Immersive IoT in Smart Cities

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***Abstract*— A rapidly increasing and vast number of "things" will be connected to the Internet, in all sectors of society (people, places, sensors, homes, industry, government services, etc.). The urgency of finding sustainable solutions requires "things" and services of the overall system to display autonomic intelligent behavior. The ability of cloud infrastructure to orchestrate the fine-grained and agile control of "things" is limited. This mandates an alternative approach intelligently moving control to the "things". Thereby we minimize the reliance on cloud infrastructure, and are able to build more agile, intelligent and effective solutions in various application areas, such as Health, Transport and through Automation. We provide examples of such novel solutions tested in "Urban ICT Arena", a large-scale smart city testbed in Stockholm.**

Keywords: Decentralized IoT, 5G, Smart Cities

I. INTRODUCTION

We seek to build agile, intelligent and effective solutions in various application areas in order to meet the challenges that face our societies. Current solutions in a wide range of areas are not sustainable, such as Health, Transport, and in Industry. Increased levels of Automation by some orders of magnitude has been identified as a key factor for achieving sustainable solutions. We seek entirely new levels of Automation by leveraging a rapidly increasing and vast number of "things" connected to the Internet, in all sectors of society (people, places, sensors, homes, industry, government services, etc.).

The Internet-of-Things (IoT) is thus transforming every business sector. Currently, much effort is being spent on Big Data and Analytics, since the perception is that the ability to store sensor information and extracting patterns from them is essential to building successful solutions that display intelligent responses or orchestrate components in large systems to attain high levels of automation.

A. Centralized IoT

The common assumption underlying these efforts is to use Cloud Services and Cloud Infrastructure since these have become cost-effective with respect to storage and availability. This assumption has a price. From an organizational point of view it is sub-optimal to rely on one entity (a Cloud service) for coordination. Also it constitutes a single point of failure as demonstrated by security incidents as Cloud Hopper [1]. Maintaining intelligence and coordination in the cloud or at most delegate management to edge gateways prevents sensors and end devices to act autonomously on local and global sensor information.

B. Decentralized IoT

The underlying idea of the Internet-of-Things is that every*thing* in the world can be online as the result of advances in miniaturization and communication. Electronics can connect any*thing* with anyone and any place in order for them to collaborate and achieve a common goal. More importantly, this reverses the perspective of a cloud to coordinate all things. Humans and non-humans protagonists need to collaborate in order to achieve a common goal immersed in a universe of sensing [2].

This idea is illustrated in Figure 1 below showing how things go from being "puppets" connected to and orchestrated by one entity (a centralized cloud service) to autonomous actors with relations between them. The Distributed Context exChange Protocol (DCXP) [3], which is further discussed below, allows objects to take action based on shared context knowledge, which unlike BlockChain [4] is not required to be present in a node, only the capability to reach it, therefore being resource efficient and suitable for small devices.

The remainder of this paper is structured as follows. Section II discusses motivations, requirements for Immersive IoT in comparison to related work. Section II.C examines the properties and role of DCXP as Immersive IoT. Section IV presents a novel method for programmable map-reduce interworking with Clouds based on local and global sensor information. Section V presents case studies with prototypes built with the open-source platform based on our architecture, and finally Section VI summarizes our conclusions and discusses directions for future work.

II. TOWARDS IMMERSIVE IOT

In this section we briefly discuss the motivations and requirements behind Immersive IoT.

A. Requirements

Internet-of-Thing platforms today are built to slow operations down by design although management of communication links and other processing may be delegated to edge-gateways (a.k.a. Edge and Fog Computing). Such solutions maximize control by maintaining it in Cloud infrastructure, sacrificing autonomy, flexibility and equally importantly speed in end devices. Centralized storage and management information

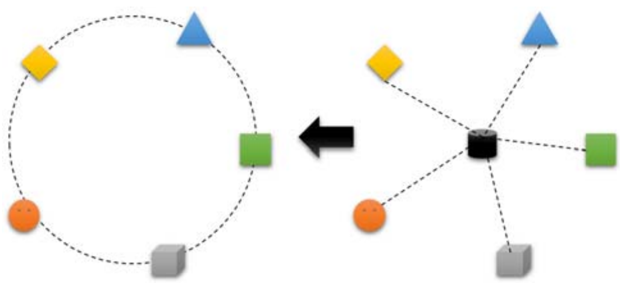

Figure 1. Decentralizing "Things"

and data has a cost as Analysis & AI operating in datacenters are slow to respond in comparison.

