New Paradigms for Pervasive & Sustainable IoT

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***Abstract* — The Internet of Things is already a reality in many different application domains, and it is expected to evolve towards the so-called Pervasive IoT. The latter will be characterized by a very large number of quite different devices, connected trough different communication technologies. It will be a complex system, where intelligent functionalities will be deployed along the Cloud-to-Thing continuum, and will require a number of novel paradigms to address the new challenges posed by the new environment. Due to the large number of connected objects, sustainability issues will require a special attention. In this presentation, we tackle the main challenges posed by the future Pervasive IoT, and discuss some novel paradigms necessary to address these challenges.**

Keywords— Pervasive IoT, device heterogeneity, mobility-by-design, joint resource management, battery-less IoT, intermittent computing.

I. Future Pervasive IoT

The Internet of Things is already a reality in many application domains, ranging from industrial settings to smart cities, from healthcare to logistics and transportation. According to the report of the IoT Observatory at the Politecnico di Milano [1], the number of connected IoT devices in Italy, in 2023, has reached 140 million, approximately 2.4 objects per inhabitant. In the same year, the IoT market increases up to 9% with respect to the 2022, reaching 9 billion €. Specifically, most of the budget in market related to the IoT is concentrated on Smart Car (17% of the overall budget in 2023), Smart Metering (16%), Smart Building (15%), Smart City (10.6%), Smart Factory (10%), Smart Home (9%), Smart Logistics (8.6%), Smart Agriculture (6%), Smart Asset Management (4%).

This trend is expected to increase more and more, and evolve towards the so-called *Pervasive IoT*. The future Pervasive IoT will be an extremely complex environment, where communication and sensing functionalities will be strictly integrated, exploiting a multitude of complementary enabling technologies. In addition, functionalities will also be embedded into users and IoT devices (beyond the edge), which will become an integral part of the pervasive network.

Specifically, the Pervasive IoT will be characterized by a very large number of heterogeneous devices, ranging from wearable and personal devices to high-end IoT devices, such as Unmanned Aerial Vehicles (UAVs). These very different devices will be connected through many, heterogeneous communication technologies including, but not limited to, 4G/5G/B5G, WiFi, 802.15.4, BLE, UWB. As an example, Figure 1 shows how the Pervasive IoT paradigm can be applied in an industrial context, i.e., the so called *Pervasive Industrial IoT.*

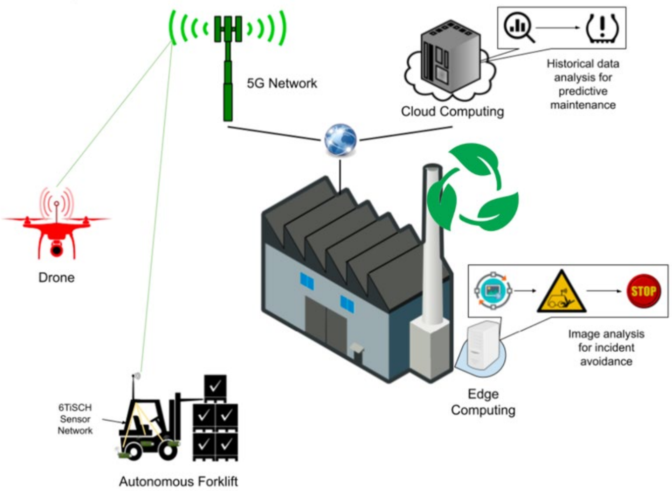

Figure 1 - Pervasive IIoT

Depending on the specific application domain, more or less stringent Quality of Service (QoS) constraints will be required, regarding timeliness, reliability and security. The large number of devices, coupled with the QoS requirements, will ask for new computing and communication paradigms. At the same time, new models, algorithms and systems will be required for localization and tracking in complex scenarios with heterogeneous radio devices, based on integrated sensing and communication approaches. Finally, sustainability and environmental impact will be also very relevant aspects, due to the large number of devices and their impact, in terms of energy consumption, device management and disposal.

