EXEGESIS: Extreme Edge Resource Harvesting for a Virtualized Fog Environment

Evangelos K. Markakis, Kimon Karras, Nikolaos Zotos, Anargyros Sideris, Theoharris Moysiadis, Angelo Corsaro, George Alexiou, Charalabos Skianis, George Mastorakis, Constandinos X. Mavromoustakis, and Evangelos Pallis

Abstract

Currently there is an active debate about how the existing cloud paradigm can cope with the volume, variety, and velocity of the data generated by end devices (e.g., Internet of Things sensors). It is expected that there will be over 50 billion of these devices by 2020, which will create more than two Exabytes worth of data each day. Additionally, the vast number of edge devices create a huge ocean of digital resources close to the data source, which, however, remain so far unexploited to their full extent. EXEGESIS proposes to harness these unutilized resources via a three-layer architecture that encompasses the mist, fog, and cloud. The mist network is located at the very bottom, where interconnected objects (Internet of Things devices, small servers, etc.) create neighborhoods of objects. This arrangement is enhanced by a virtual fog layer, which allows for dynamic, ad hoc interconnections among the various neighborhoods. At the top layer resides the cloud with its abundant resources that can also be included in one or more virtual fog neighborhoods. Thus, this article complements and leverages existing cloud architectures, enabling them to interact with this new edge-centric ecosystem of devices/resources, and benefit from the fact that critical data are available where they can add the most value.

Introduction and Context

Nowadays a lot of discussion is going on regarding the way the cloud paradigm can cope with the volume, variety, and velocity of the data generated by end devices (e.g. Internet of Things [IoT] sensors). It is expected to have over 50 billion of these end devices [1], currently referred to as "things," by 2020, which will create more than two Exabytes' worth of data each day. It is clear that shipping all of that data to the cloud, and processing and storing them there, as the current paradigm dictates, can run into significant bottlenecks in terms of latency and network capacity. On the other hand, it is hard to miss that the vast number of end devices, most of them utilizing some form of processing power, storage space, and network connectivity, could constitute a pristine "ocean" of digital resources, which could be harnessed and used to address the bottlenecks of the current cloud paradigm by processing and storing data close to where they are created.

In this context, EXEGESIS, building on and extending existing concepts [2, 3] such us as micro data centers, cloudlets, mobile edge computing (MEC), and fog computing (http://www.openfogconsortium.org/news; retrieved July 2016) proposes a novel three-layered architecture that is able to not only reap the resources of end users' devices, but also couple them to the cloud by providing a cross-layer orchestration platform able to deploy services that have a cloud and mist component and to provide a distributed marketplace where these resources can be traded off by any EXEGESIS stakeholder: a local authority in Athens, a small-medium enterprise (SME) in Madrid, or a corporation in Brussels. In this way, EXEGESIS envisages that it can steer new and innovative services and process efficiencies not possible with cloud computing alone.

The EXEGESIS high-level architecture is composed of three layers (Fig. 1). At the very bottom, the mist network is located, where interconnected objects (probes, sensors, cell phones, home appliance devices, small servers, small cell controllers, etc.) create a neighborhood. This arrangement is enhanced by the *virtual fog* (vFog) layer, which allows for dynamic, ad hoc interconnections among the various neighborhoods, allowing sub-groupings called "suburbs" to be formed. At the top layer resides the conventional cloud with its abundant resources that can also be included in one or more "suburbs" in order to provide compute resources and facilitate the interconnection of the various vFog elements. In this context, EXEGESIS complements and even leverages existing cloud architectures as it enables them to interact with this new edge-centric ecosystem of devices/resources and benefit from the fact that critical data are available where they can add the most value.

