# Industrial Wireless Monitoring with Energy-Harvesting Devices

Vibration monitoring and analysis techniques are used increasingly for predictive maintenance. While traditional vibration monitoring relies on wired sensor networks, recent industrial technologies such as WirelessHART, ISA100.11a, and IEEE 802.15.4e have brought a paradigm shift in the automation sector by integrating the flexibility of wireless technologies with the versatility of the Internet. However, these wireless technologies aren't designed to support strict resource constraint devices, and thus are still unable to fulfill the needs of many modern industrial applications. This article describes a new industrial wireless monitoring system capable of supporting energy-harvested devices through intelligent sensing and network management.

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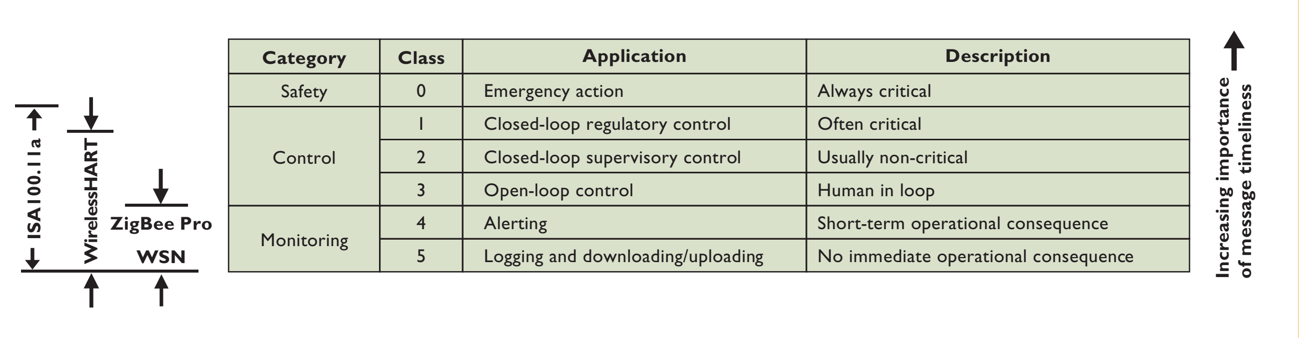
Vibration is a natural phenomenon in every industrial facility that causes wear and tear on machine parts, leading to equipment or structural failure. Active vibration monitoring and control by analyzing the vibration patterns of machinery can prevent such occurrences, which in turn improves overall system performance, efficiency, lifetime, and safety. However, traditional, wired automation systems have several limitations such as an inability to monitor the factory areas that are difficult to reach (for example, moving machine parts), a rigid nature due to the inflexible wired network, a high failure probability due to corrosion, and so on.

Over the last decade, developments of wireless sensor networks have been driving the industries to move toward complete wireless automation to address the aforementioned issues. These systems have already brought significant advantages in the industry, such as reduced installation and maintenance cost, increased flexibility and scalability, improved robustness, and so on. However, the inclusion of wireless technologies also introduces a set of challenges. First, wireless communication is usually considered as an unreliable means of information exchange, especially when several networks might coexist in the same space. If they aren't carefully deployed, widely accepted radio standards such as ZigBee Pro and Wi-Fi that operate in the unlicensed 2.4-GHz industrial, scientific, and medical (ISM) band often experience high packet losses due to collisions.[1] As a consequence, these systems often fail to guarantee reliable communication in industrial environments. Luckily, recently developed industrial standards – such as the HART communication foundation's



| Category | Class | Application | Description |
|---|---|---|---|
| Safety | 0 | Emergency action | Always critical |
| Control | 1 | Closed-loop regulatory control | Often critical |
| | 2 | Closed-loop supervisory control | Usually non-critical |
| | 3 | Open-loop control | Human in loop |
| Monitoring | 4 | Alerting | Short-term operational consequence |
| | 5 | Logging and downloading/uploading | No immediate operational consequence |

*Figure 1. Industrial application classes. The International Society of Automation (ISA) has classified the industrial applications as safety applications, control applications, and monitoring applications, according to their maximum acceptable communication latency.*

