# The Three Generations of Field-Level Networks—Evolution and Compatibility Issues

Thilo Sauter, *Senior Member, IEEE*

***Abstract*—Field-level networks have been one of the keys to modern automation systems. Be it in factory, process, or building automation, networks allow for horizontal and vertical integration of distributed devices and functions. This paper reviews the evolution of field-level networks comprising fieldbus systems, industrial Ethernet, and recent industrial wireless networks. The main focus is on demonstrating the continuity in the development of the three generations that ensured backward compatibility at the expense of radical innovation. Given the wide set of modern communication technologies, this paper then discusses how architectures for future automation networks might look. Particular emphasis is put on hybrid architectures for combined wired/wireless networks. A generic concept for integration of multiple wireless segments will be presented that supports seamless roaming for mobile nodes in industrial environment.**

***Index Terms*—Automation networks, fieldbus systems, hybrid networks, industrial Ethernet, wireless networks.**

## I. What Are Field-Level Networks?

FIELD-LEVEL communication systems have been an essential part of automation for a quarter of a century now. More than that, they have made automation what it is today. Since the very beginning, these networks have become known as "fieldbus systems," a term originally referring to the process field in, e.g., chemical plants [1]. Apart from this ethymological detail, the term is considerably ill defined. The "definition" that is given in the International Electrotechnical Commission (IEC) 61158 fieldbus standard is more of a programmatic declaration or a least common multiple compromise than a concise formulation [2]: "A fieldbus is a digital, serial, multidrop, data bus for communication with industrial control and instrumentation devices such as—but not limited to—transducers, actuators and local controllers." In the original mission statement of the IEC work, it was stated that "the Field Bus will be a serial digital communication standard which can replace present signalling techniques such as 4–20 mA... so that more information can flow in both directions between intelligent field devices and the higher level control systems over shared communication medium..." [3].

Manuscript received January 8, 2009; revised April 22, 2009, October 12, 2009, and April 30, 2010; accepted June 17, 2010. Date of publication August 3, 2010; date of current version October 13, 2010. This work was supported in part by the European Regional Development Fund and in part by the Province of Lower Austria.

The author is with the Institute for Integrated Sensor Systems, Austrian Academy of Sciences, 2700 Wiener Neustadt, Austria, and also with the Institute of Computer Technology, Vienna University of Technology, 1040 Vienna, Austria (e-mail: thilo.sauter@oeaw.ac.at).

Digital Object Identifier 10.1109/TIE.2010.2062473

An essential driving force at the beginning of the fieldbus development was the intention to replace the starlike point-to-point connections between the process control computers and the sensors or actuators (the field devices) with a single serial bus system. Nevertheless, the network concept provided many more benefits, above all increased flexibility and modularity of installations, or the facilitation of system configuration, commissioning, and maintenance [4]. A forward-looking aspect was the possibility to create real distributed systems also from an application perspective. As the initial conditions were similar in many application fields, it is no wonder that fieldbus systems emerged and are employed in diverse automation domains ranging from the aforementioned process and factory areas to building and home automation, machine building, automotive and railway applications, as well as avionics. For the context of this paper, however, we will focus on process, factory, and building automation because, in these fields, continuity and compatibility are most challenging.

Originally, field-level networks were specifically developed for automation purposes, and therefore, they were very different from the well-known computer networks, particularly with respect to data and traffic characteristics. Typical for LANs were (and still are) high data rates and large amounts of data in large packets. Timeliness is not a primary concern, and real-time behavior is not required. Field-level networks, by contrast, used to have low data rates. Since they transport mainly process data, the size of the data packets is small, and real-time capabilities are crucial.

In recent years, however, the communication technology basis for field-level networks has changed, and networks originally developed for the office information technology (IT) world (such as Ethernet and wireless solutions) are penetrating the lowest automation level. The boundaries between the networks are becoming blurred, and today, it is much more appropriate to define a field-level network from an application viewpoint just as a network used in automation, irrespective of data rates, protocols, or real-time requirements. Nevertheless, an essential difference between IT and automation is that installations in the latter domain have much longer lifetimes (ten years and more compared with typically three for IT systems). Therefore, as field-level communication technologies progress, backward compatibility with existing solutions plays an important role. While this is obvious from an end user's viewpoint, it is not easy to achieve in practice and sets limitations to the range of possible communication architectures.

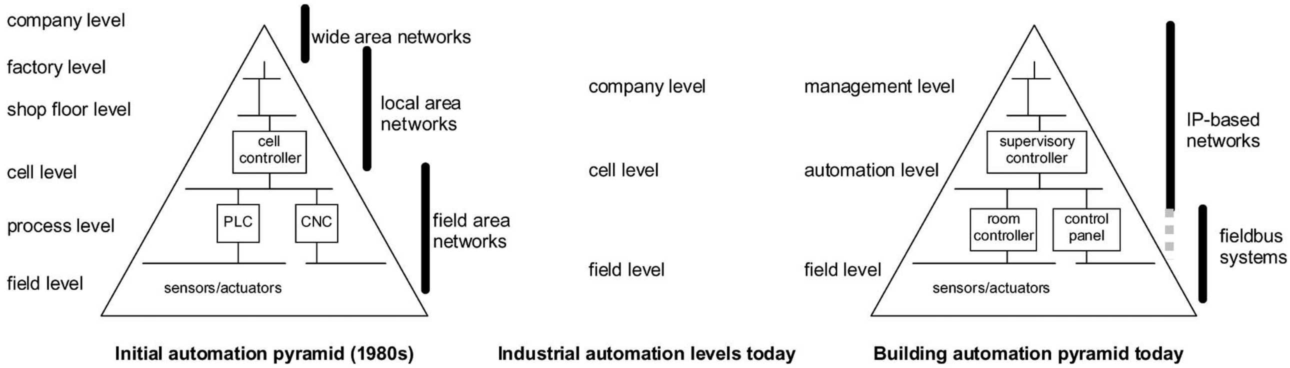


Fig. 1. Automation hierarchy in process/factory automation and building automation, together with associated network structures.

The goal of this survey paper is to give a comprehensive overview of how field-level networks evolved and what was done to make this evolution continuous. Although individual technologies were meant to be (or advertised as) radical innovations, the overall evolution went very smoothly. Section II deals with the development of the classical fieldbus systems, and Section III addresses the next step, i.e., the introduction of industrial Ethernet. Section IV discusses the challenges of wireless networks in automation, whereas Section V is devoted to their combination with wired systems. Section VI presents some related research, and Section VII finally attempts to give an outlook to the future.