The key idea and challenge here is to be able to partition the three-layer infrastructure consisting of the mist, vFog, and cloud layers into logical networks whose membership can partially overlap with that of other such logical networks and to be able to dynamically remold this partitioning to ensure optimal performance and utilization of the available resources

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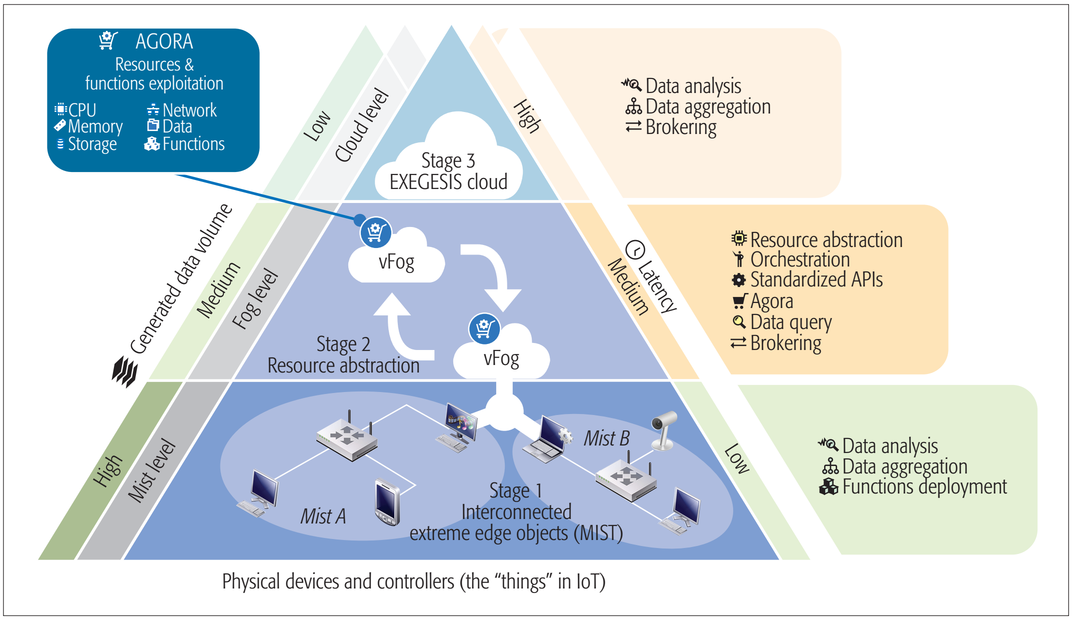

Figure 1. High-level view of the EXEGESIS concept.

Furthermore, EXEGESIS aims to enable business innovation via the deployment and use of suburb-based marketplaces named "AGORAs," stemming from a Greek word which means the place where all social and economic activity takes place. The AGORA is for EXEGESIS the system through which every infrastructure/platform provider offers over-the-top (OTT) and on-demand accelerated service/network/connectivity applications to requesting entities.

In other words, EXEGESIS aims to radically reshape the mist, fog, and cloud landscapes by merging them into one coherent whole, and then slicing and dicing that into logical entities in order to achieve optimal performance and resource utilization.

Background and Related Work

Concept

EXEGESIS, building on the concepts of edge computing [4], frugality of resources [5] and democratization of the digital economy (https://ec.europa.eu/digital-single-market/en/digital-single-market, retrieved July 2016), envisages a future where the processing, storage. and networking resources of the devices residing at the edge of the network can be harnessed and integrated seamlessly and dynamically in a flexible system architecture. In making this a reality, EXEGESIS provides the means to establish vFogs — overlays of interconnected end devices that can be intertwined with cloud resources — forming ad hoc isles of connectivity and computing, setting the basis for a common marketplace where services can easily be deployed across all layers.

The following sections describe the methodology that EXEGESIS follows in order to reach its objectives as well as the technological aspects utilized for realizing these objectives

Technical Approach

EXEGESIS proposes a new interaction ecosystem composed of three layers. At the very bottom, the mist layer is located, where interconnected objects create a neighborhood. This arrangement is enhanced by the vFog layer, which allows for dynamic, ad hoc interconnections among various mist elements, allowing sub-groupings called "suburbs" to be formed. Cloud layer resources can also be included in a suburb in order to provide resources and facilitate the interconnection of the various elements. The key idea here is to be able to partition the three-layer infrastructure consisting of the mist, fog, and cloud layers into logical virtual networks whose membership can partially overlap with that of other vFog networks, and to be able to dynamically remold this partitioning to ensure optimal utilization of the available resources.

