# 6TiSCH: Deterministic IP-Enabled Industrial Internet (of Things)

In November 2013 the new 6TiSCH IETF working group was created to "glue" together a link-layer standard offering industrial performance in terms of reliability and power consumption, and an IP-enabled upper stack. This working group is standardizing mechanisms for 6TiSCH networks to operate at the trade-off between throughput, latency, and power consumption most appropriate for the application, while maintaining ultra-high reliability.

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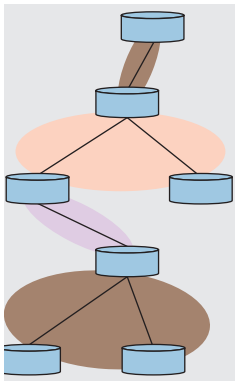
Abstract

Industrial and IP-enabled low-power wireless networking technologies are converging, resulting in the Industrial Internet of Things. On the one hand, low-power wireless solutions are available today that answer the strict reliability and power consumption requirements of industrial applications. These solutions are based on Time-Synchronized Channel Hopping, a medium access control technique at the heart of industrial standards such as the WirelessHART and ISA100.11a, and layer 1 and 2 standards such as IEEE802.15.4e. On the other hand, a range of standards have been published to allow low-power wireless devices to communicate using the Internet Protocol (IP), thereby becoming true "fingers of the Internet," and greatly simplifying their integration into existing networks.

This article acknowledges the standardization effort to combine those capabilities. The networks resulting from this convergence exhibit reliability and power consumption performances compatible with demanding industrial applications, while being easy to integrate, and following the end-to-end paradigm of today's Internet. In particular, this article presents the work being done in 6TiSCH, a newly-formed working group in the Internet Engineering Task Force, which is standardizing the mechanisms making the Industrial Internet of Things a reality.

Introduction

Steel mills, oil refineries, and offshore drilling platforms implement complex industrial processes, which require a tight control and a scalable diagnostic transport. Thousands of sensing points are used to report temperature, pressure, and tank fill levels to an industrial process control center. This center, either in an automated way or through human intervention, uses that information to control an actuator, start a new production stage, schedule maintenance, or trigger an alarm. Communication between sensors, actuators, and the control center is done through an industrial network. This class of network needs to offer ultra-high reliability, while operating reliably in harsh environments. Network failures can have catastrophic consequences, and are therefore not an option. In order to gain higher security and reliability, an industrial network is classically partitioned in a hierarchical manner per the Purdue Enterprise Reference Architecture (PERA), using different technologies at each level, and wireless networks are used at the last hop(s) to the field devices. Industrial networking technology has developed over the last 40 years to satisfy those requirements. A major industrial standard is HART [1], a set of standards covering the protocol, connectors, and wires interconnecting the different networked elements.

Depending on the safety regulations in use, the price of drawing cables across an industrial plant can run from $100s/ft to $1,000s/ft. Planning, installing, and maintaining these cables represents a large portion of the cost of ownership of such a wired industrial network. As detailed in this article, advances in reliable wireless technology enable low-power wireless networks to exhibit 99.999% end-to-end reliability and a decade of battery lifetime [2], making them a suitable alternative to wires. This has triggered a trend for industrial networks to "go wireless."

Since 2007, a constant standardization effort, in particular at the IETF, has enabled constrained wireless devices to behave as regular Internet hosts, by acquiring IPv6 addresses, forming multi-hop meshes, and interacting with Internet clients and servers through standard application-layer protocols. Such networks are much easier to integrate in a production system, most of which have already moved toward an IP-based architecture. This ease of integration has triggered a trend for industrial networks to "go IP."

The development of wireless, IP-enabled industrial networks is a factor in the convergence between industrial networks and traditional networks, a trend known as "IT/OT convergence." Operational Technology (OT) refers to industrial networks, which focus on highly reliable, secure, and deterministic networking. Information Technology (IT) refers to the Internet, which relies on selective queuing and discarding of packets to achieve end-to-end flow control. The goal of the IT/OT convergence is to leverage IT technologies to solve OT problems, for instance, by applying the concept of Device Virtualization to emulate field logic controllers and instrumentation and simplify the deployments, or use Big Data/Analytic techniques, operating on large historical repositories as well as vast amounts of live feeds from large scale monitoring installations, to optimize industrial processes, effectively implementing the concept of the Industrial Internet.

