higher than 20 GHz, under licensed bands, with a few kilometer coverage and is intended to be used in densely populated areas requiring large amounts of bandwidth. However, LMDS propagation characteristics are more restrictive: the higher the frequency, the higher the attenuation. The effects of rain and atmospheric absorption are also noticeable and the reflections increase affecting the communications negatively.

The advantage of MMDS over LMDS is that the former operates at lower frequencies, improving propagation behavior and requiring less expensive equipment. MMDS uses OFDM, which is very robust against multipath propagation, but also very sensitive to phase and synchronization errors. In both cases, line of sight between devices and base station is mandatory.

4.7.3.2. Industrial applications of WLL. WLL is typically used in the same industrial areas as the cellular systems (see Section 4.7.2), but with the requirement that stations must be fixed. If the particular application obeys this requisite, WLL offers high capacity and reasonable cost.

4.7.4. Trunking

Trunked systems are those where the number of clients exceeds the amount of connections that can take place at a time. Trunking is based on the unlikelihood that all users want to make use of network at the same time. Public wired telephony systems are a recurrent example of trunking systems. Observe that this notion comprises almost all wireless systems. For instance, using this definition GSM has a trunking structure. Nevertheless, in commercial areas, ‘‘trunking’’ has gradually turned its meaning into ‘‘communications for professionals’’, like policemen, taxi drivers, etc. As such they offer low cost, security, and common needs for these collectives.

4.7.4.1. TETRA. Terrestrial Trunked Radio (TETRA) [64,65] is an open digital trunked radio standard defined by the ETSI [52]. It was originally developed for public safety services, but later it evolved to a world standard. Its goal is to meet the needs of professional mobile radio users. As such, it is fully oriented toward business and industrial requirements, focused on organizational communication and as a management tool, rather than being individuals communication-oriented, such as GSM and the like.

As a standard, it ensures interoperability between vendors. In addition to conventional digital mobile systems, it offers: group communications, Direct Mode Operation (DMO): direct communication between two, or several TETRA terminals without the use of a trunking network infrastructure, "always connected" feature, fast call setup (<300 ms), very high security with strong end-to-end encryption, and authentication of networks and mobiles. Data transmission is offered in two modes: IP packet enabled and a circuit mode data for specialized applications like video surveillance or real-time services.

TETRA–air interface is conceptually similar to GSM. It uses 25 kHz carriers, each divided into four TDMA slots. Voice call uses one slot, and data up to four slots to achieve high data bit rates. Within TETRA both voice and data can be transmitted simultaneously in different time-slots.

There are several frequency bands assigned to TETRA: 380–400 MHz for emergency services, 410–430 MHz reserved to civil authorities, 450–470 MHz planned for future use, and the 806–921 MHz band.

For industrial usage, ATEX certified equipments, like Motorola MTP700 [66] and NIROS Titan family [67], which are available. TETRA also offers high availability through DMO and real-time services.

4.7.4.2. Industrial applications of TETRA. Trunking systems, and TETRA specifically, offer cellular-like applications (see Section 4.7.2). As an advantage over classical cellular systems competitors, TETRA offers low cost plus support to machine-to-machine communications.

4.7.5. Indoor wireless communications

With the progressive advent of wired telephony, companies seek to private communications alternatives, so that they can reduce costs and increase workers productivity. The same reasons cause the introduction of private indoor wireless telephony. Both wired and wireless systems are intensively used and demanded by firms.

4.7.5.1. DECT. Digital European Cordless Telecommunications (DECT) [68,69] is the ETSI standard for private wireless indoor, and the only IMT-2000 family member broadly used nowadays. It achieved a great success in the market.

DECT provides for voice and multimedia traffic, and is able to interwork with other fixed and wireless services, such as ISDN and GSM. It uses a method called Dynamic Channel Selection/Dynamic Channel Allocation (DCS/DCA) that guarantees the best radio channels available to be used. This capability ensures that DECT can co-exist with other DECT applications and with other systems in the same frequency, with high quality, robust and secure communications for end-users. For this reason, it has also attracted industry attention.

