Industrial Internet Education: Issues and Opportunities

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***Abstract*—We propose an approach for addressing the challenges and meeting the needs of industrial networking education. The approach is based on using open source resources, key networking technologies, and an experimental framework to revolutionize the way industrial networking ought to be taught at higher learning institutions around the world. Based on the approach a new type of industrial networking course has been designed, developed, and offered with positive outcomes.**

Keywords—Internet of Things, Industrial Internet, Educacion, Industrial Networks, Industrial communications and protocols.

I. Introduction

Teaching and learning industrial communications in a university environment has always been challenging due to the broad and specialized nature of some of the topics and the requirement of tailored and often costly equipment and laboratories. At most schools, the approach being used to teach industrial networks is to base it on traditional computer network courses, supplemented with material involving some industrial equipment such as PLCs. The time is ripe for a new approach for teaching and learning the subject of industrial communication networks at universities and technical institutes around the world that appears promising to overcome some of its challenges. This is so because we are at at the frontier of a new wave of networking technologies and endeavors that promise to significantly change the landscape of networking in general and more specifically the industrial sector including its education and training aspects.

Currently, the field of computer networking is very broad covering subjects ranging from fundamentals, protocols, routing, reliable data transfer, Internet, devices, wireless, security, standards, network management, performance, multimedia, software defined networking (SDN), virtualization, applications, etc. There are a number of excellent textbooks on the subject to choose from [1-3]. If one adds subjects related to industrial systems then the number and nature of subjects increase, making the design of industrial networking courses difficult. What should be the main criteria for choosing appropriate topics and experiments for such a course? By far, the answer to this question is not trivial. The first author for this paper wrote one of the first textbooks on industrial networking but the approach used to write such textbook is no longer applicable today [4]. This problem is compounded if the course or materials includes laboratory experiments using industrial networks.

It is not that there is a lack of good industrial networks to choose from, far from it. In fact, the technologies of industrial networks are quite mature in some respects and there are several successful and widely used industrial networks around the world such as Ethernet/IP, Profinet, EtherCAT, Modbus, HART, Foundation Fieldbus, Profibus, and countless others. While these networks work extremely well in their industrial niches, they are complex, difficult, and often too costly to be used in a teaching and learning environment at universities. Thus, these networks succeeded at their main goal, effectively interconnect industrial devices in their application field and thus they are very specialized at what they do. There are of course industrial training courses that cover these networks but they are aimed at objectives that include operation, installation, commissioning, maintenance, and troubleshooting aspects and not at learning and understanding industrial computer networks at a more fundamental level [5]. Thus these industrial networks and courses are not well suited for universities where the aim is to teach at more fundamental and generic levels.

Why are we at a frontier of a new wave of networking technologies that promises to significantly change the landscape of teaching and learning industrial networking? The reason is that important paradigms, key efforts , and key technologies are converging to deliver powerful solutions in the networking landscape. The key paradigms that are beginning to bear fruit are the so-called Internet of Things (IoT) and Industrial Internet (II), the key efforts include the availability of powerful open source solutions that include both software and hardware, and the key technologies include software defined radio (SDR), cognitive radio, new standards (particularly wireless in the family 802.11xy), and the widespread availability of low cost microcontrollers and development environments.

As noted, there are two recent paradigms or frameworks that are taking shape called the Internet of Things and the Industrial Internet [6-11]. Although some of the concepts in these two important paradigms are similar, in this paper we view II as a subset of the IoT dealing only with industrial applications. Practitioners have coined other similar terms for these frameworks or their components, such as M2M (machine to machine) and Manufacturing Internet of Things (MIoT). There is a great deal of worldwide interest in these endeavors and the level of dynamics is high [12-14].

