Virtualization as a Driver for the Evolution of the Internet of Things: Remaining Challenges and Opportunities Towards Smart Cities

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Abstract— **Fueled by advances in microelectronics, wireless communications and the availability of affordable mobile connectivity, the last decade has seen an unprecedented proliferation in the number of interconnected devices. 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 we are already living in the IoT era, 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. This is particularly important towards the vision of Smart Cities, where physical infrastructure is complemented by the availability of intellectual and social capital, increasing both urban competitiveness and quality of life. 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. In this paper we elaborate on the different trends, as well as the remaining open problems and we show how 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.

Such promises are particularly important when viewed in the context of the global urbanization trend and the challenges that accompany it. With 60% of the world population projected to live in urban cities by 2025, the efficient use of resources becomes a topic of paramount importance. Such efficiency calls for situational awareness of the Smart City across multiple domains in an unprecedented level.

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].

Beyond offering pervasive connectivity, the IoT ecosystem is composed of smart things, objects, and applications. This notion of smartness is taking different forms in the literature. For example, the user experience of a mediated context-aware mobile system which is enabled by modern smart phones and is focusing on urban environments is presented in [5]. Approaches that support the exploitation of semantic technologies in context aware smart space applications are described in [6]. The presented technologies enable the creation of pervasive computing systems. A new flow-based programming paradigm for smart objects and the IoT is introduced in [7]. New workflow models suitable for embedded devices have been proposed, as well as orchestration techniques for the ad-hoc combination of smart objects. Smart spaces are discussed in [8] as a way to meet challenges such as interoperability, information processing, security and privacy towards the deployment of IoT.

Combining the notions of pervasive connectivity and smartness, different understandings and definitions have been reported in the literature [9]-[11] regarding what the Internet of Things is about. However, while it is possible to argue that the IoT is already here [12], the next (r)evolutions are already on the horizon, ranging from the open effort to the Future Internet and the rapidly spawning Smart City projects around the world up to industry driven initiatives. The latter include efforts such as the National Instruments Data Acquisition Technology Outlook [13], the General Electric concept of "Industrial Internet" [14], and the

CISCO initiated "Internet of Everything" [12], [15]. 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. Smart Cities are going to be at the forefront of this paradigm shift, therefore a lot of the examples and use cases discussed in following Sections are coming from the domain of Smart Cities.

The rest of the paper is organized as follows: Section II highlights the main challenges of Smart Cities and the costs associated to the lack of data integration across multiple verticals. The lack of such data integration capability can be seen as a driver for 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. Section III introduces the Virtualization layers and the main functionality that each layer is responsible for. It gives also a broad overview of which virtualization types promise to address each of the core areas. The selected areas and the nature of the challenges in each of them are then discussed in more detail in Sections IV-VII. Section VIII 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 IX concludes the paper.

II. Towards Smart Cities: Identification of Relevant Networking Trends

Amassing large numbers of people, urban environments have long exhibited high population densities and now account for more than 50% of the world's population [16]. With 60% of the world population projected to live in urban cities by 2025, the number of megacities (i.e., cities with at least 10 million people in population) is expected to increase also. It is estimated that, by 2023, there will be 30 megacities globally. Considering that cities currently occupy 2% of global land area, consume 75% of global energy resources and produce 80% of global carbon emissions, the benefit of even marginally better efficiency in their operation will be substantial [16]. For instance, the Confederation of British Industries (CBI) estimates that the cost of road congestion in the UK is GBP 20 billion (i.e., USD 38 billion) annually. In London alone, introduction of an integrated ICT solution for traffic management resulted in a 20% reduction of street traffic, 150 thousand tons of CO_2 less emissions per year and a 37% acceleration in traffic flow [17].

Being unprecedentedly dense venues for the interactions (economic, social and of other kind) between people, goods and services, megacities also entail significant challenges. These relate to the efficient use of resources across multiple domains (e.g., energy supply and demand, building and site management, public and private transportation, healthcare, safety and security, etc.). To address these challenges, a more intelligent approach in managing assets and coordinating the use of resources is envisioned, based on the embodiment of sensor and actuator technologies throughout the city fabric in a pervasive manner. This ubiquitous fabric will be supported by flexible communication networks and the ample processing capacity of data centers.

