A Cloud to the Ground: The New Frontier of Intelligent and Autonomous Networks of Things

Cesare Alippi, Romano Fantacci, Dania Marabissi, and Manuel Roveri

The authors introduce a novel FC-IoT paradigm designed to move computing, storage and applications/services close to IoT objects so as to reduce communication bandwidth and energy consumption as well as "decision-making" latency. The proposed IoT-based solution has been designed to have intelligent and autonomous IoT objects that are integrated with a FC and Fog Networking approach.

ABSTRACT

The Internet of Things paradigm is supporting — and will support — an ever increasing number of services and applications impacting on almost every aspect of our everyday life. The current trend is forecasting IoT to connect tens of billions of objects by 2020 yielding a very high volume of data to be acquired, transmitted, and processed. IoT typically relies on cloud computing to process, analyze, and store the data acquired by IoT entities. Unfortunately, the need to transmit all data from the information producing objects to the cloud for a subsequent processing/analysis phase would require a large bandwidth and increase the latency in the decision making process whenever decisions/reactions must be promptly made by the IoT units. The fog computing paradigm aims to address these problems by extending cloud computing toward the edge of the network. In this direction, this article introduces a novel FC-IoT paradigm designed to move computing, storage, and applications/services close to IoT objects so as to reduce communication bandwidth and energy consumption as well as decision making latency. The proposed IoT-based solution has been designed to have intelligent and autonomous IoT objects that are integrated with an FC and fog networking approach. The distinguishing features of the intelligent FC-IoT platform are low latency, self-adaptation, low energy consumption, and spectrum efficiency.

INTRODUCTION

The Internet of Things (IoT) paradigm [1, 2] relies on physical objects (e.g., devices, machines, vehicles) that are connected together to acquire and exchange data. This network of objects represents a novel and emerging technological framework to support strict and valuable integration between the physical and cyber domains, hence improving the efficiency, effectiveness, and economic values of IoT-based solutions. This is the reason that within the next decade the IoT revolution will lead to billions of connected objects supporting novel and ground-breaking applications impacting almost every aspect of our lives, such as smart home and buildings, smart cars, e-health, intelligent monitoring systems, smart grids, and smart transportation.

Effective and efficient processing of data acquired and exchanged by IoT objects is crucial to achieve performance and credibility in IoT-based solutions. A common approach considers the IoT as a network of distributed acquisition-transmission objects, the goal of which is to gather measurements from the environment and transmit them to a centralized storage and processing entity. In such a scenario, cloud computing (CC) provides IoT applications with ubiquitous, on-demand network access to remote computing and storage platforms.

The transmission of data collected from the IoT to the cloud enables sophisticated data processing capabilities (to be run at the cloud level) and, at the same time, frees IoT designers from taking into consideration non-application-oriented aspects (e.g., storage, availability, and consistency of data).

Unfortunately, the transmission of all data to the cloud for subsequent processing and analysis would require large bandwidth, hence making the whole communication procedure (possibly very) inefficient, energy-hungry, or even critical in case of scarce available bandwidth resources or massive concurrent accesses. In addition, the need to move all data to the cloud for processing and analysis might introduce an unacceptable latency in the decision making process. This is particularly critical whenever actions or decisions must be promptly made by IoT objects to keep an appropriate quality of service for the envisaged applications/services.

Above constraints suggest to consider an enhanced IoT-based solution moving processing and communication as close as possible to IoT objects in order to reduce required bandwidth, energy consumption and minimize the "data production to decision making"-latency. This is exactly where the emerging paradigm of Fog Computing (FC) [3] comes into play. Indeed, the FC paradigm somehow complements the CC one by moving storage and computation close to end-devices also by taking advantage of relationships in space and time existing among acquired (or collectable) information. For this purpose, the FC paradigm relies on local highly performing computational units meant to collect, store, and hence process, data acquired by IoT objects.

The distinguishing characteristic of IoT solutions supporting FC is that part of the application processing is executed directly at IoT objects

Cesare Alippi and Manuel Roveri are with Politecnico di Milano;
Cesare Alippi is also with Università della Svizzera Italiana;
Romano Fantacci and Dania Marabissi are with the Università degli Studi di Firenze.

This work was supported by the project "GAUChO — A Green Adaptive Fog Computing and Networking Architecture" funded by PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE (PRIN) Bando 2015.

To access the final edited and published work see http://dx.doi.org/10.1109/MCOM.2016.1600541CM

and only when needed; more complex and resource-consuming tasks are transferred to higher-level units, called *FC units*, or directly to the cloud. The proposed paradigm integrating IoT and FC, referred to hereinafter as FC-IoT, allows the efficiency of the solution to be improved while reducing latency and energy consumption of traditional IoT-based solutions by reducing the amount of data that need to be exchanged with the cloud. This is a crucial aspect in the proposed FC-IoT paradigm since the local processing of data at IoT objects and FC units allows avoiding their transmission to the cloud, hence reducing the (relevant) energy consumption for the requested transmission.