Mist for EXEGESIS is the unified extreme edge playground where a variety of end-user (an end user can also be a company that utilizes EXEGESIS solution) devices cooperate toward abstracting, in a common virtual pool, their available resources and as such enable any legitimate entity to use these resources for hosting a variety of compute and networking tasks. The EXEGESIS mist overlay "copies" the hybrid peer-to-peer (P2P) approach where a peer can be *primus inter pares*.[1] In this context, the EXEGESIS mist network has two classes of peers (Fig. 2), *regular mist nodes* (RMNs) and *super mist nodes* (SMNs).

An RMN can be any end device having at least some processing and communication capabilities that will allow EXEGESIS to deploy its solution on it and thus transform the device to a fully operational EXEGESIS mist node. An RMN is able to interact with its corresponding SMN, first to inform it about the device's available resources and second to receive and carry out the assigned computational and/or networking tasks. To that end, a special kind of software, called the vFog agent, runs on each RMN. An RMN can be any physical or virtual entity having even a "pinch" of processing and communication capabilities.

An SMN plays two roles inside the EXEGESIS ecosystem: the role of the mist's intra-manager and the role of the mist's envoy to the vFog orchestrator. As an intra-manager, an SMN:

[1] First among equals.

- Oversees the formation of the mist network by performing operations such as the (de) registering of mist nodes
- Queries the registered mist nodes about their state and their available resources
- Creates a logical topology of the mist network along with a virtual pool of the RMNs' available resources

As an envoy, an SMN interacts with the vFog orchestrator toward:
- (De)registering a mist network to the vFog overlay
- Providing a "copy" of the SMN's virtual pool of resources, therefore enabling the vFog orchestrator to have a clear image about the available resources across the whole vFog overlay
- Mediating between vFog orchestrator and RMNs for reserving resources, assigning computational tasks, or even deploying network functions virtualization infrastructure (NFVI) elements

Following hybrid P2P's paradigm, an SMN is elected from the currently running RMNs taking into account several attributes like processing and memory capabilities, network capacity, and power level/type, among others. Acknowledging that the uncontrolled participation of mist nodes in the election process could pose security threats, EXEGESIS provides the means for "screening" the candidates list based on the EXEGESIS stakeholder's policies. The SMN is elected from the existing RMNs; it manages RMNs, and it is the point of contact to the vFog orchestrator.

The tremendous number and vast heterogeneity of the devices living on the edge of the network poses a significant challenge for EXEGESIS in forming manageable and efficiently operating mist networks. To handle this challenge, EXEGESIS proposes the development and exploitation of a middleware solution that will sit on top of each device's operating system (OS). The middleware utilizes a southbound application programming interface (API) for interacting with the OS and acquiring access to the device's actual resources and a northbound API for communicating with its vFog orchestrator. A hypervisor will be exploited for deploying in containerized form — reducing the system's footprint and increasing services deployability — the RMN/SMN module and, if assigned from the vFog orchestrator, other software units that carry out computational tasks or realize a service.

EXEGESIS proposes the idea of a vFog for managing the underlying mist networks and harnessing their available resources. As the name implies, a vFog assumes the operations of a conventional fog network (e.g., coordination of the fog nodes, provisioning of the available resources to third parties, management operations) but is not deployed over dedicated equipment pre-installed at specific places; a vFog lives on top of mist networks as an overlaid virtual entity (Fig. 2). In these configurations, the underlying SMNs will be the vFog nodes utilizing an election protocol to select, based on a set of predefined criteria (e.g., processing capabilities, storage space, network capacity, power level), the SMN that will undertake the role of the vFog orchestrator; the mind and heart of vFog's overlay. In a nutshell, the vFog orchestrator will carry out the following key tasks:

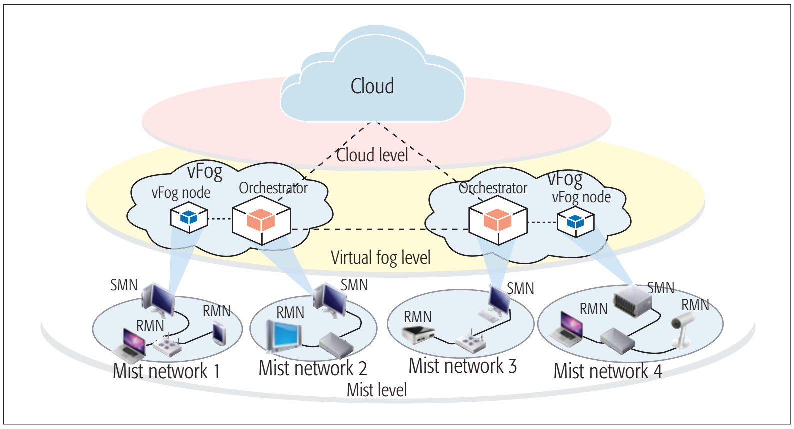

Figure 2. Two vFog neighborhoods accommodating two mist networks each.

