MOBILE COMMUNICATIONS AND NETWORKS

A Square Peg in a Round Hole: The Complex Path for Wireless in the Manufacturing Industry

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ABSTRACT

The manufacturing industry is at the edge of the fourth industrial revolution, a paradigm of integrated architectures in which the entire production chain (composed of machines, workers, and products) is intrinsically connected. Wireless technologies can add further value in this manufacturing revolution. However, we identify some signs which indicate that wireless technology could be left out of the next generation of smart factory equipment. This is particularly relevant considering that the heavy machinery characteristic of this sector can last for decades. We argue that at the core of this issue there is a mismatch between industrial needs and the interests of academic and partly academic sectors (e.g., standardization bodies). We base our claims on surveys from renowned advisory firms and interviews with industrial actors, which we contrast with results from content analysis of scientific articles. Finally, we propose some convergence paths that, while still retaining the degree of novelty required for academic purposes, are more aligned with industrial concerns.

INTRODUCTION

The success of wireless communication is unquestionable today. Wireless technologies have become a commodity in our society, in which ubiquitous connectivity of mobile gadgets, wearables, and home appliances is the norm. Connection to wireless networks is now possible in a range of scenarios, including urban, rural, indoor, and transportation systems. Some industries have also integrated wireless communications in their operations. To name a few, wireless is now present in critical infrastructure monitoring, logistics, traffic management, utility metering, and healthcare solutions. However, despite the efforts to provide industrial wireless solutions, some sectors seem resistant to widespread adoption. This is the case, to a large extent, for the manufacturing industry, including the manufacturing process, electronics, aerospace, automotive, and machine tool sectors.

The lack of massive adoption of wireless technologies by the manufacturing industry should be at least somewhat surprising to academics. The efforts over recent years dedicated to transforming wireless technologies into suitable industrial solutions have been huge [1]. The Industrial Internet of Things (IIoT), which should enable the hyper-connected vision of Industry 4.0 (Fig. 1), has indeed gathered the interest of many researchers. Plenty of solutions have been designed to cope with industrial requirements or, more precisely, with what academics believe manufacturing industrial requirements are. Despite these efforts, it is not by any means clear when this massive adoption will occur and, more importantly, what are the reasons for this apparent delay.

It seems that industry is indeed aware of potential wireless benefits. Wireless has succeeded in other industrial sectors (e.g., chemical, oil, and gas). In these factories, most of the flow metering equipment used the Highway Addressable Remote Transducer (HART) protocol, a fieldbus protocol designed in the 1980s. Later, in the 2000s, a wireless extension of HART was promoted by a consortium of 37 leading companies in order to bring wireless connectivity while keeping protocol features and semantics. WirelessHART became a natural evolution that succeeded in these factories. Thus, if the technology seems ready and industry is aware of its potential benefits, the question arises: Why is wireless not yet succeeding in the manufacturing sector?

This article attempts to gain insight into that question with special focus on the role of academia and partly academic actors (e.g., standardization bodies). In particular, we:

• Use different indicators to assess the penetration of wireless technologies in the manufacturing industry. Direct evaluation is beyond our means, so we rely on opinion surveys conducted by renowned advisory firms (e.g., Gartner and Morgan Stanley), interviews with industrial representatives, and the inspection of machinery portfolios.
• Point out the potential causes preventing wireless adoption by this sector based on the information gathered.
• Carry out an honest self-reflection exercise to analyze to what extent academia contributes to this lack of success. As a result, we identify and examine a mismatch between research directions and industrial reality.
• Devise academic-industrial convergence paths to move forward, hoping to contribute to the materialization of a wireless industrial revolution in the upcoming years.
Note that this article does not aim to analyze industrial barriers related to internal organization, accountability, upfront investments, or functional strata. It also does not aim to delve into other potential barriers such as the lack of predisposition of the manufacturing sector toward promoting research activities. Although probably equally important to the barriers discussed in this article, these other obstacles are beyond both our expertise and the scope of academia.

A REALITY CHECK

In this section we analyze the status of the IIoT and assess the level to which wireless has been adopted by the manufacturing industry based on indicators such as surveys from advisory firms, interviews with industrial actors, and portfolio inspection.