To fully support this novel FC-IoT paradigm, IoT-based solutions must be rethought and tackled from different points of view. In particular, objects forming this novel FC-IoT paradigm must be augmented with self-configuration, management, healing, and energy awareness functionalities to locally process data and make autonomous decisions. These requirements have led FC-IoT designers to consider self- adaptive solutions [4, 5] with FC-IoT objects endowed with intelligent mechanisms able to process data and autonomously adapt their behaviors in response to changes affecting either the system itself or the environment in which they are deployed. Moreover, to efficiently enable the communication among intelligent objects and FC units, and deal with the steadily increasing traffic demand in future FC-IoT applications, a new type of network management, fog networking [6], must be adopted by considering decentralized networking and communication solutions.

The aim of this article is to introduce and critically discuss the proposed FC-IoT paradigm for distributed and heterogeneous solutions integrating FC and IoT. Inspired by the proposed paradigm, here we describe an intelligent FC-IoT platform with the distinguishing features of decision making, low latency, energy awareness, self-adaptation, and spectrum efficiency. In addition, the proposed intelligent FC-IoT platform allows the support of a wide range of features that are relevant in IoT scenarios such as ubiquity, decentralized management, cooperation, proximity to end users, dense geographical distribution, and efficient support for mobility and real-time applications.

These properties are achieved through a novel architecture as well as novel solutions and mechanisms characterizing the proposed intelligent FC-IoT platform. In more detail, as shown in Fig. 1, the proposed platform encompasses three different FC-IoT units, each characterized by different constraints on computation ability, memory, and energy availability: the intelligent objects, the FC units, and the cloud. Intelligent objects are meant to acquire measurements from the environment in which they are deployed and (whenever possible or needed) perform control actions or activate reaction mechanisms. These objects are organized into subnetworks, called FogNets (FNs), to locally exchange information and satisfy service/application needs. Each FN is meant to support a small cloud at the edge of the network where intelligent objects manage themselves in an autonomous and distributed way. In addition, intelligent objects are connected to FC units that provide (when needed) the computational resources for more complex and resource-demanding application tasks/processing. FC units are interconnected through fog networking and linked to the cloud depending on application needs and constraints.

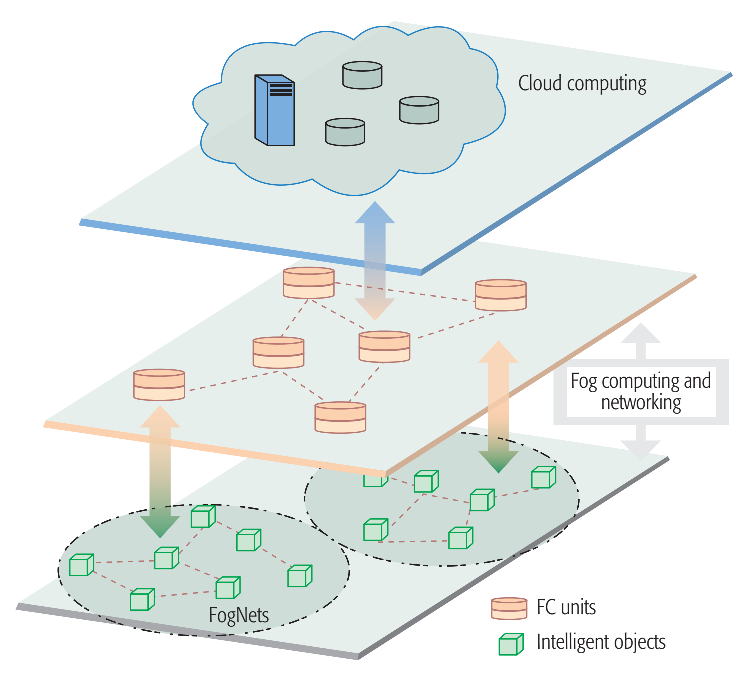

Figure 1. The high-level view of the intelligent FC-IoT platform. The lower level collects the intelligent objects that are meant to acquire data from the environment and communicate with the FC units through suitably defined FogNets. FC units, being part of the middle level, provide intelligent objects with computational resources for complex and resource-demanding application tasks/processing. FC units are linked to the cloud (upper layer) depending on application needs and constraints.

The article is organized as follows. We describe the high-level architecture of the proposed intelligent FC-IoT platform, and detail its main modules (i.e., communication, computing, and intelligent processing). A challenging and relevant application scenario of the proposed platform is presented, while conclusions are finally drawn.