By aggregating data feeds and applying data processing algorithms to reveal the main relationships in the data, the situational awareness of the Smart City across multiple domains (e.g., transportation, safety, health, energy, etc.) at the executive level is greatly facilitated. For instance, by leveraging its open data initiative, the city of London provides a dashboard application demonstrating the kind of high-level overview and insight achievable by cross-silo data integration and innovative analytic applications [18]. However, this vision entails significant challenges on the design of the sensory fabric and the application model through which sensory data are discovered, accessed and consumed. It is currently understood that an intermediary layer of abstraction between the actual sensors and the applications utilizing them will be necessary [19].

The role of such a layer is to abstract the peculiarities of the sensor hardware from the applications, thus facilitating interoperability; to provide opportunities for forming shared resource pools, therefore increasing the efficiency and scalability of the system; and to allow creation of sandboxed islands that enforce the least privilege principle, thus enabling privacy protection (e.g., particularly important for a lot of healthcare applications in Smart Cities). Related activities towards such goals have been in the scope of various initiatives, focusing both on the scalable interconnection part, as well as on efficiency and privacy topics. All of these objectives have to be supported in a transparent way through well-established and standardized discovery and negotiation protocols, so that the devices can autonomously perform them with only minimal or no human intervention.

In parallel with the efforts towards efficiently and transparently 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 Future Internet Assembly (FIA) [20], 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* [20], 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 [20].
- *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 [12]. 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 [12], [14], [15], [21], [22]. 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], [21], [22].

In the majority of cases, wireless network development is guided by horizontal mass-markets ("one size fits all"). On the other hand, typically different verticals and niche markets require dedicated applications [22]. 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. Both of these properties are not attractive in a Smart City environment, while the second one is strictly unacceptable for a large number of relative vertical areas that form the backbone of the city infrastructure, such as water and electricity supply networks, Intelligent Transportation Systems, etc.

On the other hand, dynamic changes during operation typically allow for only a limited subset or scope of updates, which may not be sufficient for example if the goals of the network have to be radically changed in order to support a mega-event or provide emergency services in case of a catastrophic event such as an earthquake or flood. Even in normal operation, the ability to evolve significantly the objectives of the networking infrastructure over a period of time might provide opportunities for cutting costs, making it easier to integrate new systems as they become available or change the scope of a network to a secondary objective, while still being able to provide backup capacity to the new primary network in case it is required. 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 [21], [22], [23].

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 in the Smart City environment). 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. Following a short description of the different virtualization levels, an overview of the respective trends and key open issues is provided in the sequel of this section.

III. VIRTUALISATION LEVELS

The challenges identified in Section II for the evolution of Internet of Things require solutions for the scalability, data isolation and generation of relevant information at the end-user side. The latter will inevitably trigger changes at the network level, to handle performance issues as well as network/resource management technical challenges related to the vast number of interconnected devices and huge amount of generated data. Thus, this analysis addresses the benefits of virtualization at the end-user level, complemented by related requirements at the network side.

Several types of virtualization can be distinguished at both the network and the end user side, including Virtual Machines and OS Virtualization, Sensor Virtualization, and Sensor Network Virtualization [24]. While the first two types have found their way into mainstream applications and are arguably the driving forces behind the cloud computing paradigm, the other two types are still in their infancy. In this work, we investigate sensor virtualization from the perspective of extracting relevant information from a large network of heterogeneous sensors, in a secure, efficient, and device-agnostic way.

The end-user side addresses the interconnection of the different user hardware appliances/things (e.g., sensor or embedded devices) and is closely related to the evolution of the Internet of Things. However, the biggest breakthrough envisioned in this part is to include processes and people in the loop, enabling communications that are more relevant in order to offer new capabilities, richer experiences and unprecedented economic opportunities. To pave the way for this vision, sensor virtualization will play an important role towards: (1) addressing scalability challenges in the interconnection, control and management of a plethora of heterogeneous smart things, (2) promoting cooperation between the different elements in an energy efficient way, and (3) providing a basis over which the data analytics and sensor network trends can evolve and converge, independent of manufacturer-specific hardware or software perks [1].

At the network side, virtualisation implements the abstraction of network elements and transport resources, as well as their combination into a common pool, possibly distributed among different network locations. When a static network location is considered, the physical resources of a single network element are partitioned to form virtual resources. The distributed case is realised through the relocation of specific network functions to standard hardware servers that can be placed anywhere in the network; in addition, the separation between physical resources and logical services of network elements is possible [25].