DECT operates in the 1880–1900 MHz frequency band, and uses TDMA like GSM. The maximum theoretical throughput rate of multi-bearer DECT is 552 Kbps. Single-bearer throughput is 32 kbps, plus 6.4 kbps for control and signaling.

For industry, DECT confronts reliability and availability problems by means of the DCS/DCA mechanism. It also suits well for real-time applications and multimedia services. Like other professional-oriented technologies, DECT also puts special efforts in confidential data and overall security. ATEX compatible terminals are available from several manufacturers, for instance ANT Telecom [70].

4.7.5.2. Industrial application of DECT. Companies extensively use DECT for voice calls, workers paging (alert), for messaging among different employees and/or managers, and for extending these services in the outdoor surroundings where the system is installed.

4.7.6. Wireless local area networks

New trends in computing devices, such as PDA, last generation mobile phones, and, of course, mass–market laptop usage, have led to an increasing necessity of interfaces that allow users' mobility while being backwards compatible with existing application software.

Considerable price reductions, provision for high data rates, and unlicensed operation have made WLANs a popular choice.

WLANs operate either in infrastructure mode as an extension of a wired LAN, or in ad hoc mode, where network only consists of wireless stations.

4.7.6.1. IEEE 802.11 and HIPERLAN. The most widely used specification for WLANs was developed by the IEEE 802.11 workgroup. IEEE 802.11 [71] specifies a physical and medium access layers by using spread spectrum techniques. A set of different physical layers exists for IEEE 802.11. They are commonly referred by an identification letter. For example, 802.11b, 802.11a, etc.

HIPERLAN [72] is the European alternative to IEEE 802.11. HIPERLAN Type I provides 20 Mbps with either Frequency Shift Keying (FSK) or Gaussian Minimum Shift Keying (GMSK) modulations according to the transmission rate, and HIPERLAN Type II provides up to 54 Mbps, using OFDM. Both of them are at the 5 GHz band.

When selecting one of them to study (and possibly deploy on an industrial environment) IEEE 802.11 has the advantage of a longer maturity. Development kits in the market can be easily found (at least for IEEE 802.11b); whereas, as far as authors know, there is no HIPERLAN equipment vendor. Another advantage of IEEE 802.11 is that it uses spread spectrum techniques, more suitable, a priori, for industrial environments: modulations used by HIPERLAN type I are more sensitive to noise and multipath delay. OFDM modulation employed by HIPERLAN II seems to suit better, because it considerably cuts down problems caused by multipath. Nevertheless, it forces to carefully design the circuitry: non-linear distortion and phase noise must be avoided in order not to loose the orthogonality of the carriers. But, this will probably increase the cost of the product.

Both IEEE 802.11 and HIPERLAN technologies specify the Data Link Layer. IEEE 802.11 uses Logical Link Control (LLC) at this level, which has an ‘‘Unacknowledged-Mode’’ suitable for ‘‘best-effort’’ service, and two other modes: ‘‘Connection-Mode Service’’ and the ‘‘Acknowledged Connectionless Service’’. These other two services may be more interesting for an industrial environment. The Connection-Mode Service provides a connection-oriented service to be used in low-processing capability devices, whose software layers do not implement flow control and reliability mechanisms.

The Acknowledged Connectionless Service provides a scheme to confirm information delivery without previously establishing a logical connection. In an industrial environment, it could be very useful in some contexts: in a network, a server usually connects to several client devices and needs to ensure the reception of the communication. If a connection-oriented service is used, the Logical Link Control software must maintain tables containing the status of each connection, becoming impractical because of the large number of tables that may be required. It is also useful for alarm and emergency control because the acknowledgement of the signal reception is required but the urgency of the signal dissuades from previously establishing a logical connection.

IEEE 802.11 Medium Access Control (MAC) defines, on the one hand, a distributed control access mechanism called Distribution Coordination Function (DCF), and, on the other hand, an optional centralized control mechanism called Point Coordination Function (PCF).