THE PROPOSED INTELLIGENT FC-IOT PLATFORM: SYSTEM ARCHITECTURE AND FUNCTIONALITIES

The proposed intelligent FC-IoT platform has been organized into a hierarchical architecture, where each layer has been designed to fulfill a specific goal. As shown in Fig. 2, the architecture of the proposed FC-IoT platform comprises four layers:

- The *hardware/OS layer* providing the physical mechanisms for data acquisition and processing as well as the basic software functionalities to higher levels (i.e., the operating system services)
- The *communication layer*, which efficiently and effectively supports both local data exchange among the intelligent objects and the FC units of the FC-IoT by exploiting the FN paradigm and the remote data connection with the cloud
- The *computing layer* providing the services supporting the reconfiguration of intelligent objects and FC units

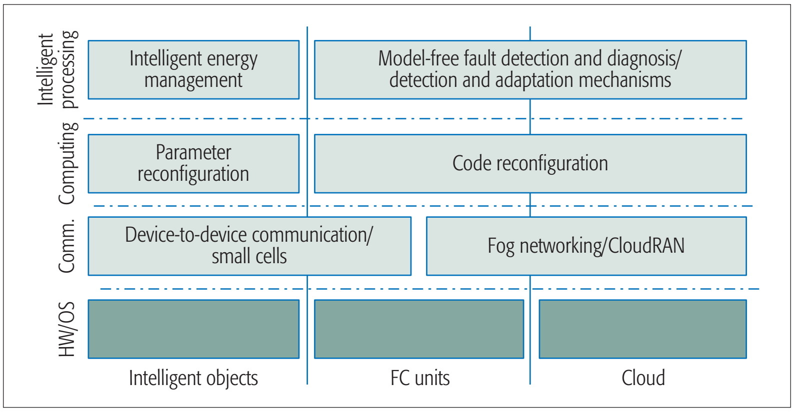

Figure 2. The layered system architecture of the proposed intelligent FC-IoT platform.

- The *intelligent processing layer*, which makes available those functionalities allowing the FC-IoT units to be self-adaptive and autonomous

Such a layered architecture is meant to be effective and efficient from both the processing and energy points of view. Each layer has been designed to exploit the functionalities provided by lower layers and provide functionalities to upper ones. The communication, computing, and intelligent processing layers are detailed hereinafter, while the HW/OS one is omitted since it is strictly application-specific.

THE COMMUNICATION LAYER

The communication layer of the FC-IoT platform must enable the FC capabilities at the edge of the network by providing reliable, scalable, low-latency, and energy-efficient data exchange to a (possibly very) high number of connected intelligent objects. Furthermore, the communication layer, suitably activated by the intelligent processing layer, has to support the adaptation mechanisms at the FC-IoT units as discussed.

To guarantee the ubiquity and pervasivity of IoT-based solutions, wireless connections have a predominant role in the proposed platform. In particular, following the FN paradigm, data acquired by intelligent objects are mainly processed and transmitted locally, through proximity direct links or through routing between adjacent FNs. In order to satisfy these communication requirements, the considered intelligent FC-IoT platform needs to resort to novel communication technologies. Among them, we consider here the device-to-device (D2D) communication approach and the use of small cells (SCs) overlapped with traditional macrocells. The joint use of these two technologies allows traffic to be offloaded from the macrocell network providing wide area connections, increasing the FC-IoT communication capacity, and reducing the energy consumption due to the communication.

A possible communication architecture for the considered intelligent FC-IoT platform is shown in Fig. 3. This encompasses several SCs, each of which creates a local FN enabling data exchange among intelligent objects within a local area through D2D direct links and through the support of an SC base station (SCBS) that acts as an FN access point. In particular, the SC performs local coordination of the radio resource usage among the intelligent objects in order to avoid interference within the FN.

In particular, in the considered architecture communications among intelligent objects and an SCBS are scheduled by the SCBS, while D2D communications between intelligent objects encompass four different solutions:

1. *No-contention mode*: A SCBS individually assigns resources to each D2D link.
2. *Random mode*: Each D2D link competes with other D2D links for resources belonging to a set reserved by the SCBS for D2D communications.
3. *Underlay mode*: A D2D link uses resources assigned to other communications that are sufficiently far, thus resulting in a low mutual interference level.
4. *Overlay mode*: A D2D link uses resources that are not used by other communications.

In the first case D2D communications rely on dedicated resources that have been specifically scheduled by the SCBS, thus preventing D2D links interference. A similar solution is provided in the second case by reducing the SCBS tasks, while suitable access resources are here considered to support the random access phase in order to guarantee low latency and high spectrum efficiency. The highest spectral efficiency is achieved in the two latter cases at the expense of increased computational complexity at the intelligent objects due to the required spectrum sensing procedure (e.g., based on energy detection, matched filter, or cyclostationary detection approaches [7, 8]). The selection of a suitable D2D communication mode is application-specific and must take into account the computational capabilities and energy constraints of the considered intelligent objects.

SCBSs may also act as FC units of the intelligent FC-IoT platform, hence locally transferring data toward other SCBSs, borrowing part of the computational/storage facilities from/to the neighboring SCBSs, and pre-elaborating traffic from/toward the intelligent objects. According to this approach, intelligent objects within the same FN can directly download data from their neighboring objects without requiring access to the core network.