## II. First Generation—Fieldbus Systems

Although the term "fieldbus" appeared only about 25 years ago, the basic idea of field-level networks is much older, and the actual roots of modern fieldbus technology are diverse [1]. Both classical electrical engineering and computer science have contributed their share to the evolution. One foundation of automation data transfer has to be seen in the classic telex networks and also in data transmission standards for telephone lines. Large distances called for serial data transmission, and many of these comparatively early standards still exist, such as V.21 (data transmission over telephone lines) and X.21 (data transmission over special data lines). Various protocols were defined, mostly rather simple, because of the limited computing power of the devices available at that time. With improved microprocessors, telephone systems gradually changed from analog to digital. This opened the possibility to transfer large amounts of data from one point to another. Together with an improved physical layer, the first really powerful data transmission protocols were defined, such as X.25 or SS7.

In parallel to this telecommunications development, a need for distributed data acquisition arose in the instrumentation and measurement field. In large-scale experimental setups, mostly in high energy physics, precise coordination of measurement and control tasks was needed. Therefore, standards such as the Computer Automated Measurement and Control (in high energy physics) and the General Purpose Interface Bus (GPIB or IEEE 488) were developed. To account for the limited data processing speed and stringent synchronization requirements, these bus systems had parallel data and control lines, much in the way parallel printer interfaces worked, which also appeared around this time. Later, the serial point-to-point connections of computer peripherals were extended to support longer distances and, finally, also multidrop arrangements. The capability of having a bus structure with more than just two connections together with increased noise immunity due to differential signal coding eventually made RS-485 a cornerstone of fieldbus technology up to the present day.

### A. Evolution of Fieldbuses

The introduction of field-level networks for automation purposes is closely linked with attempts to make data available across all functional levels of a company. A result of these ideas was the so-called automation pyramid (see Fig. 1), a hierarchical multilevel network model first defined within the scope of computer integrated manufacturing (CIM) to cope with the anticipated complexity of data in a horizontally and vertically integrated communication environment. The original application target in the 1980s was factory and process automation. Numbers vary, but typically, this model comprised up to five levels [5]. While networks for the upper levels already existed by the time the pyramid was defined, the field level was still governed by point-to-point connections. Fieldbus systems were therefore also developed with the aim of finally bridging this gap. The actual integration of field-level networks into the rest of the hierarchy was considered in early standardization [3]; for most of the proprietary developments, however, it was never the primary intention.

In building automation, the situation is slightly different. The need for automation solutions became apparent much later. Hence, the development of field-level communication systems started later, which is why there never was such an overwhelming variety of fieldbus systems. As a second consequence, the automation hierarchy in building automation always comprised only three levels [6]—what took years of evolution in process and factory automation has been there since the beginning.

From a technological viewpoint, the actual evolution of the fieldbus systems (its timeline is shown in Fig. 2) was heavily influenced by the development of computer networks, the key contribution undoubtedly being the International Organization for Standardization (ISO)/Open Systems Interconnection (OSI) model. This reference model was (and still is) the starting point for the development of many complex communication protocols. The first application of the OSI model to the domain of

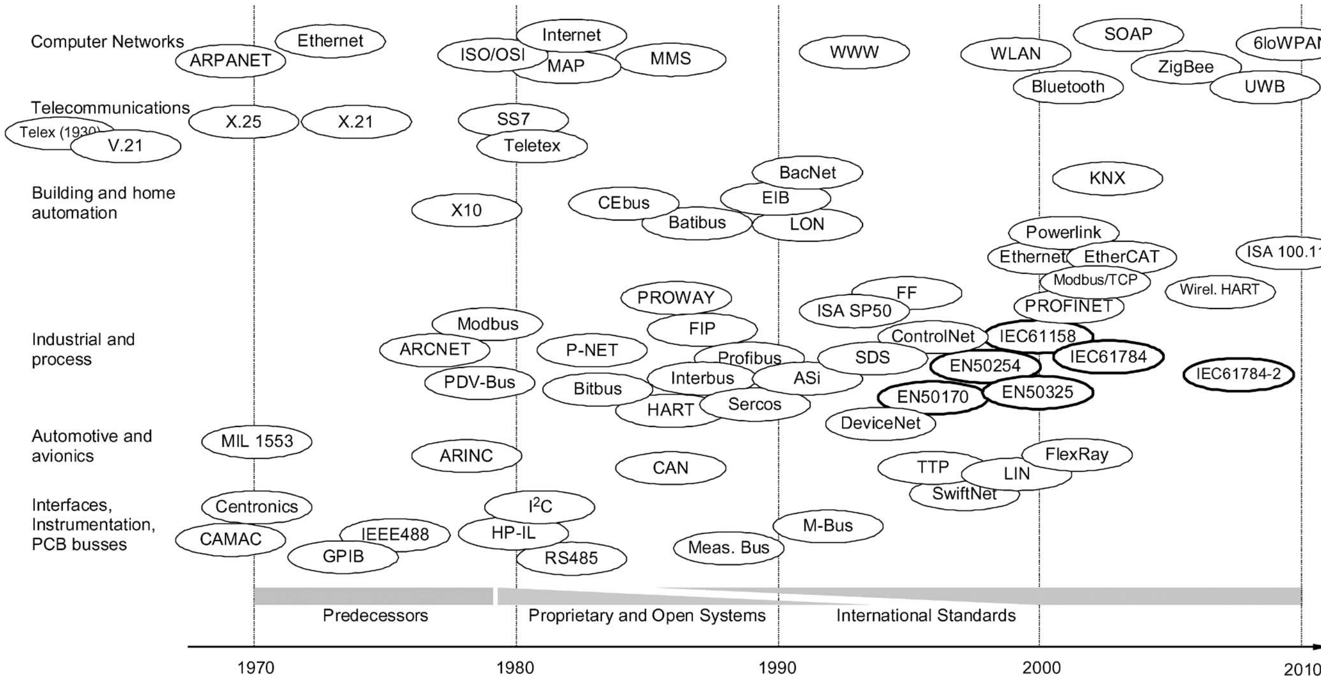


Fig. 2. Selection of important fieldbus systems and enabling technologies.

automation was the definition of the Manufacturing Automation Protocol (MAP) in the wake of the CIM idea [7]. MAP was intended to be a framework for the comprehensive control of industrial processes, and the result of the definition was not only a powerful and flexible protocol but also a too complex protocol that did not have the intended success [8]. Consequently, the protocol stack was dramatically reduced in size and complexity, and this "Mini-MAP" standard, subsequently, was a starting point for many fieldbus definitions. Similarly successful was the Manufacturing Message Specification. It defined the cooperation of automation components by means of abstract objects and services and became a role model for many field-level networks.

