Abstract—The objective of this paper is to emphasize a clear and natural distinction in strategies of sensor network design. In order to display different architectural paradigms in today’s wireless sensor networking, the classification of sensor networks as intensive and extensive ones is introduced and explained. Main paradigms representative for both technologies are compared. As follows from the discussion, the intensive and extensive sensor networks technologies supplement each other in a complementary way. The intensive sensor networks are exemplified by LonWorks platform. Dense and randomly deployed wireless sensor networks that reveal an innovative approach in last years are classified as the extensive networks.

Index Terms—intelligent sensors, communication systems, radio communication, computer architecture, protocols.

I. INTRODUCTION

Today’s remote sensing technology exploits networked systems consisting of devices that communicate and cooperate with one other over the network in order to manage a common task. The aim of system operation is to monitor and report the state of the environment being sensed in the open-loop systems, and possibly to interact with it using a feedback in the closed-loop systems [1]. The primary objective of sensing devices is to sample the residing environment and send updates with the most recent information to data collecting center(s) for further processing. Typical physical magnitudes sensed by such devices are temperature, light, vibration, sound, radiation, etc.

A. Historical Background

Before the age of electrical signals, the process control equipment used pressure signals for primitive communication between devices. Local pneumatic control had been used since the beginning of the 20th century. The signals were usually represented by pressures of 3-15 psi. Pneumatic controllers, transmitters, and valve positioners were placed at various locations within a process plant to effect control of certain plant locations. In the 60s and 70s, the 4-20 mA current loop standard became common for communication of analog electrical signals between instrument devices for long distances. Since the late 60s, the minicomputers with digital processing capability have started to be employed in process control and industrial automation applications. The processing was centralized in the minicomputer, including the analog-to-digital (A/D) and digital-to-analog (D/A) conversion. The master/slave architecture evolved where a single minicomputer polled dumb wired remote sensors and send signals to actuators via analog 4-20 mA current links. Typically, sensors and actuators were interfaced with minimal discrete electronic circuitry without any real processing capability. Although the minicomputers provided digital processing, the communication between the minicomputer and sensors/actuator instrumentation was based still on analog link, i.e., 4-20 mA current loop. The next stage in the evolution of communication systems was the introduction of digital communication techniques represented by EIA RS-232 point-to-point serial data links or 20 mA point-to-point current loops based on a simple mark/space digital coding. Consequently, the sensing and actuating devices started to be equipped with A/D and D/A converters [15].

In the early 70s, Intel developed the single-chip microprocessor allowing to provide intelligence to the sensor and actuator level. At the end of the 70s the microcomputers (i.e., microcontrollers with internal memory and input/output ports) that offer very low cost digital processing were available. In the early 1980s, smart sensors and actuators emerged providing advanced functionality in terms of information processing, reliability, fusion and integration, and implementing the communication protocol in software. Since both 20 mA current link, and RS-232 could not support sharing the communication line by many nodes, RS-485 link has been introduced to allow multiplexing a single twisted pair channel among various devices.

Fieldbus is a term used to describe a digital communication network based on a serial communication bus to allow various devices to exchange information using a common bus.

A development of communication buses was followed by a distribution of software which was just as important as the progress in communication techniques [15]. The software was evolving into a distributed model with local software at the device level cooperating with software programs within other devices. The benefit of employing local intelligence at the device level provided much additional functionality. For example, a control algorithm (e.g., PID) could be incorporated into sensor or actuator node functionality rather than implemented traditionally on a dedicated controller device.

B. Fieldbuses

To overcome some of the problems inherent in the use of proprietary distributed sensor/control systems, the process control industry has developed a number of platforms, open communication protocols including, for example, HART, PROFIBUS, WORLDFIP, LonWorks, Device-Net, and CAN protocols, which enable field devices made by different manufacturers to be used together within the same control network. In fact, any
field device that conforms to one of these protocols can be used within a process to communicate with and to be controlled by a controller that supports the protocol, even if that field device is made by a different manufacturer than the manufacturer of the DCS controller.

