Update from Wireless Standards

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Abstract:

The next percentile point of process optimization yields hundreds of billions of savings, and will be gained by leveraging the collection of currently unused measurements by widely distributed sensing devices and analytic capabilities. Gathering and processing this unused data will require the combination of the best of IT and OT technologies together, forming the IT/OT convergence, aka the Industrial Internet.

Factory networks primarily rely on wired communication networks to support Industrial Automation and Control applications. On the other hand, Wireless Sensor Networks have the power to extend the reach of Monitoring and Control to gather unused measurements beyond what is physically and economically possible with wires; to this day, the deployment of wireless communications in industrial environments has been hampered by a perceived lack of determinism.

The IEEE and the IETF are creating a new generation of Low Power wireless protocols suitable for Time Sensitive Industrial applications. The Deterministic IPv6 over IEEE802.15.4e Time slotted Channel Hopping (6TiSCH) is a new IETF Work Group that formed to enable IPv6 over the TSCH mode of the IEEE802.15.4e standard. The scope of the WG includes one or more Low-power Lossy Networks (LLNs), federated by a backbone through one or more BackBone Routers (BBRs). The Work Group will deliver a networking architecture and put together a collection of standards for centralized and distributed routing and scheduling over a TSCH MAC.

This paper will introduces the work being conducted by this new working group to the ODVA constituency.

Keywords:

Deterministic Networking, Time-Sensitive Networking, IPv6, IEEE802.15.4e, Time slotted Channel Hopping, TSCH, 6TiSCH, RPL, 6LoWPAN

Definition of terms:

Please refer to the 6TiSCH terminology document [10]
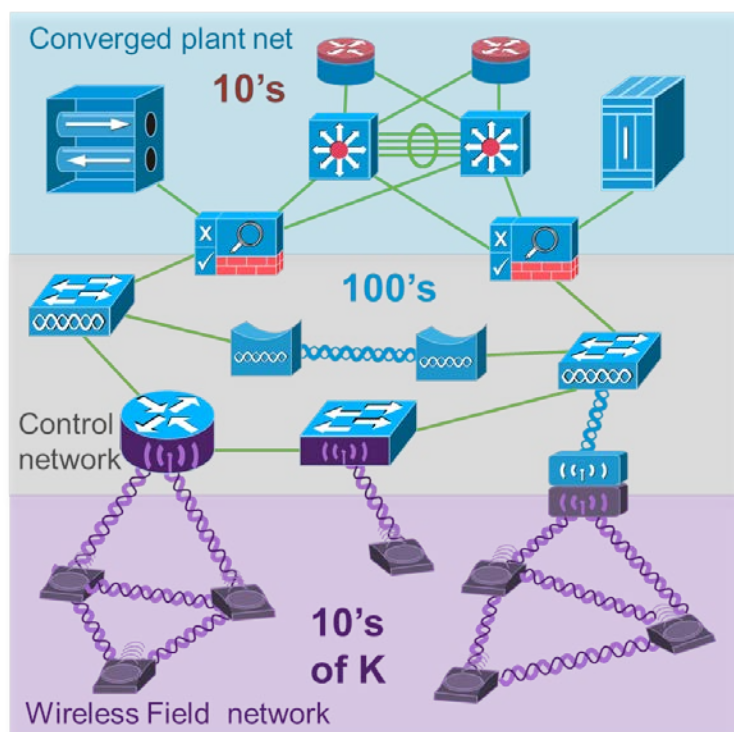
Introduction
For the last 40 years or more, Operational Technology (OT) in industrial networks developed in parallel to the Public Switched Telephone Network (PSTN), and to early data networks such as Bitnet, which was based on IBM's Systems Network Architecture (SNA).

For the last 25 years, the Internet Protocol (IP) has become the de-facto standard for the networking layer of the Information Technology (IT) and for the Internet at large. For the last 15 years, Voice over IP (VoIP) enabled a progressive convergence of voice and data networking technologies, to be soon followed by video streaming and conferencing, leading to the convergence of voice, data, and video over the IP infrastructure.

The integration of IT and OT technologies now appears to be the natural step. Due to its different goals, OT has evolved focusing on highly secure, reliable and Time-Sensitive networks, with limited scalability over a bounded area, in a sharp contrast to IT, which leveraged the end-to-end principle to scale any-to-any connectivity to the proportions of today's Internet, with much less scrutiny on delivery ratio or latency.