DCF uses a Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) suitable for asynchronous traffic. Stations listen to the medium and if it is idle, they wait a delay time before transmitting. PCF is built on top of DCF and uses a polling scheme to communicate with a coordinator point that controls other devices, according to a round-robin scheme.

To prevent PCF traffic from acquiring all the resources, a time interval called superframe is defined. This interval has a fixed duration and it is divided into two periods: ‘‘contention-free period’’ and ‘‘contention period’’. The former period is used by PCF to poll the devices and does not have a fixed duration because of the variable size of the response frame. The remaining time of the superframe is assigned to DCF traffic. If the medium is busy at the beginning of the superframe, PCF will wait until the medium is idle and the process will restart.

This mechanism is appropriate for time sensitive services but does not guarantee the polling instant in any case since the beginning of PCF is not bounded. Nevertheless, the polling mechanism of PCF is similar to the one employed by many current fieldbusses as Profibus and can be employed together with DCF, which would be used to notify state change messages, and to emulate the behavior of fieldbusses while communication characteristics are further improved. As far as the authors know, there are not commercially available IEEE 802.11 stations with PCF functionality yet.

On the other hand, HIPERLAN is used to create networks with larger radius than the coverage radius of a single station, using multi-hop transport algorithms.

Also, HIPERLAN will support QoS (and real-time) and scheduling of different classes of traffic. IEEE 802.11 supports QoS only through PCF, and the future IEEE 802.11e will also support QoS and real-time by means of DCF. QoS mechanisms allow wireless networks to emulate fieldbus behavior and to support new services aimed at improving productivity of the elements of the production process.

There is also ATEX compliance 802.11 equipments, such as Extronics iWAP 100 [73].

4.7.7. Wireless Personal Area Networks

Overlapping the aforementioned ones, Wireless Personal Area Networks (WPAN) technologies provide a shorter range and are intended for substitution of wires in simpler devices. In addition, they allow to create either LAN or ad hoc networks. These are IEEE 802.15 [74], Bluetooth [75] and IrDA [76].

4.7.7.1. Bluetooth, IEEE 802.15 and IrDA. Bluetooth and IEEE 802.15 operate in the 2.4 GHz band, with 10 m (Bluetooth class II) to 100 meters (Bluetooth class I) range and a shared bit rate of 1 Mbps. IrDa utilizes infrared, so, devices need line of sight. The last issued standards provide up to 16 Mbps: IrDa very fast IR (VFIR) (see [77]).

Bluetooth uses frequency hopping spread spectrum, with a common bandwidth of 80 MHz, divided into 79 channels. Bluetooth is also a TDMA system. In each slot, stations re-tune to a new frequency channel, which is selected by means of a pseudo-random sequence. Hop rate is 1600 hops per second, i.e., timeslot is 0.625 ms.

The basic unit of networking in Bluetooth is called piconet. It is made up of one master and up to seven slaves. Of course, all devices in a piconet share the same hopping sequence, which is calculated as a function of the master clock and identity. A device may exist in more than one piconet at a time, and may operate either as a master or as a slave in each one. Therefore, the networks may overlap and form "scatternets".

The master/slave communication is based on a poll scheme. Slaves can only transmit in response to a master. So, collisions appear only between different piconets, when both select the same frequency channel. Nevertheless, the likelihood of collision is small (around 10^{-5} if the number of piconets is small) although probability tends to increase linearly as the number of piconets also increases [78].

Bluetooth provides two types of links between a master and a slave: Synchronous Connection Oriented (SCO) and Asynchronous Connectionless (ACL). SCO packets are never re-transmitted. In an ACL link, re-transmissions are permitted.

These characteristics let Bluetooth work on an industrial environment, providing soft real-time services. However, it shows some drawbacks that generate doubts about its potential in industry: The number of devices supported at a time is small and coverage range is also small.

Bluetooth specifications define a series of usage models, as, for instance, file transfer or LAN access. At the moment, there is no usage model for industrial environments.