PREDICTIONS AND STATUS OF THE IIoT

In the 1990s, the Internet revolution redrew the business-to-consumer 21st century’s sectors such as the media, retail, and financial services. Likewise, the Internet of Things (IoT) is destined to completely redefine other sectors such as manufacturing, energy, agriculture, and transportation [2]. Although the change seems imminent, the rate of development may not be homogeneous in these different sectors.

In 2011, in a famous white paper that is still widely cited today, Cisco predicted 50 billion connected devices by 2020 [3]. Nowadays, approaching 2020, the forecasts are more conservative, calculated according to different sources between 20 and 30 billion [4]. One of the reasons for this downward revision can be attributed to more conservative sectors, among which the manufacturing industry stands out.

The manufacturing industry is expected to evolve toward a distributed organization of production with connected products, equipment, processes, and logistics [5]. These new interactions may result in unprecedented levels of productivity and operational efficiency. Companies, however, are still struggling to understand this conceptual step and, above all, to demonstrate how this concept can bring value to their operations [2]. Even though there is unquestionable interest in adopting new solutions [6], most enterprises do not know what to do with the broad spectrum of new technologies. This fact, along with other important barriers such as concerns about cyber-security, interoperability, and upfront investment [7] are slowing down adoption, at least considering the most optimistic forecasts.

A recent report from Verizon [8] indicates that although IoT is still not part of the manufacturing process, interest in it is high enough to expect high levels of adoption in the years to come, mainly to improve operational efficiency and productivity. This is precisely why the manufacturing industry is considered the sector with the greatest growth potential [7]. With high probability, we may be at a turning point.

INDICATORS OF WIRELESS ADOPTION

Building upon the conclusions above, we now aim to get more insight into the current level of penetration of wireless in this industry. As a first step, we look at the penetration of Industry 4.0 in the manufacturing sector, as wireless technologies are considered to be among its technological enablers. Infosys published a survey of more than 400 manufacturing companies across five regions (China, France, Germany, United Kingdom, United States) conducted in 2015 [9]. The results showed that the penetration of Industry 4.0 in this sector was low. That is, only 15 percent of the surveyed companies have implemented dedicated strategies for asset efficiency. Industry 4.0 may or may not include wireless technologies, so we can infer from this report that the penetration of wireless technologies may be even lower.

Despite having some limitations, another way to assess wireless adoption is to perform targeted interviews with prominent actors. In the second half of 2017 interviews were carried out with the maintenance and engineering teams of pioneering manufacturing industries in the automotive, pharmaceutical (blistering), machinery, and industrial robotics sectors [10]. These interviews revealed that none of these industries had wireless technologies integrated in their processes.

Another indicator is the availability of products with wireless I/O modules in the portfolios of industrial automation companies. We surveyed the portfolios of Rockwell Automation, ABB, Emerson, Schneider Electric, Honeywell, and Mitsubishi Electric. We observed that wireless modules are not typically integrated in their products. Indeed, with the only exception of flow meters and sensors, we did not find any industrial equipment with integrated wireless (the common practice is to offer external wireless modules that can be attached to their products). While the absence of wireless in native equipment does not provide a quantitative measure of the degree of wireless penetration, it is indeed an indicator that the use is not widespread. Otherwise, we would expect the offer of machinery with integrated wireless to be the norm.

WIRELESS SHORTCOMINGS

One of the main obstacles identified in our interviews is the poor perception of wireless technologies, especially regarding reliability [10]. Moreover, industrialists are particularly reluctant to change something that is already working rea-
reasonably well. This can be seen as a manifestation of resistance to change, but it is also a rule derived from the industrialist’s experience. The adoption of wireless in the manufacturing process may introduce new problems alien to the technologies being replaced. For example, one of the most obvious advantages of wireless is its lower installation cost. However, in many companies, the cost of stopping a production line due to a failure in communications can be much higher than the cost of wiring during installation (which occurs before scheduled stops). The industrialist must be aware of the current limitations of wireless technologies that are relevant to industry so that we can devise ways forward. We review these next.

**PERFORMANCE AND RELIABILITY**

No one will adopt a new technology that does not offer at least similar features as the one being replaced. The new technology must be mature enough for the replacement to run smoothly. Although bandwidth may not be an issue (in many factories communication systems are over-dimensioned), it is still not straightforward for wireless systems to reach the level of reliability required by the manufacturing industry. This sector, indeed, is especially sensitive to reliability, as commercial margins are minimal, and therefore production lines are extremely optimized.