So, though appealing for its promised saving on both OpEx and CapEx, enabling OT traffic to be transported over a shared IT infrastructure yields a number of new challenges, which are different as we converge the plant network to transport supervisory flows, the control network to converge automation and monitoring flows, or the field network to access the devices themselves, be they wired or wireless.

- Achieving the convergence the Plant Network is probably now a matter of validation and acceptance. High-end fabrics propose flow isolation with Virtual LANs (VLANs) and Virtual Routing and Forwarding (VRF), guaranteed bandwidth (QoS) and High Availability (HA) features, only getting easier and more economical to manage with Software Defined Networking (SDN) and Network Function Virtualization (NFV).

- The Control Network requires more determinism for control operations, improved Packet Reliability, and more autonomic, zero-touch commissioning to simplify new deployments and allow scalable monitoring applications. These features are well on the way of standardization and productization.

- The convergence of the Field Network is more in its early stage, though ISA100.11a is showing the way with the integration of IPv6. Both ISA100.11a and WirelessHART feature Time Sensitive Networking properties through a centrally controlled routing optimization; but new work is needed to design the distributed routing and scheduling protocol suite that will enable large and affordable monitoring applications in combination with the centralized approach that was proven by those protocols. The remainder of this paper discusses the convergence of bleeding edge wireless IT and OT technologies, and the key capabilities they bring to the Industrial Internet.

IEEE 802.15.4e TSCH

Wireless communications enable a new level of cost effectiveness compared to wire, with a very low incremental cost per device once the access point (AP) is installed. Though cables are often more trusted for control operations, they can be inappropriate for multiple use cases such as rotating devices, moving cranes, robots arms or mobile handheld devices, and yield high installation and maintenance cost, long lead time and extreme difficulties to repair.

On the other hand, radios can reach from near field to orbital trajectory and are appropriate for large scale Machine-to-Machine (M2M) deployments where they can enable new usages such as widespread monitoring.

A Wireless Field Network is typically a Low power and Lossy Network (LLN) that interconnects memory-constrained battery-operated field devices to form a wireless mesh network. In some monitoring and metering use-cases, the capability for the wireless mesh to scale to the thousands of nodes is required. An additional level of scalability, beyond the actual capabilities of a given mesh technology, can be achieved by deploying border routers (BRs) as gateways between LLNs and a federating backbone, either operating at the network layer (L3) or at the application layer (L5) of the Internet Protocol (IP) reference model.

At the IETF, the 6LoWPAN, ROLL and CoRE Working Groups (WGs) have defined new protocols to address the constrained LLN devices, including an IPv6 adaptation layer, 6LoWPAN [1], a routing protocol, RPL [2] and a web transfer protocol, CoAP [3]. This protocol suite was initially defined for use on IEEE802.15.4 low-power radios [4], but limitations linked to random access and related co-channel interferences soon became apparent in the context of mesh-networking applications.

To overtake those limitations, the IEEE802.15.4e standard [5] was published in 2012 as an amendment to the IEEE802.15.4-2011 Medium Access Control (MAC) protocol [4], adding in particular the *Time slotted Channel Hopping* (TSCH) mode, which is still at this time the state-of-the-art technology for ultra-lower power Time Sensitive Networking in LLNs. At the core of the TSCH mode is a medium access technique that uses time synchronization and scheduled transmissions to achieve ultra-low-power operation, coupled with a channel-hopping method to add diversity and cope with multi-path fading and external interferences.

With TSCH, time is sliced in a Time Division Multiplexing (TDM) fashion into time slots of equal duration; a time slot is just long enough for a MAC frame of maximum size to be sent and acknowledged. A shared schedule indicates, for each active (transmit or receive) time slot, a channelOffset and the address of the communicating neighbors. The channelOffset is translated into a frequency using a specific translation function which causes pairs of neighbors to "hop" between the different available frequencies when communicating. In essence, this technology is similar to that used in industrial networking technologies such as WirelessHART and ISA100.11a, resulting in comparable performances

IEEE802.15.4e only defines the link-layer mechanisms [6] and does not amend the 802.15.4 PHY layer. Neither does it define how the network communication schedule is built and matched to the traffic requirement of the network. The definition of an adaptation layer and architectural recommendations are needed for those highly efficient LLN networks to transition to end-to-end IPv6-based solutions.