Further, telecoms are mediating all decision-making and position themselves to deliver 100% availability across low-latency networks across 5G. This is counter to the origins of the Internet which was invented to avoid a single point of failure. Everything just stops without the cloud, which is what happens in the presence of unreliable mobile communication or when Cloud infrastructure fails as when enterprises were targeted globally via managed service providers in the recent Cloud Hopper security incident [1]. Clients to cloud services typically outsource servers and components to managed service providers, thereby being subject to the effects of MSP services being compromised.

The ability of cloud infrastructure to orchestrate the fine-grained and agile control of "things" is limited. The reason is simply that the communication between a sensor or actuator and a controlling function in the cloud (typically hosted in a data center) or even when management of communication and data processing is delegated to edge gateways, the control has to pass a sensor network, access networks and core networks. What is lacking is a programming model which involves delegation to the "things" in which the sensors and actors are first-class objects.

B. Related Work

There is related work and research being carried out with respect to interworking with the Cloud, in particular: edge computing, fog computing and capillary networks, in-line with the 5G architecture [5][6][7][8].

Existing approaches which in principle allow us to move control to end-points such as fog computing and mobile ad-hoc networking rely on various routing and addressing principles. In contrast, we require a comprehensive end-to-end reachability mechanism across heterogeneous networks. Control in end-nodes must be able to negotiate communication paths as well as act on application-level events. Existing approaches such as the OpenFog framework and edge computing lack a single concrete architecture supporting these requirements [6][7].

Edge Computing employs edge gateways to delegate communications management of "things" from the Cloud. Capillary Networks offers methods to enforces administrative control to edge gateways [5].

Fog Computing is a horizontal architecture for connecting Clouds and things but that goes one step further than Edge Computing [6][7]. The OpenFog architecture also delegates processing to edge gateways by using virtualization techniques. The reason is that edge devices and sensor are thought to lack the required computing and storage resources. The OpenFog thus targets itself as a model for virtualized, distributed computing across heterogeneous networks The OpenFog architecture does not offer a programming model.

The OpenFog framework adds a hierarchy of elements between the cloud and endpoint devices [7]. Control beyond the edge of the network is not a sufficient response to the requirement that "things" must be able to negotiate situations when either wide-area communication (i.e., mobile access) is unreliable or unavailable and in such a case would benefit from communications with or via other "things".

C. Summary

In summary, the above approaches maintain control at the edge of managed network infrastructure. The advantage is enabling an Internet Service Provider (ISP) to manage the offering of services and infrastructure. Control at the edge of the network disregards requirements of scenarios where "things" need to achieve a task, and possible cooperate with immediacy and flexibility that is possible only with local decision-making.

III. Distributed Context eXchange Protocol

These limitations mandate an alternative approach intelligently moving control to the "things".

Lacking existing support meeting the requirements, we created a network-level overlay that enables agents to interconnect utilizing information-centric networking mechanisms across heterogeneous network infrastructure. The requirements and overlay are embodied in the Distributed Context Exchange Protocol (DCXP), which is an event-driven publish-subscribe architecture for sharing context-information between agents in nodes across heterogeneous networks [3][9][10][11][12][13].

The previously mentioned requirements regarding agile and autonomous behavior mandate local decision-making based on shared context knowledge. A simple example would be a crowded highway where vehicles would benefit from being aware of traffic conditions a few cars ahead in case of unexpected decelerations. Another example could be sharing information between vehicles along roads through a sparsely populated area, where deployment of mobile access networks or road side units is prohibitively costly. In these examples, acting upon events cannot wait until access networks and data centers are ready to process events [9]. That said, systems will benefit from interworking with global processes such as data analysis which run at a slower pace. Therefore a new model for interworking across edge gateways is of critical importance.