The modern sensor network concept originates from *fieldbuses, device networks and control networks* that have been developed since the 80s for industrial applications [15].

In the contemporary sensor/control networks, node communication, computation and storage, as well as interface and sensing, are combined to perform all necessary tasks on a single device. This is a key difference from the traditional Internet-based data networks containing many dedicated devices each providing a single well-defined function such as routing, storage, web-devices, connections to peripherals, user interfaces, etc.

**C. Wireless Sensor Networks**

Recent technological improvement and an enormous amount of research activity for last seven years brought about the development of small, inexpensive, low-power, randomly deployed distributed devices, capable of local processing and wireless communication. Each sensing device consists of a sensory transducer, a radio transceiver, a power unit and a processing unit. Main paradigms of this novel sensor networking approach consists in restricted resources of each node, limited importance of a single device, and existence of a wireless link. The efficiency of system operation is built more upon effective cooperation between the nodes than on advanced functionality of a single device. Many initial wireless sensor networks have been deployed for environmental monitoring, which involves collective measurements in space and time domain. On the other hand, wireless sensor networks are more than just a specific form of ad hoc networks since the economical management of energy and computation power is more critical issue in wireless sensor networks than in conventional ad hoc networks.

Nowadays, sensor networking is a very active research area encompassing either hardware, or software platforms, and increasing commercial interest. The typical network systems contain tens, hundreds, or even thousands of sensor nodes. Sensor networks have numerous applications, e.g., environmental monitoring, condition-based maintenance, seismic detection, military surveillance, smart spaces, agriculture, etc. The wireless sensor network becomes one of new technological visions of the 21st century.

However, the sensor networking is not a homogenous technology derived only from novel fundamental research but a collection of innovative propositions, and well-known methods or well-established techniques applied to a new domain and new architectural concepts. Although the term “wireless sensor networks” is widely referred to all sensor networking technologies, it is often used by default in relation to dense wireless networked systems that reveal an innovative approach in last years.

The objective of this paper is to emphasize a clear and natural distinction in strategies of sensor networking design, which to the author’s knowledge, is not displayed in the literature. Namely, the classification of sensor networks as *intensive* and *extensive* ones is introduced and explained in order to highlight different architectural paradigms in modern sensor networking.

The intensive sensor network architectures are essentially well-established, and many of application classes have a long tradition. The platforms available on the market are mature (e.g., LonWorks, CAN). On the other hand, the extensive sensor networks stay more at the stage of hotly debated concepts and propositions that often require rethinking of some basic paradigms with which communication protocols are engineered. The innovative contributions are still only partially exploited in commercial platforms. However, the interest in applying extensive network technologies to a wider variety of applications has been steadily growing (e.g., in the industrial monitoring space).

**II. LOCAL OPERATING NETWORK PLATFORM**

We exemplify a class of intensive sensor networks by Local Operating Networks (LonWorks, LON) platform, developed in the 90s and widely used in a variety of applications. LON has become a classic solution in building automation, and home networking including all key building automation subsystems: heating, ventilating, and air conditioning, lighting, security, fire detection, access control, energy monitoring, etc. Among others, LonWorks platforms are used also in semiconductor manufacturing, pulp and paper equipment, material handling, textile machinery, petrochemical, food and beverage, automotive, and wastewater treatment.

LonWorks technology allows to develop networked systems:

- with a large number of nodes that do not require synchronization and cover relatively wide distances,
- peer-to-peer architecture,
- using multiple media including wireless communication,
- supporting battery-powered nodes, normally powered down, activated only for message sending or receiving.

Most devices in LON-based building automation systems are connected by wire (heating, ventilation, lighting, access control, etc.). Wireless transmission is useful to building-to-building communication, or for environmental monitoring of particular areas of the building or of materials stored in a building. Furthermore, wireless LON devices are used among others in public transportation monitoring systems, security camera monitoring and control, gas detection, fire valve control, smoke detection [6].

