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The Internet of Things

The Importance of Cross-layer Considerations in a Standardized WSN Protocol Stack Aiming for IoT[1]

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Editor's Introduction

The Internet of Things (IoT) envisages expanding the current Internet with a huge number of intelligent communicating devices. Wireless sensor networks (WSNs) integrating IoT will rely on a set of the open standards striving to offer scalability and reliability in a variety of operating scenarios and conditions. Standardized protocols will tackle some of the major WSN challenges like energy efficiency, intrinsic impairments of low-power wireless medium, and self-organization. After more then a decade of tremendous standardization efforts, we can finally witness an integral IP-based WSN standardized protocol stack for IoT. Nevertheless, the current state of standards has redundancy issues and can benefit from further improvements. We would like to highlight some of the cross-layer aspects that need to be considered to bring further improvements to the standardized WSN protocol stack for the IoT.

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The original concept of "Internet of Things" (IoT) crafted by Kevin Ashton in 1999 [1], has evolved into the idea of transforming the current Internet by expanding it with a large number of intelligent, communicating, and remotely accessible objects (sensors, actuators, smart-phones, along with original RFIDs). Even though the IoT was initially developed around networking challenges, the enormous quantities of generated and collected data will require further processing using big data and cloud computing. Despite the fact that the IoT has been recognized and promoted for a long time as one of the technological and societal drivers by important governments, several issues stand in the way of widespread IoT deployment. A crucial issue is the existing abundance of proprietary solutions. Hence, the IoT promotes the use of open standards—unburdened by any form of intellectual property, freely licensed, and most of them openly published [2].

Wireless sensor networks (WSNs) participate in the IoT with a large amount of tiny wireless devices reliably running on meager energy resources, providing valuable measurements of the observed environment.

Energy efficiency holds the utmost importance in WSNs: whether nodes run on batteries (impractical to recharge them frequently), or rely on energy scavenging devices (environment offers sporadic and meager energy sources). Protocols for WSNs should reduce their energy footprint through reduced communication and computation loads.

Furthermore, the intrinsic wireless medium impairments (volatile, lossy) nature of low-power radio links—the unpredictable packet losses due to interference, path loss, shadowing or multipath fading [3]—influence most of the WSN communication layers. A reliable WSN protocol stack should incorporate mechanisms that account and leverage on the wireless medium downfalls.

Similarly to the plug-and-play concept from personal computers, WSNs should offer a deploy-and-forget experience to the final users. Self-organization and self-healing are thus huge challenges for WSN protocols: A substantial number of nodes should operate with no infrastructure support, while providing a fully autonomous network (no human intervention) in potentially hostile and dynamic environment (link and node breakage, battery exhaustion, and/or mobility).

The IP protocol suite has been de facto networking standard for several decades. It brought about seamless and transparent communication between a large number of devices, allowing them to deal with unprecedented amounts of information, queries, and computation in a reliable and secured fashion. The development of the successor, IPv6 protocol, will permit interconnecting even more smart devices (approximately 3.4×1038) into the IoT ecosystem, solving the long-anticipated problem of IPv4 running out of addresses.

Existing Internet protocols such as HTTP [4] and TCP [5] are quite complex due to overhead generated by encapsulation, offered end-to-end reliability, and security mechanisms. Furthermore, they are mostly engineered to run over wired, main powered networks with bi-modal links. IoT objects with low power consumptions and volatile wireless links hamper the direct use of existing Internet protocols in WSNs. Thus, we witnessed a huge standardization effort to eliminate the unnecessary abundance of proprietary solutions and provide adaptation of IP. Standardization efforts relevant to WSNs are the IEEE (link and physical layer solutions), ETSI (complete machine-to-machine solutions), ISA (regulation for control systems), and the IETF (routing and network solutions). Over the last decade an IP-based low-power WSN protocol stack has emerged. We will present briefly all protocols from the stack. Each protocol layer only communicates with adjacent layers by offering a limited and well-defined set of services. A divide and conquer strategy removes all dependencies and assumptions between the separate layers. Such strategy offers a better focus on design challenges and would lead to faster development of the IoT [2].