- Perform the vertical managerial operations needed to form and maintain the vFog overlay network.
- Query the underlying mist nodes for available resources, and create an abstract pool of them.
- Provide information about the available resources to any authorized third party (including the AGORA).
- Handle horizontal communication operations (e.g., with other vFogs and/or conventional fogs).
- Exchange data with any clouds with which it belongs to the same suburb.
- Accept and forward requests for computational tasks, storage space, and deployment of services to the vFog nodes based on the needed and available resources.
- Deploy the AGORA across the vFog network.

One of the key issues that EXEGESIS attempts to tackle is to stem the tide of data flowing into and out of the cloud. This is done by injecting SMNs into the vFog network that have increased processing capabilities. These nodes will then expose their resources to the orchestration environment so that they can be used for pre-processing and filtering of data. That processing might lead to direct decision making or to a whittled down version of it being uploaded to the cloud for further elaboration. At the core of this process are heterogeneous, programmable, logic-based nodes, which are located in the vFog network and will be used for both processing and vFog suburb management. Programmable logic was selected because it offers the critical combination of high performance, low power, and complete flexibility that is necessary to successfully meet the challenges of this role.

A heterogeneous vFog node within the context of EXEGESIS will consist of a field programmable gate array (FPGA) system-on-chip (SoC), which is an integrated circuit that combines processors, programmable fabric, and, potentially, additional logic. This combination allows us to optimally balance the task load by allowing the processors to handle control-dominated tasks, like managing a vFog network and delegating all compute-intensive tasks to the programmable logic. To accomplish this, the programmable fabric needs to be virtualized so that the orchestration environment can deploy the appropriate application on it at

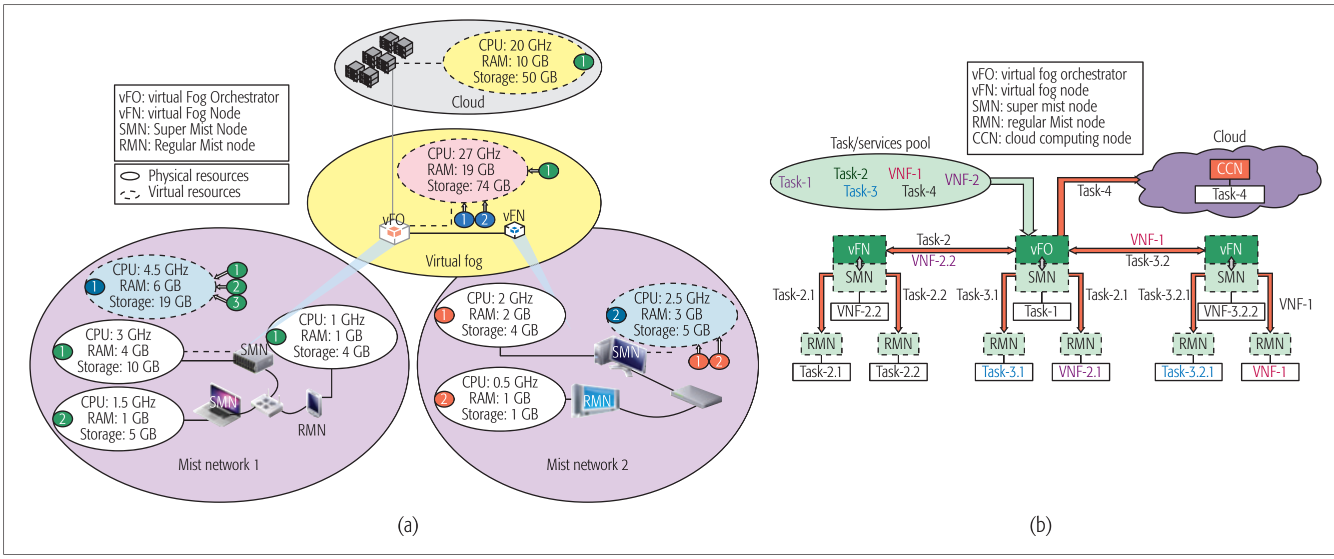

Figure 3. a) Abstraction of resources in EXEGESIS; b) deployment framework for tasks and services.