Whereas IoT is a much wider concept that covers all of the possible applications areas of the Internet, Industrial Internet covers areas strictly related to industrial systems and applications. The Internet of Things is an interdisciplinary concept that can be realized in three paradigms—internet-oriented (middleware), things oriented (sensors) and semantic-oriented (knowledge). The main IoT elements include Radio Frequency Identification (RFID), Wireless Sensor Networks (WSN), Addressing schemes, Data storage and analytics, and Visualization [6]. The Industrial Internet brings together the advances of two transformative revolutions: the myriad machines, facilities, fleets and networks that arose from the Industrial Revolution, and the more recent powerful advances in computing, information and communication systems brought to the fore by the Internet Revolution. In essence, the Industrial Internet brings together three interconnected elements: intelligent machines, advanced analytics, and people [11].

Nevertheless, the underlying technologies of the Internet of Things and the Industrial Internet are similar and include three main areas: embedded systems, connectivity, and applications [9]. By connectivity it is meant to include all aspects of networking, internetworking, interconnectivity among all possible types of devices and people, particularly across application domains (i.e., horizontal connectivity rather than vertical connectivity). The critical connectivity technologies of the IoT and Industrial Internet are at the edge of the Internet (i.e., layers 8[1], 7, 2, and 1 of the OSI reference model) rather than at the core (OSI layers 4 and 3). Core technologies, particularly TCP, UDP, IP, ICMP are well established and work extremely well and do not present mayor problems with their use, the only exception being the existence of important configuration (i.e., setup) issues. There are also protocols specifically designed for the IoT such as MQTT and MQTT-S [15]

Open source resources have a long and rich history that continues to this day with important components such as Linux, gcc (GNU C Compiler), Apache, and countless others that are readily available for free. The significance of the open source framework is that it continues to evolve and offer significant environments, developments, and tools, and this evolution includes not only software but complex hardware as well. For example, early in 2013 we witnessed the introduction of the first, Arduino like design, complete open source SDR (software defined radio) on a chip, the LMS6002D, offered by the company Lime Microsystems (www.limemicro.com). This is significant because it was the first time that such a complex device and design was made available and in this way opening the door to the world of open source RF (radio frequency) developments with important implications in the wireless industrial communications community.

Although fairly unusual in the industrial networking landscape, the Modbus protocol can also be considered an open source resource as explained in their website: www.modbus.org Modbus, one of the oldest industrial protocols initially developed by Modicon (now Schneider Electric) in 1979, is widely used today due to its simplicity and open nature and is currently maintained by the Modbus organization.

There are many key networking technologies that have recently appeared or will appear shortly, which will be relevant for industrial networking education. Although difficult to predict with certainty, we believe the following are crucial today or will be shortly: SDR, cognitive radios, new WiFi standards, and low cost microcontrollers. Software defined radios (SDR) and cognitive radios, closely related fields, are proving their effectiveness at addressing significant wireless communication issues and thus effectively making them extremely relevant for interconnecting industrial devices in a wireless fashion. With SDR and cognitive radios it is possible to overcome multiple communication problems such as multipath propagation, low signal to noise ratio, hidden terminal problems, high signal attenuation, flexible use of frequency bands, and others. It is precisely due to the effectiveness of SDRs and cognitive radios that some of their principles or components have been incorporated into the latest available or soon to be available WiFi standards in the family 802.11xy such as 802.11ac, 802.11af, and 802.11ah that are particularly promising for industrial networks because they overcome issues of extended coverage and high throughput. Extremely low cost microcontrollers and single board computers are also crucial because they enable the low cost implementation of Internet technologies in all sorts of small and tiny devices. A short list of latest and currently available low cost microcontrollers or single board computers with Ethernet interface include Arduino, Raspberry Pi Model B, BeagleBone Black, Parallella, Odroid-X2, Hackberry, Udoo, APC Rock, Cubieboard, Marsboard, A13-OlinuXino, and others. The availability of these devices are crucial because they enable a simple and cost effective implementation of effective laboratory experiments and interesting industrial internet projects. The suggested experiments to be described later can be implemented in any of these extremely low cost and small single board computers.