Nevertheless, the classical layered model allows us only to optimize different layers separately. In other words, the local optima for adjacent layers (e.g. MAC and transport routing) may be antagonist and would not lead to a global optimum. Additionally, certain particular functions of WSNs cannot be easily allocated to a single specific layer. Topology construction could be arbitrary attributed either to MAC (closer knowledge of link characteristics) or routing (global delivery goals). Finally, WSN channel impairments [3] generally affect all the layers, potentially leading to even more important optimization mismatch between different layers [6].

Work covered within revisits some of the design aspects used to develop the standardized WSN protocol stack for IoT supporting IP connectivity [7]. We emphasize some of the benefits that cross-layer considerations could bring to further improvements of a standardized protocol stack, in particular to a joint operation of two protocols—IEEE 802.15.4-2006 at the MAC layer and RPL at the network layer. Moreover, we want to highlight the need of conjoint design of some of the important functionalities—topology construction and link scheduling. Finally, we will provide an overview of state-of-the-art solutions tackling those aforementioned challenges and summarize potential directions for further development.

Related Work

IEEE 802.15.4. IEEE 802.15.4 proposes a global standard at the MAC and PHY layer for interconnecting low-power/data-rate/cost sensor and actuator networks. The standard has undergone several revisions to enlarge the pallet of supported applications and satisfy stringent requirements from the emerging industrial applications. We will provide a brief overview of the two most prominent revisions with their features and points for improvements: IEEE 802.15.4-2006 and IEEE 802.15.4e.

IEEE 802.15.4-2006 operates on a single channel from the 16 possible ones on the 2.4GHz band, which made it quite prone to interference and multipath fading. The IEEE 802.15.4-2006 standard proposed two mutually exclusive modes on a MAC layer: "non-beacon" and "beacon-enabled" modes. In non-beacon mode, all the nodes use CSMA-CA to transmit their frames: Since no synchronization is required, no node can sleep. On the contrary, in beacon-enabled mode, IEEE 802.15.4-2006 uses the concept of superframes to implement a low duty-cycle mode. The coordinator periodically sends beacons to delimit the beginning of its superframe, allow time synchronization, and disseminate control information. All the nodes participating to its superframe can access the medium with a slotted CSMA-CA during the contention access period (CAP).

In multihop, a node is both a child during the active part of its parent (uplink) and a coordinator for its own active part (downlink). The IEEE 802.15.4-2006 standard is prone to collisions in multihop topologies of both beacons and dataframes, due to a lack of elaborate methods for scheduling superframes.

IEEE 802.15.4-2006 supports three different network topologies: peer-to-peer, star, and cluster-tree (a generalization of the star). In the case of the star and cluster-tree topologies IEEE 802.15.4-2006 implements a topology control. A node needs to be associated with a coordinator before transmitting packets. A node searches for available coordinators by performing either active (explicitly transmitting beacon-requests to potential coordinators) or passive discovery (scanning through all available channels for incoming beacons). After a complete discovery, a node can initiate an association procedure to the selected coordinator. The association procedure requires a six-way handshake that spreads over several superframes. Several approaches exist in the literature to simplify and accelerate the association procedure [8, 9, 10].

The cluster-tree is not robust since a node relies on a single associated parent. Moreover, the standard only specifies the way information is exchanged during the association, not what coordinator a node should choose to associate with.

IEEE 802.15e overcomes the limitations of the IEEE 802.15.4-2006 standard (mostly related to CSMA slotted access—unbounded delay and limited reliability; a single channel operation—prone to multipath fading and interference; and to inefficiencies of multihop operation).

The 802.15.4e standard provides MAC enhancements on two levels: the general functional level and targeting a specific application domain. On the general level, 802.1.5.4e provides the possibility to operate at low duty cycle (e.g., 1 percent or below), while offering a low-delay response to the upper layers.