In addition to point-to-point links, IrDa supports LAN networking, defining three operation modes: Access Point Mode, a device managing access to a wired LAN. Peer-to-peer mode, one or more devices forming an ad hoc LAN. Hosted-mode, two or more devices connecting each other and a host, which provides access to a wired LAN.

Bluetooth faces up real-time industrial requirements if it is used in a single piconet, and soft real-time if "scatternets" are employed. They offer easy integration with existing serial busses, through its communication profiles.

4.8. Complementary technologies

4.8.1. RF Tags systems

These are passive devices that in presence of an RF Tag scanner transmit a short sequence of pre-defined bits. It is intended as an identification method and is broadly used for stock management, in stores or as an anti-theft system.

RFID [19] can be included in a more general class of systems, called Automatic Identification and Data Capture (AIDC), which is the identification and/or direct collection of data into a microprocessor controlled device, such as a computer system or a Programmable Logic Controller, without the use of a keyboard. Approaches using barcodes or smart card technologies may be also included here.

AIDC is very popular in many service industries, purchasing and distribution logistics, industry, man-

Table 2
Summary of features of some wireless technologies

Technology	Band (GHz)	Maximum bitrate (Mbps)	Physical layer	MAC	Approximate range
GSM, GPRS	0.9, 1.8	0.17	GMSK	TDMA/TDD	30 km
TETRA	0.4	0.36	DQPSK	TDMA	50 km
MMDS	2.5–2.7	27 (uplink)	OFDM/QPSK	DOCSIS	30 km
LMDS	27–31	500 (uplink)	PSK/QAM	DAMA-TDMA	4 km
IEEE 802.11b	2.4	11 (DS), 2 (FH)	SS/DS-DQPSK	CSMA/CA	200 m
IEEE 802.11a	5	54	OFDM	CSMA/CA	200 m
HIPERLAN I	5	20	GMSK	EY-NPMA	Extensible
HIPERLAN II	5	54	OFDM	TDMA/TDD	Extensible
Bluetooth	2.4	1	SS/FH	TDMA/TDD	10/100 m
IrDA	Infrared	16	PPM	IrLAP/IrLAN	1 m
DECT	1.8–1.9	2	GFSK	TDMA/TDD	50 m

ufacturing companies and material flow systems. Automatic Identification procedures exist to provide information about people, animals, goods and products in transit.

The omnipresent barcode labels that triggered a revolution in identification systems some time ago are inadequate in an increasing number of cases. Barcodes may be extremely cheap, but their low storage capacity and the fact that they cannot be reprogrammed are reducing their possibilities. The solution would be the storage of data in a silicon chip.

The most common form of electronic data-carrying device in use is the smart card based upon a contact field (telephone smart card, bank cards). However, the mechanical contact used in the smart card is often impractical. A contactless transfer of data between the data-carrying device and its reader is far more flexible. In the ideal case, the power required to operate the electronic data-carrying device would also be transferred from the reader using wireless technology.

A basic RFID system consists of an antenna, a transmitter/receiver stage and a transponder, also called RF Tag. The tag reacts to an external transmitter stimulus and sends back the information that it electronically stores.

They operate at low frequencies (30–500 kHz). These systems usually are passive (no battery), light, cheap and have a virtually unlimited operational life. However, their physical range is limited (2–5 m), their storage capacity is low, the loaded information cannot be modified, and their data rate is low. There are also active RF Tags (they incorporate a battery), which are read/written devices, with considerable storage capacity. They operate at high frequencies (850–950 MHz and 2.4–2.5 GHz). Their range is wider (up to 30 m) and their data rates are higher. But, consequently, cost is also higher. Communication protocols supported by them are usually proprietary and cannot be easily modified.

Some ongoing standardization projects for these technologies are [79,80]. As RFID may be used in a hazardous environment, ATEX compliant devices can be acquired [81].

4.8.2. Positioning systems

Currently, two satellite systems are in existence to provide a global location service; these are the United States Global Positioning Service (GPS) and the Russian GLONASS system, both military but made available to civil users. Besides, European Union is working on a full civilian system: GALILEO [82], scheduled for operational use in 2008.

