WSN Trends: Sensor Infrastructure Virtualization as a Driver Towards the Evolution of the Internet of Things

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Abstract— **Fueled by advances in microelectronics, wireless communications and the availability of affordable mobile connectivity, the last decade has seen a rapid increase in the number of devices connected to the Internet. This evolution is part of the transition to the Internet of Things (IoT), which envisions connecting anything at any time and place. While it can be argued that the IoT is already here, the next paradigm shift is already emerging on the horizon, targeting yet another order of magnitude increase in the number of interconnected devices and promising to bring people and processes in the equation. However, before such a paradigm shift can be realized, significant challenges with respect to scalability, cooperative communications, energy consumption, as well as convergence of sensor and analytics trends have to be resolved. Sensor Virtualization Technology capturing both the Virtual Sensors and Virtual Sensors Networks aspects, promises to alleviate or resolve these challenges, and pave the way towards the evolution of the Internet of Things.**

Keywords-Sensor Networks, Sensor Virtualization; Machine to Machine Communications; Internet of Things; Future Internet.

I. INTRODUCTION

Technological advances in the fields of sensor technology, low power microelectronics, and low energy wireless communications paved the way for the emergence of Wireless Sensor Networks (WSNs). These networks are currently used in a wide range of industrial, civilian and military applications, including healthcare applications, home automation, earthquake warning, traffic control and industrial process monitoring. A WSN is a system composed of small, wireless nodes that cooperate on a common distributed application under strict energy, cost, noise and maintenance constraints [1], [2]. Although many interesting applications have been implemented/developed for WSNs, further work is required for realizing their full potential as “the next big thing” that will revolutionize the way we interact with our environment.

As a promising step in this direction, during the last decade there has been a growing research interest in the Internet of Things (IoT), ranked as a disruptive technology, according to the US National Intelligence Council [3]. An early definition for the IoT envisioned a world where computers would relieve humans of the Sisyphean burden of data entry, by automatically recording, storing and processing all the information relevant to the things involved in human activities, while also providing “anytime, anyplace [...] connectivity for anything” [4].

Henceforth, and depending on the viewpoint, different understandings and definitions have been reported in the literature [5]-[7] regarding what the Internet of Things is about. However, while it is possible to argue that the IoT is already here [8], the next (r)evolutions are already on the horizon, ranging from the open effort to the Future Internet up to industry driven initiatives such as the National Instruments Data Acquisition Technology Outlook [9], the General Electric concept of “Industrial Internet” [10], and the CISCO initiated “Internet of Everything” [8], [11]. Such initiatives have differences in flavor and focus; yet, it is possible to distil the general trends and enablers that need to be in place for successfully realizing the shift to the next networking paradigm, whichever form it might take. In this paper, we argue that, among these enablers, Sensor Network Virtualization is a technology that has the potential to augment and unlock advances in several other fronts (e.g., scalability, cooperation, low energy solutions and convergence of Sensor Network and Data Analytics trends) that will pave the way towards this paradigm shift.

The rest of the paper is organized as follows: Section II presents some of the key networking trends that are commonly captured in several independent views for the next networking paradigm evolution. It finishes with a selection of four core areas where significant challenges remain unresolved. The selected areas and the nature of the challenges in each of them are then discussed in more detail in Sections III-VI. Section VII elaborates on the different aspects of sensor infrastructure virtualization. Their advantages are captured and the potential of using different virtualization flavors to address the challenges described earlier is explained. Finally, Section VIII concludes the paper.

II. IDENTIFICATION OF NETWORKING TRENDS

In parallel with the efforts towards interconnecting a myriad of smart devices according to the IoT vision, the Future Internet stands as a general term for research activities and communication paradigms towards a more up to date and efficient Internet architecture. Approaches towards the “Future Internet” cover the full range from small, incremental evolutionary steps up to complete redesigns (clean slate) of the core architecture and the underlying mechanisms, where the applied technologies are not to be limited by existing standards or paradigms (e.g., the client server networking model might evolve into co-operative peer structures). In general, most of the work in this area is summarized by the

 ISBN: 978-1-61208-289-9

Future Internet Assembly (FIA) [12], where it is underlined that whatever form the Future Internet may take, a set of core principles need to be preserved:

- *Heterogeneity support principle*, refers to supporting a plethora of devices and nodes, scheduling algorithms and queue management mechanisms, routing protocols, levels of multiplexing, protocol versions, underlying link layers or even administrative domains and pricing structures.
- *Scalability and Amplification principle*, describing the ability of a computational system to continue operating under well specified bounds when its input is increased in size or volume.
- *Robustness principle*, ensuring that each protocol implementation must transparently interoperate with other implementations.
- *Loose Coupling principle*, describing a method of interconnecting architectural components of a system so that those components depend on each other to the least extent practicable.
- *Locality principle*, which in the computer science domain focuses on the design of thrashing-proof, self-regulating, and robust logical systems.

However, apart from these principles that should only undergo small incremental changes (if any) a list of additional principles that need to be significantly adapted/relaxed or augmented is also provided. Here, we focus on a subset of this list that is related or overlapping to the IoT evolution:

- *Keep it simple, but not "stupid" principle* [12], which refers to the fact that in current Internet design, the complexity belongs always at the edges, while in a more flexible architecture inherently supporting heterogeneous "Things" this might not always be the case.
- *Polymorphism principle,* which refers to the ability to manipulate objects of various classes, and invoke methods on an object without knowing that object's type. The idea is to extend this principle to allow the same abstract components exhibiting different functional and non-functional behavior in case of changing environments or circumstances [12].
- *Unambiguous naming and addressing principle*, establishing that protocols are independent of the hardware medium and hardware addressing scheme. The proposal of the FIA initiative is to extend this principle in order to also capture the data and services.

Even more recently than the FIA initiative, CISCO has evangelized the Internet of Everything (IoE) as the next wave in the evolution of the networking paradigms [8]. With a clear all-IP focus, building on the same principles as Machine to Machine Communications (M2M) and the Internet of Things but extending them, the IoE envisions to increase the number of connections by yet another order of magnitude (from ~10 billion currently connected "Things"). However, arguably the biggest innovation is that it targets to include processes and people in the loop, facilitating and enabling communications that are more relevant in order to offer new capabilities, richer experiences and unprecedented economic opportunities.

In all the previous activities, as well as in various independent research efforts, it has already being identified that in future large-scale heterogeneous networks, the adoption of mechanisms achieving scalable, predictable and self-adaptive network behavior ("more relevant" in CISCO IoE terminology, "pushing the boundaries" in the GE Industrial Internet notion) will be a key enabler [8], [10], [11], [13], [14]. At the same time, with systems becoming continuously more complex in terms of scale and functionality, reliability and interoperability are getting increasingly important. Therefore, techniques for achieving dependable system operation under cost and energy constraints will be an important evolutionary step [2], [13], [14].

Current wireless network development is guided by horizontal mass-markets ("one size fits all"). More often than not, different verticals and niche markets require dedicated applications [14]. Consequently, the deployment or evolution of a wireless network in these areas often demands for expensive infrastructure replacement. Moreover, extending system and network capabilities, switching services or adopting the purpose of an operational network consisting of heterogeneous "Things" usually calls for costly (manual) reconfigurations and upgrades, while it often results in temporary unavailability of system services. On the other hand, dynamic changes during operation typically allow for only a limited subset or scope of updates. Solutions for such problems require capabilities for spontaneous ad-hoc cooperation between objects, self-adaptive behavior, exploitation of dynamic information, predictability of non-functional properties (e.g., energy consumption), and on-the-fly reconfiguration [13], [14], [15].

Summarizing, first and foremost, **scalability** is the key enabler for facilitating the (r)evolution of the Future Internet as the number of interconnected devices is expected to rise by yet another order of magnitude. The vast majority of these devices will be smart sensors with relatively limited computation resources. Thus, key challenges lie in efficient **cooperation** of heterogeneous network elements in order to realize advanced capabilities and services. Furthermore, innovations to **low energy solutions** create an attractive business case by offering benefits in terms of operational cost, long-term product reliability and increased lifetime of wireless and mobile elements (especially relevant for a significant portion of the myriad of electronic "Things" that will be battery powered). Last but not least, as the number of interconnected devices will increase a **convergence of the Sensor Network and Data Analytics trends** is required for effectively bringing processes and people into the equation. An overview of the respective trends, including some of the main open issues, is provided in the sequel of this section.