On the application specific level, the 802.15.4e standard provides highly optimized modes—such as, radio frequency identification blink (BLINK), deterministic and synchronous multichannel extension (DSME), low latency deterministic network (LLDN), and time slotted channel hopping (TSCH). The 802.15.4e modes strive to provide solutions for challenging application domains such as process and automation, smart metering, health care and home automation.

In a nutshell, TSCH mode resides on the combination of TDMA (time division multiple access) and FDMA (frequency division multiple access) schemes, reinforced with a channel hopping mechanism to cope with interference and multipath fading; a mechanism readily available in existing standards for industrial applications (i.e., WirelessHART [11] and ISA 100.11.a [12]).

A TSCH executes a periodic matrix structure where each cell (a doublet of a time slot and a frequency channel) can be reserved for a dedicated directional communication slot between a pair of nodes. Compared to IEEE 802.15.4-2006, several simultaneous communications are possible in a single time slot through the use of the multi-channel mechanism. Nevertheless, 802.15.4e does not generate the schedule for communication cells, but rather offers a mechanism to execute it. Attributing a unique communication cell to a specific node pair is left to upper layers.

Additionally, the 802.15.4e standard deploys enhanced beacons (EB), allowing the creation of custom beacons by including relevant control information. Association process was made optional, along with a newly introduced fast association (FastA) mechanism. Finally, the 802.15.4e standard provides a specific feedback to the networking and upper layers: MAC performance metrics capture the channel quality (number of retransmissions, backoffs, duplicated packet reception, and packet delivery rate).

RPL. The main goal of the IETF (Internet Engineering Task Force) ROLL (Routing Over Low power and Lossy networks) working group is to elaborate a new routing and self-organization protocol suitable for LLN (low power and lossy networks) in light of the new IoT paradigm. Anticipating the new IoT, ROLL requires interoperability with IPv6 and 6LoWPAN, as well as compliance with a variety of link layers, supporting both wireless and PLC (power line communication). Routing Protocol for LLN (RPL) [13] is built as a gradient routing to support a variety of network traffic patterns:

- **Multi-point-to-point (MP2P).** Also know as convergecast or upward routing, a large amount of sensing devices report their readings to a centralized processing and storing unit called sink.

- **Point-to-Multi-point (P2MP).** Downward routing that can be seen as a form of data polling where the sink requests data readings from nodes.
- **Point-to-point (P2P).** An arbitrary pair of nodes is enabled to communicate.

RPL creates a destination oriented-directed acyclic graph (DODAG) [14], an oriented graph with no loops rooted at the sink. The RPL choice of DODAG stems from the following observation: a majority of the supported traffic patterns belong to the MP2P class.

Each node belonging to a DODAG broadcasts a DAG information object (DIO) including its distance to the root of the DAG according to a given metric (e.g. hop count, link quality, delay, or jitter). The node rank (distance to the root) can serve as a routing constraint (a way of pruning potential forwarders not satisfying specific properties, e.g., use only paths traversing main powered nodes). It can also serve as an accumulative metric (a way of estimating the route cost, e.g., use the path that minimize the energy consumption).

Each node executes a distance vector algorithm to find a set of neighbors closer to the root than itself: They become its parents. A parent offering the best path toward the root is designated as "preferred parent" and subsequently used as the default forwarder for all upward traffic until such parent fails. RPL suggest the use of hysteresis to limit the frequent changes of the preferred parent due to the unstable nature of LLN links and consequent rank value changes. RPL also proposes a mechanism for fast route repair when a transient loop is detected.

Even though a DODAG results in a more robust structure compared to a cluster-tree structure, RPL does not exploit the variety in available parents to offload traffic from hotspots (a single preferred parent) and to achieve quality of service (a single metric is used to optimize traffic flow).

Contrary to efficient, simple, and well detailed (all necessary IPv6 compatible mechanisms are described as such) upward routing, RPL lacks in maturity when it comes to P2P and P2MP routing [15].