An indication of this trend is the creation in 2014 of the Industrial Internet Consortium,[1] a non-profit partnership of industry, government, and academia, created to accelerate the development and availability of intelligent industrial automation.

In November 2013 the new *6TiSCH* IETF working group was created to "glue" together a link-layer standard offering industrial performance in terms of reliability and power consumption, and an IP-enabled upper stack. This

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[1] http://www.iiconsortium.org/

working group is standardizing mechanisms for 6TiSCH networks to operate at the trade-off between throughput, latency, and power consumption most appropriate for the application, while maintaining ultra-high reliability. 6TiSCH is expected to become the standard for low-power wireless industrial monitoring applications.

This article provides an overview of the trends of industrial networking standardization activities toward wireless and IP technologies, and summarizes the ongoing standardization activity of the IETF 6TiSCH working group. We highlight the challenges faced by low-power wireless networks. We detail the standards developed to answer those challenges, and the resulting commercial products dedicated to industrial wireless. We present the goals and standardization activities in the IETF 6TiSCH working group, including different considered scheduling approaches. Finally, we conclude this article.

THE PROMISE OF WIRELESS

Wireless technology enables "peel-and-stick" deployment and requires no maintenance of cables, drastically reducing associated costs. In addition to removing the need for cables for communication, low-power wireless devices are typically powered by a combination of batteries and energy harvesting solutions, thereby also removing the need for power cables. The lifetime of the device is related to its average power consumption, so ultra low-power devices are needed.

Transmit power, modulation, and data rate all influence the power consumption of a low-power wireless device. The IEEE802.15.4 [3] standard was first published in 2003, and offers a healthy trade-off between transmit power (0–10dBm is typical), data rate (250kb/s at 2.4GHz), and maximum packet size (127 bytes). Although the standard was revised twice, the physical layer it defines hasn't changed much, and has now become the *de-facto* standard for low-power wireless radio chips. A majority of low-power wireless standards build on top of IEEE802.15.4.

One major constraint of IEEE802.15.4 is that the size of its Protocol Data Unit (PDU) is limited to 127 bytes. This is small compared to the classical 1500-byte PDU of Ethernet — a popular wired technology — and smaller than 1280 bytes, which is the minimal value expected by IPv6 for the Maximum Transmission Unit (MTU) of any given link. In 2007 the Internet Engineer Task Force (IETF) — the standardization body behind most protocols used in the Internet today — created the 6LoWPAN WG, which defined a compaction and fragmentation mechanism to efficiently transport IPv6 packets in IEEE802.15.4 frames.[2] This simple mechanism allows low-power wireless devices to appear as regular Internet hosts, thereby becoming the "fingers of the Internet." The Internet of Things (IoT) revolution had begun.

Driven by the endless possibilities of connecting "Things" to the Internet, several IETF working groups were created. They have standardized the IPv6 Routing Protocol for Low power and Lossy Networks (RPL) [4], a routing protocol designed to extend the range of those networks, and the Constrained Application Protocol (CoAP) [5], a protocol enabling client-server interaction between low-power devices and traditional Internet hosts. In parallel, a *detnet* effort is starting at the IETF to bring deterministic networking properties at both Layer-2 and Layer-3 in a homogeneous manner, extending the work that has started at the IEEE at 802.1 AVB (for audio/video bridging) in collaboration with 802.1 TSN (for time-sensitive networking).

While IPv6 capability significantly simplifies the integration of a low-power wireless network into a production system, it does not answer the main requirement: reliability. The wireless medium is unreliable in nature. A wireless link connecting two devices typically has an associated Packet Delivery Ratio (PDR) quantifying what portion of transmitted frames are received. This PDR depends largely on the environment surrounding the communication devices (walls, machinery, etc.). Since the environment changes, the PDR is not predictable in any practical sense. Two wireless phenomena severely impact the PDR: external interference and multi-path fading.

External interference is caused by a different technology (or an independent deployment of the same technology) impacting the wireless signals. Although some frequency bands are more crowded by different technologies than others, interference happens in all frequency bands, and using a dedicated frequency band, at best, pushes the problem further away.