There is no doubt that we have left out other important technologies that include RFID, WSNs (wireless sensor networks), WiMax, cellular (3G, 4G, and 5G), LiFi, and many

[1] Although the OSI reference model only defines 7 well known layers, some industrial networks such as Foundation Fieldbus and Profibus define important mechanisms above layer 7 that we call layer 8.

others. Ultimately the criteria for selecting key technologies are the degree of maturity of the technologies and their applicability for educating the next generation of industrial networking professionals.

II. CURRENT INDUSTRIAL NETWORKING EDUCATION NEEDS

We have identified several needs as it applies to the current industrial networking education field. The first need is to have a balance of appropriate networking topics and the inclusion of appropriate material of an industrial nature. As noted, the networking field has advanced so much that there could be dozens of academic networking courses each specialized on certain topics such as routing, Ipv6, wireless, security, internetworking, multimedia, peer-to-peer (P2P) protocols, voice over IP (VoIP), virtualization, cloud networking, etc. but are these topics appropriate in an industrial networking course? The problem is compounded with a similar set of industrial topics ranging from sensors, actuators, control systems, I/O subsystems, Electric drives, PLCs, NC machines, process automation, factory automation, manufacturing automation, DCS, CIF (control in the field), SCADA, M2M devices, etc.

Another need is to have appropriate laboratories with industrial devices, components, or equipment and use them in experiments, case studies, demonstrations, capstone projects, thesis projects, research projects, etc. Although this is done somewhat at some schools, having a good set of such resources is challenging due to cost considerations and the issue of industrial protocols not being generic enough to work outside their niche application area. Indeed, in some application areas, e.g., process automation with intrinsic safety, having sensor nodes is almost prohibited for some schools due to their high cost.

Still another need is to have more generic and simple industrial protocols and networks. For example, there is a big difference in simplicity with the Modbus (both Serial and TCP versions) and protocols such as Ethernet/IP and Profinet. The latter are complex and proven protocols for manufacturing automation that solve many problems in a multivendor environment. Modbus is a simple and also proven protocol for applications involving data acquisition, monitoring, and measurement. Yet, Modbus does not have the rich functionality that Ethernet/IP and Profinet offer. We are beginning to see protocols specialized for the IoT such as MQTT but we need additional simple and generic protocols with appropriate functionality.

Yet another need is to have a good set of appropriate and well developed tools, particularly in the open source category. Again, the success of the Internet is partly due to the availability of powerful tools from the very beginning including telnet, rpc, ping, traceroute arp, dns, dhcp, and others. No such set of free (or inexpensive) generic and powerful tools exist for industrial networks. Lastly, we need more educational materials for industrial networking in various formats that include lecture materials, course notes, syllabus, textbooks, laboratory manuals, etc.

III. APPROACH

So, how do we go about and begin addressing some or all of the above issues with industrial networking education? We suggest that we begin using precisely the momentum of the IoT and II (Industrial Internet), the open source solutions (both software and hardware), and the new wave of key networking technologies that is currently changing the indusrial communication landscape to address the issues and meet the needs of industrial networking education listed above. But we need to do this in a simple, generic, and flexible way as it was done with early Internet protocol and associated tools. This approach appears simple enough. IoT and II are gaining momentum. Open source, by definition is free or almost free, and using latest key networking technologies to revolutionize industrial networking education appears too good to be true.

However, following this simple recipe is much easier said than done. To begin with, the paradigms of IoT and Industrial Internet are still fuzzy, not fully developed, and with many missconceptions and disagreements even with people working in the field. Our approach is based on the following:

- Focus on the subject matter at hand (industrial networking education)
- Simplicity principle
- Depth-first and breath-next (DFBN) principle

It is important to select appropriate open source tools and key technologies that are simple not only in their approach, their use, their functionality but also in their application. Using this principle we have selected the following tools and technologies:

Tools: Mach3, Pymodbus, Wireshark, GNU radio, IntegraXor, Linux networking tools
Low Cost Computing: Arduino, Raspberry Pi.
Key technologies: SDR, cognitive radio, 802.11xy, 802.15.4, Myriad Family of Boards
Industrial Protocol: Modbus