WirelessHART and the International Society of Automation's ISA100.11a — do have mechanisms to combat interferences (such as clear channel assessment or channel hopping) and to provide reliable communications (for example, spatial diversity and multipath routing) in harsh environments. However, such mechanisms often are built upon some kind of information redundancy (such as error coding or diversity), which requires sensors and actuators (I/O devices) with a relatively high energy budget.[2]

In general, energy efficiency hasn't attracted much attention in industrial wireless systems. I/O devices in WirelessHART and ISA100.11a have substantial communication overheads in the presence of harsh industrial environments that incur high latency as well as fast battery draining.[3] The energy budget has become an important design parameter for industrial wireless networks only recently, when industrial wireless and Internet technologies started to merge.[4] Many of the industrial applications demand a long-lasting wireless power supply. To fulfill this vision, energy harvesters are becoming popular though present-day energy-harvesting technology that can only scavenge an extremely limited amount of energy, which in turn forces the harvester-powered wireless I/O devices to communicate conservatively.[5]

To address the aforementioned challenges, here we present the results of two recently completed European projects — Wireless, Self-Powered Vibration Monitoring and Control for Complex Industrial Systems (WiBRATE) and Reliable IP for Time-Synchronized Channel-Hopping Networks (RICH). These projects tackled such challenges by designing an industrial monitoring system based on harvester-powered intelligent wireless I/O devices that collaboratively predict impending machine failures and perform real-time fault diagnosis.

## Industrial Wireless Networks: Journey so Far

The International Society of Automation (ISA) has classified industrial applications as monitoring, control, and safety applications, according to their maximum acceptable communication latency (see Figure 1).[6] Industrial monitoring applications belonging to the application classes 4 and 5 have soft real-time and reliability requirements, whereas safety and control applications covering the classes 0–3 demand timely reception of the data packets. Traditional wireless sensor network technologies (such as ZigBee Pro) designed for monitoring applications often use contention-based communications to improve the network lifetime by minimizing energy consumption. However, such mechanisms are unable to provide reliable and real-time communications required for many industrial applications.[7] As a response, several standards such as WirelessHART, ISA100.11a, and IEEE 802.15.4e were developed recently to meet industrial applications' critical timing and reliability requirements by using a novel approach known as time-synchronized channel hopping (TSCH).[5] These systems use scheduled communications on top of time-division multiple access to facilitate real-time data transfer. Moreover, to improve the communication reliability in a harsh industrial environment, frequency diversity (for example, different radio channels) is used during each data transmission between a pair of devices in a TSCH network, where the radio channel selection for each instance depends on a predefined sequence known as a hopping pattern.[8]

While having many advantages, TSCH networks such as WirelessHART and ISA100.11a often use complex network protocols to provide robust and secure communications in industrial environments. For instance, to join these networks an I/O device usually needs to scan all the radio channels used by the system to receive potential advertisements from the neighboring routers. Then the I/O device selects one of its best parents (a router) to forward its join request to the central system manager (SM). The SM then constructs the routes and communication schedules for the new I/O device. This mechanism imposes huge overheads on the energy-harvesting I/O devices. The suitability of such resource-constraint I/O devices in any network is also influenced by its network-management approach. Such I/O devices might need to rejoin the network to resume their tasks in situations where they lost network connectivity due to a temporary energy shortage. However, often they lack the capabilities to handle the network joining and management overheads of a centralized TSCH network, which also incurs high latency. Thus, centralized TSCH networks such as WirelessHART and ISA100.11a can't cope with network disturbances in a real-time manner. These problems are further exacerbated as the network scales up, where the I/O devices are several hops away from the SM.

Meanwhile in 2013, an IETF working group named 6TiSCH has been formed to enable IPv6 over TSCH by using a centralized scheduling that works with distributed routing.[9] Unlike ISA100.11a and WirelessHART, the IEEE 802.15.4e (TSCH) standard doesn't specify the network joining and management aspects, which are left to be decided by the higher-layer protocols to allow low-power standards to work with some well-established IETF standards. 6TiSCH proposed to support central scheduling by allocating communication resources (cells) to each node in the network. However, how two separate decision makers (distributed routing and centralized scheduling) can work simultaneously wasn't clearly described by the group. Issues such as coping with dynamic situations can be better addressed by distributed network management schemes. However, I/O devices often lack enough resources to run complete distributed algorithms. A hierarchical network management approach that combines the benefits of distributed and centralized management schemes can fulfill the needs of the resource-constraint I/O devices in the best possible way. During the WiBRATE and RICH project phases, we designed and implemented two such policies on a TSCH network to achieve a wireless monitoring system with energy-harvested devices. The most recent 6TiSCH architecture draft has also proposed a comparable approach where the authority over blocks of resources (chunks) is delegated to the routers to manage their local I/O devices.[9]