The attempts to increase performance and reliability in the WiFi arena have been focused on eliminating collisions, but either the solutions are not available in commercial cards (e.g., PCF and MAC do not meet the requirements) or they do not provide the expected optimization. In IoT, common techniques are to allocate resources deterministically and perform frequency hopping to deal with the unreliable nature of the wireless medium. However, being optimized under a low energy constraint, these protocols provide very limited bandwidth. Other more suitable technologies, such as fifth generation (5G) ultra-reliable low-latency communications or millimeter-wave (mmWave), are either still in their infancy or have not yet been considered for these use cases.

**Obsolescence and Technology Cycles**

When a technology becomes obsolete, change is unavoidable. However, the life cycles of some industrial technologies seem to be never-ending. Some protocols still in use today, such as RS485, date from the 1970s. But when the time for change comes, there is the perception (actually well-founded) that obsolescence, the life cycles of wireless, are much shorter than that of wired technologies. The constant emergence of new technologies and their vertiginous evolution, which could be seen as an advantage, is a handicap from an industrial perspective. Indeed, the adoption of wireless technologies generates uncertainty in aspects as important as long-term maintenance and technical support. An example that illustrates this uncertainty is ZigBee, which, after 15 years of being standardized and several revisions, has not consolidated. Meanwhile, many other competitive alternatives have appeared on the market.

**Fragmentation**

There is a perception of a fragmented wireless market. Fragmentation provides opportunities but at the same time introduces uncertainty to non-expert adopters. Aside from the complexity of decision making, industrialists ask themselves how a technology will evolve and, above all, who is supporting this evolution. The current wireless landscape is not favorable. Multiple technologies have been standardized, and many proprietary alternatives are constantly being offered [1]. To name a few, we can mention, in wireless short-range and mesh networks, DECT-ULE, WirelessHART, ISA100.11a, 6TiSCH, Zigbee, Z-Wave, Thread, WiFi, and BLE/Mesh [12]. In the long-range space we can find Wireless M-Bus, LoRAWAN, Sigfox, Weightless, Ingenu, DASH7, WISUN, and NB-IoT, among others [13].

In turn, standardization committees are isolated in the creation of their own communication protocols, and these are rarely designed for interoperability, particularly if they compete for a dominant position. As an example, there is a lack of interoperability of wireless protocols such as ISA100.11a, WirelessHART, and 6TiSCH, all of them addressing similar scenarios and using the same physical and medium access control (MAC) layers.

**Security**

Wireless technologies undoubtedly introduce security concerns for industry. Typical connections in plant floors are wired, which means that there is a physical barrier for a potential attacker. In contrast, wireless systems are prone to attacks from outside the factory premises. While there has been considerable research effort dedicated to secure wireless communications, the perception of the industry is that wireless may expose their systems in some way. The cost of a security attack is too high for an industrialist to assume, especially when there are alternative wired solutions available that intrinsically minimize security issues.

**The Industry-Academia Mismatch**

Research can be a fundamental enabler for overcoming the limitations presented above. However, we have identified an imbalance between industrial needs and academic interests. In this section we analyze this mismatch as a self-reflection exercise.

In order to support our statements throughout this section, we used content analysis techniques applied to scientific articles. In particular, we analyzed a corpus of more than 20,000 contributions to distinguished scientific journals and conferences. Specifically, this corpus, obtained through IEEEExplore, consists of all the articles published in 2013, 2016, and 2017 in the following IEEE publications: IEEE Communication Letters, IEEE Communications Magazine, the IEEE Sensors Journal, IEEE Transactions on Industrial Informatics, IEEE Transactions on Mobile Computing, IEEE Transactions on Wireless Communications, and IEEE Wireless Communication Letters; as well as IEEE conferences (including their corresponding workshops): IEEE GLOBECOM, IEEE ICC, IEEE INFOCOM, IEEE Sensors, and IEEE WCNC.