III. Scalability of Communication and Management

In order to realize the vision of ~50 billion devices connected to the Internet by 2020 [8], several scalability enablers need to be in place. One can argue that some of them are already here and they have driven the evolution towards the estimated ~10 billion interconnected devices that we have

 ISBN: 978-1-61208-289-9

currently reached [8], [11]. Hardware node miniaturization, node capability enrichment and cost reduction, all fueled by Moore's law, are a good example of such enablers. Processing and storage availability are also improving thanks to the cloud computing paradigm. On the network protocol naming and addressing part, the transition to IPv6 has to take place sooner than later in order to facilitate the next jump in number of interconnected devices.

However, apart from the hardware node and protocol/ communication part, efficient management of this huge number of heterogeneous devices is also a big challenge. The concept of network management traditionally captures the methods and tools that are related to the operation, administration, maintenance, and provisioning of networked systems. In this context, operation is related to keeping the network working according to the specifications; administration is dealing with resource tracking and utilization; maintenance is concerned with changes and upgrades to the network infrastructure; and finally provisioning addresses dynamic, service-based resource allocation. However, catering for heterogeneous sensors and actuators with different requirements and operational properties calls for a paradigm shift; higher layers need to efficiently capture the changing dynamics of the systems and the lower layers need to transform this information into appropriate action, in an autonomous and scalable fashion.

In recent years, several extensions have been proposed to the traditional definition of network management that are specifically designed to address the topic of ever increasing network management complexity. The Self-Organizing Network (SON) notion was introduced by the 3rd Generation Partnership Project (3GPP) and targets to constitute future radio access networks easier to plan, configure, manage, optimize and heal compared to current state of the art. In similar direction, Autonomic Networking, inspired by the IBM initiated vision for Autonomic Computing [16], has been proposed as a means to create self-managing networks able to address the rapidly growing complexity of modern large scale networks and to enable their further growth, far beyond the size of today. The four main pillars of Autonomic Networking are self-configuration, self-healing, self-optimization, and self-protection, known also as self-CHOP features. However, the related technologies have so far found their way mostly in cellular networks or in smaller scale ah-hoc sensor networks. Frameworks for configurable and, to some extent, reusable deployment of SON functionality would be an important evolutionary step in the direction of scalable network management and lower maintenance cost.

IV. COOPERATIVE COMMUNICATIONS AND NETWORKING

Close cooperation between network elements is increasingly seen as an important driver for further evolution. In the FIA recommendations, it is referenced, for example, that the traditional client-server model will at least partially evolve into co-operative structures between peer entities. Cooperation frameworks cover the full range from information exchange, actions coordination and decision making. Moreover, such aspects are expected to be utilized in different context, thus spanning different communication layers and capabilities. A taxonomy of cooperative and collaborative frameworks was presented in [13].

In order to achieve cooperation between networks in multi-stakeholder networking environments, proper incentives need to be in place. Such incentives formulate the expected networking benefits that a single network can derive from its cooperation with another. Networks are only motivated to cooperate with other networks when this cooperation improves their performance according to such incentives [13]. However, in order to be effective and support generalization in a large scale dynamic environment, the incentives should not express low-level performance metrics, but instead indicate high level functional and network requirements. An incentive formulates a reason for cooperation between networks (i.e., if cooperation with another network can improve this high level objective, cooperation might be viable). Example incentives are (i) increasing coverage (to reach more clients), (ii) reduce energy consumption (to increase battery life), and (iii) increasing QoS guarantees (higher throughput, higher reliability, lower delay, etc.), among others [13].

Deciding, however, on the most beneficial cooperation settings requires mechanisms such as negotiation [13]. During negotiations, independent devices or complete networks with the required capabilities are identified and the utility of the cooperation is derived also as part of the cooperation incentive [17]. While significant research efforts have been invested in this area, large scale commercial application is still limited. Variations in the realization of the cooperation mechanisms and compatibility problems between the early products of different vendors are among the more important inhibitors, therefore ways to alleviate them will be particularly beneficial.