## Solutions for Wireless Monitoring with Energy-Harvesting Devices

Our first solution introduces a hierarchical network management scheme, where the central SM delegates some management responsibilities and blocks of communication resources to the routers in a TSCH network to manage harvester-powered I/O devices locally. The second solution allows the resource-constraint devices to remain transparent to the network by publishing their data asynchronously while the mesh network comprising the routers follows TSCH schedules to communicate.

### Hierarchical Network Management in TSCH Networks

Unlike centrally managed networks, the routers in hierarchical TSCH networks ask for appropriate resources from the SM based on their local I/O devices density and statistics. Then routers allocate these resources among potential I/O devices upon receiving their join requests.[10] The remaining network resources are managed by the central SM, which constructs the routing graphs and communication schedules between the routers in the service network. This is where the hierarchical TSCH networks differ from the proposed 6TiSCH solution. Figure 2 shows a sample hierarchical TSCH network topology, along with the corresponding superframe structure where the SM manages the first block of resources and the remaining resources are allocated to different routers for their own local management. The size of the blocks allocated to routers is set based on expected network load, which can vary according to the number of I/O devices associated with each router and their traffic characteristics.

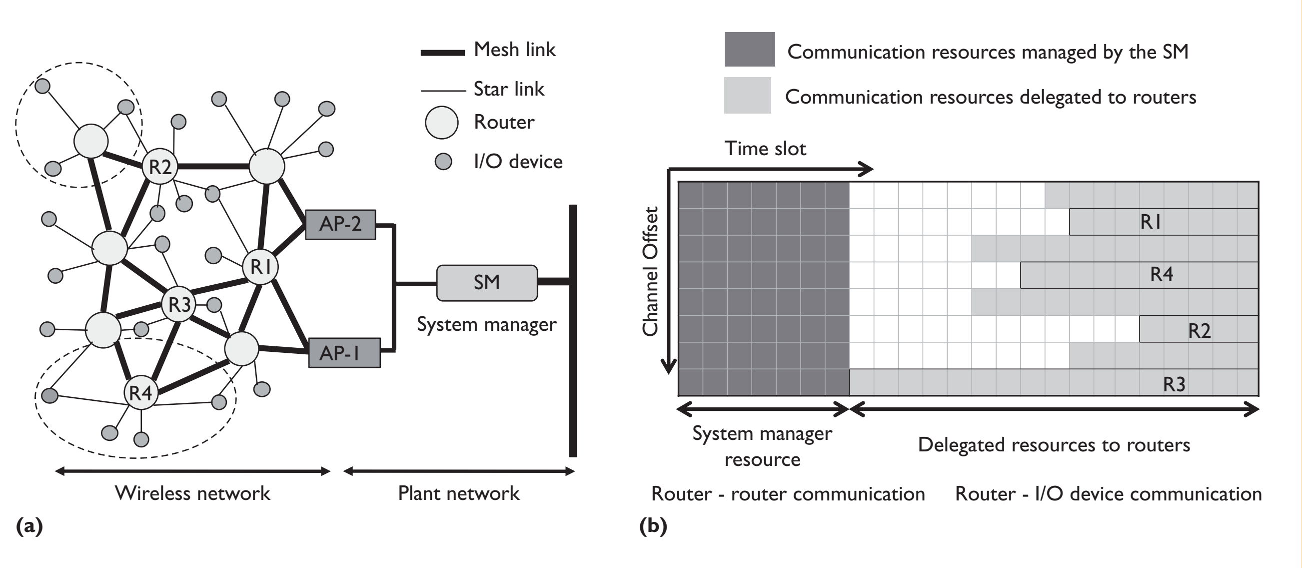


*Figure 2. Hierarchical network management in time-synchronized channel hopping (TSCH) networks. (a) Typical hierarchical TSCH network topology. (b) The superframe structure to support communications in the network.*

The routers use their own resources to manage the requirements of the local I/O devices and to communicate with other routers in the mesh network that makes I/O joining faster in the network. Because I/O devices in hierarchical TSCH networks aren't participating in routing tasks, the routers don't release the communication resources reserved for I/O devices when no updates about their presence are received for a while. This policy lets the harvester-powered I/O devices work more effectively and efficiently in situations where they might frequently shut down and lose their network connectivity.