Independent of this development in computer science, the progress in microelectronics brought forward many different integrated controllers, and new interfaces were needed to interconnect the integrated circuits in an efficient and cheap way. Consequently, electrical engineers—without the knowledge of the ISO/OSI model or similar architectures—defined simple buses such as the $I^2C$. Being interfaces rather than full-fledged bus systems, they have very simple protocols, but they were (and still are) widely used in electronic systems.

Even before the "invention" of board-level buses, the demand for a reduction of cabling weight in avionics and space technology had led to the development of the Military Standard 1553 bus, which can be regarded as the first "real" fieldbus. Released in 1970, it showed many characteristic properties of modern fieldbus systems: serial transmission of control and data information over the same line, master–slave structure, possibility to cover longer distances, and integrated controllers. Later on, similar thoughts (reduction of cabling weight and costs) resulted in the development of several bus systems not only in the automotive industry but also in the automation area. A characteristic property of these fieldbuses is that they were defined in the spirit of classical interfaces, with a focus on the lower two protocol layers, and no or nearly no application-layer definitions. The controller area network (CAN) is a classical example for this type of fieldbus. Sometimes, higher layer definitions were added later to make the system applicable to other areas, too.

Since the mid-1980s, when automation made a great leap forward with power line carriers and more intelligent sensors and actuators, a sort of gold rush has set in. At this time, many fieldbus systems were born, which are tailored to different application fields, and nearly every company in the automation business created their own bus. How diverse these approaches are can be seen by a look at the large variety of medium-access mechanisms shown in Fig. 3 for fieldbus systems that still have a significant market share. To cope with the real-time requirements, engineers were particularly inventive with respect to solving the dilemma of concurrent access to shared resources such as communication channels. Medium-access control (MAC) mechanisms are, however, only one part of a fieldbus protocol. Other aspects are communication objects and communication relations, the way data are handled on higher layers, advanced functionalities such as network management, and, more generally, the way the exchange of the two essential data classes—process and management data—is being organized. All these aspects left enough degrees of freedom for the development of innovative solutions that are optimized for particular application scenarios.

### B. Fieldbus Standardization

Most of the proprietary concepts never had a real future and quickly disappeared, either completely or in small niches, because the number of produced nodes could never justify the development and maintenance costs. After a few years

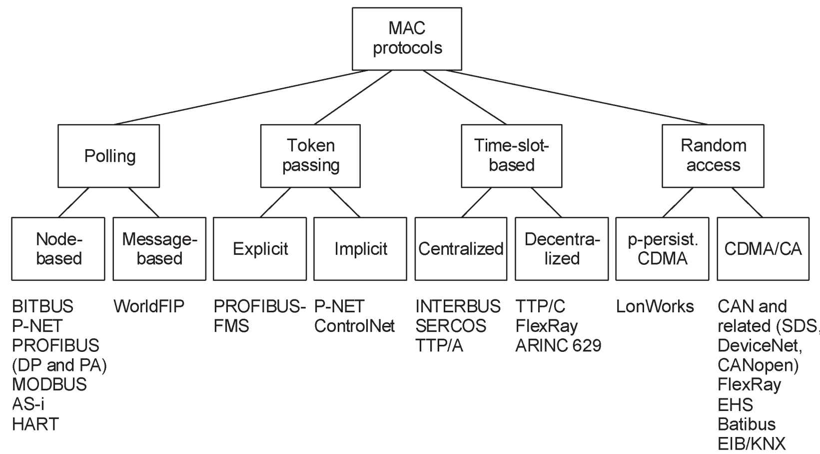


Fig. 3. Diversity of medium-access mechanisms demonstrating the large variety of fieldbus systems.

of struggle and confusion also on the user's side, it became apparent that only "open" systems could survive and gain a substantial market share. User organizations were founded to carry on the definition and promotion of the fieldbus systems that are independent of individual companies. A logical step after the publication of the definitions was to raise them into the rank of standards. The idea behind standardization was not only to make the definitions vendor independent but also to secure customer trust in the new technology and, thus, secure the market position. It was this idea of open systems that finally paved the way for the breakthrough of the fieldbus concept. To further increase interoperability between different device vendors, so-called profiles (or companion standards, user layer, or interworking standards) were developed that defined minimal data sets for specific application fields, as well as data syntax and semantics beyond the pure OSI model [1], [4].

The final step for broad market acceptance was international standardization. The need for such a standard had been recognized by the IEC quite early, when the first fieldbus developments started. In 1985, the technical subcommittee SC65C started the fieldbus project, which had the ambitious objective of creating one single universally accepted fieldbus standard for factory and process automation based on—by that time the most promising—two approaches, namely, PROcess FIeld BUS (PROFIBUS) and Factory Instrumentation Protocol (FIP) [8], [12]. Against the backdrop of a quickly evolving market, however, idealism had no chance. Enormous investment costs for already existing and proven systems, economical interests of different nations and companies, but also different constraints and demands prevented the aim of standardization to define the one and only fieldbus. Consequently, after 14 years of fierce technical and increasingly political struggles, the original goal was abandoned with the multiprotocol standards IEC 61158 and IEC 61784 [9]. Other application domains developed and standardized different networks, so that the fieldbus world today consists of a colorful collection of well-established approaches.

In the field of building automation, standardization went comparatively smoothly, although the responsibility for international standardization was not as clear as in the case of process automation, and different committees in IEC and ISO dealt with the task. Still, as stated before, there were not so many independent developments, and many of them were defined by industry consortia right from the beginning. This eliminated or at least reduced competition between device vendors already at an early stage and, to a large extent, ensured interoperability as a main criterion for user acceptance. Today, the main open standards are LonWorks, European Installation Bus/Konnex (EIB/KNX), and BACnet [6]. They are relatively complementary and frequently coexist on different levels of the automation hierarchy in complex building automation systems.

## III. Industrial Ethernet

It has been argued in Section I that one of the big problems in field-level networking was the fact that the different levels in the automation pyramid are controlled by mutually largely incompatible networking concepts: fieldbus systems and mostly Ethernet- and IP-based LANs. These integration problems were (and still are) one of the main arguments used to promote Ethernet on the field level. Using the same network technology as in the office world, both automation and office domain can, in principle, be connected to one single enterprise network. Ethernet is of course no cure-all; it is not much more than a network basis for data exchange. As such, it is an important step toward horizontal integration, but this alone is not sufficient. More relevant for integration, notably in the vertical direction, is the wide usage of the IP suite in industrial Ethernet approaches. It is this non-Ethernet-specific property that actually alleviates data exchange across the levels of the automation pyramid and makes the pyramid structure flatter and easier to handle.