All these systems offer a way to determine the absolute position on Earth with an error of a few meters. Thus, these systems are ideal for many tracking applications. From them, only Galileo will also operate in indoor environments.

5. Applications of wireless systems in industry

Once known the technical details of several wireless solutions (Section 5), the next step is matching them with real industrial environments. Each single case needs an individual study to properly reach the correct solutions. Nevertheless, the following general conclusions regarding advantages of wireless in industry can be inferred from Section 5:

- Adopting wireless as field communication network solves physical barrier problems inherent in wiring, decreases installation costs, improves flexibility when reconfiguring systems, and speeds up the deployment of the network.
- It allows to minimize incompatibility between existing technologies (Section 3) by providing standardized MAC protocols. Adopting a wireless technology implies adopting a standard, with its associated advantages. Thus, it is easier the integration with upper levels of the system.
- Real-time services are crucial to industrial automation. Most of wireless network technologies provide some type of real-time services [83,84] (see Section 4), offering, to some extent, a solution for the requirement of determinism. Despite they all suffer from a degree of uncertainty, there still exists enough flexibility to implement soft real-time mechanisms. Koulamas et al. [85] discuss the achievement degree of real-time requirements of Profibus DP by UMTS, IEEE 802.11 and HIPERLAN, showing that at least IEEE 802.11 and HIPERLAN are suitable to implement a wireless system extension.
- Wireless network bandwidth is steadily increasing (see Table 2 and Fig. 4) so new multimedia services become feasible and system performance can also be improved.
- New scenarios, which add value to production processes, arise when communication among mobile elements is allowed. For instance, workers provided with multimedia terminals are able to gain continuous access to control and information systems from any location in a factory and gain access to any network resource all the time, e.g., downloading of planes and reports from a database.

These and other exposed reasons show that wireless has a considerable potential as industrial communication infrastructure.

Of course, deploying these technologies implies solving new problems. One of the basic difficulties to face is the way of co-existence of wired and wireless technologies. On this topic, a number of approaches have been proposed [86,87], such as the interconnection of all devices to an isolated wireless network, or use of repeaters, bridges or gateways, each of them with their particularities. It must be ensured that, in spite of delays generated by interconnection nodes, temporal requirements are satisfied and performance is maintained. It must also be taken into account the capability of adding wireless interfaces to devices.

Despite these and other issues regarding migration and co-existence of technologies, the fundamental problems related to the deployment of wireless in industry are interference and multipath propagation. Some research carried out [88,89] is promising regarding the performance achieved in these environments.

The area extension in which the system will be deployed also determines the selection. Cellular communication and systems, such as GSM, GPRS or UMTS and trunking, may be appropriated when the area is not bounded since, despite higher operation cost (time or data billing), there is no installation cost. However, WLANs, WPANs and indoor wireless suit better for bounded areas where installation may be assumed by a company.

In the search for integration of wireless technologies with classic industrial networks it must be also mentioned the R-Fieldbus [90] European initiative. It contributes to the development of an architecture for a wireless fieldbus which would integrate current industrial networks with emerging wireless technologies. Other approaches have been [91] and the standard ANSI/EIA 709.1 [92].

Providing a global rule to select a standard in any case makes no sense. Instead, some specific approaches to the problem of matching technologies and environments are shown in next section.

5.1. Application scenarios

Industrial activities may be classified in two very general business processes: Management and production. Design, engineering, purchasing, production management and supply chain management may be included within management. Manufacturing, physical distribution and plant and field work in general may be included within production. Management processes exist in all type of companies, i.e., a manufacturing company will have a management level on top of the other business levels.