Other unique features of a hierarchical TSCH network that differ from the centrally managed 6TiSCH network include the I/O devices' ability to dynamically choose preferred parents (routers) based on their local statistics and rank of the routers, and the ability to acquire required communication resources (that is, cells) locally from the chosen router. The ranks are basically qualifying numbers defining the router's relative position with respect to the SM based on different quality matrices such as reliability, latency, power consumption, and bandwidth. This is inspired by the routing protocol for low-power and lossy networks (RPL).[11] In contrast to the RPL, the hierarchical TSCH network calculates the ranks centrally. The ability of changing routers helps the I/O device to (re) join quickly in large-scale dynamic networks, where network connectivity changes frequently due network disturbances. Such mechanisms improve the overall efficiency, as previously allocated resources often become obsolete and useless. The number of advertisement channels in the hierarchical TSCH network has been reduced to minimize the I/O scanning time, and thus the energy spent on this activity. Such a policy makes the joining faster and affordable for harvester-powered I/O devices.[12]

## Asynchronous Communication Scheme for I/O Devices in TSCH Networks

Our hierarchical management scheme reduces the management overhead from I/O devices in a TSCH network. However, the I/O devices still must go through the network joining process, which is a burden for I/O devices with strict energy constraints.

In ideal situations, harvester-powered I/O devices should be allowed to transmit their data as soon as they harvest sufficient energy. However, such a mechanism demands contention-based communications, where routers must listen continuously to receive data packets from the I/O devices. Although the routers might afford such overheads due to the possibility of systematic placement near the power supply in the factories, such an approach can't fulfill the timing and reliability requirements of the industrial applications. Moreover, it's impractical to keep the battery-powered routers on for a long duration. Thus, a mixed approach combining contention-free and contention-based communications can best address the needs of energy-harvesting industrial applications.

The ISA100.11a standard exploits such a mixed approach known as active joining, in which routers occasionally listen for packets (solicitations) from I/O devices to facilitate quick joining. However, to use this scheme, I/O devices also need (loose) clock synchronization, which makes it inappropriate for the harvester-powered I/O devices we're targeting.

In response, we developed an asynchronous communication scheme for resource-limited I/O devices that can coexist with the industrial networks designed for real-time monitoring and control applications.[12] To support scheduled communication and contention-based communication in the same system, the SM reserves separate portions in the superframe for scheduled communications and asynchronous data publications (using slow hopping). Different routers place the slow-hopping period in different locations in their superframe, which lets the I/O devices transmit their data without having superframe synchronization.

## Use Case Scenarios

The industrial wireless monitoring technology that we present in this article has been validated by conducting field trials and tests in the following two installations.

### Automotive Manufacturing

In the automotive industry, the state and balance of bearings in machinery are critical for the final product's quality. Due to the continuous motion, friction, and external pressure, bearings frequently are subject to failures. To prevent premature failures, automotive manufacturers usually conduct predictive maintenance. Such maintenance leads to reduced operational costs and a smaller mean time to repair. Generally speaking, the condition-monitoring systems don't need to be very active, and thus such operations can be scheduled during machine shutdown periods (for a few minutes per day, for example).

A typical monitoring network for automotive industries can contain hundreds of I/O devices. For precise analysis of the machine's condition, these I/O devices are expected to collect vibration samples with a high sampling rate (such as 10 KHz). When local processing is supported, only the high-level features can be transmitted to the monitoring center. The communication latency in this use case isn't critical (application classes 4–5). However, successful delivery of the vibration features is expected. The I/O devices developed for the automotive use case can operate for long periods (8 or more hours) on their internal battery, which can be recharged by the energy harvester.