6LoWPAN. The 6LoWPAN (IPv6 over Low power WPAN) Working Group [16] was formed to define an IPv6 compliant operation over the IEEE 802.15.4-2006 networks. 6LoWPAN implements an adaptation layer between the data link and the network layer in the TCP/IP protocol stacks. 6LoWPAN offers bootstrapping capabilities (neighborhood discovery (ND)), IPv6 address resolution capabilities, and the transmission of IPv6 packets over the IEEE 802.15.4-2006 networks:

- **Header compression.** Large IPv6 packets should be reduced to fit 127B offered by the IEEE 802.15.4-2006 standard. The 6LoWPAN adaptation layer dramatically reduces the IPv6 transmission overhead. All unnecessary fields are completely eliminated from the original packet and the remaining fields are resized.
- **Fragmentation.** 6LoWPAN ensures that IPv6 data fragments transmitted over multiple hops are reassembled at the destination.

6LoWPAN bootstrapping offers an alternative to ND proposed by the IEEE802.15.4-2006 standard. 6LoWPAN adapts existing ND for wired networks to low-power, low-rate, and low-duty cycle WSN. 6LoWPAN ND is based on observing the data packet progress, thus leading to inefficient and slow link breakage detection.

CoAP. The IETF Constrained RESTful Environments Working Group (CORE WG) defines an adaptation of the RESTful architecture. An example is the client/server model defined by the application layer protocol HTTP. Constrained Application Protocol (CoAP) [17] defines a subset of the RESTful specification, adapted to constrained aWSN environment. CoAP aims to offer simplicity, very low overhead, and minimized fragmentation while still providing interoperability with HTTP.

Even with the adoption of UDP (user datagram protocol) at the transport layer, CoAP provides reliability mechanisms through the use of dual layers. The transaction layer handles the single message exchange between end points (acting both as clients and servers). The request/response layer maps asynchronous requests to responses and their underlying context. CORE WG also covers the security of the application layer through protection of CoAP messages. CORE WG has proposed a framework based on the DTLS protocol [18]. Use of robust and reliable certificate mode, permits both authentication and key negotiation mechanisms through the X.509 certificates validated by an authority.

Cross-layer Considerations and Challenges

Topology construction. As previously stated, a topology construction could be arbitrary attributed either to MAC (closer knowledge of link characteristics), or routing (global delivery goals). Both standards, IEEE 802.15.4-2006 and RPL, maintain a separate topological structure—respectively a cluster-tree and a DODAG—that make the interoperability of the two standards impossible in the original version. Maintaining two different topology structures is not only redundant but also highly energy inefficient. Authors [19] propose to modify the cluster-tree structure into a cluster-directed acyclic graph (DAG) at the MAC layer that leads to improvements of the robustness and redundancy the topology, as well as a routing delay.

Recently, IEEE 802.15.4e entirely omitted the topology construction; now it solely remains a responsibility of RPL. Nevertheless, when it comes to neighborhood discovery (ND) that initiate the topology construction, redundant mechanisms still remain on several layers: an optional FastAssociation with active/passive scans of IEEE 802.15.4e, DIO packet exchanges at RPL, and adaptation of ND mechanisms from wired networks at 6LowPAN. An open issue remains: How to develop an efficient and unique ND mechanism on a single layer that will take into account operational requirements from all layers.

The final RPL topology is determined by the best parent selection that is done according to a given metric (e.g., hop count, link quality, delay, or jitter) [20]. Concrete mechanisms to measure these metrics are out of the scope of RPL and expected to be provided by other layers from the IoT stack.

Link quality measurements traditionally belong to MAC and PHY layers. Over the years there have been numerous attempts to establish a fast, reliable, and standardized mechanism for link quality assessment based on expected transmission count (ETX) [21, 22] and low-level physical indicators like RSSI [23], LQI [24], and DSSS chip errors [25]. Ultimately, none of them became part of the previous IEEE 802.15.4-2006 standard, where the novel IEEE 802.15.4e standard simply defines a rudimentary list of quality indicators for each single data frame transmission (number of retransmissions, backoffs, duplicated packet reception, and packet delivery rate).