When we require sensors and "things" to be represented by objects in a "fog" of things, this really means that the communication has to be based on programmable relations between objects that are maintained across the Internet. These relations have to be maintained and remain operational even without access to either cloud services or network services, such as DNS. This means that our infrastructure has to be self-contained and that clients (peers) can be implemented with a small footprint on small devices to operate even via low-power short-range/wide-area radio networks. For this reason, we only require the capability to reach the next node and a unique identity, Universal Context Identifier (UCI), in order to find context information associated with an object. This scheme can be resilient as it can benefit from delay-tolerant networking across heterogeneous wireless and mobile links.

As the number of devices and objected connected to the Internet is rapidly increasing we require a mechanism to maintain only awareness of objects with context of high relevance for which we can use machine-learning algorithms. This allows us to query objects as a distributed relational database and employ triggers operating on event streams across publish-subscribe eventing across relations. Security can be arranged initially to a satisfactory degree by self-issued certificates as a hash of the object identity similar to BlockChain. Information security based on

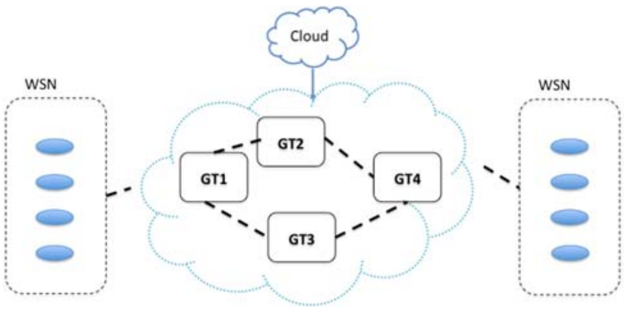

Figure 2. Context-based Gateway Selection

encryption of communication may then benefit from anonymization of the information sources in each node, effectively creating a DarkNet for sensor information.

In order to address the lack of a distributed programming model for "things" as well as in Fog Computing, we proposed Context Networks based on the Distributed Context Exchange Protocol (DCXP) [3]. The purpose of Context Networks and DCXP is to allow "things" to become autonomous entities that are able to make decisions based on local and global context information acquired from sensors. DCXP offers both an information and programming model, and one which allows decision-making and control to occur in end-nodes. Computations in end-nodes may occur in local virtualization environment. Therefore DCXP is compatible with the Open Fog architecture. DCXP is a self-contained Fog Computing architecture with respect to naming and reachability mechanisms and therefore not reliant on Open Fog or other distributed support targeted at IoT, such as FI-WARE [14].

DCXP peers, named Context User Agents (CUAs), include a Lookup service which allows them to reach other CUAs by means of a Universal Context Identifier and establish relationships based on Publish-Subscribe methods. In fact, DCXP does not distinguish between different sources of information. It offers nodes a mechanism to subscribe to any source of information.

A. *Reachability*

Addressing is based on names which are registered in a distributed hash table contained in each node. Although a node may node know the exact location of the end-node, it will be able to point the next intermediate node as a result of its entry in the DHT. DCXP connects so-called Context User Agents (CUA.

Thus, the overlay constitutes a distributed agent architecture in which each agent contains context information organized in an entity-relationship model of its peers, with local caching of information. Algorithm running in nodes may rank the relations based on closeness of context resulting in a clustering of peer agents (and consequently deselection of others and discarding of irrelevant information). Nodes can make decisions based on context at two levels in response to a) the (un)availability of communications paths and b) application level events and context changes.

IV. Interworking with the Cloud

The question remains how to extend 5G and an edge gateway to enable local decision-making in IoT nodes ("things") based on global knowledge that is propagated between them and the cloud service.