SCs are part of a wide area network and are overlapped with the macrocells, thus allowing the exchange of data among FC units and with the cloud. Unfortunately, this might lead to a high interference level — mainly due to high-power macrocells — that can strongly affect the reliability of low-power SCs and D2D links, hence compromising the quality of service (QoS) of the intelligent FC-IoT platform. This means that the communication layer of the proposed platform must be able to deal with inter-cell interference. This problem is efficiently and effectively addressed through the cloud radio access network (C-RAN) approach, which foresees central coordination of the resource usage among different cells (even based on different radio access technologies) and is able to support complex but efficient global performance optimization. As a consequence, SCs have two levels of coordination:

- A fog level that allows a distributed coordination of the SCs within the FN to which they belong

- A cloud level that allows centralized coordination among macro and SCs (i.e., within the overall network), for some network functionalities such as interference management

In particular, the solution for inter-cell interference management we considered in the proposed platform relies on inter-cell interference coordination (ICIC), which reserves orthogonal portions of the available resources for the FN communications [9, 10]. The C-RAN centralized control allows strict coordination among the cells (both macro and small cells) identifying the right amount of resources to be reserved to the FNs following suitable criteria, and optimizing the trade-off between the need to reduce the interference in local communications and the reduced capacity of the wide area macrocell network.

Furthermore, to support the strict requirements in terms of low latency and energy consumption as well as to adapt spectral resource demands in response to modified application and QoS requirements over time, the communication layer must encompass novel solutions to boost communication capacity. To achieve this goal we considered efficient exploitation of the unlicensed spectrum, representing a novel and promising approach in the field of communication networks. Toward this goal, it is mandatory to carefully define:

- Efficient methodologies that SCBSs can use to discover, mainly in autonomous mode, the availability of unlicensed bandwidths in their proximity
- Suitable criteria that the C-RAN coordinator can use to optimize the shared use of licensed and unlicensed spectrum among the cells exploiting the discovery information coming from the SCs

THE COMPUTING LAYER

The computing layer provides the software mechanisms to support the reconfigurable computing on FC-IoT units at runtime. Reconfiguration of the computation running on FC-IoT units refers to the capability to modify or update the software code and/or the parameters of such units during their operational life. This ability is crucial in large-scale FC-IoT systems with units (possibly) deployed in remote areas since it allows both updating the applications running on FC-IoT units over time (e.g., to adapt to new or unforeseen working conditions) and providing new functionalities (e.g., introduce new algorithms to increase the computational efficiency and reduce energy consumption).

The software mechanisms provided by this layer are triggered by the intelligence processing layer (presented below) to allow the FC-IoT platform to adapt both variations in the FC-IoT units (e.g., a fault affecting a sensor or a processing board) and changes in the environment/application scenario in which FC-IoT units are deployed (e.g., due to seasonality or periodicity effects).

Reconfiguration of FC-IoT units at runtime is achieved through two mechanisms differing in complexity and reconfiguration target: parameter and code reconfiguration.

Parameter reconfiguration refers to the remote update of code parameters running on FC-IoT units (filter taps, duty cycling parameters, event detection thresholds, etc.). This mechanism is specifically meant for low-power low-complexity units that cannot support complex reconfiguration frameworks (e.g., virtual machines [VMs] or boot loaders). Parameter reconfiguration is implemented through modification of the computation parameters at runtime without modifying the code. When needed, parameter updates are transmitted from the cloud to the intelligent objects/FC units to be reconfigured (or exchanged among FC units) through the communication and networking mechanisms described earlier. Once these parameter updates reach the target FC-IoT unit, they are interpreted, and the updates are implemented through a suitably defined low-level reconfiguration mechanism [11].

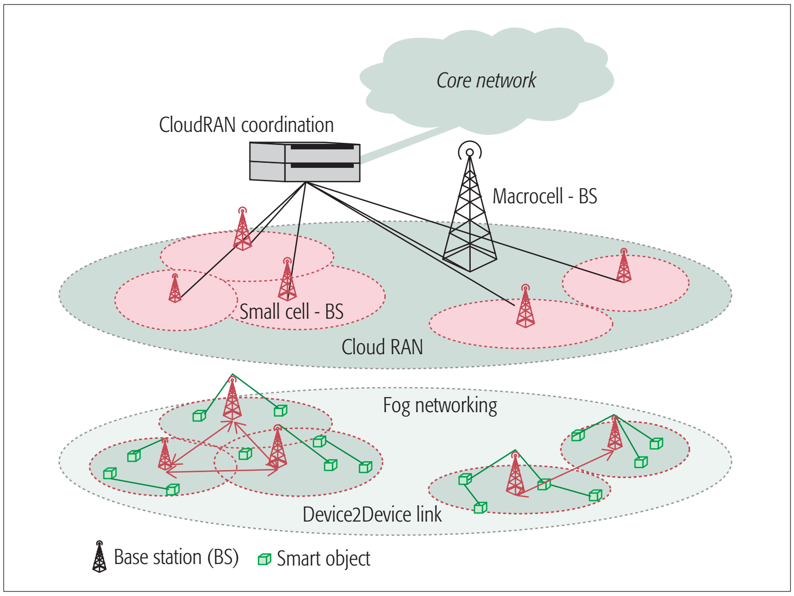

Figure 3. The communication architecture of the proposed intelligent FC-IoT platform.