Ethernet had attracted the interest of researchers soon after its invention. At that time, however, the obvious lack of real-time capabilities prevented the wide usage in industry. A number of methods have been proposed to cope with the problem, such as traffic smoothing [10]. However, the great leap forward came with the development of switching and full-duplex technology [11]. As a consequence, Ethernet has now also become interesting for industry, and in fact, the industrial Ethernet movement is largely driven by device vendors [12], even if also switched Ethernet per se is not fully deterministic and leaves room for further research [13].

In the beginning, all research work carefully avoided any concepts violating the Ethernet standard. Compatibility and

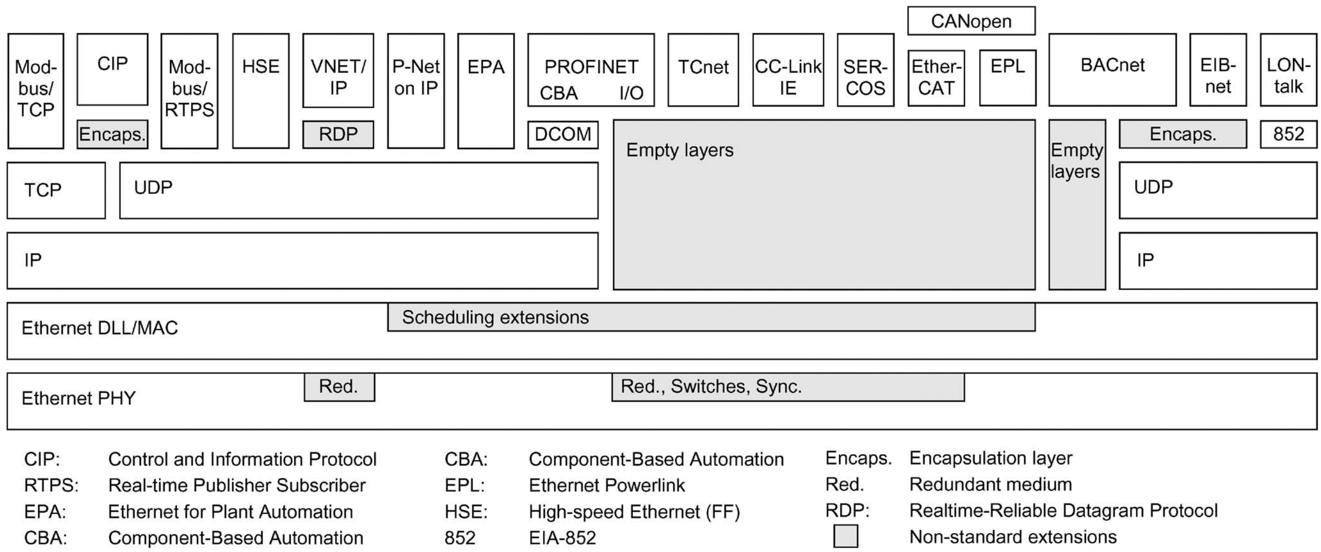


Fig. 4. Protocol architecture of selected real-time Ethernet solutions proposed for IEC 61784-2, as well as Ethernet-based building automation networks.

conformity was the prime goal. Industrial solutions that began to appear, however, were not always so restrictive. If one takes a closer look at industrial Ethernet as it is today, it turns out that the appraised uniqueness is more wishful thinking than reality. In fact, not even the use of standard Ethernet is really a common denominator, and above the data-link layer, the approaches are completely different. Some use standard Transmission Control Protocol (TCP)/User Diagram Protocol (UDP)/IP mechanisms for transmitting data, which maybe enhanced by additional software layers to support both real- and nonreal-time communication, whereas others use dedicated communication stacks that bypass the entire IP suite. Some employ well-known fieldbus application protocols to maintain some backward compatibility with the fieldbus world, and some are entirely new developments. Fig. 4 sketches the various appearances of the protocol stack.

Manifold differences are also possible on the physical and medium-access layers. Some approaches foresee redundant media (Vnet/IP, TCnet), PROFINET IO uses dedicated built-in switches to reduce the data transmission jitter [14], and EtherCAT and SERCOS III need dedicated controllers [12]. Ethernet Powerlink uses the traditional shared Ethernet and places a master–slave scheduling system on top of it. Common to many proposed networks is that they employ clock synchronization to support real-time applications. To this end, the IEEE 1588 standard [15], which originally emerged in the instrumentation area, was also officially adopted by IEC. The specific requirements in the automation domain have led to several suggestions for improvement of the standard [16], [17] that were taken into account in the recent revision.

A look at Fig. 4 reveals that the original hope arising from the fieldbus standardization disaster, i.e., that Ethernet could be the basis for a unique industrial communication solution, was futile. In fact, the situation has not changed too much compared with the heterogeneity of the traditional fieldbus systems. Interoperability between different industrial Ethernet solutions is not possible in a direct way. Nevertheless, as many industrial Ethernet solutions were developed by the same companies who already have fieldbus systems on the market, care was taken to allow for backward compatibility and cooperation between the "old" fieldbuses and "new" Ethernet installations. This was again done to increase market acceptance and to provide a migration path for the steady replacement of the fieldbus systems by industrial Ethernet. A direct interconnection by means of bridges between different media types is not possible without losing timing guarantees. Still, higher layer protocols (particularly application-layer protocols) and at least data objects are compatible and allow for an interconnection on a high level. From this compatibility viewpoint, four different classes of networks exist.

1) Full compatibility of higher layer protocols with preexisting fieldbus solutions. This applies to MODBUS/TCP, MODBUS/RTPS, high-speed Ethernet (Foundation Fieldbus over UDP/IP), Ethernet/IP (which uses the Common Industrial Protocol (CIP) common to ControlNet and DeviceNet), P-Net on IP, Vnet/IP (compatible with Vnet from Yokogawa), SERCOS III (structure of telegrams has been retained from the earlier fiber-optics-based versions), and CC-Link IE (using the existing CC-Link protocol over Ethernet). Building automation networks take particular advantage of this architecture. BACnet, LonWorks, and EIBnet all use IP-based networks (or plain Ethernet as an alternative for BACnet) as a transport medium for the higher layer protocols [6].
2) Compatibility of data models and objects with preexisting fieldbuses. This is the case for PROFINET, where proxy solutions exist to incorporate legacy PROFIBUS devices and networks.
3) Usage of application-layer profiles from preexisting fieldbuses without direct compatibility. This applies to Ethernet Powerlink and EtherCAT, which use the CANopen application layer to achieve compatibility with widely used device profiles, e.g., for drives.
4) Completely new industrial Ethernet developments without backward compatibility. This is the case for the Asian networks Ethernet for Plant Automation (EPA) and TCnet.