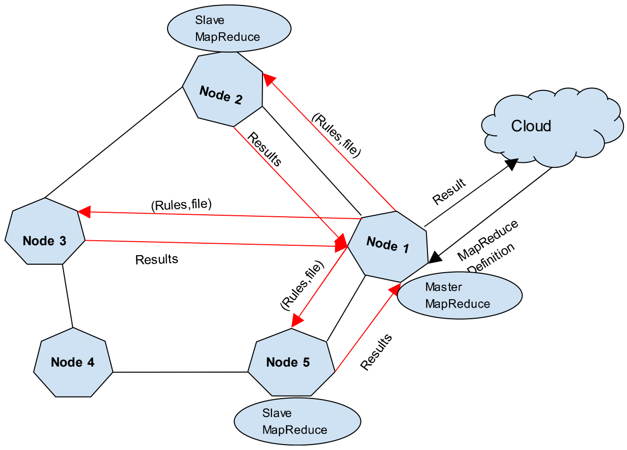

Figure 3. Cloud-to-Fog Map Reduce operation

A. Gateway *Selection based on Clustered Pub/Sub*

Gateways selection and connection support for large scale IoT deployment infrastructure as illustrated by Figure 2 is based on Clustered Publish/Subscribe. This means that Edge Gateways act as DCXP boot-strap nodes resulting in fault-tolerance. Selection of a particular Edge Gateway is achieved based on ranking of context information, such that WSNs can take into account the cost and availability to communicate with Edge Gateways. This is particularly useful in the presence of unreliable communication infrastructure. The ranking algorithm is based on relational proximity as described in [15].

B. *Map-Reduce*

Finally, we require interworking between this overlay, which in essence, is a peer-to-peer IoT infrastructure and a cloud-based IoT services platform hosted in a data-center as illustrated in Figure 2. Typically, the CUA acting as bootstrap node is collocated with the edge gateway. In support of delegation from a cloud-based IoT platform we designed and implemented an interworking function which is able to interpret scripted instructions from a cloud platform and return the results after delegating it to the swarm of IoT nodes. This is allowed to function in two ways:

1. Map-Reduce (operating on local data): the interworking function sends a script with context data to nodes satisfying some criteria (be it a name or context property) after which the received results from computation on local data are put together by the interworking function and handed back to the cloud-based IoT platform.

   An example scenario is the command to look for a certain occurrence in the log files of nodes a smart grid. This capability saves substantial resources in time and energy for the IoT management platform in that it neither has to search the addresses as a name suffices due to information-centric networking support nor does it have to send such a command to each node individually.

2. Map-Reduce (operating on global data): the interworking function sends a script with a selection of context data to nodes satisfying some criteria (be it a name or context property) after which the received results from computation on a selection of this global data are put together by the interworking

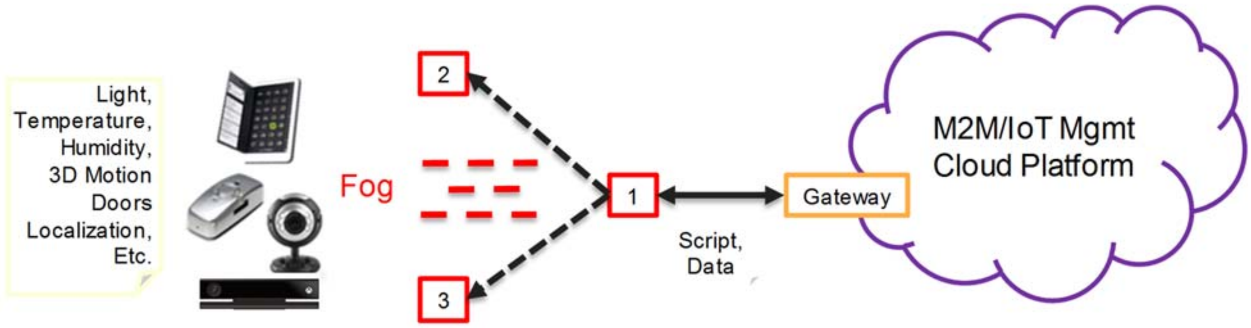

Figure 4. Delegation to Actors in the Fog

function and handed back to the cloud-based IoT platform.