IETF 6TiSCH

It must be noted that TSCH does not amend the physical layer, i.e., it can operate on any IEEE802.15.4-compliant hardware. The clean layer model of IEEE802.15.4e allows for TSCH to fit under IPv6 in a protocol stack for LLNs, as exemplified in Figure 1 with the 6TiSCH client stack. But the addition of a Logical Link Control (LLC) layer is required between those two layers to provide IP with the link abstraction over which it can operate.

Additionally, IPv6 comes with a suite of protocols that can be difficult to apprehend from the standpoint of a Standard Defining Organization (SDO) that is external to the IETF, such as ODVA, HCF, ISA or IEC. There is a clear need to position the required Request For Comments (RFC) documents that will come into play in an open standard LLN solution, which role they cover in the broad picture, and how they relate with one another.

To fill this gap, a new Working Group (WG) called 6iTSCH has formed at the IETF. 6TiSCH aims to link IEEE802.15.4e TSCH capabilities with prior IETF 6LoWPAN and ROLL standardization efforts and recommendations [7]. In detail, it will (i) define an open standard-based architecture, re-using existing protocols when possible, and (ii) specify the required LLC operation to provide a link abstraction for IPv6.

Doing so, 6TiSCH will inherit from architecture work that was done for ZigbeeIP, ISA100.11a and WirelessHART and experience gathered during their deployments. As it goes, most of the 6TiSCH architecture blocks are already deployed, either as standard-based or proprietary implementations, and the new work mostly consists in selecting

existing and proven IETF components and adapting them to the constraints of the LLN devices. 6TiSCH will document an open standards-based architecture, highlight best practices, and standardize the missing components to achieve industrial-grade performance in terms of jitter, latency, scalability, reliability and low-power operation for IPv6 over IEEE802.15.4e TSCH [5]. Although not addressed directly by 6TiSCH, it is envisioned that the resulting techniques will be applicable to technologies other than 2.4GHz IEEE802.15.4 [4].

Figure 1 summarizes the 6TiSCH client stack. A major ingredient of this stack, compared to ISA100.11a and WirelessHART, is the addition of distributed routing with the RPL routing protocol. The RPL protocol is already in use and deployed with ZigbeeIP and WiSUN for application in energy distribution with the SmartGrid.
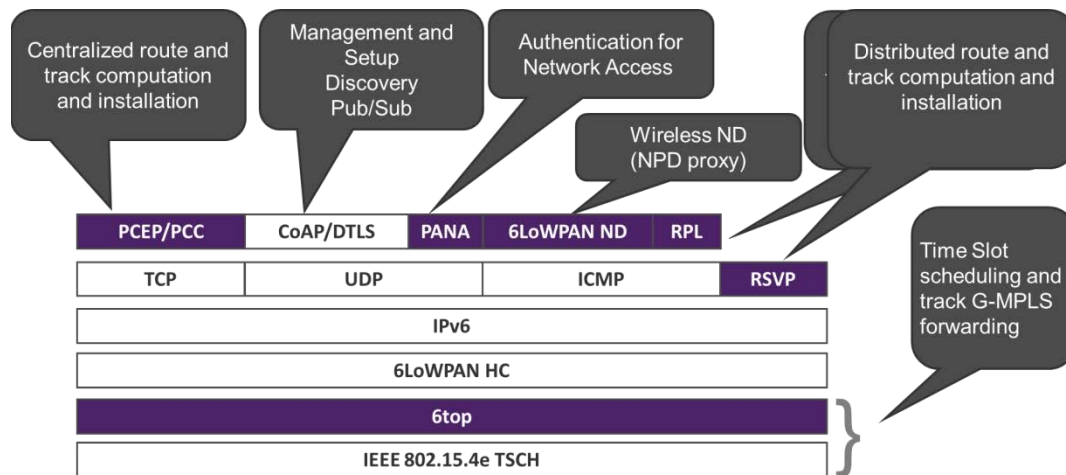

Figure 1

With 6TiSCH, a RPL parent is delegated a number of responsibilities centralized such as time slots allocation that are classically; this allows the central controller to maintain a more abstract view of the network and thus allows the system to scale to large numbers.