To begin with, since we are dealing with the Industrial Internet, it is understood that we are using the well known underlying protocols including Ethernet, IP, UDP, TCP, ICMP, HTTP, SMTP, and DNS and we do not mention them explicitly in the above list. The selection of the Modbus protocol may surprise some readers but its choice was based on its simplicity and open nature. Although not open source, Mach3 (http://www.machsupport.com/software/mach3/), a commercial tool, was also selected because it is free to use unless used in conjunction with actual equipment it supports. Pymodbus is a Linux based complete implementation of the Modbus protocol, both the RTU and TCP versions. Wireshark is a well known network sniffer tool for the analysis of Internet protocols and countless others including Modbus. GNU radio is a tool for the analysis and design of rf communication systems including cellular, 802.11xy, and 802.15.4 technologies. Lantz is an open source software environment to design and implement automation and instrumentation virtual instruments with Internet connectivity. We have selected SDR, cognitive radio, 802.11xy, and 802.15.4 because we believe they are key for current and future wireless industrial networking.

The depth-first and breath-next (DFBN) principle consists of delving into an endeavor deep first (this is the depth component) and next consider its breath. Covering the vast industrial networking area comprehensively but only superficially would be breath-first and this approach is not recommended as in depth insights, experience, and knowledge is difficult to be gained. On the other hand, covering the vast industrial networking area comprehensively and in depth is not possible because there is not enough time, expertise, knowledge, and resources to do this. Yet, covering a subject area in depth, including theoretical, experimental, and practical aspects is arguably the best way to really master such subject. Thus, given that it is practically impossible to cover all topics in depth, the DFBN principle is to select only a few topics to be treated in depth and treat the remaining ones in the breath fashion. We considered several well established industrial protocols and selected the Modbus network precisely because it enabled us to use the DFBN principle and because it is a simple protocol enabling much simpler and less costly analysis and experimentation compared to other industrial networks. This was made possible using an open source implementation of Modbus/RTU on Arduino. Later on, we implemented Modbus/TCP on an Arduino as part of a *distributed control system* over an Industrial Internet platform (patent pending).

IV. IMPLEMENTATION

Now that we understand the context, the need, and the approach how do we actually design an effective curriculum or a course on industrial networking? We suggest to begin with the main modules of the curriculum or course, i.e., main fairly large areas of knowledge or technology that could later be separated under more specific courses, chapters, or lectures. Even if we do this there are other choices. For example in industrial systems, do we start with small devices, sensors, components, and move to the more integrated, system level or viceversa? In networking there is a similar choice; do we begin at the physical layer and move gradually to the application layer of the OSI reference model? We suggest to start at the highest level which is the system or application level and move to the nitty-gritty details gradually, to lower levels of abstraction and implementation and this option is called the top-down approach with the book of Kurose and Ross [1] being one of the first to use this option successfully.

Once the modules and chapters have been decided, the associated laboratory experiments should be developed simultaneously. It is likely that some of the experiments will be challenging to develop, to implement, and to describe them in lab instructions. At the end of the instructions of the laboratory experiments, the instructor should develop a set of thoughtful questions for the student designed to make them think of other aspects of the material not explicitly covered by the experiment, or questions designed to spark their interest and further study or experimentation on the subject matter.

Based on the above implementation guidelines, we have come up with the following. We have developed 10 modules in two categories, monolithic and distributed. Monolithic modules consists of materials that can be covered in bulk fashion in separate but fairly self-contained chapters or sections and in contrast, distributed modules consists of materials that are covered through the entire curriculum or course as needed. The monolithic modules are:

1. Introduction
2. Main applications
3. Main Industrial Networks and Protocols (Emphasis on Modbus)
4. Higher Layer Protocols
5. Lower Layer Protocols
6. Wireless networking
7. Emerging technologies

The distributed modules are:

1. Low cost microcontrollers and development environments
2. Open source developments and tools
3. Security

As the name implies, the *Introduction* module serves to introduce the subject matter emphasizing the emerging paradigms of the IoT and Industrial Internet together with the approach used. A high level thorough introduction to computer communications and industrial systems should also be provided. The module on *Main industrial applications* details main industrial sectors, types of applications (data acquisition, monitoring, synchronization, control, and measurement), main application domains (process automation, factory automation, manufacturing automation, etc.) and their communication requirements. An overview and summary of the main industrial protocols and networks is provided in the *Main Industrial Networks and Protocols* module that includes Ethernet/IP, Profinet, Modbus, EtherCAT, Foundation Fieldbus, Profibus/PA, and HART with Emphasis on Modbus/RTU and Modbus/TCP because they are the protocols used in most laboratory experiments. The module on Higher Layer Protocols should provide a summary of Internet protocols HTTP, SMTP, DNS, TCP,UDP, IP, the application layers of Modbus/RTU and Modbus/TCP, and details of the application layer of selected industrial networks, e.g., Ethernet/IP. Likewise, the module on Lower Layer Protocols should provide a summary of Ethernet, and details of the lower layers of selected industrial networks, e.g., Profibus, DeviceNet, and Foundation Fieldbus. As the name implies, the module on *Wireless networking* discusses communication protocols in a wireless environment with emphasis on IEEE 802.11 and 802.15.4 protocols and standards. Finally, the module on *Emerging technologies* discusses the latest developments or trends such as IPv6, SDR, SDN (software defined networking), cognitive radio, virtualization, etc. and their implications on future technology, standards, and applications in the industrial landscape.

Following the approach suggested in this paper, we have developed, tested, and offered them in an industrial networking course at UTEC a set of experiments to support each module. The main experiments associated with the monolithic modules are:

1. Manufacturing device communication with Modbus/RTU
2. Distributed PLC application with Modbus/RTU
3. A security system
4. Industrial Internet protocols: Upper layers
5. Modbus/TCP
6. Distributed Control Systems (DCS) with Modbus/TCP over wireless links
7. Industrial Internet protocols: Lower layers
8. Design of a SCADA system

In the experiment *Manufacturing device communication with Modbus/RTU*, we use a commercial application called Mach3 for small NC machines which includes a Modbus interface and a Modbus/RTU implementation on an Arduino. The main goal of the experiment is to extend the I/O capability of an NC machine controlled by Mach3 by using all of the extended I/O pins of the Arduino UNO. Mach3 also includes a small but highly functional PLC that is used in the *Distributed PLC application with Modbus/RTU* lab experiment to provide distributed functionality to a PLC application. A highly functional but sturdy security system to protect access to property such as houses, apartments, building, industrial sites, etc. is undertaken in the experiment *A security system*. The experiment *Industrial Internet protocols: Upper layer*s actually covers several experiments to provide experience with HTTP, TCP, UDP, and IP. Details of *Modbus/TCP* is provided in the experiment by the same name. One of the most interesting experiments is *Distributed Control Systems with Modbus/TCP over wireless links,* which covers the design and implementation of a complete distributed control system implemented on Arduinos having an implementation of the Modbus/TCP protocol. In the experiment *Industrial Internet protocols: Lower layers,* we concentrate on the details of layers 1 and 2 of Modbus/RTU. The experiment *Design of a SCADA* system is a sort of capstone experiment where the objective is to design a SCADA system from scratch using *IntegraXor*, an open source tool for designing SCADA systems [16].

Implementation Issues. Most of the experiments used a wireless Ethernet interface implemented using a WiFi Shield for the Arduino UNO board and this posed a variety of networking problems including security issues and a low level of reliability provided by the Arduino WiFi shields. These problems are overcome as more experience is gained by trying the numerous simple experiments that come with the WiFi Shield software. The security problem can be overcome by using an ad-hoc (i.e., rather that using a University inftrastructure one) WiFi Access Point with incorporated router. For example, in the DCS experiment with wireless links, the nodes in the distributed system could not establish a connection even though the nodes obtained their IP address from the same Access Point. We attributed this issue to security policies by the University and the fact that they recently upgraded the wireless infractructure to use 802.11n with a high degree of security. We solved this problem by using a dedicated and much older Access Point.