From these 20,000 contributions, we then filtered the papers in which any of the following terms related to wireless appear in the abstract: wireless, wifi, mmwave, mmw, wsn, lte, ridd, zigbee, bluetooth, vanet, 4g, 5g, LoRa, Sigfox, ipwa, and tsch. This filtering resulted in 9011 papers,
which are the ones that we use in the following analysis. From these articles we analyzed both their INSPEC Controlled Terms and the contents of the abstracts. The INSPEC Terms are used to extract conclusions on what are the most popular topics according to academia, while the contents of the abstracts allow checking the frequency of certain words we associate with some topics. While the analysis of keywords is more generic, the abstracts provide a deeper understanding of specific interests.

**Macrosopic View**

To gain more insight into the most relevant academic interests, we analyzed the frequency of the INSPEC Terms in our corpus. In Fig. 2, we compare the identified barriers for IIoT adoption that the industry reported in [14] with the nine most frequent terms. We fail to see any evident manifestation of the barriers perceived by the industry in the most popular interests of academia. For instance, security and standardization are not among the major academic interests.

One could argue that the manufacturing sector is just a small fraction of the potential users of wireless technologies. However, as shown in Fig. 3 (left), this industry is the sector with the highest IoT economic potential, considerably higher than that of smart cities and transportation systems [8].

In Fig. 3 (right), we compare this potential impact with the percentage of papers that include any wireless-related term in their abstracts and one of the tokens vehicle/vehicular, ehealth/healthcare, home, smart-city/cities, office, or factory/factories in Fig. 3 (right). We find that the terms vehicle/vehicular, ehealth/healthcare, home, smart-city/cities, office, or factory/factories appear in 235 abstracts (2.6 percent of the sample), and we have to bear in mind that they often appear associated with other concepts, such as packet instead of market fragmentation.

**Undervalued Industrial Interests**

We analyze now in more detail industrial concerns, which are far from academic research trends. These are mainly related to the long life span of industrial machines (which may exceed 20 years) as well as the typically long payback periods (around 10 years). This has serious implications, as it is necessary to fit in the current technological context machinery that appeared even before the Internet was born, as well as to devise a clear roadmap for the candidate technologies.

**Retrofitting:** Legacy equipment is the main pillar of most of today’s factories. Retrofitting involves using IoT-ready connectivity solutions that extend the capabilities of legacy equipment. Protocol conversion is key in this context in order to enable communication between the legacy protocols used by the equipment’s components and modern assets that rely on Internet-based connectivity. However, this must-have aspect has attracted little academic attention in recent years. For instance, we found only 130 articles (1.4 percent of the total) in which at least one of the following word stems appear: retro-, obsole-, langs-, or legacy (all of which can be associated to the concept retrofitting). This contrasts with the vision of the industry (Fig. 2), in which the legacy-installed base is among the top three concerns.

**Interoperability:** Machine interoperability has important open issues. Legacy equipment was not designed to communicate with other devices and systems. The proprietary nature of legacy protocols was even seen as a method of market positioning. This makes the understanding between multi-vendor equipment complex. This issue remained latent for years in isolated production lines, but it can emerge now that the smart factory vision requires a high degree of interoperability. This partly explains why the industry considers standardization to be among the most important challenges to IIoT adoption (Fig. 2). However, it seems that this problem has attracted little interest in the academic community. For example, stems related to the concept interoperability (e.g., interop, fragmen, compatib, and compl) appear in 235 abstracts (2.6 percent of the sample), and we have to bear in mind that they often appear associated with other concepts, such as packet instead of market fragmentation.

**Maintainability:** Reliability is perhaps the main preoccupation in the manufacturing industry. However, when industrialists use this term, they are usually expressing a broader concern, beyond the concept specifically tied to reliable communications. Maintenance is a cross-dimensional discipline that is implicitly addressed in...
most of the topics discussed previously. For example, preventive maintenance is an active effort to improve reliability at the system level. In turn, once a failure occurs, effective and fast repair is required. From this perspective (i.e., corrective maintenance), the need for standardization arises naturally. It also justifies the fear of fragmentation, raising the value of compatibility for mitigating long-term concerns about equipment.