any given time. This is accomplished by executing cloud software on the processors of the FPGA SoC, which, together with the specialized hardware, enables the deployment of hardware virtual machines on the programmable logic.

Abstraction of Resources in EXEGESIS

Starting at the mist layer (Fig. 3a), each RMN, during its registration process or upon a status update, informs the SMN about the amount and type of physical resources it is willing to provide to the EXEGESIS platform. The SMN in turn abstracts this information to construct a virtual resources pool aggregating the physical resources of all the mist network nodes. Following the same paradigm, each SMN, after registering as a vFog node, delegates information about its virtual resources pool to the vFog orchestrator. At the same time, the vFog orchestrator can request and bind, if needed, more resources from a conventional cloud. In this way, the vFog orchestrator forges a new virtual pool that holds in abstracted form the physical resources across the whole vFog network.

Deployment of Services and Tasks in EXEGESIS

EXEGESIS will deploy services and perform computational tasks following a hybrid operational scheme (Fig. 3b). In such a scheme, the vFog orchestrators can receive the requests for computational tasks and service deployment. After that, the orchestrator, based on the vFog's available resources and policies and also taking into account the incoming task/service requirements, can assign each task or service to one or more vFog nodes (including itself if appropriate). In doing so, the orchestrator will utilize and extend existing work to optimize task allocation [6, 7]. In turn, each vFog node passes the request to its SMN module and, based on the mist's resources and the assigned operation's requirements, forwards the tasks to itself and also, if needed, to the appropriate RMNs. It is noted here that if a task exceeds the capacity of a vFog, the orchestrator can forward the task to another vFog or assign it to cloud computing resources. EXEGESIS' deployment framework has segmentation of tasks and services at its core. In this way, barring any security policies or specific task requirements, EXEGESIS can optimally fragment and distribute tasks to resources as required to ensure that performance targets are met.

Use Cases

Security cameras, mobile phones, machine sensors, environmental sensors, and so on are just a few of the items in daily use that create data that can be mined and analyzed. Add to it the data created in smart cities, manufacturing plants, financial institutions, oil and gas drilling platforms, pipelines, and processing plants, and it is not hard to understand that the deluge of streaming and IoT sensor data can — and will — very quickly overwhelm today's traditional data analytics tools. Organizations are beginning to look to edge computing as the answer. Edge computing exploits vFog and mist, and promotes data thinning at the edge that can dramatically reduce the amount of data that needs to be transmitted to a data center or cloud infrastructure. Without having to move unnecessary data to a central location, analytics or distributed processes at the edge can simplify and drastically speed up analysis while also cutting costs. This drastic shift in data processing paradigm propounded in EXEGESIS can be utilized in many diverse use cases. The proposed concept thus includes and investigates two concrete use cases where the proposed architecture can prove to be a game changer compared to the currently available infrastructure. These use cases, among others, are illustrated in Fig. 4, which demonstrates one possible example of an EXEGESIS architectural configuration where the four scenarios presented in the following sections are served by three vFog suburbs, each with its own mist node neighborhood. All three suburbs share a common cloud infrastructure, while each use case runs different tasks that are executed on their respective suburbs.