Apart from the large backward compatibility, the second conceivable improvement compared with classical fieldbus technology is that despite all proprietary modifications, Ethernet and, to a large extent, also the IP suite are being recognized as a technological basis for the new generation of industrial communication systems. All approaches allow for a standard TCP/UDP/IP communication channel in parallel to process data communication. Even the real-time Ethernet solutions (such as PROFINET, Ethernet Powerlink, EtherCAT, etc.) have such a conventional channel for configuration purposes. The separation of real- and nonreal-time traffic is accomplished on an Ethernet MAC level with prioritization or time-division multiple-access (TDMA) schemes, together with appropriate bandwidth allocation strategies such as time-slotting mechanisms or token passing. In such a parallel two-stack model, IP channels are no longer stepchildren of industrial communication but offer sufficient performance to be used for regular data transfer. While this enables, in principle, the coexistence of automation and nonautomation applications on industrial Ethernet segments, the mixing of automation and office is not advisable for performance but, more importantly, for security reasons. The value of this standard IP channel is rather to be seen in a simple direct access path to the field devices. Therefore, the currently favored solutions for configuration tools (i.e., Extensible Markup Language (XML), Simple Object Access Protocol (SOAP), and, more generally, Web technology) can be consistently used. This again does not mean that industrial Ethernet solutions are interoperable or use the same configuration tools, but at least, the basic principles are the same.

All this could have already been done with traditional fieldbus systems as well, and it certainly would have been done had particularly the achievements of the Internet and the World Wide Web been available in the early 1980s. Thus, what we see today with the rapid evolution of Ethernet in automation can in fact be regarded as a second wave of fieldbus development, which takes into account all the technological achievements of the last decade and exploits them for field-level communication.

## IV. Wireless Networks in Automation

The next logical step in the evolution of field-level communication is the inclusion of wireless networks. This has been a challenging research topic for a long time and still is far from being exhausted. Contrary to industrial Ethernet, which is widely seen as a long-term replacement of classical fieldbus systems, it is currently not to be expected that wireless networks will completely supersede wired automation networks. Rather, they will complement them where necessary and reasonable. Purely wireless systems, such as in the case of wireless sensor networks with huge numbers of nodes and strongly indeterminate time-varying topologies, are an extreme example not typical for automation applications in whatever form. The usual case will be that wireless or wired systems will interact and form a hybrid network with the requirement for largely transparent data exchange.

For field-level networks in automation applications, an interesting trend can be observed: During the classical fieldbus era, it was very common to develop new communication technologies completely from scratch, including also the lower OSI layers. This has changed in recent years. The common understanding now is that it does not pay off for cost and market acceptance reasons to develop new communication technologies and that it is far better to rely on proven standards whenever possible. This attitude can be seen as the predominant factor in the broad acceptance of Ethernet in automation. The trend of reusing existing standard technologies also plays an important role in the wireless domain. Apart from specific proprietary solutions, industry favors wireless standards at least for the lower protocol layers [18]. The currently most interesting wireless technologies are listed here.

1) IEEE 802.11 [wireless LAN (WLAN)] in its many facets. This is the *de facto* standard for wireless networks in the office area and is seen as a natural wireless extension of Ethernet. Therefore, it is also employed in the automation field.
2) IEEE 802.15.4 [wireless personal area network (WPAN)], in particular with additional higher protocol layers of ZigBee. This is the most promising candidate for wireless sensor networks due its power-saving capabilities and therefore particularly interesting for building automation. It is also the basis for WirelessHART and the more comprehensive standard ISA 100.11a, which is still under construction.
3) IEEE 802.15.1 (Bluetooth) is widely used in industrial automation, although version 1 is limited to short-range networks [30]. Nevertheless, the upcoming version 2 will overcome the range restriction.
4) IEEE 802.16 [Worldwide Interoperability For Microwave Access (WiMAX)] is a broadband standard that is intended to cover long-range networks. It is currently not widely applied in automation but may be interesting in the future.
5) UWB (ultrawideband, formerly IEEE 802.15.3a) is a set of physical layer technologies providing high data rates for short-range networks. The current standardization situation is unclear; it might, however, become interesting in the form of wireless Universal Serial Bus (USB) and Bluetooth 3.0.

To maintain utmost compatibility with existing wired field-level networks, it is advisable to adopt the strategy from industrial Ethernet and use only the lower layers of the wireless technologies (these are the ones that are typically standardized, anyway). The higher protocol layers could then be taken from wired field-level networks. Depending on the capabilities of the wireless technology and the requirements of the wired field-level protocol, the resulting protocol architecture can be different (see Fig. 5), and the endpoint of the migration path can be anything between pure data object compatibility and tight integration of wireless links as extensions of a wired network.

From a protocol stack perspective and with a view to backward compatibility, the extension of today's Ethernet-based field-level networks into the wireless range seems to be quite straightforward for the solutions using plain Ethernet and maybe TCP/UDP encapsulation of fieldbus application layers (see also Fig. 4), such as Ethernet/IP with the CIP or MODBUS. In these cases, Ethernet could be replaced by a

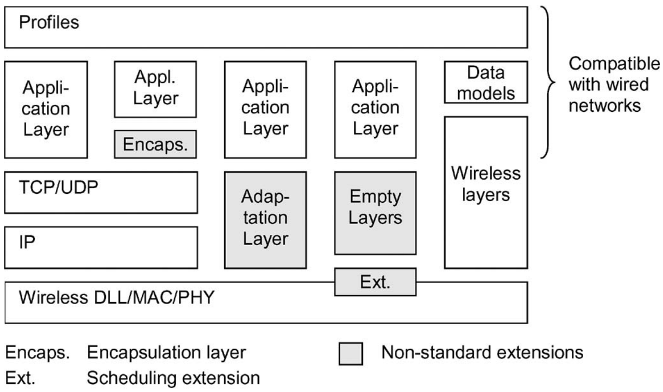


Fig. 5. Possible protocol architectures for wireless field-level communication systems to maintain compatibility with existing wired solutions.