A sample scenario could be the division and distribution of tasks into smaller ones among a vast number of nodes in a large WSN, which amounts to substantial computational resources.

Moreover, as is clear from Figure 3, the rules of the information in nodes can trigger events cascading across relations. Thus, much more complex scenarios operating on combined scenarios are possible. Figure 4 further illustrated this, permitting different end-devices to make-joint decisions based on context-information available in each node and send the result back to the platform. The utility of this becomes evident in Subsection V.B "Ambient Assisted Living in Smart Homes".

V. Case Studies

The following case studies evaluate the validity of the requirements and approach. The architecture and open-source distribution of DCXP and associated support (mediasense.se) was made available to partners in different EU projects and recently the Urban ICT Arena (urbanictarena.se) constituting a smart city testbed for novel services based on fiber, 5G and IoT infrastructures.

A. *Decentralized Intelligent Transport Services*

The EU FP7 MOBIS project (2012-2015) [16] created Personalized Mobility Services for Energy Efficiency and security through advanced Artificial Intelligence techniques employing the decentralized IoT platform (mediasense.se) for crowd-sensing purposes to federate novel artificial intelligence services and traditional information platform services coming from the following sources:

- existing transport private or public service providers,
- ambient data, based on sensor infrastructures and
- social networking data.

Figure 5 shows an overview of the system where the longer term AI and analysis processes are located in the central platform, while objects on the left are maintaining direct relations, sharing context information via the Internet. Figure 5 further illustrates how transportation resources in a city wide network collaborate in order to achieve an optimal travel experience whilst minimizing the overall energy footprint.

The advantage of the approach delegating autonomy to the individual actors based on the platform (mediasense.se) were multiple. The actors could take immediate action based on observed local context changes whilst aware of non-local events (such as availability of other modes of transportation). Coordination by the cloud would not have been as responsive. Moreover as none of the end-devices were

Equally importantly, there was a guarantee of continued operation even without access to cloud services, as mobile communication is inherently unreliable. Finally, based on relevance and relations between persons, transportation (connected bikes, vehicles, etc.) and homes irrespective of which access network provider was involved, actors could make decisions relevant to the local context. For instance, a home could reduce its heating during the day but turn on the heat once its occupants were on their way home. Leveraging such capabilities, the direct collaboration of the sources and sinks minimized the overall energy footprint even further.

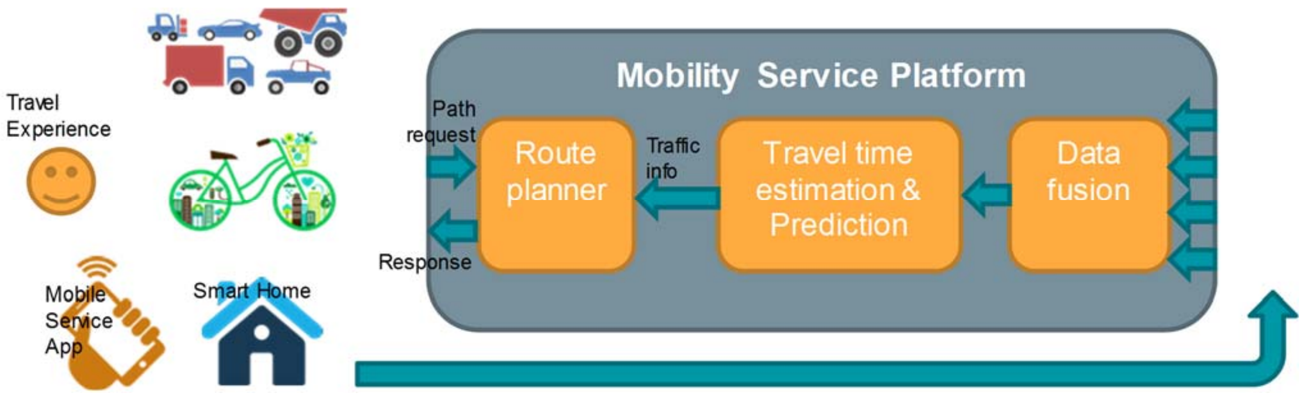

Figure 5. Optimized Personal Mobility with Minimized Overall Energy Footprint in Smart City