Enabling and Enhancing Services for Smart Cities

Cameras are ubiquitous in modern cities, and they can be used for various purposes, among which are traffic management and surveillance. Both of these applications can benefit from acceleration in the form of advanced image processing

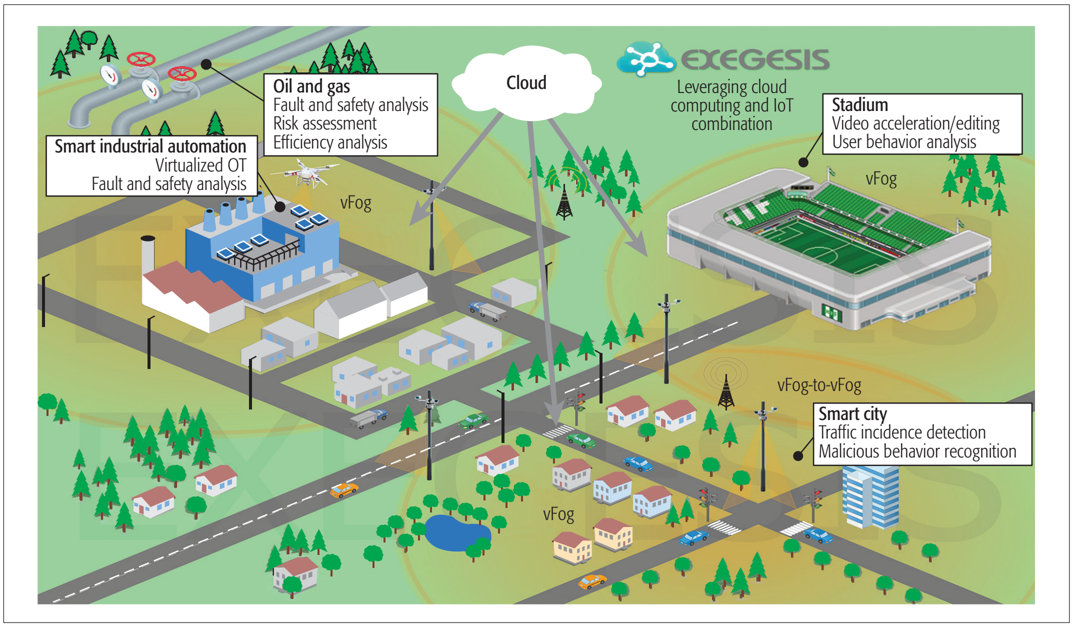

Figure 4. EXEGESIS use cases playground.

The smart city is going to be one of the major revolutions of the coming decades, with large urban areas, under ever-increasing pressure to accommodate a busy, fast-paced life for their citizens, turning to IoT to optimize the use of their infrastructure and thus save on cost and enable new services.

but require that different algorithms be executed (e.g., traffic management requires that the number of cars per lane or the number of cars violating traffic laws are counted, whereas surveillance demands that specific individuals must be identified).

The smart city is going to be one of the major revolutions of the coming decades, with large urban areas, under ever-increasing pressure to accommodate a busy, fast-paced life for their citizens, turning to IoT to optimize the use of their infrastructure and thus save on cost and enable new services. This entails everything from smart lightning to smart water supply to smart security, among others.

There are two issues where today's architecture is lacking: the reuse of existing infrastructure and the complexity in implementing data analysis solutions over that infrastructure. The former means that a set of input devices, say cameras in this scenario, is installed in order to be used only for one function (e.g., traffic monitoring). That function cannot be changed unless the infrastructure itself is physically altered, replaced, or duplicated. The latter refers to the fact that the process of retrieving the data from the input devices, analyzing, reaching a decision, and applying that decision is prohibitively slow and complex since all city infrastructure today is purpose built.

The architecture proposed in this article can solve both issues by creating two separate fog segments, both sharing the same FPGA-accelerated node through which the data pas that performs the appropriate analysis. The orchestrator platform makes sure the accelerated node executes the required functionality at any given time. The switch between the two tasks can be performed very swiftly, which will allow the node to perform both tasks seemingly at the same time much like a typical CPU appears to parallelize thread execution. The results of this analysis can then be either sent on for further processing (e.g., after identifying suspicious activity) to the cloud or trigger automatic reactions in other systems

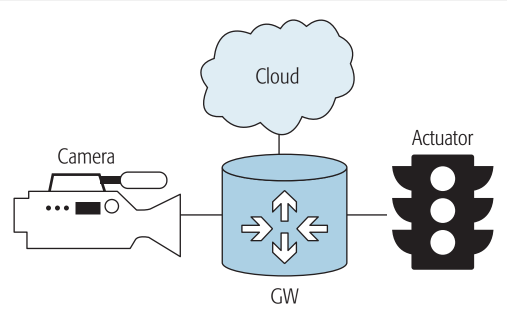

Figure 5. Overview of the simulated scenario.