V. LOW ENERGY SOLUTIONS

Energy efficiency is commonly perceived as one of the most important design and performance factors of a Wireless Sensor Network (WSN). This fact is only expected to increase in relevance as a myriad of additional mobile and portable devices will be connected to the Future Internet. The desired low energy behavior can be achieved by optimizing the sensor node as well as the communication protocol [18]. The goal is to reduce energy consumption and, consequently, increase the lifetime of the system.

At the level of the independent nodes, the fundamental limit of the energy requirements is calculated by taking into account the energy consumption of every hardware (HW) component on a WSN node like sensors and conditioning electronic circuitry, processing and storage, radio, etc. The components selected in the final node architecture will have a significant impact on the nodes' capabilities and lifetime. Thus, a holistic low-power system design should be pursued from the very beginning, creating the correct HW infrastructure base for further network, protocol, software and algorithmic energy efficiency optimization.

This holistic low-power system approach can further incorporate methods for energy harvesting from the environment in order to utilize ambient energy sources (e.g., mechanical, thermal, radiant and chemical) that will allow extending lifetime and minimizing or possibly removing the need for battery replacement. Such a scenario would enable the development of autonomous wireless sensor networks with theoretically unlimited lifetime. Still focused on the sensor node level, but on the algorithmic part, ongoing efforts are made to design the sensor nodes in an inherent power-aware approach. The goal is to develop an adaptable system that is able to prioritize either system lifetime or output quality at the user's request. The radio communication and network protocol part is the other major source of energy consumption that can be targeted for optimization. Optimizing the network protocol is typically done with respect to a specific application domain, usually to favor bursts of transmission followed by cycles of low or no activity. As the range of transmission is also a very important parameter, low energy operation of a specific protocol version is often achieved only for a selected range, whereas other protocols are more efficient beyond that range.

Optimizations for low energy are a relatively mature field that has been (in different forms) around for a long time. However, most of the available solutions are customized for specific applications and are not directly transferable across different verticals and application domains. For example, a low energy protocol is typically "optimal" only with respect to a specific communication range and bandwidth, while other solutions might be preferable outside of this area. This implies that making the best selection usually requires a thorough understanding of the specific requirements and peculiarities of the targeted application domain and environment, so that the energy optimization can be appropriately tailored to these parameters. Therefore, a more transparent on-the-fly mechanism for node reconfigurations between different Pareto-optimal states is required to enhance sensor node reusability in the context of different vertical applications.

VI. CONVERGENCE OF THE SENSOR NETWORK AND DATA ANALYTICS TRENDS

In order to efficiently integrate processes and people in the IoT (as envisioned by the Internet of Everything), connected "Things" will need to share higher-level information with distributed peer entities, as well as with centralized processing units or people for further evaluation and decision making. This transformation from data sharing to information sharing is considered as particularly important in the IoE notion because it will facilitate faster, more intelligent decisions, as well as more effective control of our environment [8]. Similarly, in the field of industrial automation, there is clear movement towards keeping the pace with the rapidly increasing data footprint by a paradigm shift in data acquisition and processing [9].

In parallel with these activities, a significant evolution is taking place in the data analytics domain. In this case, the trend is to evolve from "descriptive analytics" that capture what is happening to "predictive analytics" that describe what is likely to happen. Similarly, a little further down the road is the progress from "diagnostic analytics" that describe why something is happening to "prescriptive analytics" that describe what should happen. Fusion of "hard" data coming from sensors with "soft" data from e.g., social networks is another important trend in this domain, which is already going in the direction of bringing humans into the equation. "Pervasive analytics" (in some cases even referenced as "butler analytics") are envisioning to bring the power of analytics in an ever increasing range of day-to-day applications and make them available to non-experts. The relation between sensor and analytic trends is depicted in Figure 1.