In order to realize this separation, the Network Infrastructure Virtualization layer supports resource reusability and flexible resource pooling at the PHY and MAC layers. Its main purpose is to facilitate efficient usage of the network resources and not to abstract and aggregate their management from a central point. Thus, it facilitates the virtualization at the end-user side.

In the end-user side we introduce the Thin Software Virtualization layer, to support dynamic formulation, merging and splitting of sensor network subsets that serve different applications and are possibly administered by different entities. This software is embedded in the end-user devices. It caters for (1) interoperability of heterogeneous sensors from different vendors, (2) exposure of the sensor basic functionality to the data consumer and sensor assignment to tasks, (3) data isolation and enforcement of the least privilege properties, and (4) collaboration with other sensors and/or consideration of analytic models that connect the underlying phenomena so that the sensed data can be transformed to relevant information, produced and transmitted on demand.

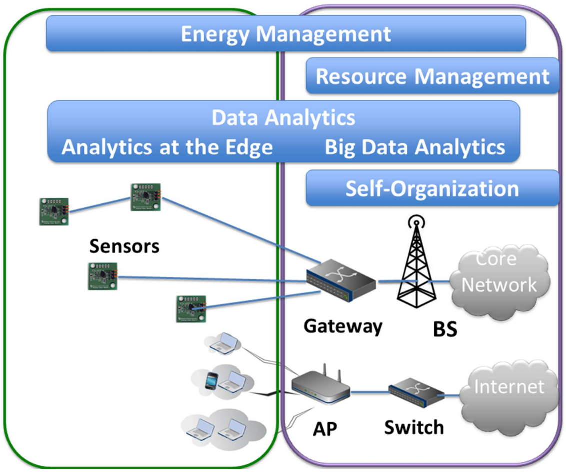

Figure 1: Virtualization layers and supporting functions

In addition, we propose the introduction of the following functionality within the layers (Figure 1): a) the Energy Management function, which spans across both the end-user and the network side - at the end-user side, an example of such functionality are the various LEACH variants or similar protocols that can be part of the node operating system; b) the Resource Management function, which realizes the fair dynamic resources allocation to the end-user devices; c) the Data Analytics function, which is responsible for making sense of the collected information and extracting value from it, and d) the Self-Organization Function, residing at the network side to support the dynamic sensor collaboration.

IV. Scalability of Communication and Management

In order to realize the vision of ~50 billion devices connected to the Internet by 2020 [12], 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 currently reached [12], [15]. 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 deployed in Smart Cities, each 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 [26], 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.

V. 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 [21].

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 [21]. 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 [21].

Deciding, however, on the most beneficial cooperation settings requires mechanisms such as negotiation [21], [27]. 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 [28], [29], [30]. 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.

VI. 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 [31]. 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 targeting 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.

Optimizations for low energy are a relatively mature field that has been (in different forms) around for a long time. For example, the radio communication and network protocol part is a major source of energy consumption that is often targeted for optimization. However, most of the available solutions are not directly transferable across different verticals and application domains.

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. Thus, a certain 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.

VII. Convergence of the Sensor Network and Data Analytics Trends

In order to efficiently bring together "Things" with processes and people 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 [12]. 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 [13].

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, i.e., what is the optimal response. Fusion of "hard" data coming from sensors with "soft" data from, e.g., social networks (often called also soft fusion or social fusion) 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 2.