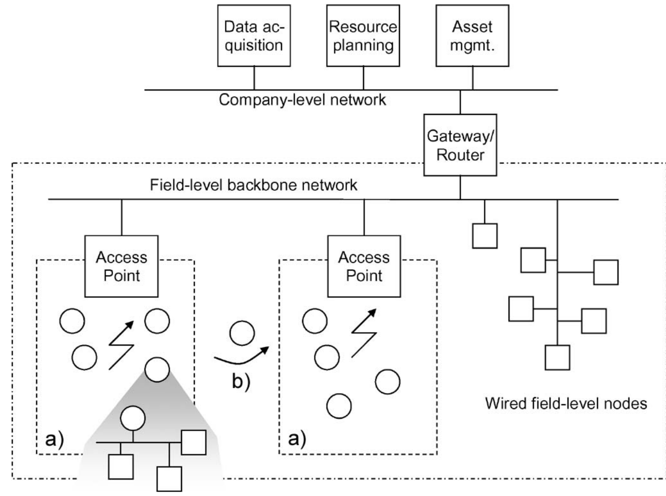


Fig. 6. (a) Hybrid wired/wireless network topology with isolated wireless clusters. (b) Multiple radio cells requiring integration and roaming of mobile nodes.

wireless technology providing an IP channel. The availability of an IP layer is not a matter, of course, in the various wireless technologies currently considered for automation networks. It exists for WLAN but not natively for WPAN. The current work on 6loWPAN (IPv6 over WPAN, in particular IEEE 802.15.4) will mitigate this problem.

Industrial Ethernet protocols not using IP as the network layer might need an intermediate protocol layer to adapt the interfaces of the wireless data link and the fieldbus application layer. In both cases, the interconnection of the two communication technologies can be accomplished—if needed—by a bridge approach translating between the data-link layers and being transparent for the higher layers, in particular for the application layer. Again, the services that are offered by the wireless layers may impose restrictions. WPAN, for instance, has an inherent centralized structure; thus, it does not easily lend itself to the implementation of multicast services that are needed for producer/consumer-type communication models.

It is obvious that timing properties cannot be easily preserved across a bridge connecting wired and wireless segments. This is even more evident if the wired field-level networks use specific scheduling extensions on top of Ethernet to achieve particular real-time qualities or if the Ethernet layers as such are modified. To obtain similar functionalities, modifications to the wireless network would be needed as well. It has been shown that, e.g., a prioritization mechanism can be placed on top of IEEE 802.11 without violating the standard [19], but such solutions may not be possible for every Ethernet-based field-level network—not to speak about the performance penalties that the transition from wired to wireless will entail. Nevertheless, reusing the known application layer may be beneficial even if the performance of the wired counterpart cannot be reached. Moreover, like in Industrial Ethernet, a parallel IP channel (if available) could be foreseen for unscheduled traffic to access the field devices, e.g., for configuration purposes via Web technologies.

The last option is to dispense with the application-layer protocol (or most of it) and retain only the data models of the wired field-level network and/or profiles that might exist on top of it. The wireless communication network can then be any, and the interconnection between wired and wireless networks must be achieved on a high level by means of a gateway. A tight integration with respect to timing of the data transfer between the segments is not possible in this case, but at least, the syntax and semantics of the data can be preserved, and the reuse of high-level tools for engineering and data acquisition should be feasible.

## V. Hybrid Automation Networks

From a topological viewpoint, it can be envisaged that automation will continue to require structured networks even if they are partly wireless. A typical configuration will therefore consist of a two-level hierarchy with a wireless lower (field) level and a wired field-level backbone network likely based on Ethernet (see Fig. 6). The wireless segments will not be organized in a peer-to-peer fashion but will each have a central access point connected to the backbone network, which will typically belong to the middle level of the automation pyramid shown in Fig. 1. The field-level backbone, in turn, will typically be connected to a company network through some sort of gateway. On the company level, field-level data will be gathered and processed for various purposes, including resource planning, quality control, or—in building automation—facility management.

Depending on the application requirements, there are two possibilities with regard to the interaction of the wireless segments. The first and simpler option is that wireless clusters may be fully independent and form autonomous islands that need not exchange data—at least not with real-time requirements [see Fig. 6(a)]. In this case, the interconnection between wired and wireless segments can be based on bridges, as discussed above, to take the advantage of transparent higher protocol layers. On the other hand, the wireless clusters may also have a completely different possibly very simple protocol, and the access point may then act as a gateway interfacing with the upper levels of the network hierarchy. Since the individual wireless clusters need no direct interaction, the delays that are introduced by the protocol and data translation in the gateways are not relevant. To speed up the data exchange and better separate the data-exchange mechanisms on either side of the gateway, the access-point application may also feature a caching strategy. This scenario of isolated wireless networks is very promising for building automation, where sensors and actuators have to cooperate only inside one room and can be connected using an inexpensive sensor network, whereas the individual room controllers are linked via a wired network on Ethernet and IP basis using the structured cabling that is present for IT purposes anyway.

Things are more complex if multiple wireless segments need seamless integration. This may be the case in large installations, where several access points are needed to cover the entire area and where the automation application cannot be divided into independent islands [see Fig. 6(b)]. The situation becomes even more complicated if mobile nodes need to be considered, which may roam between access points. This scenario is typical for industrial applications, e.g., in manufacturing, where pallets, transportation vehicles, or half-assembled products are equipped with wireless data containers to steer the manufacturing process [20]. In such a case, a relatively simple gateway approach is no longer feasible, and the access points need proper synchronization to retain consistency throughout the network. A bridging solution ensuring consistent application layers is mandatory, but this alone is not sufficient. The wireless parts, together with the backbone and also possibly conventional wired field devices, form a uniform domain with stringent timing requirements. This may also include small remote segments that are connected via a wireless link (like in the left corner of Fig. 6).

To allow for seamless integration of multiple wireless and wired segments while still retaining compatibility with existing communication standards on the lower protocol layers and proven field-level application protocols on the higher layers, additional software layers have to be added to the communication architecture in the form of a middleware, as proposed by the European research project flexWARE [21]. This project specifically addresses WLAN infrastructures in industrial environments, but the concept is more generic. An essential requirement is that the network infrastructure can transparently switch between access points. This is evident if nodes are mobile, but roaming may also be induced by changing conditions, particularly in harsh industrial environments, where the quality of communication paths may change with time. To implement sufficient flexibility, the access points have to interact to organize this roaming between clusters. Roaming within real-time wireless networks can be further supported by location awareness of the nodes, such that the handover from one access point to another can be prescheduled by making appropriate bandwidth reservations when a node approaches a cell border [22]. Such predictable roaming will also prevent active communication channels from being disrupted when a node traverses the boundary between access points. A prerequisite is, of course, that the wireless networks are not fully loaded and that sufficient resources are available in adjacent cells.