### Railway Transport

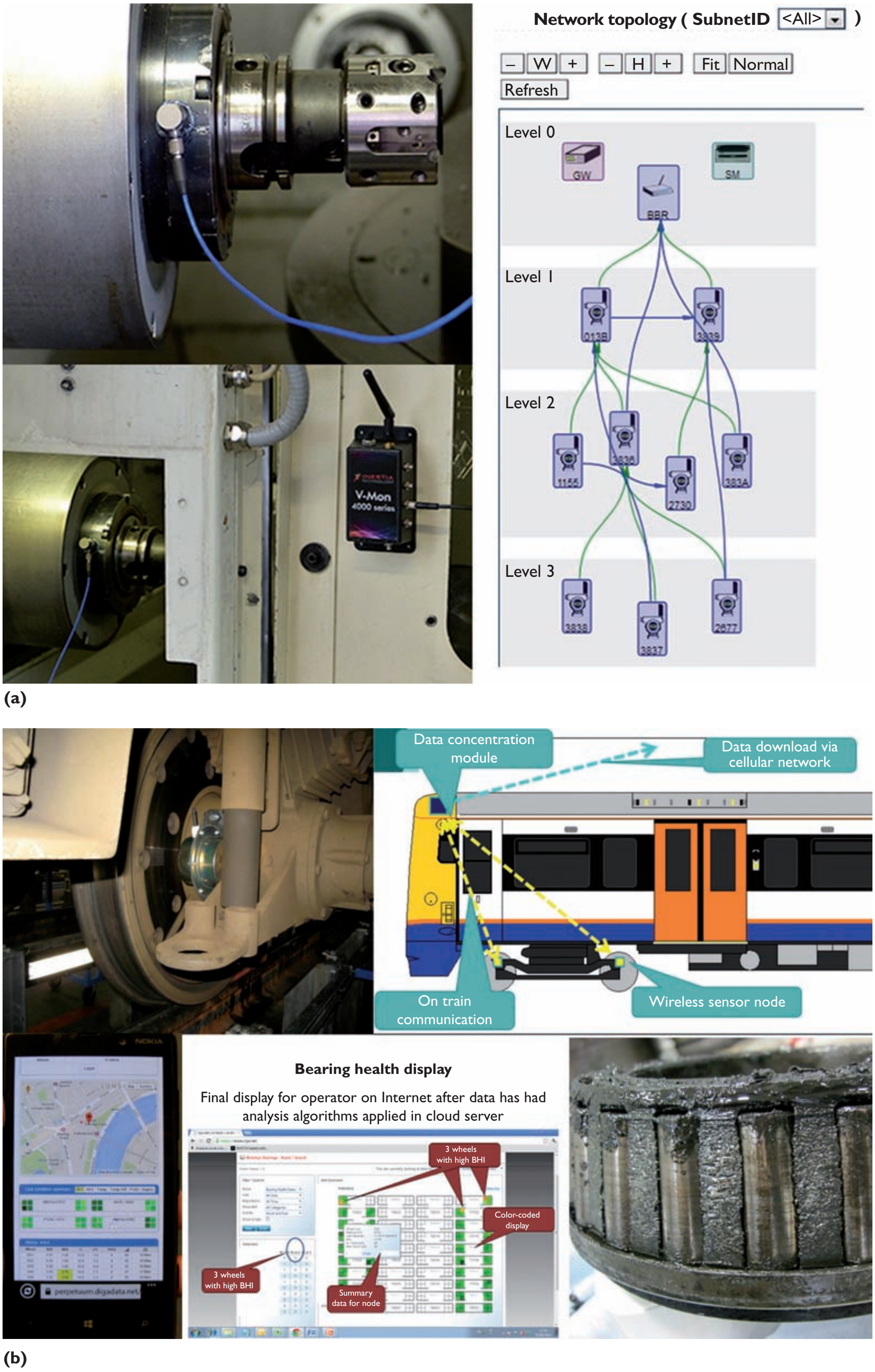
The second use case we considered is a railway transport monitoring system developed by Perpetuum, which aims to detect faults on bearings and wheels to enable condition-based maintenance. Traditionally, temperature sensing is used for condition monitoring in the railway industry, which can be used only in potentially dangerous scenarios (for example, close to complete failure requiring an immediate train stop). Vibration monitoring, on the other hand, enables an informed maintenance process, increasing safety, and reducing maintenance costs at the same time.