Differently, *code reconfiguration* allows remote update of the code running on FC-IoT units. To achieve this goal, FC-IoT units must rely on VMs, the goal of which is to provide an abstraction framework able to support remote reprogrammability of code at runtime. For this reason, code reconfiguration is allowed on FC-IoT units characterized by adequate computational, memory, and energy resources. The main advantages of VMs w.r.t. other solutions (e.g., native code loaders) are the ability to generate and manage size-optimized code (hence, reducing the energy consumption required for the transmission of code through the networks) and the capability to operate on (possibly) heterogeneous units (in terms of hardware/OS). Unfortunately, VMs generally suffer from reduced efficiency in terms of computational efficiency and memory overhead. To support the features of low latency and computational efficiency proper of the proposed intelligent FC-IoT platform, we designed a real-time, computationally efficient, reprogrammable framework (REEL) [12] that has been optimized for the processing of the acquired data on FC-IoT units. This framework is meant to integrate the flexibility and code-size efficiency of VMs together with the computational efficiency that is typically provided by solutions based on native code loaders. To

> FC-IoT based systems are of special interest in several application scenarios, including smart grids, connected vehicles, wireless sensor/actuator networks, smart buildings, and critical environment control. Within the critical environment control, rock collapse and landslides represent critical and harmful natural hazards in mountain regions.

achieve these goals we designed a VM specifically tailored for data stream processing in IoT scenarios. This solution allows the guarantee of a high computational efficiency (typical of native code loader solutions) as well as reduced sizes of programming code (typical of VM solutions) [12]. A comparison of the computational efficiency of the proposed REEL framework w.r.t. other solutions is shown later.

In addition, in order to reduce the effects of the reprogramming on the software tasks running on the FC-IoT units (i.e., those that are not directly involved in the code update), we designed a reprogramming paradigm and a set of related tools and facilities specifically meant to remotely reprogram FC-IoT units [13]. Such a solution allows organization of the software tasks running on FC-IoT units from the functional point of view and guarantees that the effect of the reprogramming is minimized on those tasks not directly involved in the reprogramming phase. This allows maintenance of the QoS of FC-IoT units involved in such a task and the coherence of the execution of the tasks running in such units after the completion of the reprogramming phase. This ability is crucial when many and complex software tasks are executed at the FC-IoT units (as in the case of FC and SCBSs) that are target of the reprogramming.

INTELLIGENT PROCESSING LAYER

The intelligent processing layer is meant to provide self-adaptivity, autonomy, and smart energy management functionalities to FC-IoT units. In more detail, this layer provides the FC-IoT units with the functions permitting:

- Optimal energy management
- Assessment of the quality of incoming data to identify fault-affected samples that would negatively affect the application QoS if not detected and isolated
- Adaptation of the application behavior to time variance of the environment

To achieve these goals, the intelligent processing layer takes advantage of functionalities provided by the communication and computing layer presented above.

The *optimal energy management* functionality aims at managing the energy consumption at FC-IoT units while maintaining the application performance. This is achieved by jointly considering adaptive sampling mechanisms, energy harvesting mechanisms when available [5], and smart energy management policies. More specifically, adaptive sampling aims to control the energy consumption in both data acquisition (crucial in case of energy-hungry sensors) and transmission by either scaling the sampling frequency, interleaving transmission of data and models of data, or predicting the next sensor acquisition. Differently, smart energy management policies are revealed to be successful in reducing the energy consumption of the FC-IoT units by acting mostly at the hardware level and considering simple yet effective strategies such as gradual self-switching off hardware or software modules when the residual energy decreases below a threshold as well as dynamically scaling voltage and frequency of the microprocessor [5]. To update parameters on FC-IoT units (e.g., the sampling frequency and the duty-cycling), the intelligent processing layer relies on the parameter reconfiguration mechanism described earlier.

Assessing the quality of data acquired by FC-IoT units is crucial to identify errors or outliers that would negatively affect the QoS application if not promptly detected and diagnosed. Such errors or outliers are typically induced by permanent or transient faults, aging effects, or thermal drifts affecting the sensor apparatus or the embedded electronics. Hence, the intelligent processing layer encompasses a model-free fault detection/diagnosis system able to jointly operate, in a distributed way and without requiring any a priori knowledge about the monitored phenomena, on the intelligent objects and FC units [14]. By exploiting the functional relationships present in the acquired data streams (through the learning of a "dependency graph"), the model-free fault detection/diagnosis system is able to distinguish between time variance in the environment/system under inspection (i.e., changes in the environment/system where the FC-IoT units are deployed) and possible faults affecting sensor/actuators of intelligent objects/FC units. The ability to distinguish between time variance affecting the environment and faults is crucial to support intelligent mitigation mechanisms and maintain, whenever possible, the requested QoS of the application.

Finally, the intelligent processing layer provides the functionalities that allow the FC-IoT units to be characterized by *adaptive and autonomous behavior* w.r.t. changes in the environment. To achieve this goal, FC-IoT units are endowed with intelligent model-free mechanisms for change detection at the sensor device level representing the building blocks of the intelligent FC-IoT platform for the analysis of acquired measurements. These mechanisms are meant to detect changes in the environment in which intelligent objects operate (and activate subsequent reactions) as well as the (possible) variations in the provided application QoS. Once a change in the data stream has been detected, energy-efficient adaptation mechanisms able to exploit both information about the change (e.g., the time instant the change occurred and its type/magnitude) and location-aware information to support the self-adaptation/reconfiguration of FC-IoT units are considered. These adaptation mechanisms exploit the parameter/code reconfiguration mechanisms provided by the computing layer.