The generic architecture approach to support the aforementioned features is shown in Fig. 7. The central communication middleware is in charge of the coordination between nodes at the interface of the wireless segments and ensures timely guaranteed transmission of data over the system. It uses the services of several additional modules.

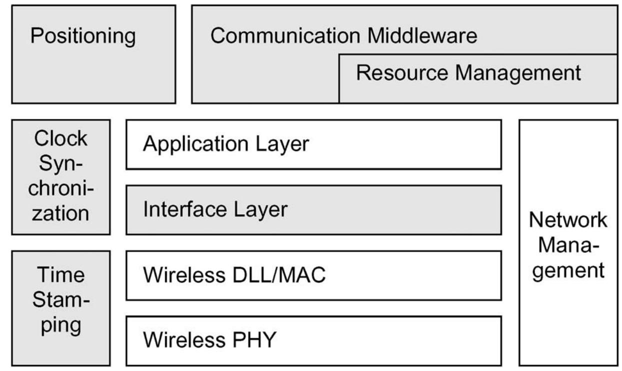


Fig. 7. Protocol and middleware architecture to support seamless integration of multiple wireless segments based on node tracking.

1) The resource management is responsible for roaming, control of the real-time communication and bandwidth resources, communication between access points, as well as network management.
2) The virtual clock synchronization establishes a system-wide notion of time to facilitate global resource planning, as well as localization of wireless nodes. To achieve appropriate accuracy that is needed for position determination, the clock synchronization relies on a hardware-assisted time stamping that is implemented in parallel to the lower communication protocol layers.
3) The positioning middleware calculates the actual physical position of a node in a map to support predictable roaming by means of trajectory tracking. In addition, awareness about the position may be used for implementing various location-based services [23].

In this architecture, the actual communication protocol layers can be kept compliant with existing standards. The interaction between the middleware and the protocol stack will largely be done via the network management, maybe with the help of an additional interface layer on top of the data-link layer. Nevertheless, to achieve an optimum performance, modifications might be required for fast roaming and real-time QoS monitoring, which are not yet standardized but may be interesting in the future.

## VI. Related Work

Wireless field-level networks have been a research topic for over a decade. Most attempts in the past were focused on providing wireless extensions for fieldbus systems to include remote segments and mobile nodes [24]. Contrary to the current trend, wireless networks were also considered as backbone solutions for the interconnection of remote wired segments [25].

Much previous work was devoted to PROFIBUS. Reference [26] used a gateway approach with a polling strategy that is superimposed on the WLAN to attach a set of mobile nodes. Polling as an alternative MAC protocol to achieve better real-time performance for wireless PROFIBUS extensions based on WLAN technology was also suggested in [27]. In the European Union research project R-Fieldbus, it was proven that, in selected cases, an integration of wireless communication channels and traditional fieldbus systems (PROFIBUS was again used as an example) is possible using dedicated repeaters or bridges. This approach yields a flat network structure combining wired and wireless segments without sacrificing real-time capabilities but requires substantial effort [28], [29]. An implementation of a PROFIBUS decentralized peripheral on top of Ethernet and Bluetooth as communication media was studied in [30]. Interconnection of the two different networks was achieved not by means of a transparent device acting as a bridge or a repeater but by a master node linking both wired and wireless segments. The two networks thus remain clearly separated. On the other hand, [31] suggests ignoring higher layer compatibility completely—even on the profile or user-layer level—by means of a gateway acting as a proxy for a ZigBee segment in a Foundation Fieldbus installation. A gateway solution is also proposed in [32] to integrate WirelessHART devices in a PROFIBUS or PROFINET environment. Here, the gateway plays the role of a modular device proxy where each wireless node is mapped into a dedicated slot to achieve compatibility with the PROFIBUS addressing scheme.

A large ongoing European research project in the field is the virtual automation network, which also addresses horizontal integration of remote network segments via public telecommunication networks [33]. To cope with a large variety of communication technologies, a kind of middleware solution is developed, which provides relatively abstract application services. Wireless network segments (particularly sensor networks) are included by proxies [34].

In building automation, fieldbuses such as EIB/KNX and LonWorks have always included radio links as one of many media options [6]. However, these wireless media were—because of their early development—very specific solutions tailored to the needs of the individual fieldbus systems. More recently, ZigBee has become very popular because of the potentially large networks. Reference [35] suggests tunneling KNX/EIB over a 802.15.4-based backbone, arguing that wired backbone infrastructures are no option in building automation. In this approach, data frames from a wired segment are wrapped and distributed via packets on the wireless network. By contrast, [36] proposes protocol conversion between ZigBee and KNX by means of a gateway, and [37] investigated the possibility of using ZigBee as a transparent wireless medium for BACnet network and application layers. An experimental building automation network based on a common IP layer over standard Ethernet (or existing two-wire cabling) and ZigBee is presented in [38]. On the higher protocol layers, this approach uses Hypertext Transfer Protocol, SOAP, and Universal Plug and Play for network setup and operation.

If one does not care about backward compatibility of wired field-level protocols, the path is free for the development of new application-layer protocols that can exploit the specific properties of wireless technologies, such as those proposed in [39] for WLAN and WPAN. The protocol used in this case study was not completely new but combined elements from standard fieldbus systems such as WorldFIP, PROFIBUS, or CAN. To improve performance of WLANs in automation, there is a multitude of suggested modifications to achieve better coexistence of real- and nonreal-time traffic. To name but a few, [19] proposes an embedded token-passing scheme, [40] proposes a modified MAC protocol enabling collision avoidance, and [41] investigates the application of QoS to improve latency and reliability in infrastructure-mode WLANs. There are also examples of dedicated sensor networks that are designed for a specific purpose on the basis of standard physical layers. Typical for such approaches is that they use modified access control mechanisms to improve the real-time performance of the wireless networks. 802.15.4 was used in [42] to implement a small-scale network for machine control. Above the physical layer, a proprietary combination of TDMA and carrier-sense multiple access/collision avoidance was proposed. ZigBee, together with CAN, is used in [43] for a simple but energy-efficient hybrid sensor network. A time-slot-based protocol was also defined for Wireless Interface for Sensors and Actuators [44], which is based on the 802.15.1 physical layer and, in addition, supports wireless power supply of the nodes. In [45], a nonstandard physical layer in the industrial, scientific, and medical band, together with a combined TDMA/frequency-division multiple-access scheme, was used to devise a wireless sensor–actuator network within the EnAS research project.