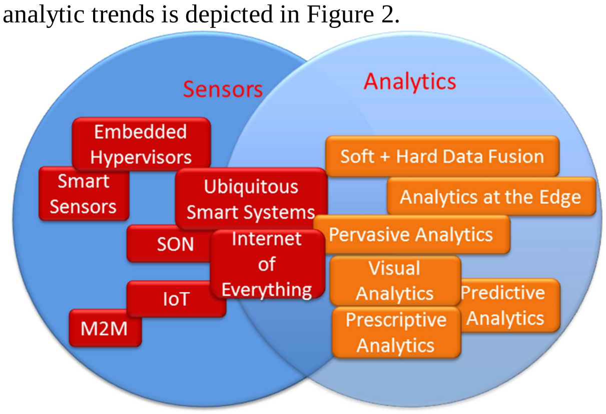

Figure 2: Convergence between sensor and analytic trends

At the same time, as the amount of data generated by this ever increasing number of sensors (augmented also by the social fusion trend) reaches new heights, the defining 3Vs of Big Data (Volume, Variety and Velocity) require revisiting in order to cope with the new requirements. In this direction, IBM has added Veracity as a fourth dimension that captures the uncertainty of the data. And while Volume and Velocity are to some extent infrastructure planning issues, a fundamental paradigm shift might be needed in order to address Variety and Veracity in a generic framework that is able to handle the requirements of all the data types without the need to develop from scratch algorithms for each of them. Deep Learning is a novel idea in machine learning that promises to do exactly that, extracting the relevant information (features) from different types of raw data, without the need for (expensive and time consuming) manual feature engineering by human experts [32].

Although data sharing and access to sensor information enables a number of new and innovative applications beneficial for users, a major effort is needed to ensure that data protection and privacy policies are met. In order to leverage the full potential of IoT, work needs to be done beyond identity and access management – trust and reputation systems need to be introduced which can serve the needs of widely distributed and highly scalable mobile networks, while offering mechanisms to preserve privacy for the users.

Whenever users are accessing Smart City services in the IoT enabled world, identity related data must be handled according to existing regulations and principles. In order for the system to work efficiently at full capacity, sensitive data need to be exchanged between multiple devices. The challenges in the future IoE environment are even more complex as protecting privacy is evolving to a continuous effort. For example, privacy protection cannot stop with the end of the users' session as the focus is not only on protecting the identity on short term. Location of users, content of queries, as well as the footprint everybody is creating by using services in IoT is of interest [33]. Unless proper precautions are taken, aspects such as people location, previously considered very hard to trace, will become traceable. At the same time, an adversary employing an IoT enabled attack will have a vast capacity for data collection and thus a large attack surface. The research community is faced with new challenges that have yet to be fully addressed [34].

A nice example of a future Smart City / IoT service is participatory sensing enabled environmental monitoring. In this scenario people are encouraged to provide data on pollution throughout the city using measurements from personal mobile sensors. Even this simple example shows how easy the users' location together with a measurement timestamp can give more information than originally intended. The success of numerous Internet of things applications of similar nature will depend on the ability of contributors to preserve their privacy while maintaining accountability [35]. Despite the numerous challenges, some important steps in the required direction have already been made. New techniques combining anonymization, pseudonyms, and statistical disclosure control, will allow users to keep track of their privacy footprint [36], including also the information they are disclosing indirectly.

Having processed the IoT generated information by some advanced data analytics algorithm, one scenario is that certain actions are then automatically realized without human intervention. However, there are cases that the final decision process might still be desirable to be done by a human expert, especially in the context of Smart Cities in the IoE vision where people are also an important part of the equation. In the latter case, Visual Analytics are coming into play in order to make the information perceptible to humans. Visual Analytics are a combination of machine learning tools and advanced information visualization methods with the goal of facilitating analytical reasoning. Such techniques might be for example of particular interest in the detection of trends and their possible causes inside an ocean of unstructured sensor data, so that informed decisions that combine human judgment and relevant data evidence can be made.

Nevertheless, in order to apply all these advanced Data and Visual Analytics algorithms major impediments such as the limitations in bandwidth and storage (for example when dealing with devices generating a large data footprint, such as video camera streams) have to be tackled. To overcome these limitations arising from the current systems for M2M applications, novel approaches have been proposed which are based on the following principle: storing and processing the data as close as possible, both in space and time, to where they are generated and consumed, hence enabling the so-called *analytics at the edge* [37].

It is worth mentioning that developments in pervasive analytics and analytics at the edge go hand in hand, as both are aiming for migrating analytics capability to the "Things", i.e., towards the edge of the network. An indicative realization of those proposals will be defined by a content-centric platform distributed over a local cloud, hosted by the gateways or advanced edge devices with process and storage capabilities. This approach will not only alleviate the big-data problem as data is processed where it is created, but also will reduce network traffic and communication costs and can facilitate faster reactions when an event or an alarm is generated.

The desired destination in the convergence of IoT and Data Analytics 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, can be the recipe for disaster [38]. Frameworks that can provide different tradeoffs of accuracy, execution time and easiness to interpret, enforce privacy policies, and at least make the users aware of model limitations and constraints would be an important driver towards approaching this vision.