Each LON device is equipped with the Neuron Chip microcontroller. Neuron Chip, manufactured by Toshiba and Cypress, is a system-on-chip, including three 8-bit CPUs. Two of them (Network Processor and MAC Processor) handle LonTalk protocol stack, the third one (Application Processor) executes the node application program developed by a user. For a survey of engineering solutions used in LON technology, please see references, e.g., [3, 4, 8].
III. INTENSIVE VS. EXTENSIVE SENSOR NETWORKS

A. Singular vs. Collaborative Event Detection

As the intensive sensor network we define a networked system where usually only a single node reports an event of interest. Similarly, the extensive sensor network is classified as a dense network (i.e., a large-scale network), where a certain event is reported by multiple sensor nodes. When an event occurs (e.g., a sudden temperature change), the nearby sensors report their observations to the data collection station called sink. The goal of an extensive sensor network operation is a collaborative detection of specified events of interest in a sensor field, and sensing range of devices often overlaps one another.

Note that the distinction between both paradigms does not consist in the size of the network. Both network types might contain similar number of nodes. The extensive network size ranges from tens or hundreds to thousands of nodes. On the other hand, the addressing space offered by Network Layer of LonTalk/EIA-709.1 is also really large (up to 32,385 nodes per a single domain) and hierarchically structured in domains, subnets and groups [2]. However, a typical size of the intensive network is smaller than the extensive one. The difference relies on the various strategies of event detection (i.e., singular versus collective sensing). A distinction made above has a crucial consequences to designing effective network architectures for both design strategies.

The intensive networks use broadcast or multicast for data dissemination where a transmitting node is a source of data for multiple recipients, or even for all the nodes in the particular network subsystem. Thus, the flow of data is from a single node to a set of nodes in the network.

The extensive networks exploit convergecast for data collection which is the opposite paradigm to broadcast or multicast. Convergecast refers to a communication pattern in which the data flow from a set of nodes to a single node in the network. This concept describes the notion of collecting data from several sources at a central point. Convergecast is likely to be one of crucial abstractions in extensive networks, closely connected with notion of in-network processing and data aggregation.

B. Reliability of Information Delivery

Transport Layer of LonTalk/EIA-709.1 like other traditional transport protocols have been designed to support a reliable end-to-end delivery of data packets according to the assumption that each packet carries unique, significant and non-redundant information. A variety of message services is provided: the acknowledged service, unacknowledged service, and acknowledged repeated one. The acknowledged service is based on the classical PAR transport protocol (Positive Acknowledgements and Retransmission), where recipient(s) send the acknowledgement(s) back to the sender [5]. If the acknowledgement(s) are not all received, the sender times out and retries the transaction. The number of retries and the time-out are configurable. In the unacknowledged (repeated) service, acknowledgements are not applicable [2].

The acknowledgement packets constitutes control packet overhead and do not carry application data. If collision detection is not provided, sending an acknowledgement by a destination node is the only way to notify the sender of a successful message reception. However, a transmission of acknowledgements increases the collision rate, the mean access delay, and in fact degrades the global reliability of packet delivery. This is a price for back information about a result of successful completing a particular transaction. Thus, acknowledgement message service improves the end-to-end reliability of individual transactions, but degrades the global reliability of packet delivery.

In classical extensive wireless sensor network applications, the sink (e.g., a base station gathering data) is only interested in the collective information provided by numerous sensor nodes, but not in their individual reports. Since, many sensor readings include redundant data, it is pointless to transmit all of them to the sink. Hence, the in-network data aggregation is needed. New reliable transport schemes for wireless sensor networks called the event-to-sink protocols, have been invented, e.g., ESRT [12].