On the other hand, we believe the delay metric should be dually defined and measured at both MAC (IEEE 802.15.4e) and application layer (CoAP) to reflect link level delays, but also end-to-end delays experienced by the end user. Moreover, end-to-end delay measurements should not only give simple values of experienced delay but also reasons that caused it (e.g., congestion, low-link quality, path breakage, etc.). In return, a tighter cross-layer collaboration is necessary to acquire those in depth delay indicators.

The bottom line is this; the existing work on convergecast topology construction [26], including the RPL standard itself, often favors a single, local, and greedy optimization goal (metric) from the perspective of each node. Let us take an example where RPL nodes select as a preferred parent, the neighbor that offers the best quality path (ETX metric) to the DODAG root (sink). Such a choice leads to a possible increase of load and congestion experienced on this route, and finally to a premature battery exhaustion. We do not strive to exclude the link quality metric from the observation with this example, but rather argue it should be jointly considered with other metrics. Thereafter, we correspondingly propose a set of cross-layer considerations that should be taken into account to help achieve global optimization goals. For each of the items, we suggest the most appropriate layer to measure each individual metric.

- **Link quality considerations.** A stable and efficient radio link saves energy that would be otherwise unnecessarily spent on additional contention and packet re-transmissions. Nodes should favor proper link quality estimation, rather than prematurely choosing suboptimal parents that would end up in oscillatory behavior, such as frequent changes of parents. IEEE 802.15.4e should provide low-layer link quality estimations preferably directly available from PHY layer similarly to DSSS chip errors [25].
- **Bottleneck effect.** The convergecast traffic often leads to a funneling effect [27]: The zone around the DODAG root must transmit more packets, creating congestion. To limit this phenomenon, the direct DODAG root descendants (1st rank nodes) should all have approximately the same volume of traffic to forward. On one hand, CoAP could provide a projection of traffic load required by users and experienced end-to-end delay. On the other hand, RPL could provide a real experienced level of traffic based on buffer levels and forwarding activity.
- **Avoid congested zones.** Nodes should avoid associating to parents offering paths leading through high-density network zones, i.e., high congestion zones. Contrary to the funneling effect, a high-density zone also can appear further from the DODAG root. Opting for other parents would alleviate unnecessary delay and extra traffic accumulation in this already congested zones. Similarly to our previous point, CoAP and

RPL could extrapolate traffic levels (estimated and experienced) and aggregate them in form of measurable metric.

- **Self-healing.** A node detects and corrects inconsistencies so the global objectives stay preserved. For instance, a node should monitor the link quality and change its parent selection if it changes significantly. Currently, RPL provides a hysteresis mechanism to cope with rank changes relative to a single measured metric. Also, a resulting convergecast structure should incorporate the new arrival nodes or react to disappearing nodes (battery exhaustion, link failures, etc.).

Link Scheduling. In simple terms, the main goals of link scheduling in multi-hop WSNs are to reduce collisions, increase bandwidth, while achieving energy efficiency.

Historically, there are three main approaches in the literature to reduce the number of collisions in multi-hop IEEE 802.15.4-2006. In the "beacon only period" (BOP) solution, nodes implement a TDMA approach to send their beacons while keeping the same network wide CAP. Simulations showed performance quickly degrades if hidden terminals are frequent [28].

A second solution is equivalent to scheduling the active parts of superframe with a TDMA approach. Villaverde et al. [29] have experimentally proved this approach leads to improved performance. Nevertheless, the approach can lead to bandwidth waste due to coordinators without children, and consequently to scalability limitations.

A third solution tackles the impairments of both previous approaches by applying A TDMA approach for both beacon and active periods [19] that avoids the collisions while limiting bandwidth waste even in dense WSN networks. Additionally, two distributed strategies (random and greedy) have been developed and demonstrated as efficient and requiring low complexity. Both require two-hop neighborhood knowledge, available through a localized and limited control packet exchanges. The random approach proposes a very naive and simple mechanism where each coordinator randomly selects one superframe slot not used by any of its parents. The greedy approach avoids interference with all two-hop coordinators. If all slots are occupied (e.g., dense network), a node avoids collisions with a coordinator with children. Both mechanisms have proven self-stabilizing property (convergence to a legal state in a finite number of steps).