VIII. 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, as discussed in the Virtualization Levels Section.

Virtual Sensor Networks (VSNs) are emerging as a novel form of collaborative wireless sensor networks [39] that can establish the basis over which the evolution from connecting “Things” to the efficient interaction of the “Things” with processes and people can be realized [1]. A VSN can be formed by supporting logical connectivity among collaborative sensors [24], [39], [40]. 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 - VS) could be part of a VSN if they permit sensing nodes to communicate through them. Thus, VSNs can utilize intermediate nodes, networks, or other VSNs to deliver messages across VSN members. The same physical infrastructure can be reused for multiple applications, promoting scalability and resource efficiency. In addition, VSN at the end user side allows for devices sharing among several virtual networks serving different purposes/applications. This concept builds upon the Service Oriented Architecture (SOA) paradigm, which provides a flexible infrastructure and processing environment for service-based software design. SOA lays its foundation in service provision to end-user applications/other services distributed in a network and comprises functionality for describing, publishing and discovering services as well as service composition and management [41], [42]. Using SOA, each end-user device may use one or more of the available services independent of the other devices. In a similar manner, respective functionality will be supported by the VSN at the end user side for the mapping of the devices to the virtual networks, the aggregation of the application based on the functions available in each node and the over VSN management. All of these architectural considerations are relevant for creating a unified situational awareness picture of the Smart City, as discussed in Section II.

The VSNs 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 or processes having access rights 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 role, etc.). This node grouping, merging and splitting property makes it easier to define, apply, and update policies (e.g., least privilege access) based on conceptual models rather than by configuring each of the myriad nodes independently.

Having alleviated part of the scalability and information protection/privacy requirements through the VSN concept is a good starting point for progressing on an even more ambitious front: going from data exchange between sensors to the sharing of relevant information, produced on the spot as and when required, so that it can be consumed on demand by processes and people. This paradigm is also promising to address the transmission and processing challenges that traditional large scale sensor installations face. The latter include various Big Data scalability issues with respect to the centralized gathering, logging and processing of the sensor data. The Virtual Sensor notion is instrumental in this effort.

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 [1]. The VS can be a thin layer of virtualization software that is executed on physical sensors (often referred as embedded hypervisor) or it can be a mathematical model for aggregating information residing in a sensor management platform similar to [41].

These different realizations of the VS notion face different types of challenges. For example, centralized or hybrid semi-centralized solutions based on analytic engines have to address the challenges of data fusion from heterogeneous sources, both functional (different credibility levels of the sensors, co-dependent sensor observations, difficulty to link human information needs to sensor control, etc.) and non-functional (scalability and performance problems, security and privacy requirements, etc.). It should be noted at this point that the non-functional requirements such as scalability and privacy can prove critical in a Smart City context were a multitude of private and public devices need to interoperate and exchange potentially sensitive information.

At the same time, the embedded hypervisors have to cope with the integrated nature of embedded systems, and the related need for isolated functional blocks within the system to communicate rapidly, to achieve real-time/deterministic performance, and to meet a wide range of security and reliability requirements [2], [44]. In this context, bringing more processing capacity and intelligence in the end devices is both inevitable and necessary in order to cope with scalability challenges [21]. The related analytics at the edge effort (see Section VII) is focusing on realizing this transition from centralized to (semi)distributed analytics.

However, despite the different types of challenges, both embedded hypervisors and analytically/computationally realized virtual sensors share a number of key properties. First and foremost, the VS 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. Furthermore, such models can even be learned by data over time in a (partially) unsupervised manner, according to the Deep Learning paradigm [32] as indicated in Section VII.

An interesting use case for this translation process in an urban setting is the estimation of car pollution based on a model that combines car counting (e.g., by induction loops or cameras) and weather conditions, while possibly utilizing also the information from the few available pollution sensors [1]. In this case, the VS can be configured to report periodically the estimated pollution value and give a warning if the pollution is above certain regulations (relevant information), instead of continuously reporting all the data.

Another example that is applicable in smart grid scenarios is the calculation of electric grid parameters (e.g., the load on given points in the transmission network, or the sag of transmission lines). Such information can be deduced by the Virtual Sensor indirectly from correlated values and a model of the related phenomena, even with a sparse network of different sensors (e.g., voltage and temperature sensors for the sag case, coupled with measurements of wind speed from a nearby weather station). Again the VS can issue warnings or alerts when some dynamic threshold values are exceeded instead of producing and transmitting all the information continuously. It is important to note that both the embedded hypervisor and the platform-based realizations of Virtual Sensors can employ state of the art signal processing techniques such as compressive sensing (for efficiently reconstructing a signal from relatively few measurements taking advantage of sparseness properties) or robust statistics (for copying with outliers, impulsive interference, etc.).