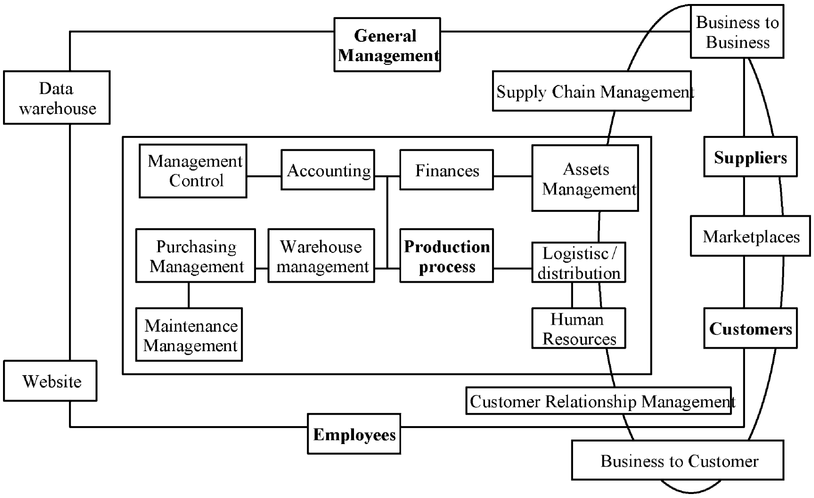

Fig. 5. Typical workflows.

Fig. 5 shows a general schema of an industry that has to address the implementation of an ERP, a CRM, to improve its B2B, etc. Every ‘‘box’’ generates output data and receives input data from the other ‘‘boxes’’, i.e., there is a relationship between entities in terms of input/output of data streams.

Data streams must be obtained through a telecommunications infrastructure, evaluating the possibilities and benefits of using wireless as the underlying networking infrastructure. At this point, it should be clear that the selection of a particular wireless technology is not a straightforward task.

5.1.1. Examples of management processes

Management processes get a crucial support from ERP, CRM systems and other office-oriented applications. Therefore, wireless is to be used in an office environment. Which is precisely the environment these technologies have been mainly designed for and widely tested. Their performance has proven to be very satisfactory.

WLAN (IEEE 802.11) is here the usual choice as the wireless communication infrastructure. Its data rate (up to 54 Mbps) supports the high-volume data exchange requirement for these business management applications, showing similar performance to that of a wired Ethernet network. When the infrastructure is started from scratch a considerable cutting down of installation cost is achieved. But, probably, the main advantage is the flexibility provided when an existing network has to be extended. Running cables is time-consuming, expensive and may require construction. Using wireless results in a rapid deployment of the new network segments. Adding a new network segment is just done by connecting an access point to the wired network, and adding a new user is only a matter of authorization. Finally, network can be brought to previously unreachable areas, as leisure areas, or specific areas, according to necessities.

Bluetooth may be used for substitution of wires in office devices or as a means of interchanging data among different devices (a PDA and a computer). Although these uses may be seen as minor or even frivolous applications, they can result in a great improvement of comfort and working conditions, and this should conceivably lead to an improvement of productivity.

DECT has long been used in offices and its advantages are clear. But it may also be used together with a Voice over IP (VoIP) [93,94] application for the enterprise voice communications which provides two benefits: first, it may be the beginning of the integration of enterprise systems (trends in communication are the integration of the heterogeneous services on IP networks); second, saving costs [95] (companies claim up to 90% of telephony costs, especially for long-distance calls). IEEE 802.11 can also be used as the infrastructure for mobile VoIP communication. Indeed, it is expected to be the largest market for VoIP by 2006 [96].

All these technologies work in unlicensed bands. Their common features are: flexibility, low-cost and high reliability in this environment.

As an example of the industrial trends, there is an increasing number of software products for ERP and CRM from leading providers as Oracle, SAP or Siebel, that take into account wireless technologies as well as its requirements and constraints and how to interface to them [97–102]. The main technologies are IEEE 802.11, Bluetooth and GSM/GPRS.

Reference [103] presents the integration of an existing SAP ERP and a radio frequency system for a logistics enterprise to develop a fully automated end-to-end supply chain at its warehousing facilities. Their benefits are: improved stock accuracy, enhanced scheduling, reduced manual picking and increased throughput. Another example is a wireless study from IBM [104] where it is estimated up to 26% productivity savings.