Despite its connection with all these important topics, the term maintenance appears in less than 0.8 percent of the articles analyzed. Furthermore, in many cases it is associated with the replacement of batteries, which, as we see next, are rarely found inside a factory. A concept commonly used in telecommunications is maintainability, which measures the expected time to recover the operating state of a system. It is therefore an indicator that aggregates many of the concerns related to maintenance. Notably, this term appears only once.

**Unfit ted Research Interests**

We now focus on the aspects to which academia dedicates considerable research efforts but that, according to Fig. 2 and our interviews, are considered irrelevant in the current digital transformation. We argue that despite the potential of IIoT in this industry, academia is driven by other interests.

**Energy Efficiency:** Perhaps one of the most surprising mismatches identified in our interviews is the apparent lack of concern for low-power communication. This is also confirmed in Fig. 2, where power consumption does not even appear among the main challenges for IIoT adoption. This is not the case in many other contexts. Energy efficiency is important in cellular communications, wearables, and, in general, any battery-powered device. Even in IoT, applications such as agriculture monitoring and utility metering are sensitive to energy consumption. However, mostly all factories have access to electrical outlets everywhere, and the energy required for communications is negligible compared to the total electrical supply in a manufacturing plant. The important aspect here is that protocols targeting low-power wireless communications intrinsically entail a trade-off between consumption and reliability, while the latter is key to this sector.

However, energy efficiency is indeed gathering considerable research attention from academia, most probably motivated by the many other contexts in which energy consumption is pivotal. Among the 9011 articles in our dataset, we found 1697 abstracts (18.8 percent) with one or more of the following stems: battery, lowpower, energyharvest, energyeffi, and lowener, which indicates that the focus in academia on wireless energy efficiency is huge.

**Wireless Sensor Networks Heritage:** The wireless sensor network (WSN) literature is vast. 14.2 percent of the articles published in the last three years in selected conferences and journals include wireless sensor networks as a keyword (Fig. 2). The impact of WSNs in the real world is out of the scope of this article. What is clear, though, is that the research community has been greatly attracted to WSN application scenarios, which are distant from the industrial landscape. Additionally, many researchers have evolved from WSN research to IIoT. However, although the profiles of IIoT and WSN researchers may be similar, the two topics do not have very much in common.

This progression of WSN researchers to the IIoT sphere results in proposals for IIoT that are reasonable for WSNs but far from industrial requirements. Energy efficiency, already described above, can also be considered part of the WSN legacy.

Another illustrative example is compressive sensing (66 matches in our database). While exploiting spatial and temporal correlations might make sense in the typical scenarios envisioned by the WSN community (e.g., environmental monitoring), it becomes inapplicable in an industrial setting.

**Research Trends:** The academic community is constantly seduced by new research trends. For instance, consider the recently increasing attention on single-hop, long-range communications (110 abstracts contain terms such as lora, single-hop, and longrange-l). This focus reflects the needs of certain IoT applications (e.g., utility metering), which in recent years have been addressed by technologies such as SigFox and LoRa. This situation reminds us of the great research effort carried out on multihop technologies influenced by the expectations created by WSNs and encouraged
by the success in sectors such as oil and gas (we still found 239 abstracts containing multihop in the 2015–2017 period). In that case the main driver was energy optimization, and currently it is reaching the Internet at long distances (still under strict energy constraints). However, the focus on these and other hot topics has left little room for more suitable technologies in this industry.

CONVERGENCE PATHS

We could imagine the heavy machinery, characteristic of the manufacturing industry, as the structure of an old building that we are compelled to preserve. From this perspective, wireless adoption resembles a restoration task: reinforcing the structure (i.e., machinery) and building on top of existing elements. We next propose some paths to materializing this vision as ways for academia to move forward.

ADDED VALUE IN THE CURRENT MACHINERY

Factories are designed for easy access. The hard-to-reach places are found in the depths of the machinery: sensors in spots that require high insulation, parts with complex 3D movements, rotating heads, and so on. Machines are full of connecting tubes that wrap signal buses. The rigidity of these hoses, especially those that enclose fiber optic connections, hinder and slow down the movements of internal parts. Wire replacement can give machines more freedom for 3D movements and faster mechanics. Collaboration with machine vendors is essential for understanding these mechanical limitations and offering solutions compatible with existing equipment. Forget about low power; wire replacement requires performance and reliability to achieve links comparable to the technologies being replaced.