Multi-path fading is less often taken into account, yet is in some sense more destructive than interference. It happens when multiple "echoes" of the same wireless signal interfere constructively and/or destructively at the receiver's antenna. These echoes have bounced off objects in the environment, and a slight change in the environment causes the PDR of a wireless link to severely swing, leading to very unstable connectivity within a network operating on a single frequency. Multi-path fading is extremely sensitive to both frequency and location, and will change dramatically if a device, or some reflector in the environment, moves.

Fortunately, frequency diversity is efficient at combating both phenomena, and is therefore used in many wireless technologies, from Bluetooth to cellular systems. Using multiple frequencies reduces the impact of interference, as interference typically affects only some of the available frequencies at a given moment. Also, different frequencies have different multi-path constructive/destructive self-interference patterns, so using multiple frequencies "smoothens" away the impact of multi-path fading.

In an IEEE802.15.4 system, frequency diversity can be obtained without changes in the physical layer through a technique known as "channel hopping." When channel hopping, sender and receiver devices change frequency at each packet transmission, following a pseudo-random hopping pattern. The result is that, if a transmission is unsuccessful (possibly due to external interference or multi-path fading), retransmission occurs on a different frequency. The key is that retransmitting on a different frequency has a higher probability of success than using the same frequency again.

The idea of channel hopping was a key enabler for industrial wireless, with now three protocols competing in the industrial process

[2] 6LoWPAN is now succeeded at the IETF by the 6lo working group, which maintains the protocols and generalizes the work to other media.
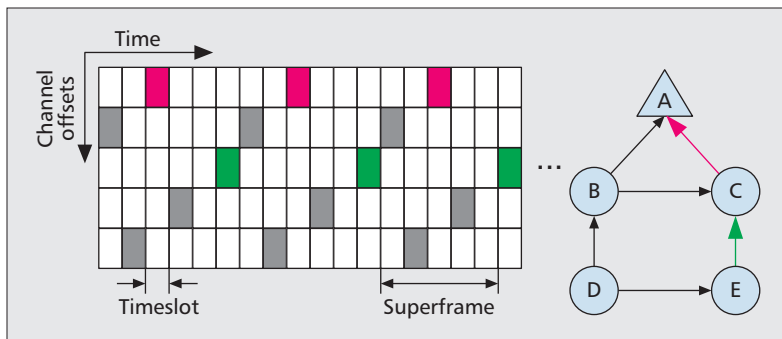
Figure 1. In a TSCH network, a schedule orchestrates all communication.

control space alone, all deriving from that same base technology.

The Emergence of Industrial Wireless

Channel Hopping is used in a class of communication protocols known as Time Synchronized Channel Hopping (TSCH). In a TSCH network, time is sliced into timeslots, and timeslots are grouped into a slotframe (typically 10's to 1,000's of timeslots long). The timeslot duration (typically 10ms) is large enough to accommodate the longest data frame, and leave time for the receiver to send back an acknowledgement (ACK) indicating successful reception. If the transmitter does not receive an ACK after transmitting, it can decide to re-transmit at a later time.

A schedule coordinates all of the communication in a TSCH network. It indicates to a node what do to in each timeslot: transmit, receive, or sleep. For each transmit or receive slot, the schedule also indicates the neighbor to communicate with, and a channel offset to communicate on. This channel offset is translated into a frequency on-the-fly using a pseudo-random pattern, resulting in channel hopping.

Timeslots in the schedule can be seen as atomic link-layer resources. Scheduling more transmit/receive timeslots increases the throughput of the network, but also increases the average power consumption of the nodes.

Figure 1 shows a canonical example of a communication schedule. Time is sliced up into timeslot, and (in this example) four timeslots form a slotframe that repeats over time. Each row represents a different channel offset; multiple communications can happen in the network at the same time, but on a different channel offset without interfering. When node *E* wants to send a packet to node *A*, it waits for cell colored green to send the packet to *C*. Similarly, node *C* sends it to *A*. If any of those transmissions fail (i.e. the transmitter does not receive an ACK), the transmitter tries again at the next opportunity, possibly at the next iteration of the slotframe.

Channel hopping, which exploits frequency diversity, can be combined with path diversity. With the latter, a packet can travel multiple disjoint paths to the destination, giving additional redundancy to further increase the reliability of the network.