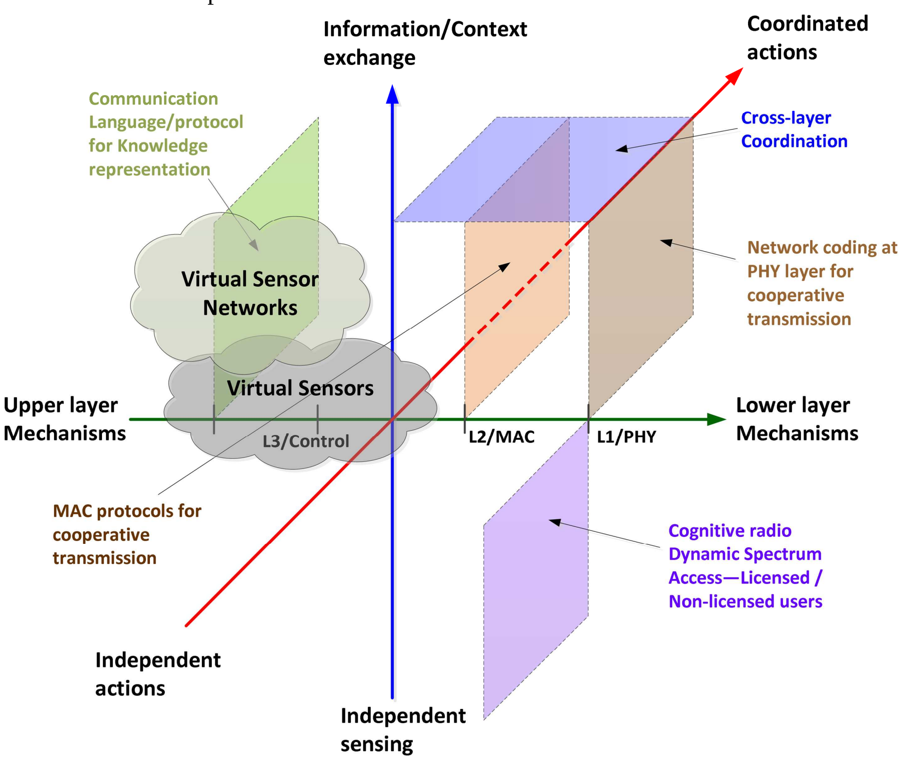

Figure 3: Sensor Infrastructure Virtulization depicted over the various dimensions of cooperative decision making and control.

At their core, VSNs and VS are building on and/or extending existing collaborative networking paradigms, therefore classifying them with respect to the ways that cooperation is realized in more conventional cooperative communication schemes is of great value. Taking into consideration the properties of Virtual Sensors and VSNs discussed previously, an updated model of the 3D cooperative methods taxonomy introduced in [21] that also captures the different sensor-level virtualization aspects is provided below. Figure 3 depicts the scope of the cooperation as planes in a 3D space. Specifically, the 3 axis are: 1) information exchange, with the extreme values being independent sensing and full context exchange, 2) decision and configuration control with the extreme values being independent actions and fully coordinated actions, and 3) layer mechanisms, with the extreme values being upper layer and lower layer mechanisms.

Each of these dimensions is being associated to a set of enablers and technical areas [1]. For example, cross-layer coordination spans the range of medium and low layer mechanisms, it requires a high information exchange level, and the level of coordination varies from medium/high to very high. Similarly, Virtual Sensors are depicted in the representation as a 3D cloud that spans medium to upper layer mechanisms. This cloud covers low/medium to high information exchange (because a VS can be either realized on the nodes as thin virtualization software or implemented as an aggregation software component running in a centralized platform). Finally, the cloud is mostly touching the area around medium action coordination since the state of the art efforts are mainly focusing more on the sensing rather than the actuation. The cloud that represents a VS can therefore expand to cover more of the axis that represents actions, in case virtualized actuation becomes more relevant in the future.

IX. 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 next evolution of the IoT. The latter is expected to trigger disruptive innovation across different domains, laying the foundation for the Smart Cities of the future.

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