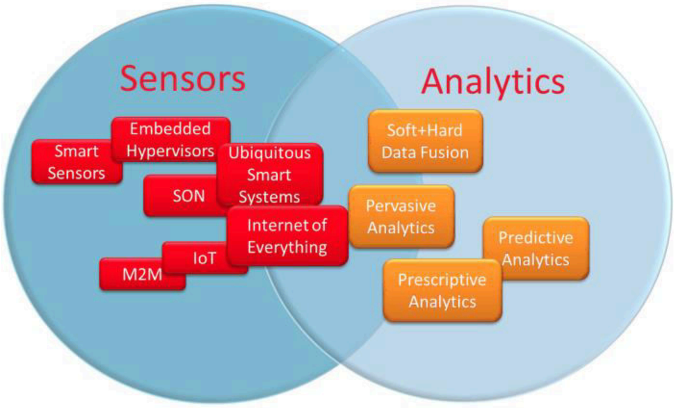

Figure 1. Convergence between sensor and analytic trends

The desired destination in this convergence is a framework of abundant sensor information taping at the "anytime, anyplace […] connectivity for anything" notion of the IoT combined with advanced analytic models that can provide real insight (in the form of human-consumable prediction and recommendation) for any situation and usable by everyone.

However, significant steps need to be taken before this vision is realized. "Analytics" is a very broad and varying field, and while wrapping them in a user friendly package is easy, using them in an irresponsive way without knowledge or respect for possible limitations or model constraints, to be the recipe for disaster [19]. Frameworks that can provide different tradeoffs of accuracy and execution time or easiness to interpret and (even more importantly) can at least make the users aware of model limitations and constraints would be an important driver towards approaching this vision.

VII. SENSOR INFRASTRUCTURE VIRTUALIZATION AS A DRIVER TOWARDS THE FUTURE INTERNET

Achieving a significant progress in the four open challenges identified in the previous sections calls for frameworks that either facilitate innovation or minimize the cost/risk for each of the four pillars identified previously (scalability, cooperation, low energy solutions and convergence of Sensor Network and Data Analytics trends). It is also important to underline that these pillars are not completely autonomous, but are mutually dependent. For example, one of the objectives of cooperation might be low energy operation, while the cooperation process by itself has to be scalable. Therefore, an important constraint is that possible solutions for each challenge are as transparent as possible to the other topics, to avoid setbacks in other fronts. A promising paradigm for addressing challenges in terms of decreasing the cost/risk as well as facilitating innovation in some of the topics identified previously is virtualization. Several types of virtualization can be distinguished, including Virtual Machines and OS Virtualization [20], Sensor Virtualization [21], and Sensor Network Virtualization [22].

While the first two types of virtualization have found their way into mainstream applications and are arguably the driving forces behind the cloud computing paradigm, the other two types are still not so widely used and there is some ambiguity in their definition in related literature. In this paper, we use the term Virtual Sensor (VS) to refer to a software entity that can serve as an aggregation point for multiple sensors, using physical sensor entities and a computational model to combine their measurements. There are several points that need to be elaborated in this definition. The Virtual Sensor can exist either in-field as a thin layer of virtualization software that is executed on physical sensors or it can be a mathematical model for aggregating information residing in a sensor management platform similar to [23]. Moreover, in both cases, the virtual sensor is doing more than interpolating values of physical sensors measuring the same phenomenon, as translation between different types of physical sensors is a far more interesting topic when models for the relations between the underlying phenomena are available. For example, one can estimate car pollution based on a model that combines car counting and weather conditions, while possibly utilizing on also the information from the few available pollution sensors.

Beyond independent Virtual Sensors, Virtual Sensor Networks (VSNs) are emerging as a novel form of collaborative wireless sensor networks [24] that can provide the common layer over which the evolution from connecting “Things” to the efficient interaction of the “Things” with processes and people can be realized. To some extent, VSNs are an evolution of the overlay network principle, which describes a network built on top of another network. The main differentiator of VSNs to overlays is that the latter are typically realized in the application layer only and constitute a temporary solution of true virtualization of the sensor network.

A VSN can be formed by providing logical connectivity among collaborative sensors [22], [25]. Nodes are grouped into different VSNs based on the phenomenon they track (e.g., number of cars vs. NO_2 concentration) or the task they perform (e.g., environmental monitoring vs. traffic control). VSNs are expected to provide the protocol support for formation, usage, adaptation, and maintenance of the subset of sensors collaborating on a specific task(s). Even nodes that do not sense the particular event/phenomenon (directly or indirectly by the notion of Virtual Sensor) could be part of a VSN if they allow sensing nodes to communicate through them. Thus, VSNs make use of intermediate nodes, networks, or other VSNs to deliver messages across VSN members [22].