TSCH technology was first commercialized by Dust Networks as Time Synchronized Mesh Protocol (TSMP), which achieves over 99.999% end-to-

end reliability and ultra-low power consumption. Elements of this technology were adopted in WirelessHART [6] (IEC62591). TSCH is also at the heart of ISA100.11a (IEC 62734). TSCH has become the *de-facto* technology for highly reliable, low-power wireless sensor networking technology, with tens of thousands of networks deployed today.[3]

In 2012 the IEEE802.15.4e-2012 amendment [7] was published, reusing the core ideas of TSCH in a well-layered approach, allowing "upper stack" protocols to run on top.

For the IEEE802.15.4e TSCH with IETF standards such as 6LoWPAN, RPL and CoAP combination to work, a standardization "gap" needs to be filled. IEEE802.15.4e TSCH defines what a node does to execute a schedule, but does not detail how to build and maintain that schedule. Similarly, an IETF standard such as RPL organizes an existing topology into a multi-hop routing structure, but is agnostic to the underlying link layer technology, and hence to the notion of a TSCH communication schedule.

What is missing is a sublayer that allows a scheduling entity to manage the TSCH schedule in the network. This standardization "gap" is currently being filled by 6TiSCH ("IPv6 over the TSCH mode of IEEE 802.15.4e"), a new IETF working group dedicated to enabling IPv6 over the TSCH mode of the IEEE802.15.4e standard.[4] The resulting protocol stack is depicted in Fig. 2. 6TiSCH, and the scheduling mechanisms it introduces, are detailed below.

6TiSCH: IPv6 over IEEE802.15.4e TSCH

In a TSCH network, the communication schedule orchestrates all communication. Building a communication schedule involves assigning timeslots to communication between neighbor nodes, as atomic link-layer resources. Assigning multiple timeslots to the same neighbors increases the available throughput (the number of packets these neighbors can exchange per second), and lowers the latency of that communication. It also requires the radios of those nodes to be *on* more often, thereby increasing the average energy consumption, resulting in a shorter battery lifetime.

6TiSCH defines a new global concept that is called a Channel distribution/usage (CDU) matrix; a Channel distribution/usage (CDU) matrix is a matrix of so-called "cells" with a height equal to the number of available frequencies (indexed by ChannelOffsets), and a width in timeslots that is the period of the network scheduling operation (indexed by slotOffsets). The CDU matrix can be partitioned into chunks. As seen in Fig. 3, a Chunk is a well known list of cells, well distributed in time and frequency, within the CDU matrix. The partition of the CDU in chunks is globally known by all the nodes in the network to support the appropriation process, which is a negotiation between nodes within an interference domain. As illustrated in Fig. 4, a node that appropriates a chunk gets to decide which transmissions will occur over the cells in the chunk within its interference domain. Ultimately, a chunk represents some amount of bandwidth and can be seen as the generalization of a transmission channel in the time/frequency domain.

[3] Including over 35,000 networks currently operating Dust Networks' TSCH-based SmartMesh products [2].

[4] http://tools.ietf.org/wg/6tisch/charters.

ARCHITECTURE

6TiSCH is chartered with the uncommon milestone of delivering an architecture that encompasses multiple standards from multiple areas within the IETF, as well as external work from Standards Development Organizations (SDOs) such as the IEEE. The 6TiSCH architecture is currently being designed with a goal to provide the high delivery ratios and deterministic jitter and latency that are typical to Industrial Wireless Sensor Network (WSN) protocols such as WirelessHART and ISA100.11a, and at the same time also enable large-scale monitoring deployments in order to achieve the Industrial Internet paradigm.

In order to scale while maintaining throughput, a 6TiSCH network is envisioned to typically comprise a number of small wireless mesh networks federated by a spanning high-speed backbone. The 6LoWPAN Neighbor Discovery (ND) operation is leveraged inside the meshes to eliminate the need for widespread multicast inherent to the classical IPv6 ND operation, and a new functionality is introduced in the backbone router to redistribute that operation inside the backbone, effectively forming a large IPv6 multi-link subnet, as illustrated in Fig. 5.