C. How to Cope with Information Redundancy

The extensive networks have to deal with high information redundancy since, by the definition, multiple nodes report the event of interest in a sensor field. Adjacent nodes can have similar data. Whereas the extensive network is robust to highly correlated traffic, the intensive sensor network is not intended to cope with huge information redundancy in a normal type of operation. Unlike dense data-centric networks, LonWorks technology has not been designed for the collective detection of event of interest in the sensor field. However, the intensive network exploiting the event-triggered architecture is prone to the effect of event shower, i.e., burst of events, often released by a single physical event that cause congestion of the system [5]. In case of the event shower, the traffic in the channel really includes a lot of redundant event information. Such a situation can occur for example when a fire is detected in a building and a number of redundant temperature and smoke sensors begin reporting the event.

In terms of the traffic management, either the event shower, or the collaborative event detection in data-centric dense networks, cause similar effects in the network channel. However, the former is undesirable although possible result that may occur in the intensive sensor network, and the latter is present in a normal type of operation of the extensive network.

D. Data-Centric vs. Node-Centric Routing

The intensive sensor networks use statically-assigned addresses that are guaranteed to be unique, i.e., each node has a unique identification number (ID) used for routing. The hierarchical addressing is applied. For example, in LON networks, the address identifies a domain, a subnet or a group, and a node number within the subnet or the group. Moreover, multiple addresses might be assigned to every node since a node can be a member of multiple groups. The intensive sensor networks can be described as node-centric since data are requested from a specific node. Thus, traditional wired and wireless networks should be classified as the intensive networks since they are definitely node-centric.

In the extensive networks, the importance of any particular node is significantly limited as compared to intensive networks. Furthermore, in order to maximize the
Comparison of Intensive and Extensive Sensor Networking Technologies

lifetime of the sensor devices, it is critical to maximize the usefulness of every bit transmitted or received [10].

Since data observed by the nodes are more important than the ability to identify the particular nodes, the extensive sensor networks are data-centric, meaning that data is requested based on certain attributes such as, which area has temperature greater than 20°C? [10]. The attribute-based addressing, where nodes are described by attributes other than addresses, are more effective for the extensive networks. In such a scheme nodes randomly select probabilistically unique identifiers for each new transaction so in fact this is the address-free architecture [10].

The evolution of the node-centric architecture into the data-centric one stems from that fact that the content-based addresses seem to be a more natural response to extensive network needs than the conventional addresses.

Consequently, the data-centric networks enable a systematic spatial monitoring of the sensor field. When the exact location of a particular phenomenon is unknown, distributed sensing allows a closer placement to the phenomenon than a single sensor would permit. Indeed, data-centric routing is perhaps also the core abstraction of extensive sensor networks.

TABLE I. COMPARISON OF MAIN ARCHITECTURAL PARADIGMS IN EXTENSIVE AND INTENSIVE SENSOR NETWORKS

<table>
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<tr>
<th>Comparison of Main Architectural Paradigms in Extensive and Intensive Sensor Networks</th>
<th>Extensive Sensor Networks</th>
<th>Intensive Sensor Networks</th>
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<tr>
<td>Detection of event of interest in a sensor field</td>
<td>Collective detection by multiple nodes</td>
<td>Singular detection by individual nodes</td>
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<td>Routing</td>
<td>Data-centric</td>
<td>Node-centric</td>
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<td>Spatial data collection</td>
<td>From a specific area</td>
<td>From a selected device</td>
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<td>Deployment</td>
<td>Systematic coverage of a sensor field</td>
<td>Selected points of interest in a sensor field</td>
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<td>Sensor device location</td>
<td>Random (unknown a priori)</td>
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</tr>
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<td>Self-organizing</td>
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<td>Data aggregation</td>
<td>In-network processing and aggregation</td>
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<tr>
<td>Processing power and memory size of a single node</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Functionality of a single node</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Battery/power supply</td>
<td>Irreplaceable</td>
<td>Replaceable</td>
</tr>
<tr>
<td>Communication</td>
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<td>Architectural paradigm</td>
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<td>Design objective</td>
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<td>Throughput/delay characteristics</td>
</tr>
</tbody>
</table>

Instead, the node-centric networks are able to gather data from a selected points of interest (e.g., a room), where the knowledge of the spatial distribution of a physical magnitude being measured is not important. Then, a location of the sensing device is “deterministic”, i.e. known a priori. In the extensive network, the sensors are deployed in ad hoc manner at random locations in a field (e.g., from an airplane), thus its location is not known a priori, and must be determined later. It is up to the nodes to identify their localization, see [14] for one of the localization techniques. The densely deployed wireless networked systems must thus have self-organizing capability.