5.1.2. Examples of production processes

There are a lot of promising examples that illustrate the penetration of radio frequency equipment in the production process.

Reference [105] demonstrates that there are commercial products and systems available for a SCADA with radio-frequency. Also, reference [106] shows the use of a PDA, connected to a PLC using IEEE 802.11b, for monitoring and controlling a process.

In references [107,108], we find a variety of wireless instrumentation and equipment, together with industrial requirements, that comply the appropriate standards to operate in an industrial plant.

Tetra has been successfully used in the Hamburg Harbor [109], where it offers voice and data service to 1000 users. It will also be used to support an Automatic Vehicle Location service for tracking and locating containers. But the paradigm in this case is probably the Schneider's Global Scheduling System (GSS), which is based on Qualcomm's OmniTracks System [110]. Even though it involved an investment of US$ 30 million, its success led to the adoption of this type of systems by more than 1000 fleet trucking companies. The system has evolved from a truck tracking system to a comprehensive logistics and management system, integrating all business operations: from customer service and relationship, truck fleet maintenance, and employee comfort and productivity. There are two different reasons for the rapid adoption of wireless technology by the trucking sector: technologically, it is the only feasible technology and, economically, it provides a clear and quick return of investment.

5.1.2.1. New application scenario: a shipyard. This section shows an example of how systems previously described help to introduce new application fields in industry. As an example, the case of Izar shipyard will be discussed. Izar is the main military and civil shipbuilder in Spain [111] and the Polytechnic University of Cartagena collaborates with the process of automating its key tasks of the repair line. The project to apply wireless technologies for the improvement of the production process of a shipyard is included in the activity of the IZAR-Carenas Chair.

The working place comprises a considerably large extension (650 m × 155 m), which is plenty of metallic mobile elements, where it is impossible to construct and very costly to install a wired system, except for the outer perimeter of the facilities.

The repair line is in charge of tuning and fixing ships. A critical issue is the unpredictable job arrival. It generates a need for constant dialogue among all company levels: from management to production engineers, and from the latter to workmen, suppliers, warehouses, etc. The main goal of the repair line is that the operators work on demand. Therefore, the workflow should change weekly, even daily. It is not possible to properly foresee the actual load of work for a given week. In addition, materials and human resources are scarce and should not be wasted.

One of the main problems arise on a daily basis: there are more than 180 mobile workers. No computer application is used to feedback on-line to the production manager (for example finished job, extra needs, run out of materials, etc.) and readapt and reorganize the production process in real-time. Due to the constrains inherent to this industrial environment, the only way to overcome these problems is to develop a custom tool to make every employee work in a collaborative manner, i.e., integrating completely the employee into the production process. This type of tool and its corresponding devices might be developed but relies on a networking infrastructure that does not exist. The only way of achieving this goal is by means of wireless technologies. Research effort is focused on analyzing and evaluating the suitable technologies in this hazardous and complex industrial environment, planning the infrastructure and deploying it in the working place. According to internal company reports, repairing time may be reduced up to 20% if any employee were permanently connected.

6. Conclusions

Wireless networking offers benefits and new functions, but also has many drawbacks that make it difficult to select between a wired or a wireless solution. Also, selecting a specific wireless technology is a delicate task, depends on many parameters (see Section 4) and requires a deep knowledge of both technology and its potential. In this paper it is shown that there are technologies that may face industrial requisites: high availability, QoS, real-time, interference, immunity, etc.

Wireless solves physical barrier problems inherent in wiring, decreases installation costs, improves flexibility when reconfiguring systems and speeds up the deployment of the network. In addition, new scenarios, which add value to production processes, arise when communication among mobile elements is allowed.

Future work includes a performance evaluation of IEEE 802.11 standard in a shipyard and studying the integration of wireless sensors networks both in the shipyard and as a location system for ecological containers. Wireless sensor network is a novel concept to which a great research effort is devoted at the moment.

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