In this installation, I/O devices are mounted on a bogie (train chassis) to record vibration samples of a small duration (such as 4 seconds of data every 4 minutes), which are then analyzed and classified. Worn or faulty bearings typically produce vibration patterns that are different from healthy ones. As the vibration patterns are analyzed on the node itself, only high-level features need to be sent periodically, and throughput and latency aren't critical. However, the application is safety related, which implies that the system must be tolerant to transmission failures.

Typically, tens of I/O devices must be supported in a train monitoring network to enable monitoring for all the train's wheels. The nodes are exclusively self-powered from the embedded energy harvester. As the level of vibration in trains is quite high, adequate power for sensing and short communications can be generated easily. However, the amount of harvested energy might vary during different modes of operations.

## Implementation and Validation

Addressing the special requirements of industrial monitoring applications, we designed wireless sensor nodes capable of real-time signal acquisition, processing, and communication.



Final display for operator on Internet after data has had analysis algorithms applied in cloud server

*Figure 3. Our two implementations. (a) At the Machining Center, Centro Ricerche Fiat, Italy. (b) Testing the Electrostar fleet of Southeastern Railway, UK.*

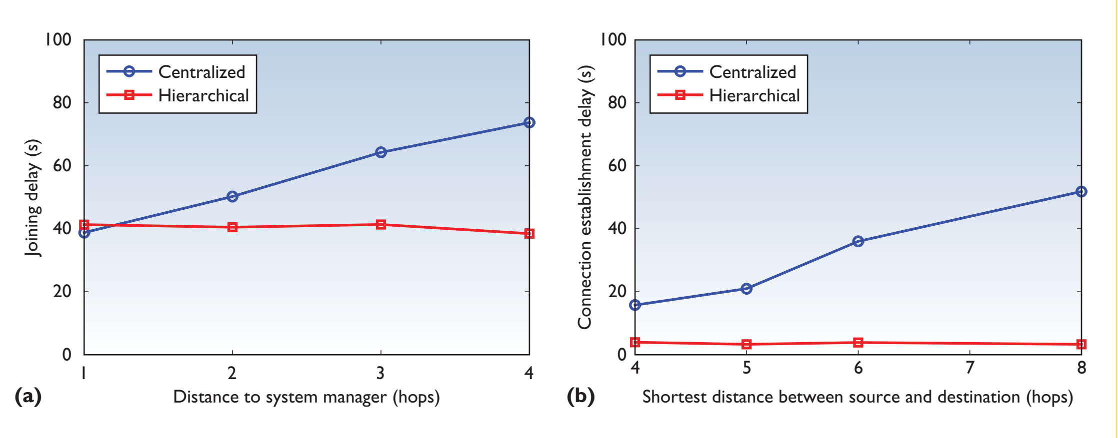


*Figure 4. Comparison of management efficiency between centralized and hierarchical network management. These results are generated by considering I/O devices in TSCH networks (such as ISA100.11a or WirelessHART) with different management schemes.*

We developed two versions — one for rail monitoring and the other for manufacturing applications. They have a modular design, allowing quick customization and adaptation for specific applications. The nodes are powered from electromagnetic energy harvesters (Perpetuum Versanode 210) capable of producing up to 27 milliwatts (mW) of usable energy harvested from mechanical vibration.

In the automotive manufacturing scenario, vibration patterns are collected from three milling machines over a period of one week using three industrial accelerometers at the Centro Ricerche Fiat (CRF) facility in Italy (see Figure 3a). The samples are collected for short durations, and features are extracted by processing, which are then sent to a monitoring unit through the SM for classification, decision making, and fault detection. Another five wireless nodes are used to relay the data up to the control center by forming a mesh network. The network topology obtained during the experiments with I/O devices shows that they form a network with devices up to three hops apart from the SM. The experiments showed that end-to-end path reliability and data reliability of the deployed network were quite good (100 percent), even though up to 9 percent packet losses were seen. This was achieved with the standard retransmissions and channel hopping techniques of TSCH. This field trial also shows that the prototypes developed comply with the ISA100.11a standard and are fully integrated to the system.