The experience from industrial WSN supports a centralized approach, enabling a total control and optimization of the network operation from a central compute engine with a "God's view," which is called a Network Manager or a System Manager in the art, and which corresponds to the IETF concept of a Path Computation Element (PCE). The PCE considers all the flows and all the network capacity and computes the optimum set of end-to-end tracks, which are pushed to the network to support individual flows in a pre-determined fashion. In a number of aspects, the centralized approach simplifies the problem: the number of nodes is limited in a given mesh to limit the computational complexity, and all the nodes are expected to be in a same interference domain, so any given slot is attributed at most to one critical flow. In that model, each flow is associated with a reserved track, leading to a deterministic use of the medium.

On the other hand, the experience from the Advanced Metering Infrastructure (AMI)/Automatic Meter Reading (AMR) space demonstrates the value of distributed routing with RPL, and when applicable, distributed scheduling. RPL, the IPv6 Routing Protocol for low-power wireless networks, is the 4th routing protocol standardized by the IETF, after RIP, OSPF, and BGP. RPL is a generic distance-vector (DV) protocol that was designed at the IETF to be very economical in the control plane so as to serve Internet of Things (IoT) applications. The protocol computes abstract Directed Acyclic Graphs (DAGs) to support Non-Equal Cost Multipath (NECM) redundant topologies that are optimized for various application needs by specific Objective Functions, which are a kind of plug-in to the generic protocol. In that model, multiple flows are merged along a DAG, leading a statistical use of the medium.

TSCH has major differences with Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), widely used in wireless technologies. The low-power nature of TSCH allows rout-
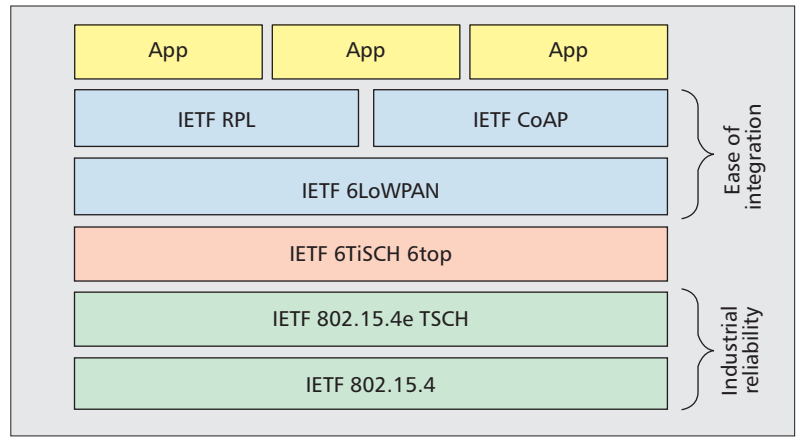

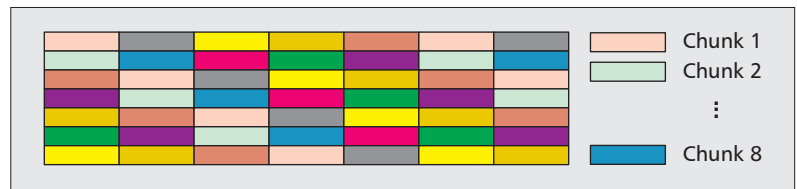**Figure 2.** The protocol stack for the Industrial Internet (of Things).

Figure 3. Example of chunks in a channel distribution/usage matrix (CDU).

ing nodes to *not* need line power, opening up many new applications. Moreover, with TSCH, the spectrum is partitioned in timeslots that are individually reserved to one communication, whereas with CSMA every device may get access to the spectrum at any time. The reservation mechanism is required to protect the most critical flows, but yields the drawback of potentially wasting resources when the critical flows are not present. In order to compensate, the 6TiSCH architecture supports the opportunistic reuse of timeslots along deterministic tracks in the centralized approach. In the distributed approach, the effective use of the bundles of timeslots that implement the link abstraction for the IP routing function is much more dynamic, and avoiding waste is much more challenging. Mechanisms such as On-the-Fly scheduling are evaluated to provide a most reactive arbitration with a very limited signaling overhead, as detailed later.