When more complex and resource-consuming intelligent mechanisms are needed (e.g., when more powerful change detection mechanisms or classification algorithms are required), acquired data (together with possibly pre-processed features) are moved from intelligent objects/FC units to the cloud for further processing. This is achieved through the communication layer presented above and, in particular, through the C-RAN approach, which efficiently handles the communications among remote SCBSs and the core network.

We emphasize that IoT objects and FC units exposing intelligent mechanisms represent a novel and promising solution in both the FC and IoT scenario. Such a solution has never been explored in the related literature.

AN APPLICATION EXAMPLE: FC-IOT INTO THE WILD

FC-IoT based systems are of special interest in several application scenarios, including smart grids, connected vehicles, wireless sensor/actuator networks, smart buildings, and critical environment control. Within the critical environment control, rock collapse and landslides represent critical and harmful natural hazards in mountain regions. An effective and low-latency risk assessment of such hazards is crucial to provide timely alarms and activate suitable emergency responses. In addition, forecasting systems for rock collapse and landslides must operate in remote regions and harsh environmental conditions, making energy efficiency and self-adaptation crucial assets to guarantee QoS. All these aspects make rock collapse and landslide forecasting a relevant and valuable application scenario for the proposed intelligent FC-IoT platform [11, 15].

As shown in Fig. 4, the considered intelligent FC-IoT system for rock collapse and landslide forecasting is composed of a large set of intelligent objects endowed with (possibly) heterogeneous environmental sensors (e.g., temperature and humidity sensors, clinometer, strain-gauge, accelerometers, geophones). These intelligent objects, which are deployed in different areas of the Italian Alps (i.e., Monte San Martino, Premana, Gallivaggio, Torrioni di Rialba), are connected through the communication and networking mechanisms described earlier to FC units providing access to core network and cloud. In particular, thanks to these mechanisms, the intelligent objects are able to locally exchange data and rely on long-range cellular connections to access the cloud.

In such a critical scenario, the processing is distributed through the FC-IoT units to guarantee low latency and energy efficiency. In more detail, intelligent objects acquire measurements from the environment, locally process them, and, if needed, scale the processing of anomalous situations (e.g., micro-acoustic emissions, local variations in the slope, or enlargements of existing fractures) to FC units or the cloud for more detailed analysis (by also exploiting data acquired by other FC-IoT units). The preliminary phase, carried out at the intelligent objects, acts as a triggering mechanism by identifying those data that are worth being remotely transmitted to the FC units/cloud for deeper analysis. This triggering mechanisms allows avoiding the transmission of uninteresting/irrelevant data, hence reducing the overall energy consumption and required bandwidth. In addition, the analysis carried out at intelligent objects allows autonomous switching of the working modality of intelligent objects/FC units from normal to alarm mode (highlighting a potentially critical situation) so as to increase, for example, acquisition and transmission rates. Figure 5 shows the number of recorded microacoustic acquisitions, also called bursts, that have been acquired by intelligent objects after the deployment in the area of Torrioni di Rialba and have been transmitted to the corresponding FC unit for processing and analysis. The detection and analysis of these bursts is crucial in rock collapse and landslide forecasting since they represent possible forerunners of the collapse of a rock face. An anomalous peak of burst recordings is highlighted on day 21, as shown in Fig. 5a. In particular, the detail in Fig. 5b shows two peaks of burst recordings on day 21, which correspond to a micro-acoustic emission artificially introduced by the operators through a pneumatic drill (around 8.30 am), thus corresponding to false alarms, and to an actual fracture in the rock (around 11 am), respectively. In both situations the involved FC-IoT units autonomously switched to the alarm working mode: the updated transmission and acquisition rates are transmitted from the FC units to the involved intelligent objects through the parameter reconfiguration mechanism described earlier.