Overviews of wireless technologies and design considerations for hybrid wired/wireless fieldbus systems are presented in [46] and [47]. More recent studies have also addressed industrial Ethernet and possible architectures for wireless extensions based on 802.11 and 802.15.4 [48]. The challenges for real-time Ethernet are discussed in [49] for the example of Ethernet Powerlink and in [50] for the case of PROFINET IO. Contrary to the proposal made in Section V, these approaches typically use wireless networks as small-scale limited extensions of the wired field-level network [see Fig. 6(a)] rather than attempting a large-scale hybrid automation network.

## VII. Conclusion

Field-level networks have come a long way from the very first attempts of industrial networking to contemporary highly specialized automation networks. What this paper has tried to show is that despite the extreme heterogeneity of solutions that are tailored to the needs of all possible application fields, there is a relatively clear migration path that connects the three major generations in field-level networking: the original fieldbus systems, the recent industrial Ethernet, and the upcoming wireless field-level networks. This migration path foresees that the application-layer protocols are being reused—at least in the form of device or application profiles on top of the OSI protocol stack—to retain compatibility with existing networks and installations on a high level. From an industrial perspective, this strategy is not surprising because it preserves the value of investments in automation systems, which in most cases have very long life cycles.

The migration path, which is straightforward as it may be, has, of course, limitations. The most obvious is that changing communication technologies within a data transmission path does not preserve end-to-end timing properties on the lower protocol layers and makes a seamless integration of different communication technologies—such as fieldbus and Ethernet, or Ethernet and wireless networks—far from simple if real-time requirements are to be met. All studies in the past have shown that, unless response times play no particular role, hybrid networks require additional integration efforts or modifications typically at lower protocol layers. Nevertheless, hybrid networks will remain the norm for the near future, particularly when it comes to the inclusion of wireless devices, because wired segments still have dependability advantages, particularly if used as the backbone.

To deal with the integration problems in heterogeneous network environments under real-time constraints, the common strategy today is to introduce middleware or adaptation layers that translate protocol services. If such translation is not possible in a straightforward manner, they dynamically adjust QoS parameters, such as resource allocations or message priorities, or encapsulate protocols in others. Such middleware solutions are usually complex and resource consuming—sometimes a high price for "seamless" integration of diverse field-level networks. Even if cross-network compatibility is implemented without regard to real-time capabilities only on the application or profile level, this might be too complex for resource-limited field devices.

On the other hand, compatibility across field-level network generations is no dogma. It facilitates integration and reuse of legacy tools and applications but is not a must. Modern communication technologies, above all Ethernet and the IP suite, have caused the automation pyramid to become significantly flatter. For the future, it might be reasonable to envision a combination of IEEE 802.x-based networking solutions in both the wired and wireless domains. Very interesting could be the current standardization work on ISA 100.11a and 6loWPAN. Both can be expected to further facilitate network integration, the former with respect to the intended application-layer compatibility with legacy field-level networks and the latter with respect to a promising combination of low-power WPAN technology and wide-range IP connectivity. In this context, IPv6 is frequently regarded as the ultimate solution to the addressing limitations in typical automation networks, which make large-scale networks (such as in building automation) cumbersome to engineer and maintain. Overcoming the need for address translation and having a consistent network layer across a heterogeneous network would certainly be an advantage. However, one must not overlook the fact that IPv6 substantially requires more resources in the field devices.

Although they are interesting for many applications, wireless networks are regarded, particularly by industry, with some skepticism. One typical concern is security, although modern wireless networks include reasonable security mechanisms—in contrast to most existing wired field-level networks. Nevertheless, for hybrid heterogeneous networks, additional security concepts such as defense-in-depth approaches need to be integrated. A second concern is the dependability of wireless channels in automation applications. Many applications, in particular safety-critical ones, require media redundancy to achieve given reliability levels. While this problem is essentially solved for wired field-level networks (also for those based on Ethernet), it is still a research issue for the wireless domain. Concepts based on overlapping cells combined with seamless roaming, such as that presented in Section V, or completely redundant cells might be a step toward higher dependability. Reliability concerns are also the reason for industry to prefer relatively easy-to-plan infrastructure network setups, whereas dynamic ad hoc scenarios are still mainly of academic interest.

Related to the reliability aspect of wireless channels, an emerging problem for practical applications is the interference between neighboring cells or other wireless networks using the same frequency range. Coexistence is a research topic on its own and requires, on the one hand, additional fairness mechanisms in the protocols themselves. On the other hand, very careful network layouts are needed to minimize the probability for conflicts.

Finally, all standardization and migration efforts discussed before seem to be mainly suitable for the mainstream field-level networks we know today. There will, however, be application domains (and building automation could be one of them) demanding sensor and actuator networks exhibiting very low power consumption, extreme simplicity, lowest cost, or utmost robustness. Networks designed for such niches—no matter if wired or wireless—will often be too specialized to care for backward protocol compatibility. At best, they may share high-level profiles with the "large" networks for data compatibility. From the protocol viewpoint, they might be independent subsystems that are integrated via gateways or proxies into more powerful backbone networks. At any rate, the evolution of field-level networks has not reached its end.

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**Thilo Sauter** (M'93–SM'09) received the Dipl.Ing. and Ph.D. degrees in electrical engineering from Vienna University of Technology, Vienna, Austria, in 1992 and 1999, respectively.

From 1992 to 1996, he was a Research Assistant with the Institute of General Electrical Engineering, University of Rostock, Rostock, Germany, working in the area of programmable logic and analog application-specified integrated circuit design. In 1996, he joined the Institute of Computer Technology, Vienna University of Technology, where he was the Head of the Center of Excellence for Fieldbus Systems and led the Factory Communications Group. Since 2006, he has been a Tenure Assistant Professor at Vienna University of Technology. Since 2004, he has also been the Director of the Institute for Integrated Sensor Systems, Austrian Academy of Sciences, Wiener Neustadt, Austria. His current research interests are integrated sensor systems and communication networks in automation, with a focus on interconnection issues of fieldbus systems and IP-based networks, as well as industrial Ethernet.

Dr. Sauter is a member of the Austrian technical committee OVE MR65SC and a delegate to the CENELEC committee TC65CX, both concerned with fieldbus standardization. Furthermore, he is the Chair of the IEEE Industrial Electronics Society (IES) Technical Committee on Factory Automation, an IES representative in the Administrative Committee of the IEEE Sensors Council, and the Treasurer of the IEEE Austria Section.