The 6TiSCH architecture must also cover all-encompassing components such as security and management. These components affect many aspects of the device operations, and for each, several techniques exist in the art that could be relevant for 6TiSCH. But the constraints in memory, CPU, bandwidth, and latency render most existing solutions impractical, and the need for high scalability with low maintenance encourages the use of more bleeding edge autonomic practices. 6TiSCH aims at reusing code for multiple components so as to avoid any functional duplication. This is why the group is considering management over CoAP so as to reuse the code that will serve to report sensor data, and the Datagram Transport Layer Security (DTLS) security that protects it. For the same reason, the group is also considering using Extensible Authentication Protocol (EAP) — Transport Layer Security (TLS) to protect the device communications from the
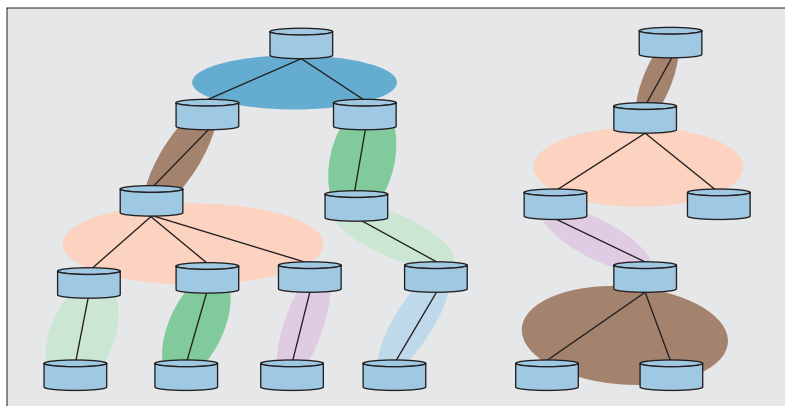
Figure 4. Chunk assignment for an example node topology.

joining time on, sharing capabilities to parse certificates and support public keys between the authentication and authorization flows in the join process and the data traffic. The support of a shared secret to bootstrap a network may be acceptable on some deployments that are limited in number, space, and time, but is not generally a recommended idea, and though it is not barred by the architecture, it will not be documented either.

SCHEDULING MECHANISMS

Scheduling a TSCH network involves a policy using several mechanisms to manage the TSCH schedule operating in the network.

The policy is in charge of determining which timeslot is allocated to which nodes. Scheduling can be seen as an optimization problem where timeslots are assigned to pairs of communicating neighbor nodes to satisfy application-level networking requirements. These requirements can be expressed as metrics that the scheduling algorithm needs to optimize. Metrics can involve allocation collisions, energy consumption, latency, or a combination thereof. The scheduling algorithm itself can follow a variety of approaches, including genetic algorithms, stochastic approaches, or combinatorial optimization. To allow maximum flexibility, the scheduling policy is *not* standardized by 6TiSCH.

6TiSCH makes no assumption of the scheduling entity. It can be centralized (an entity in the network, for example the PCE in Fig. 5, is in charge of computing a schedule) or distributed (nodes communicate with one another to agree on a schedule).

The scheduling entity relies on scheduling mechanisms (e.g. packet formats) to access the TSCH schedule on the nodes in the network, thereby controlling the communication schedule operating in the network. 6TiSCH is standardizing these mechanisms to support the different scheduling approaches detailed in the following paragraphs.

In the simplest case, the TSCH schedule can be static. Once a node has acquired this schedule (it is either pre-programmed, or learned during the joining process), the schedule is never changed. Since no scheduling entity is required in this case, this "minimal" schedule [8] can be used as a bootstrap mechanism (i.e. operating before a scheduling entity is operational) or a fall-back mechanism (i.e. operating after the scheduling entity has failed). The pre-configured

slots can be seen as a control plane to enable other mechanisms to operate the network.

Another approach is centralized scheduling. 6TiSCH is standardizing a set of CoAP resources [9] enabling an external entity to control the TSCH schedule. These CoAP resources turn a node into the constrained equivalent of a web server. The central scheduler acts as a browser, downloading current state and uploading new configurations to that CoAP server.

Another alternative is distributed scheduling, in which neighbor nodes negotiate the use of timeslots with one another, without requiring intervention from a central entity. 6TiSCH is standardizing the format of the packets exchanged between neighbor nodes to conduct this negotiation [10].

The distributed scheduling policy currently being finalized by 6TiSCH is called "On-The-Fly scheduling" (OTF) [11]. When using OTF, a node monitors the state of its outgoing packet queue (stored in its internal memory). If the queue fills up, OTF determines that there is not enough "outbound" bandwidth, and triggers the negotiation of additional timeslots with the appropriate neighbor(s). Similarly, if the queue is often empty, it negotiates the removal of outbound timeslots. OTF describes the structure, policies, and interfaces of the distributed scheduling scheme, while leaving the bandwidth estimation algorithm out-of-scope for greater flexibility.