Assessment. The approach needs to be validated and this can be performed through a proper assessment that will be done in the near future and will have three components: student assessment, UTEC faculty assessment, and external assessment. The results of these assessments will be made available in a separate publication.

V. BENEFITS

The main benefit of the proposed approach is that, by design, a more appropriate or tailored curriculum or courses can be constructed, one that takes into account the latest trends and advances in the field, and one that is experimental based with well thought out laboratory experiments. Also by design, the laboratory experiments are based on open source hardware and software or commercially available counterparts that are either free to use or very inexpensive. If the approach is implemented right, the curriculum and courses should result in deep learning of the principles, intricacies, and applications of industrial networking rather than simply a collection of operation, installation, commissioning, maintenance, and troubleshooting lectures and experiments. This sort of deep learning is difficult to achieve if we use commercially available industrial networks because the materials in these types of courses include additional material on the company culture and their way of doing or implementing things. In addition, a great deal of the information is considered confidential and therefore, not open. Likewise, if the approach is implemented right, the curriculum and courses that result should enable and encourage students further experimentation, development, and even research. The suggested modules and experiments are appropriate for undergraduate or beginning graduate level courses. Nevertheless the complexity of some of the environments and tools clearly support more advanced research and development such as doctoral dissertations.

Another important benefit is that this approach enables unprecedented flexibility for learning and experimenting with industrial networks at minimum costs. Because we are dealing at fundamental or basic levels, in terms of protocols, tools, programming, interfacing, etc. there is a great deal of flexibility to re-arrange modules, interfaces, protocols, programs, implementations, etc. and end up with different versions of experiments, developments, or projects. Such level of flexibility and costs is unheard of in the commercial landscape of industrial networks.

Lastly, it is hoped that the proposed approach enables and encourages further innovation in critical areas. A great deal of innovation is already happening in the IoT and Industrial Internet frameworks. It is hoped that educational materials such as this will contribute to address important needs, tackle difficult problems in fundamental ways, and address important challenges to materialize the frameworks of IoT and Industrial Internet. Hopefully, many innovations and inventions will result. In fact, this approach has already inspired one possible patent we are pursuing in Peru and soon in the USA.

VI. SUMMARY AND CONCLUSSIONS

Teaching and learning industrial communications in a university environment has always been challenging but there is currently an outstanding opportunity for overcoming some of the most significant challenges. This is so because recent developments in the Internet of Things, Industrial Internet, open source resources, and key networking technologies promise to significantly change the landscape of networking in general and more specifically the industrial sector including its education and training aspects. Some of the key technologies include software defined radio (SDR), cognitive radio, new standards (particularly wireless in the family 802.11xy), and the widespread availability of low cost microcontrollers and development environments.

There are currently several educational needs in industrial networking education that include having more emphasis on industrial content, with more appropriate materials, syllabus, textbooks, manuals, and lab experiments, having more cost effective, generic, and appropriate lab equipment, having more experiments, case studies, experimental studies suitable for academic courses, and having more general purpose industrial networking tools, free of cost or at very low costs. We have proposed an approach that consists of using available open source resources and key technologies in a simple fashion and using the DFBN (depth-first and breath-next) principle. Using the approach we designed a course on industrial networking and ended up with 7 bulk modules, 3 distributed modules, and 8 fully worked out laboratory experiments.

The benefits of the approach include more appropriate and tailored course materials, less expensive or free laboratory resources including tools, a process and materials that enable deep learning and experimentation, a process that enables unprecedented flexibility and cost effectiveness, and a process that enables innovation. We have developed an industrial networking course at UTEC in Lima, Peru and offered it during the fall of 2013 with positive outcomes.

ACKNOWLEDGMENTS

J. R. Pimentel thanks the colleagues at UTEC and TECSUP (www.tecsup.edu.pe) for their help with some experiments and helpful discussions.

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