Figure 2

As illustrated in Figure 2, the scope of the architecture is an IPv6 multi-link subnet that is spread over a high speed powered backbone and a number of IEEE802.15.4e TSCH wireless mesh networks connected to the backbone by synchronized backbone routers (BBRs).

The 6TiSCH architecture (in progress) [9] and its associated terminology [10] specify how packets that belong to a deterministic IPv6 flow are marked and routed or forwarded over the mesh within jitter and latency budgets. The document covers link management for the IPv6 network layer, neighbor discovery and routing. The security will probably be described in a separate document initially but should be merged ultimately for publication.
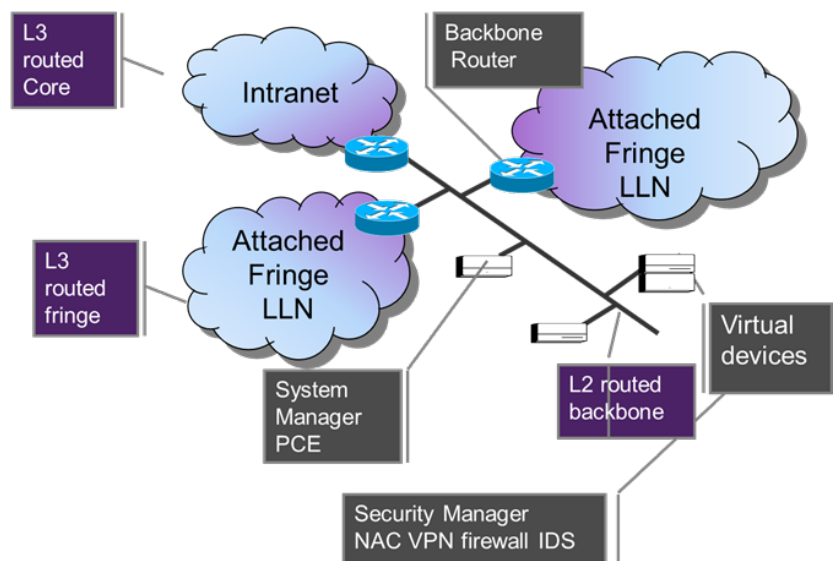
The state of the current work on the LLC layer is found in the 6top draft [11]. Cells– time slots- are grouped in a bundle of equal quality of service (QoS), and 6top is responsible for matching outgoing IP packets to available cells,

based on their QoS requirements. Ultimately, the 6top sublayer will be able to negotiate with its peers a variable number of cells associated with the IP link abstraction, so as to provide dynamic bandwidth allocation that follows closely the needs of the best effort forwarding plane.

RPL and distributed Routing.

Existing industrial Wireless Field Network protocols rely on a central route computation to establish an end-to-end sequence of time slots along a path between nodes. This enables a degree of determinism for time-sensitive flows, whereby the path and the time of arrival are determined, though the actual delivery ratio can be optimized but not guaranteed.
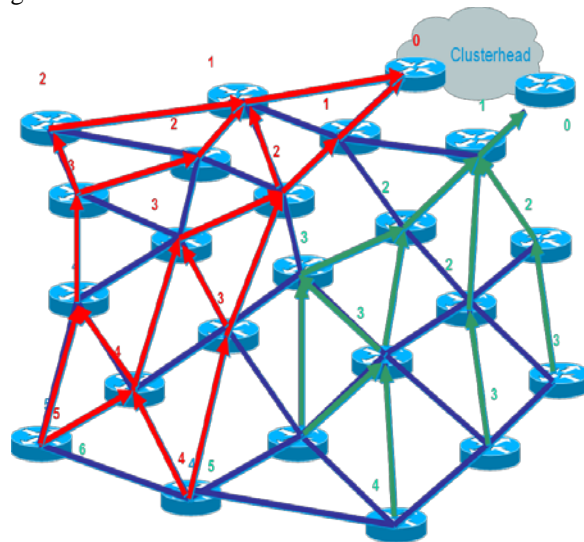
The modus operandi is really designed with control loops in mind; in practice though, wireless deployments are mostly aimed at monitoring, with oftentimes less strict requirements of time sensitivity but higher demands for scalability and lower cost. This is where a distributed routing protocol becomes fashionable; and RPL [2], which was designed at the IETF for routing inside an LLN, is the protocol of choice.