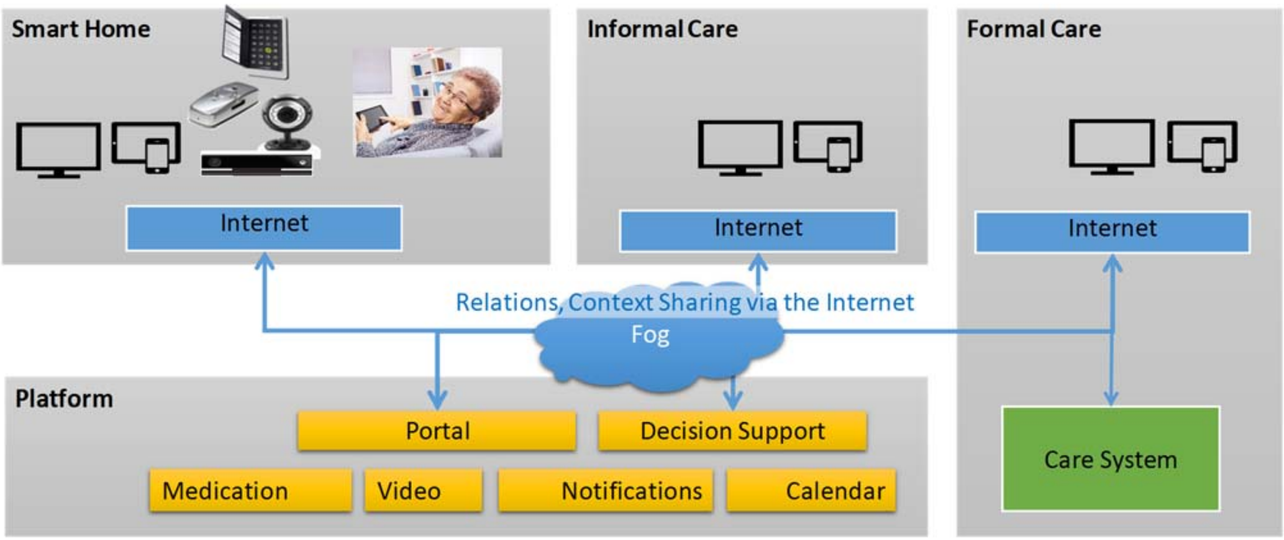

Figure 6. Shared Awareness of Well-Being for Ambient Assistant Living in Smart Homes

Extending the scenario for ITS and transport, in [9] we outlined support for Cooperative Autonomous Systems, such as for autonomous vehicles, with resilient (co-) operation across unreliable infrastructure. Due to the interworking and delegation support presented in Section IV on p. this may orchestrated on a larger scale from a Remote Operations Center in the cloud via Edge Gateways, which is highly relevant to Industrial Internet in general.

B. Ambient Assisted Living in Smart Homes

The EU AAL SALIG++ Project (2013-2016) [17] created a distributed solution for the shared awareness of well-being between elderly, informal caregivers and professional care as depicted in Figure 6.

A gateway for SmartHomes that hosts a DCXP peer makes sensors and appliances not only accessible from the Internet and to all participants within the elderly's AAL community but more importantly as if these we local to them as well. The gateways are connected through the distributed information sharing system (mediasense.se). This service enables communication with sensors and agents running in SmartHome devices agnostic of IP addresses since Context User Agents (CUAs) running in devices are accessed by the Universal Context Identifier (UCIs) that is employed by the DCXP protocol.