E. Design Optimization

The sensing devices in the extensive networks are battery-powered and use almost exclusively the wireless communication. Then, a main constraint of wireless sensor devices is the limited battery life. The average battery lifetime is of a number of months. Usually, it is either impossible, or impractical to replace batteries so the operational lifetime of the sensor device is equal to its battery life. The only option to lengthen the sensor lifetime is to reduce the waste of energy in a device operation. Thus, all the aspects of network operation (e.g., MAC protocols design, routing, etc.) are focused on efficient energy management. The performance of extensive networks is of secondary importance in system design.

Wireless communication is a major source of energy consumption. Since every message uses up the low device energy resources, the number of messages sent through the sensor network should be as low as possible. It is worth being aware that every bit transmitted can reduce the lifetime of the wireless sensor network [10]. The communication dominates data processing in energy consumption. In a typical scenario, a sensor node can execute 3000 instructions for the same energy cost of sensing a single bit at the distance of 100 meters by radio [13]. The sleep mode together with the event-based data collecting (i.e. send-on-delta concept) might be used to minimize the waste of energy [9].

The intensive networks are wired or wireless. Even if devices are battery-powered, the energy consumption is at most of secondary importance since the battery might be replaced as needed. The main objective of the intensive network design is to optimize its performance, first of all, the channel throughput and the channel access delay.

As stated, the extensive networks are almost exclusively wireless. The transmission media different from radio communication are also occasionally considered, e.g., optical communication or ultra-sound for underwater-applications.

F. Node Functionality and Processing Resources

In general, the node processing and storage capability in the intensive networks are relatively high, especially in the system with peer-to-peer architecture. In LON systems they are determined by the Neuron Chip microcontroller resources. As mentioned, the Neuron Chip is a multiprocessor system-on-chip handling the protocol stack and executing the application program.

On the other hand, the extensive networks exploit quite simple microcontrollers, such as Atmel or the Texas...
Instrument MSP 430. The individual nodes in dense sensor networking have a limited capability, and are intended only to respond to events of interest in a sensor field. However, they are capable of achieving a big task through coordinated effort in a network.

Next, functionality of a typical LonWorks device is wide-ranging and offers a variety of application programming techniques: detection of predefined events in hardware, concept of network variables, event-driven task scheduling, authentication, client/server support, etc. Each node has operational autonomy, and might be reprogrammed if needed.

The architectural paradigms that have been compared throughout Section 3 are summarized in Table 1.

IV. CONCLUSIONS

Indeed, the today’s sensor networking is the eclectic technology where the old and the new ideas coexist. They are designed in a variety of ways to address different priorities and make the appropriate technology tradeoffs according to specific application requirements.

Although several commercial platforms are introduced to the market, wireless sensor network domain is still a subject of stormy scientific debate with numerous novel concepts and contributions proposed. Some underlying problems are not yet completely solved, and many techniques are not ultimately established. The practical implementation of various innovative solutions are not available yet. Nevertheless, a great attention of researchers and engineers builds hope that these problems could be resolved in the near future.

Intensive and extensive sensor networks technologies supplement each other in a complementary way. This short study does not aspire to be a comprehensive survey of all the aspects of both paradigms. We want just to indicate fundamental differences following the distinct application demands. Such a classification matches roughly the distinction between networked sensor/control systems for industrial applications and the technology of dense wireless networking for environmental monitoring. However, the boundary between application classes representative for both technologies is not sharp, and depend on user requirements.

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