IEEE 802.15.4e goes one step further toward efficient link scheduling by defining a joint use of TDMA and FDMA approaches. A cell (a doublet of a time slot and a frequency channel) can be reserved for highly efficient and collision-free communication in multi-hop topologies. Nevertheless, mechanism to devise a link scheduling (attribution of cells to pairwise communication) is out of the scope of IEEE 802.15.4e. Scheduling, per se, is not a trivial task, especially when it comes to low-power WSN networks for the IoT. The problem is even more challenging in dynamic networks where the topology changes over time (e.g., due to mobile nodes or unstable wireless links). Efficient scheduling is highly impacted by several aspects, not necessarily belonging to a single layer in the standardized protocol stack. Recently, scheduling design has been attributed to an IETF 6TiSCH working group.

We want to highlight some of the aspects that an efficient link-scheduling algorithm should take into account:

- **Neighborhood interference list** is the building stone for efficient link scheduling algorithm. A mechanism to build such list needs to be established, preferably at the IEEE 802.15.4e layer, where it is currently not available.
- **Topology construction** requires link scheduling to reflect the decisions taken to build the topology at RPL. A routing path through preferred parents will be translated to a necessary number of dedicated communication cells. Tight collaboration with RPL is necessary to exchange information in a timely manner respective to topology change.
- **Traffic load** requested at application layer dictates the amount of necessary communication cells to be scheduled. Traffic load projections, estimations, and measurements are essential for link scheduling. Eventually, CoAP could provide requested and projected traffic loads (on-demand and periodic traffic), while RPL buffer and queue levels could reflect ongoing status and past trends.
- **Network dynamic** (both accounting for node mobility and link variance) will influence the link scheduling recalculations necessary to optimally respond to a changing network state. A link-scheduling algorithm should have tight information exchange with ND mechanism.

A TSCH link-scheduling task can be performed in centralized and distributed fashion. Recent literature documents the surge of several novel link-scheduling algorithms for TSCH stemming from the work of 6TiSCH working group.

TASA [30] offers a typical centralized algorithm where a single master node (DODAG root) collects the entire topology information, calculates the scheduling, and finally redistributes the exact cell mapping in the network. TASA takes into account a simplified traffic consideration where each node generates, on average, the same amount of convergecast traffic over time. TASA is adapted for fairly static networks, since the link schedule has to be rebuilt each time the network topology and traffic volumes change.

DeTAS [31] goes a step further and proposes a distributed traffic-aware scheduling algorithm. DeTAS constructs optimal and collision-free schedules for multi-hop IEEE802.15.4e TSCH networks. DeTAS, similarly to other distributed algorithms, exchanges a small amount of information only between neighboring nodes on a local level. Parent nodes can locally devise estimated traffic loads in its sub-trees based on the assumption of periodic traffic. Additionally, DeTAS considers local queue levels and avoids congestion and buffer overflows by interleaving transmit and receive cells for each coordinator. DeTAS outperforms TASA, especially in case of larger networks, where queue occupation remains constant regardless of the network size.

Further improvements of DeTAS could include quality of service considerations (traffic prioritization according to quality of service criteria, e.g., end-to-end delay), load-balancing, the possibility to use more preferred parents (forwarders), and non-periodic traffic patterns.

Conclusion

We have presented a brief overview of what have nowadays converged to be called an IP-based WSN standardized protocol stack for the IoT. We have highlighted some of the issues for each individual layer that would benefit from further improvements. Furthermore, we have discussed and argued for the necessity of cross-layer considerations when designing further improvements to the WSN standardized stack, most notably to topology construction and communication scheduling mechanisms. Due to intrinsic impairments of low-power wireless communication and the necessity for extreme energy efficiency, mechanisms belonging to a specific layer cannot be considered individually without the back thought of how it will impact overall performance. In the future, we plan to put cross-layer considerations into practice.

Firstly, by proposing a set of locally measured metrics and combining them to build an optimized DODAG topology. Secondly, we plan to devise a link scheduling mechanism on top of constructed topology that will inherit and take into account multitude of previously considered metrics.

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