However, the main goal of VSNs is to enable and promote sensor reusability and facilitate resource efficient, collaborative WSNs. By collaboration, nodes achieve application objectives of different use cases in a more resource efficient way. These networks may also evolve into a dynamically varying subset of sensor nodes (e.g., when a phenomenon develops in the spatial domain, the sensors that can detect it change over time). Similarly, the subset of the users having access to different subsets of the VSN can vary (e.g., the people that have access to the network change with time or specific operations on a sensor network subset are only available to specific groups of people based on their access rights, etc.). Finally, combined with the Virtual Sensor notion described earlier, VSNs can enable the same physical sensor, i.e., an induction loop or an LPR (License Plate Recognition) camera to support its primary application of traffic control, but also secondary applications such as environmental monitoring.

With respect to the challenges identified in previous sections of this paper, different flavors of sensor virtualization can provide answers to different facets of the open problems. For example, the Sensor Virtualization aspect that is based on introducing a thin abstraction middleware is a promising way to address sensor configurability and deployment issues related to network scalability, while it can also reduce the risk/cost of supporting a closed manufacturer solution (identified as an inhibitor for early adoption of related efforts). Moreover, to the extent that the sensors can execute different virtualization middleware versions with different configurations, performing on-the-fly reconfigurations between different Pareto-optimal states of energy/performance or accuracy/execution time will be easier. Finally, the virtual sensor aspect that aggregates sensor measurements to compensate for missing physical sensors of a given type is a significant step towards the vision of converged sensor and analytics in the IoE and the pervasive analytics notions.

On the VSNs side, a Virtual Sensor Network is inherently a collaborative networking paradigm that promotes node reusability in a resource efficient way. Thus, they are a particularly promising base for cooperative communications but also as a way to streamline sensor operations related to the management part of network scalability. Taking this property of VSNs (see first paragraph of Section IV) into account, an updated model of the 3D cooperative methods taxonomy introduced in [13] that also captures the different virtualization aspects described above and is provided in Figure 2.

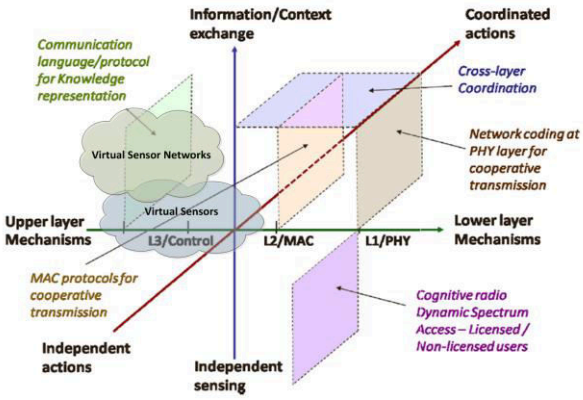

Figure 2. Sensor Infrastructure Virtulization depicted over the various dimensions of cooperative decision making and control.

The figure captures the scope of the cooperation as planes in a 3D space (information exchange, decision and configuration control, and layer mechanisms), where each dimension is associated with a set of enablers and technical areas.

Finally, with respect to the convergence of sensor and analytic trends, it is the most promising but arguably the most challenging of the four pillars. Bringing together in a dependable way an ever increasing number of sensor networks, owned from different stakeholders and forming on top of this infrastructure subsets of sensor nodes based on various criteria (e.g., temporal, spatial, thematic, etc.) is a good basis to generate an abundance of diverse data. Analytics can be applied in this ocean of data to make predictions by aggregating or excluding WSN subsets, fusing the data or the decisions of different subsets (according to the "analytics at the edge" notion [26], etc.). Nevertheless, any model can be misused if its constraints are ignored; making such limitations visible to the user is feasible (and virtualization can help), it is however his final responsibility to adhere to them.

VIII. CONCLUSION

The rapid proliferation in the number of devices connected to the Internet that occurred during the last decade is expected to continue, targeting yet another order of magnitude increase and promising to bring people and processes in the equation. However, in order to realize this paradigm shift, important challenges with respect to scalability, cooperative communications, energy consumption, as well convergence of sensor and analytics trends need to be addressed. In this paper, we have elaborated on the different flavors of Sensor Infrastructure Virtualization as a powerful enabler that can pave the way towards the Future Internet.

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 ISBN: 978-1-61208-289-9