In the railway monitoring scenario, wireless I/O devices are attached to the wheel bearing housing of 10 trains of Southeastern Railway's Electrostar fleet (see Figure 3b). The I/O devices containing an accelerometer and a temperate sensor are specially designed for attaching it to the axle bearing box of trains. Vibration data samples collected are processed locally and high-level features are transmitted to routers or directly to a central data concentrator. One central unit collects data from a total of 40 I/O devices from five wagons, which is then transmitted to the monitoring center over the cellular network where signatures associated with the degradation of the bearing health and the wheel condition are extracted. The output of this process is a bearing health index, which is a quantifier number for the condition of the bearing at that moment. This trial not only correctly identified failing bearings in three wheels of the test train wagons (such as the one shown in Figure 3b), but also enabled easy identification of wheel flats. The success of the trial led to a multimillion Euro order in 2015 from Southeastern to equip a fleet of 148 trains and subsequently to orders from several other countries.

## Performance Evaluation

Several analysis and field trials were conducted to evaluate the performance of the developed wireless vibration-monitoring technology.

### Management Efficiency

We compared the management efficiency between a centralized TSCH network and a hierarchical

TSCH network during the network-joining and connection-establishment phases. As Figure 4 shows, the joining and connection establishment delay in the centrally managed TSCH network increases significantly when the (hop) distance between an I/O device and SM/destination increases, whereas in the hierarchical TSCH network, these values remain more or less constant. This is because in a centralized TSCH network, the routers forward the I/O device's join and connection establishment requests to the SM via several intermediate nodes, which takes a long time to receive the response and reserve communication resources, while the routers in the hierarchical TSCH network handles those locally. The results show that hierarchical management performs far better than centralized management in large-scale networks, and in situations where energy-harvested I/O devices join and leave the network frequently.

## Energy Consumption

Figure 5 provides a complete overview of the energy consumed by an I/O device during different phases — namely joining, advertisement reception, and data publication in the network. The average energy consumption of the I/O devices in the steady-state phase are calculated for 5 minutes of data communication with a traffic rate of one packet per I/O device per superframe. On the other hand, the joining energy consumption is independent of this period and is only required during the network (re)joining. This portion of the energy must be harvested at first so that the nodes can (re)join the network.

Due to the quicker responses during joining and connection-establishment phases, the I/O devices in the hierarchical TSCH network consume much less energy compared to that of the centralized TSCH network. The asynchronous communication scheme can remove the management overheads completely. In addition, this scheme doesn't suffer from the issues arising from network disconnectivity.

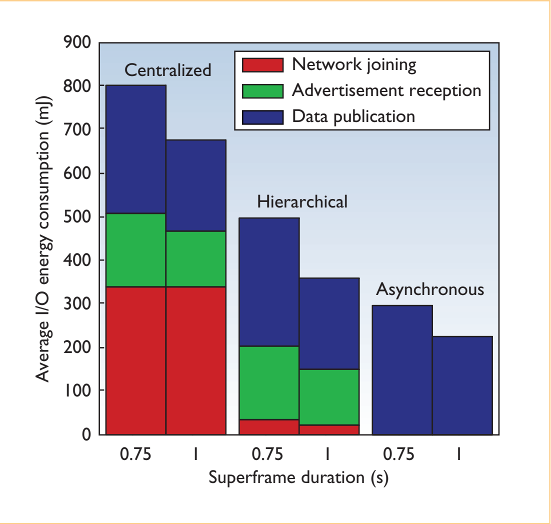


*Figure 5. Comparison of I/O energy consumption in millijoules (mJ) in the TSCH networks following centralized, hierarchical, and asynchronous management schemes. The results are generated by considering I/O devices in TSCH networks (such as ISA100.11a or WirelessHART).*

Industrial wireless automation is replacing its wired counterparts. It's clear that emerging technologies such as the energy-harvesting wireless monitoring system presented here will support many modern industrial applications. The wireless monitoring system we developed is fully standard-integrated and compliant. Although this technology has been tested for monitoring applications belonging to classes 3–5 during the project phase, it also can be applied for control applications belonging to classes 1–2 after proper adjustments of the protocols. One major difficulty in the adaptation of such systems, however, lies in the standardization process.

**Acknowledgments**

We thank Emi Mathews (TNO-ESI), Mihai Marin-Perianu (Inertia Technology), Alessandro Zanella (Centro Ricerche Fiat), Roy Freeland (Perpetuum), and Hugh Maaskant (NXP Semiconductors) for their input.

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