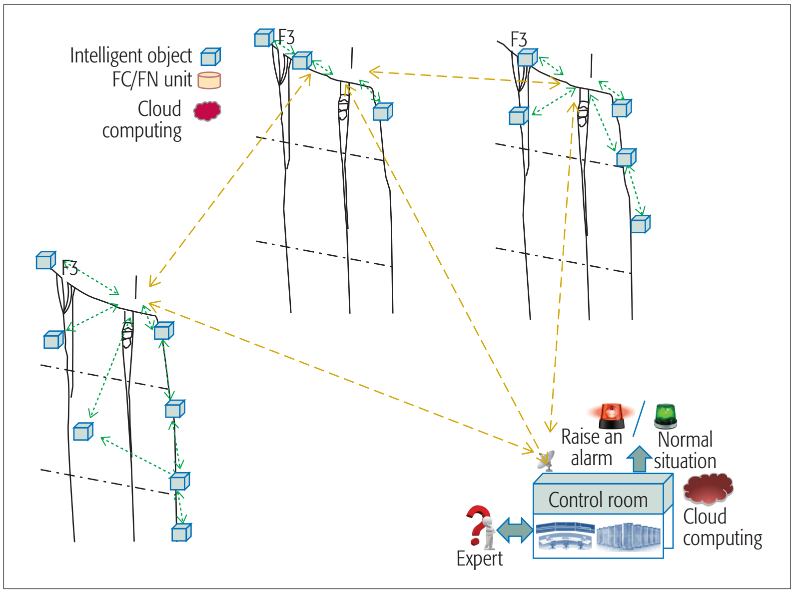

Figure 4. The application scenario for FC-IoT: an intelligent monitoring system. The intelligent objects (blue boxes) acquire measurements from the environments and locally process them by means of low-complexity triggering mechanisms to inspect for micro-acoustic emissions, variations in the slope of the mountain, or enlargements of fractures in the rock. Once an anomalous situation is triggered by an intelligent object, it sends data to the FC/FN units (orange cylinders) and the cloud (located in the control room) for deeper analysis, which is also able to exploit data coming from other intelligent objects.

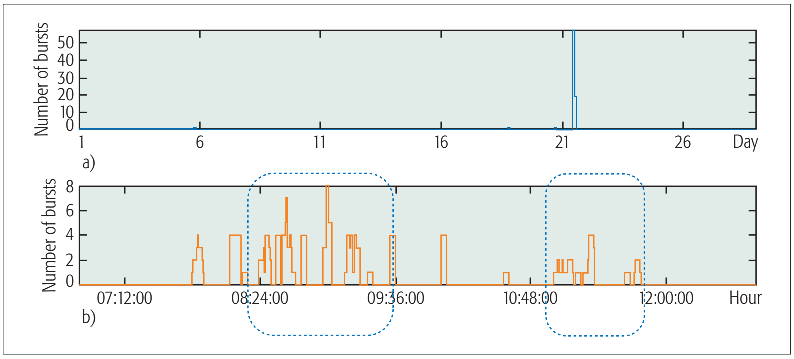

Figure 5. The burst recording in the area of Torrioni di Rialba (Northern Italy): a) shows the burst recording of the first 30 days; b) details the burst recordings between 7.00 am and 12.00 pm of day 21.

In a scenario where FC-IoT units are deployed in a mountain environment, remote reconfigurability is crucial to support updating/adaptation/fine-tuning of the rock collapse and landslide forecasting system during its operational life (i.e.,

	BubbleSort		Median Filter		Burst Detection	
	128 elem.	256 elem.	Window size 3	Window size 9	64/128	128/256
Darjeeling	4970.7	19988.8	404.4	733.7	58.8	117.1
REELVM	1051.5	4208.2	21.6	27.0	0.9	1.8
NATIVE	556.7	2228.4	18.1	23.5	0.8	1.4

Table 1. Comparison of execution times (in milliseconds) of the Burst Detection algorithm and two benchmarks (i.e., BubbleSort and Median Filter) on the proposed REEL VM w.r.t. Darjeeling and Native Code [12].

after its deployment). This ability is essential for this application scenario where knowledge about the physical phenomena (e.g., the propagation of micro-acoustic emissions inducing the collapse of rock faces) is still incomplete, and its physics and evolution are (partly) unknown. In more detail, we relied on the REEL reprogrammabLe framework described previously to update the algorithm for the detection of bursts, named Burst Detection, running on intelligent objects of the intelligent FC-IoT system. Table 1 shows a comparison of the execution times of the Burst Detection algorithm (as well as two other benchmarks, Bubblesort and Median Filter) of the proposed REEL framework w.r.t.:

- Darjeeling, a well-known VM for wireless sensor networks present in the literature
- Native code [12]

In particular, in this experimental analysis, we considered two configurations of BubbleSort (128 and 256 elements), two lengths of the Median Filter (i.e., 3 and 9), and two configurations of the windows of the Burst Detection algorithm (i.e., 64/128 and 128/256). For further details about the two benchmarks and the Burst Detection algorithm, the reader can refer to [12, 15]. Results show that the execution times provided by REEL are significantly lower than those of Darjeeling and in line with those of native code. This corroborates the ability of the intelligent FC-IoT platform to guarantee high computational efficiency even in a reconfiguration framework.

CONCLUSIONS

Nowadays, fog computing represents a viable and promising solution to reduce energy consumption, communication network congestion, and the decision making latency (as well as to increase reliability and availability) in IoT-based applications. FC extends cloud computing to the IoT objects that acquire and process data, and can be placed anywhere exploiting efficient wireless connections. This article introduces an intelligent FC-IoT platform able to efficiently distribute data processing and analysis between intelligent objects, FC units, and the cloud, thus enabling effective and efficient IoT-based solutions. The proposed platform is based on a hierarchical architecture, supporting novel solutions and mechanisms for communication, computing, and intelligent processing. A relevant and challenging application scenario of the intelligent FC-IoT platform is presented, validating the effectiveness and efficiency of what has been proposed in the context of rock collapse and landslide forecasting.

REFERENCES

[1] A. Al-Fuqaha *et al.*, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 4, 2015, pp. 2347–76.