(e.g., manipulating traffic signals when detecting an accident and notifying emergency services automatically).

Even within the narrower confines of smart traffic management, fog computing improves the performance of the application in terms of response time and bandwidth consumption. A smart traffic management system can be realized by a set of stream queries executing on data generated by sensors deployed throughout the city. Typical examples of such queries are real-time calculations of congestion (for route planning) and detection of traffic incidents. One possible case study, further elaborated on later in this article, could compare the performance of a DETECT_TRAFFIC_INCIDENT query on fog infrastructure [8] vs. the typical cloud implementation. In the query, the sensors deployed on roads send the speed of each crossing vehicle to the query processing engine. The operator Average Speed Calculation calculates the average speed of the vehicles from the sensor readings over a given timeframe and sends this information to the next operator. The operator Congestion Calculation calculates the level of congestion in each lane based on the average speed of vehicles in that lane. The operator Incident Detection, based on the average level of congestion, detects whether an incident has occurred or not. This process

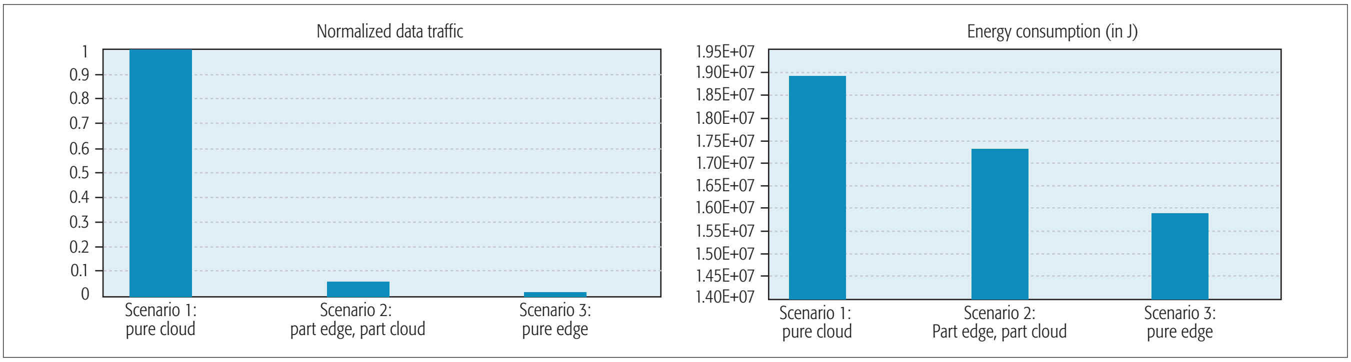

Figure 6. Simulation results showing: a) normalized network usage; b) system energy consumption.

will be implemented and executed on both fog- as well as cloud-based stream query processing engines, which will highlight the faster response times and bandwidth savings offered by the fog-based alternative.

Smart Industrial Automation

The new trend in automation is that of virtualizing as much as possible the operational technologies (OT) side of the system over contemporary IT infrastructure. The idea is simple: as virtual machines have virtualized hardware in IT, the automation industry is trying to virtualize OT hardware such as programmable logic controllers and run them over, more or less, traditional IT infrastructure.

The automation industry has been challenged for several years by the difference in innovation cycles and obsolescence rate existing between OT and IT. The result of this divergence in change rates has left the automation floor replete with obsolete IT technologies that have often introduced security breaches and in general reduce the productivity and usability of the entire system.

Fog and mist computing has been identified as the most natural approach to leverage the benefits of functions virtualization while maintaining the performance constraints typical of OT systems. This, however, is one side of the coin as companies also like to leverage the advantage of the cloud, that is, large storage and massive data analytics to identify issues and bottlenecks in production and flesh them out.

The EXEGESIS platform provides the ideal deployment target for software defined automation as it can enable mist computing to address the deployment and management of virtualized OT functions and services over industrial hardware, and fog computing to address the consolidation of higher-level control and analytics on more computationally capable hardware deployed on the edge of the system.