OPEN ISSUES AND OUTLOOK

In accordance with its chartered mission to document an overall architecture, 6TiSCH needs to examine building blocks that were designed in different working groups at the IETF and that are not necessarily optimized to fit with one another, and then to steer work in the original working group(s) so as to round up the angles.

A typical example of this is the need to enable some interaction between 6LoWPAN-ND [12] and the RPL routing protocol [4]. 6LoWPAN-ND is an extension to IPv6 Neighbor Discovery [13] that is adapted to low-power, duty-cycled devices. 6LoWPAN-ND replaces the classical ND model (heavily based on multicast, which can be inefficient in low-power wireless systems) with a registration model involving only unicast communication. RPL was specifically designed to address low-power wireless networks and constrained devices, but the information in 6LoWPAN-ND is not sufficient for a RPL router to represent a 6LoWPAN node adequately.

The most intriguing aspect of the work to come is in the distribution of schedule and more specifically in the dynamic allocation of time slots in the distributed approach. Basically, the question is how to resolve the tension between the optimal usage of the bandwidth for statistically multiplexed traffic and the reservation mechanism that is inherent to exclusive time-slotted operation.

CONCLUSION

The Internet Protocol (IP) is the cornerstone of today's Internet. Through an important standardization effort at the IETF, standards such as 6LoWPAN allow low-power wireless devices to

behave like any other Internet host, greatly simplifying the integration of low-power wireless networks into a larger networking system.

Low-power wireless technologies based on Time Synchronized Channel Hopping (TSCH) proved to satisfy the stringent reliability and low-power requirements of industrial applications, and therefore become part of the heart of standards such as WirlessHART, ISA100.11a, and IEEE802.15.4e TSCH.

These standardization efforts triggered the trend of industrial deterministic networks to both "go wireless" and "go IP." For this convergence to be possible, however, a standardization gap had to be filled: standards are needed to allow TSCH schedules to be managed in an IP-enabled infrastructure, thus empowering industrial performance with the ease-of-use of IP.

Closing that standardization gap is the goal of the newly created 6TiSCH working group ("IPv6 over the TSCH mode of IEEE 802.15.4e") at the IETF, dedicated to enabling IPv6 over the TSCH mode of the IEEE802.15.4e standard. 6TiSCH is standardizing mechanisms supporting different scheduling approaches, including centralized, distributed, and hybrid.

With this effort, industrial applications are heading toward the integration of Information and Operation Technologies. The use of a common protocol stack to enable seamless communication between heterogeneous devices, from powerful data servers to tiny sensing nodes, has the potential to create a wide range of applications, including those based on Big Data storage and analysis engines.

ACKNOWLEDGMENTS

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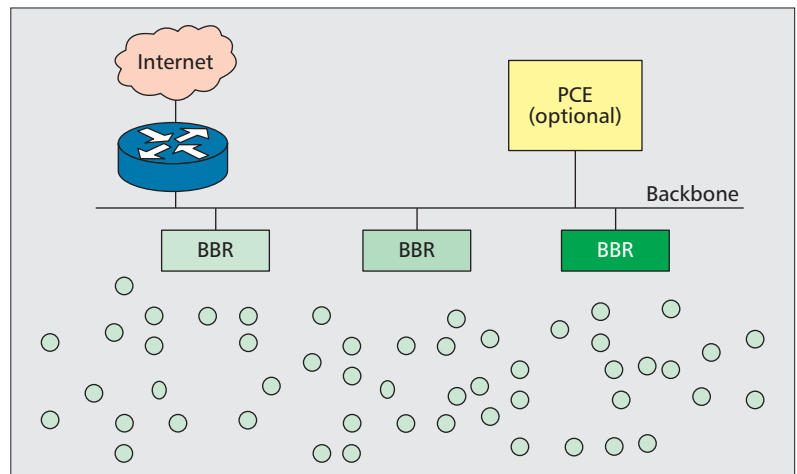
Figure 5. Architecture of a full-featured 6TiSCH network, where multiple backbone routers interconnect different mesh networks.

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BIOGRAPHIES

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