One solution for addressing wire replacement in machinery can be mmWave. mmWave is the only technology at this moment able to provide fiber optic performance and thus deliver the required bandwidth to the most demanding industrial applications. In this setting, the distances to cover are small, and even if no line of sight is possible, there is the possibility to take advantage of reflective surfaces, which are common in an industrial context. We believe this is a new research area that may potentially help close the current academia-industrial gap. It will involve the study of mmWave physical channel measurements, models of the industrial setting, and evaluation of the performance at higher layers of the protocol stack, with a special emphasis on reliability [15].

NEW OPPORTUNITIES

Wireless communication is particularly useful when the agents are mobile. In the manufacturing industry, we can find several examples of mobile targets, ranging from tools and auxiliary machinery (like forklifts) to workers and items being produced. The heterogeneity and mobile nature of the assets involved make this topic a new opportunity for wireless.

To make this a reality, researchers must work in collaboration with the industrial counterparts, defining realistic specifications in terms of required bandwidth, latency, and reliability. Based on these requirements, the use of licensed-band technologies will most probably be required in order to meet the specifications. This may be achieved by forthcoming 5G ultra-reliable low-latency services [1] and by renting resources to network operators via, for instance, slicing and/or private LTE networks. This prospective research topic includes evaluating network performance as well as economic incentives, business models, and novel service level agreements.

INTEROPERABILITY AND BACKWARD/FORWARD COMPATIBILITY

Plug-in technologies must maintain interoperability with legacy interfaces and eventually bridge to new or evolved standards. Academia and standardization bodies should look at the long-term coexistence of legacy and recent technologies and define mechanisms to ensure forward-compatible specifications, robust to a multi-decade evolution. These can take advantage of the directions taken by the Internet Engineering Task Force (IETF) to promote the full deployment of IPv6. Moreover, the seamless interoperability proposed in the design of 5G (e.g., extended numerology in New Radio, NR) can be used as a reference model. If this model becomes fully adopted in the industry, it is possible to take advantage of long-lasting equipment as its extensible design can facilitate coexistence and the upgradeability of the installed base.

In addition, despite having seen in the last 10 years an increasing growth in software defined radio (SDR), we do not perceive an obvious use of the technology to achieve future-proof and universal interoperability (interestingly, forward-compatibility does not even appear in the analyzed corpus). Research lines in that direction may pave the way to quick adoption of new wireless standards as a simple firmware update.

MATERIALIZING SECURITY

Academia is already focusing on security in wireless communications. Following the analysis presented in the previous section, we found that the stems secret–, privac–, eavesdrop–, jamm–, and auth– appear in 459 abstracts (5.1 percent of the total). We believe these efforts should continue and materialize into products in the years to come. An important aspect to note is that highly directional communications, like those mentioned earlier, also offer advantages in terms of security, as these links are less prone to security attacks compared to omnidirectional transmissions.

DEMONSTRATING RELIABLE WIRELESS COMMUNICATIONS

Wireless research is largely devoted to improving wireless reliability. Indeed, in the analysis presented above, we found that stems related to reliability ( qos, qualityof–, and redundant–) appear in 696 abstracts (7.7 percent of the total). Indeed, as we have previously seen, reliability is imperative for the industry. However, wireless technologies have yet to demonstrate the reliability and guaranteed latency required by industrial applications.

FINAL REMARKS

The needs of the manufacturing industry are characterized mainly by the fact that the equipment used is built to last for several decades. While concerns such as reliability and security are accompanied by considerable research efforts,
aspects related to long-lasting machinery, such as retrofitting, interoperability, and maintainability, seem to not be among the most important academic interests. Wireless research is instead largely influenced by other design considerations such as energy efficiency, and it is affected by the WSN heritage. As a consequence, the common requirements and settings of proposed wireless solutions are distant from the needs of this industry.

We propose directions for change that aim to contribute to an effective wireless revolution in the manufacturing industry in coming years, thus helping to materialize the Industry 4.0 concepts. These include continued efforts toward reliability and security, novel research on high-frequency and directional technologies such as mmWave, private/rented cellular 5G networks, and virtualizable radio equipment. All of these should aim to add value to existing equipment, devising new opportunities and even revisiting unsolved problems that may no longer qualify as hot topics.

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