[2] F. Chiti *et al.*, "Context-Aware Wireless Mobile Autonomic Computing and Communications: Research Trends and Emerging Applications," *IEEE Wireless Commun.*, vol. 23, Apr. 2016, pp. 86–92.

[3] F. Bonomi *et al.*, "Fog Computing and Its Role in the Internet of Things," *Proc. 1st Ed. MCC Wksp. Mobile Cloud Computing*, 2012, pp. 13–16.

[4] C. Krupitzer *et al.*, "A Survey on Engineering Approaches for Self-Adaptive Systems," *Pervasive and Mobile Computing*, vol. 17, 2015, pp. 184–206.

[5] C. Alippi, *Intelligence for Embedded Systems*, Springer, 2014.

[6] S. C. Hung *et al.*, "Architecture Harmonization between Cloud Radio Access Networks and Fog Networks," *IEEE Access*, vol. 3, 2015, pp. 3019–34.

[7] A. Tani, R. Fantacci, and D. Marabissi, "A Low-Complexity Cyclostationary Spectrum Sensing for Interference Avoidance in Femto-Cells LTE-A Based Networks," *IEEE Trans. Vehic. Tech.*, vol. 65, no. 4, 2016, pp. 2747–53.

[8] D. Tarchi, R. Fantacci, and D. Marabissi, "Proposal of a Cognitive Based MAC Protocol for m2m Environments," *2013 IEEE 24th Annual Int'l. Symp. Personal, Indoor, and Mobile Radio Commun.*, Sept 2013, pp. 1609–13.

[9] D. Marabissi *et al.*, "An Optimized Comp Transmission for a Heterogeneous Network Using Eicic Approach," *IEEE Trans. Vehic. Tech.*, vol. 65, no.10, 2016, pp. 8230–39.

[10] T. Taleb, A. Ksentini, and A. Kobbane, "Lightweight Mobile Core Networks for Machine Type Communications," *IEEE Access*, vol. 2, 2014, pp. 1128–37.

[11] C. Alippi, G. Boracchi, and M. Roveri, "A Reprogrammable and Intelligent Monitoring System for Rock-Collapse Forecasting," *IEEE Sys. J.*, vol. PP, no. 99, 2015, pp. 1–12.

[12] C. Alippi *et al.*, "Reel: A Real-Time, Computationally-Efficient, Reprogrammable Framework for Wireless Sensor Networks," *2011 IEEE Sensors*, 2011, pp. 1193–96.

[13] A. Antola, A. L. Mezzalira, and M. Roveri, "Ginger: A Minimizing-Effects Reprogramming Paradigm for Distributed Sensor Networks," *2014 IEEE Int'l. Symp. Robotic and Sensors Environments,* pp. 88–93.

[14] C. Alippi, S. Ntalampiras, and M. Roveri, "A Cognitive Fault Diagnosis System for Distributed Sensor Networks," *IEEE Trans. Neural Networks and Learning Sys.*, vol. 24, no. 8, 2013, pp. 1213–26.

[15] C. Alippi *et al.*, "A High-Frequency Sampling Monitoring System for Environmental and Structural Applications," *ACM Trans. Sensor Networks*, vol. 9, no. 4, 2013, article no. 41, pp. 41:1–41:32.

BIOGRAPHIES

CESARE ALIPPI [F'05] (cesare.alippi@polimi.it, cesare.alippi@usi.ch) is a professor at Politecnico di Milano, Italy, and Universita della Svizzera Italiana, Switzerland. He received the INNS Gabor award and the Outstanding *IEEE Transactions on Neural Networks and Learning Systems* Paper Award. Current research addresses Intelligence for embedded and cyber-physical systems.

ROMANO FANTACCI [F'05] (romano.fantacci@unifi.it) is a full professor at the University of Florence, Italy.He received the IEE IERE Benefactor premium in 1990, an IEEE ComSoc Award for Distinguished Contributions to Satellite Communications in 2002, and an IEEE ComSoc Wireless Communications Recognition Award in 2015. He was an Associate Editor for *IEEE Transactions on Communications* and *IEEE Network*, and a Founding Area Editor for *IEEE Transactions on Wireless Communications*. He is currently serving as an Associate Editor for the *International Journal on Communications Systems* and a Regional Editor for *IET Communications*.

DANIA MARABISSI [SM'13] (dania.marabissi@unifi.it) received her Ph.D. degree in informatics and telecommunications engineering in 2004 from the University of Florence, where she works as an assistant professor. She was the winner of the FIR-2013 contest funded by the Italian Ministry of Education. She is an Associate Editor of *IEEE Transactions on Vehicular Technology*, *IEEE Transactions on Emerging Telecommunications Technologies*, *IET Communications*, and the *Hindawi Scientific World Journal*.

MANUEL ROVERI (manuel.roveri@polimi.it) is an associate professor at the Politecnico di Milano. He is an Associate Editor of *IEEE Transactions on Neural Networks and Learning Systems* and received the *Outstanding IEEE Transactions on Neural Networks and Learning Systems* Paper Award in 2016. His current research activity addresses learning in non-stationary environments and intelligence for cyber-physical systems.