Similar to the case study in the previous section, the service portal contains functionality for the longer term decision support and functions that are expected in such a health service, such as a calendar and medication schedule. What is novel is that the service detects anomalies as the result of the collaboration between two end devices such as a pillbox and image recognition installed in the smart home. The pillbox reasons about context changes as which pill has been taken and whether it follows a schedule. The image recognition can detect different social states, such as sleeping, eating, and in this case a pill. When occurring shortly after one another, there is near certitude that the elderly has taken his or her medication otherwise the portal is alerted.

The fact that the service platform delegates these tasks to the sensors makes the solution resilient to unreliable communication, which is important not only in urban environments but also in remote areas. Further, the relations and context-sharing that occurs seamlessly across the Internet enables next-of-kin as well as professional care to maintain shared awareness irrespective of location. Also the system is plug & play across the Internet allowing new relations ad hoc such that new members as well as sensors can be added to increase shared awareness of well-being. For instance, for safety we added flood-detection, window and door sensors, stove on/off etc.

C. Mobile-AR and IoT-GIS for Creative Industries

In [2], we demonstrated how our decentralized IoT infrastructure enabled scenarios in prototypes that employ Mobile Augmented Reality (M-AR) and IoT Geographic Information System (GIS) Applications. In M-AR applications, immediate responses on par with the human reaction times (~0.1 sec.) are key to realistic human experience and decision-making, underlining the importance of our approach.

IoT-GIS applications in such scenarios can further benefit from our approach since ranking can prevent unnecessary data-streaming of sensor information via wireless and mobile networks, since sensors themselves can make decisions about their relevance in a particular context [15]. Thereby we can minimize OPEX, while maximize utility of the overall system by sending only what is important in a global context.

VI. Conclusions and Future Work

In this paper, we presented the motivations behind and urgency of decentralizing IoT due to limitations in a centralized approach but also because enabling autonomy of things in principle requires decision-making to move to end-devices. The principle to keep decision-making in managed services infrastructure makes sense when it comes to longer term decision-making involving analytics utilizing machine-learning to discover patterns in vast amounts of stored data. Agile responses matter to a person accomplishing a task or devices with autonomous behavior. 5G, edge computing and more recently fog computing allow data processing and management of communication to move to the edge of the network. This does not solve the problem which is that a network service is involved. The ability and agility for "things" to make decisions to respond is predicated by the speed and availability of this service.

In response to the fact that neither fog computing nor edge computing have provided a sufficient answer, we created a peer-to-peer IoT infrastructure. The platform (mediasense.se) is compliant with the OpenFog architecture, but goes beyond the capabilities offered in mobile edge computing and fog computing to intelligently moving control to the "things". Our approach extends and enables cloud IoT infrastructure to orchestrate the fine-grained and agile control of "things", based on sharing of context across heterogeneous network infrastructure based on Information-Centric Networking principles. Thereby cloud IoT infrastructure can remain agnostic to the exact location of things and even delegate crowd-sourcing campaigns and map-reduce operations to fog-infrastructure even when the availability of nodes cannot be guaranteed. Independent decision-making in nodes, in cooperation with other nodes driven by eventing via publish-subscribe relationships in a distributed context entity-relationship model constitutes a powerful programming paradigm. This was verified in a number of projects, such as the the case studies presented above [16][17]. The overlay has been made available as an open-source distribution via a public website (mediasense.se) in order to facilitate experimentation also within the context of EU-FIRE, several EU projects and associated testbeds, educational programs at several universities in and outside Europe, and recently Stockholm Smart-City testbed: Urban ICT Arena (urbanictarena.se).

Our future work involves addressing security issues due to the use of self-issued certificates and identities, as well as secure transactions involving interworking with BlockChain infrastructures. Moreover, we are working on strategies beyond map-reduce to put the combined computing capabilities of swarms of devices into any*thing*. Analytics does no longer to have to stay inside the Network.

Finally, we are studying interworking with cloud services for the automatic translation to autonomic behavior which is distributed among nodes in sensing campaigns, such as to negotiate heterogeneous wireless and mobile infrastructure in order to maximize the capabilities in an enterprise platform.

ACKNOWLEDGMENT

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