Preliminary Evaluation

This section provides an initial investigation into how the EXEGESIS edge compute paradigm influences the amount of data flowing throughout a network. This is accomplished by simulating a simple scenario similar to the traffic camera use case described in the previous section. In order to perform the evaluation we use an open source fog environment simulator called iFogSim [9]. We tested three separate scenarios, all of them comprising a camera that collects information, a programmable-logic accelerated gateway device that connects the camera to the cloud, an actuator that receives commands after analysis of the camera data and performs the appropriate actions, and finally the cloud itself, as shown in Fig. 5:

- In the first scenario the camera input stream is forwarded through the gateway to the cloud, which performs the analysis and decision making and returns the decision to the actuator. This scenario is most akin to the current paradigm.
- The second scenario performs motion detection in the fog using the gateway device but sends the clip to the cloud for detailed analysis and decision making, representing a middle ground between a pure cloud and a pure edge approach.
- The third scenario implements all the processing, including motion detection, analysis, and decision making, at the edge on the gateway device and only sends a notification of actions taken to the cloud.

We evaluate two important parameters for all three scenarios. The first is normalized network usage (Fig. 6a), and the second is the energy consumption for the entire system (Fig. 6b).

It is plainly evident that the edge compute variant (scenario 3) is clearly superior in both metrics. Energy usage reduction is to be attributed to the advantages of using programmable logic to perform the computation at the edge but also at the constrained network traffic, which also factors into energy use. Network traffic is whittled down by performing all the processing close to the source and only sending a small action report to the cloud instead of an entire camera stream. These results underpin the claim that the EXEGESIS architecture can yield important potential benefits in multiple areas if realized at scale.

Conclusions

Future 5G networks are being viewed as the key technology that will allow for the realization of a "hyper-connected society" where billions of IoT devices will be able to exchange data and offer/receive services at a high quality of service level. Toward this, the fifth generation (5G) aims to support high data speed at the networks' edges (1–10 Gb/s) and achieve ultra-low end to end latency (~1 ms); however, these alone may not be enough, especially with highly heterogeneous and fragmented network environments, a vast number and huge variety of devices residing at the network edges, and the colossal amount of generated data that are slowly coming to the foreground. To overcome this, EXEGESIS exploits and advances the fog and mist paradigms to propose a beyond 5G ecosystem where heterogeneous fixed and mobile edge nodes (e.g., home gateways, small cells, smartphones, SME servers, IoT devices, vehicles) will form an archipelago of interconnected islands of resources (e.g., storage, computing, network) where each island can be viewed as the successor of a small cell and the archipelago as the evolution of the macrocell. A preliminary simulation-based investigation hinted at the significant benefits that can be derived from moving to the edge-centric EXEGESIS architecture. Future work will involve the implementation of a real-life prototype and the validation of the EXEGESIS paradigm in real-life scenarios.

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Biographies

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Kimon Karras received his Ph.D. in embedded systems design from the Technical University of Munich and has spent four years at Xilinx Research Labs working on data center acceleration through FPGAs and innovative high-level synthesis applications. For the past year, he has been with Future Intelligence Ltd. where he is responsible for the development of the company programmable cloud platform.

Nikos Zotos, CIO, holds an M.Sc. in data communication systems. He has worked for various enterprises and research centers, holding active and key roles and positions. Currently he holds the position of chief innovation officer of Future Intelligence Ltd. His expertise includes design of large-scale heterogeneous networks, QoS over heterogeneous networks, IoT solutions for smart cities, next generation networks, energy efficiency networking, virtualized network environments, and cloud computing technologies.

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Angelo Corsaro, Ph.D., is chief technology officer at ADLINK Technology. As CTO he looks after technology strategy and innovation for ADLINK's Industrial Internet of Things (IIoT) platform. He is a well-known and cited expert in the area of high-performance and large-scale distributed systems with hundreds of publications in referred journals, conferences, workshops, and magazines.

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A preliminary simulation-based investigation hinted at the significant benefits that can be derived from moving to the edge-centric EXEGESIS architecture. Future work will involve the implementation of a real-life prototype and the validation of the EXEGESIS paradigm in real-life scenarios.