RPL provides a generic distance-vector (DV) operation that is designed to be complemented by an Objective Function (OF) to address any particular use case. An OF ties together metrics and logic that will optimize the routing topology for the particular needs, and produce as an outcome a scalar metric for use by RPL to form a logical topology, as a directed acyclic graph (DAG).

Figure 3 A RPL DAG

The DAG is directed towards a root, and indicates the default route for traffic. Roots can be interconnected by a backbone to form a larger IPv6 subnet, in which case they need to advertise their devices in some fashion, for instance by extending RPL to the backbone with a virtual root, or by proxying IPv6 ND on behalf of their attached LLN devices. To serve multiple needs for different optimizations, RPL introduces the concept of an instance, each instance defining its own topology based on its own Objective Function.

Compared to a link state (LS) protocol, the DV operation limits the amount of topological information that has to be exchanged and maintained at each node to the extreme. In addition, RPL allows for lazy routing updates, and routing inconsistencies can be detected through and fixed reactively based on information that is placed in the packets that would travel through a broken route, in a process called the data-path validation.

To address ultra-constrained nodes, RPL proposes a non-storing mode that relies on source routing to reach individual devices from a root of the DAG. For more capable devices, or when the use case such as long lines that are not appropriate for routing headers, RPL also proposes a more classical storing mode, whereby packets are routed up the DAG till the common parent and then down. The routing stretch is the classical consequence of an economy of routing state, and the result is that only routes towards and from the root are really optimized whereby any-to-any will incur a stretch.
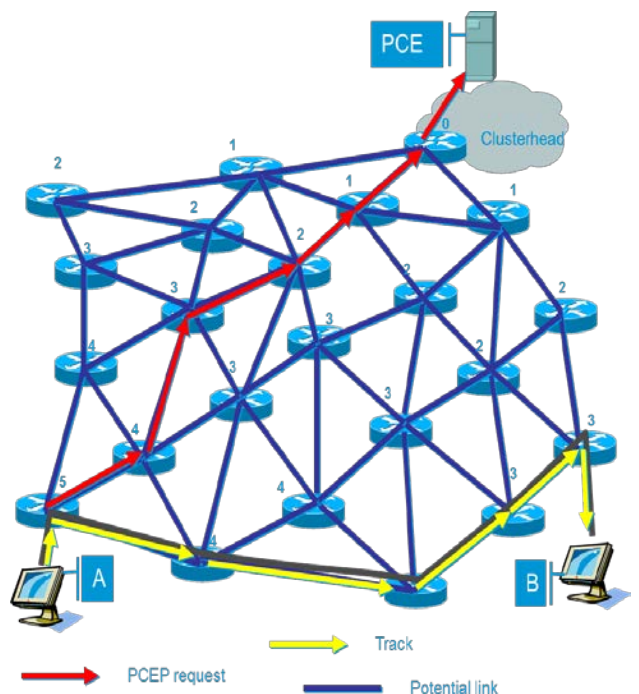
6TiSCH routing and forwarding

With 6TiSCH, routing states are computed either in a centralized fashion by a Path Computation Entity (PCE), which is located either on the backbone or farther in the IPv6 network over a backhaul, or in a distributed fashion using RPL. Moreover, the allocation of a sequence of time slots along a path (aka a track) can be globally optimized and then pushed on the network from the PCE that computes the routes, and/or managed by a distributed scheduling protocol along routes that are computed by RPL.

The architecture will ultimately specify a framework for scheduling frames over time slots that supports three models:

1. A centralized route computation that builds and maintains the communication schedule, and distributes it to the nodes. This schedule includes forwarding information associated to time slots; RPL operations only apply to emergency repair actions when the reference topology becomes unusable. A number of existing protocols could be extended to push the schedule from the PCE to the device, including the PCE communication Protocol (PCEP) [12], Forwarding and Control Element Separation (ForCES) [13], Software-Defined Networking (SDN) OpenFlow or even through network management over the Constrained Application Protocol (CoAP) [3].
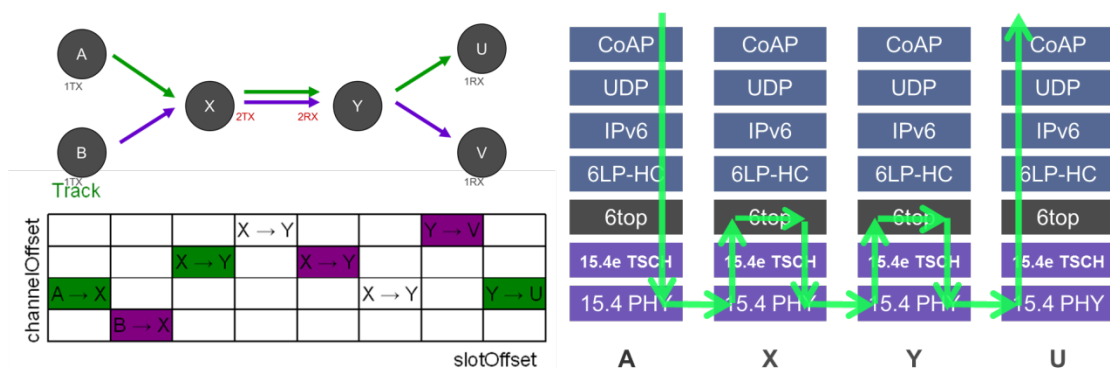

Figure 4 track (G-MPLS like [14], [15]) forwarding for reserved bandwidth

2. A distributed resource reservation and signaling protocol that establishes tracks between source and destination nodes along multi-hop routes identified by RPL. The track may be setup by extensions to the legacy Resource ReSerVation Protocol (RSVP) [16] or the more recent but rather heavy Next Steps in Signaling (NSIS) protocol [17].

3. A best effort resource allocation that is used to transport data frames on a per hop basis in the absence of a reservation protocol.
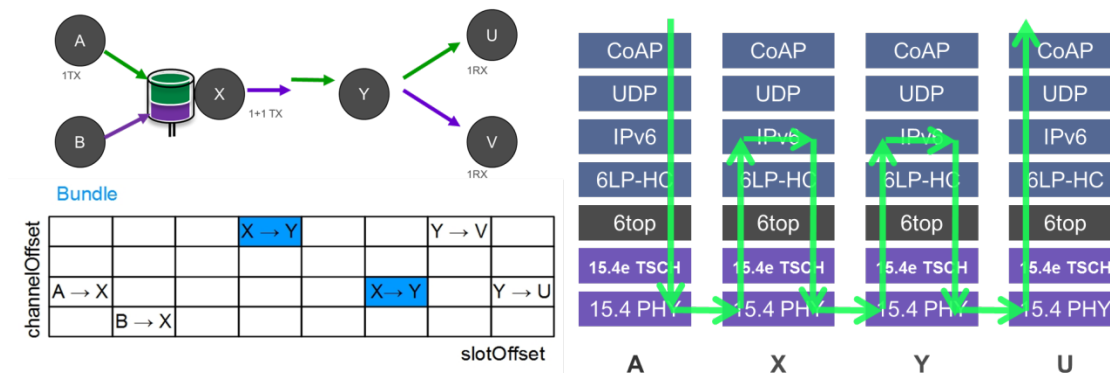

Figure 5 best effort (L3) forwarding

6TiSCH scalability and backbone operation

As detailed in Figure 1, when possible, the 6TiSCH group will reuse existing protocols such as IP6 Neighbor Discovery (ND) [8], IPv6 Low power Wireless Personal Area Networks (6LoWPAN) [1], and the Routing Protocol for Low Power and Lossy Networks (RPL) [2], with the minimum adaptation required to meet criteria for reliability and determinism within the mesh, and scalability over the backbone.
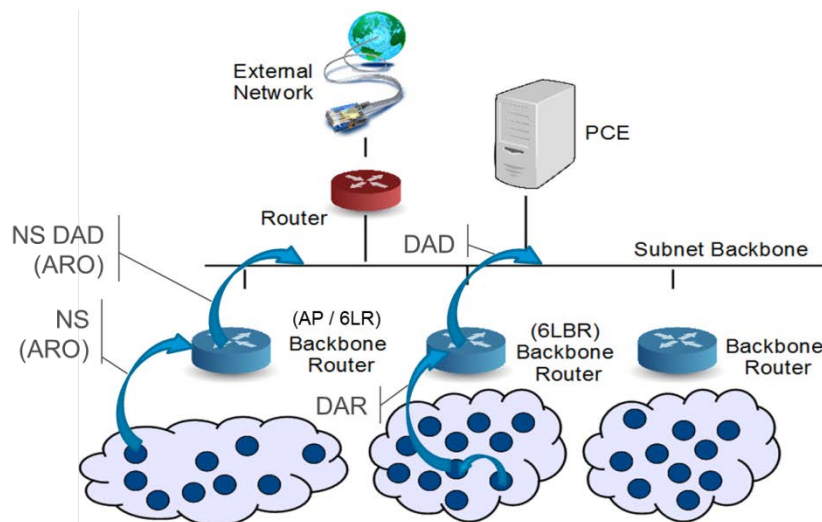
As illustrated in Figure 2, the 6TiSCH architecture also addresses how multiple BBRs are supported for a higher degree of scalability and reliability, and how nodes maintain synchronization in the presence of multiple BBR.

This work implies new IPv6 ND operations called Wireless ND, extending RFC 6775 6LoWPAN ND registration [18] for use in a generic low power of wireless network as described in [19].

Figure 6 RFC 6775 6LoWPAN ND registration

The Backbone Router Internet draft [20] specifies how host routes learnt from RPL can be turned into ND proxy states, and defended over the backbone. This way, the backbone router attracts backbone packets that are destined to LLN nodes, and then forwards them over the LLN along RPL routes, as illustrated in Figure 6 Backbone Router operation.
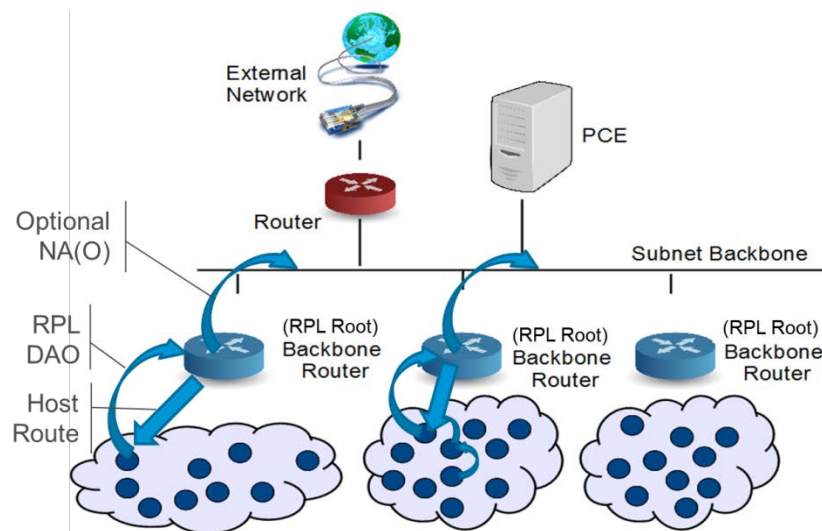

As a result, the 6TiSCH architecture will enable a new range of use cases for LLNs, including both:
 (a)   Control loops in a wireless process control network, in which high reliability and a fully deterministic behavior are required, based on PCE computed routes; and
 (b)   Scalable monitoring networks covering potentially large area or long area, based on distributed route computation with RPL.

Figure 7 Backbone Router operation

Conclusion

Existing industrial Wireless Sensor Network technologies have demonstrated that the IEEE802.15.4e Time slotted Channel Hopping (TSCH) effectively enables industrial grade deterministic properties for slow speed control loops with low latency, ultra-low jitter and a high reliability. It makes sense to extend this support, which is essentially based on centralized routing, to a distributed mode that can be cheaper and simpler to deploy, at the expense of the optimization that only a centralized approach can obtain.

The IETF is now starting an effort, called 6TiSCH, which will provide both centralized and distributed operation, based on open standards, and which will enable a new range of applications in scalable monitoring and automation (home, city, building) as well as man-to-machine interfaces (cars, planes), thus optimizing processes and saving energy and optimizing resources for a greener planet.

Deeper dive-in into TSCH and 6TiSCH is available in a paper presented at ESIOT in July [21] and a book chapter soon to be published [22].

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