In this presentation we intend to introduce and discuss some of the new (computation and communication) paradigms required in the future Pervasive IoT.

II. Device and Technology Heterogeinity

The Pervasive IoT will be characterized by a very large number of heterogeneous devices connected through different communication technologies including cellular communication, LPWA networks, WiFi, 802.15.4, BLE, UWB, and so on.

Depending on the specific application domain, more or less stringent QoS constraints will be required. In addition,

[1] https://www.osservatori.net/it/ricerche/comunicati-stampa/internet-of-things-italia-mercato

different devices and applications will ask for different QoS requirements. Hence, novel mechanisms for *joint allocation* of computing and network resources will be required. The heterogeneity of communication technologies will also require novel solutions for providing the required QoS on paths involving different network technologies and for automatic reconfiguration in case of faults.

III. Mobility

In the future Pervasive IoT many objects will be mobile, such as mobile robots, autonomous vehicles, sensors mounted rotating parts, wearable devices carried by people. Mobility introduces a new challenge in the QoS provisioning, especially in domains characterized by stringent QoS requirements. In such environments, joint computing-communication allocation strategies must take mobility into account. Hence, a *mobility-by-design* approach is necessary that allows (**i**) an optimal coverage of the area in terms of communication opportunity, (**ii**) an efficient management of mobility, in terms of computing/communication resource utilization, and (**iii**) a fast reconfiguration of allocated computing and communication resources.

IV. Cloud Integration and Joint resource management

The future cloud-to-things continuum environment will represent a challenge, in particular for managing both computing and networking resources in a scalable and efficient manner. Service provisioning and deployment, resource allocation and network configuration (e.g., routing and scheduling) and the integration of a large number of IoT devices, will require novel approaches to handle the extreme heterogeneity of the available computation, network resources and IoT devices, especially when critical applications, i.e., applications with stringent QoS requirements, are considered.

To this aim, novel joint cross-layer/cross-tier approaches will be required to manage different aspects of such infrastructure from service composition, orchestration, network and IoT management. Such holistic approach will allow to optimize the configuration of the infrastructure and to support proper reconfiguration in case of context or infrastructure status changes.

V. Sustainability

Sustainability will play a very relevant role in the future Pervasive IoT era. The very large number of deployed smart objects poses a number of challenges, mainly concerning (**i**) energy consumption, (**ii**) device management and disposal, and (**iii**) environmental impact. Although these challenges are not completely new, they are made more and more relevant by the increasing number of connected objects. Recently, battery-less solutions have been investigated for addressing the problem of energy consumption and environmental impact. Based on energy harvesting systems capable of scavenging energy from the external environment, battery-less solutions avoid the problem of recharging batteries and, in principle, allows and endless lifetime. On the other side, energy may not be available at any time and, hence, an intermittent computing paradigm must be considered when taking a battery-less approach.

VI. research Activities

The above-mentioned challenges are currently tackled by two collaborative research projects: the CAVIA and JOULE projects.

The CAVIA project ("enabling the Cloud-to-Autonomous-Vehicles continuum for future Industrial Applications") aims at paving the way for this novel approach by defining an ecosystem of solutions capable of enabling the next generation of the cloud-to-autonomous-vehicle continuum. Specifically, two main areas are covered: (**i**) network management solutions to ensure efficient data collection with mobility support for reliable and timed communication between AVs and the infrastructure; (**ii**) models and algorithms for service composition and deployment with reconfiguration of network and computing resource allocation with the aim to ensure efficient orchestration of management services in the cloud-to-vehicle continuum by considering service requirements in terms of latency and reliability.

The JOULE project ("JOint ResoUrce Management in ReconfigurabLE I4.0 Factories") aims to explore, model, design, and evaluate specific QoS management mechanisms and strategies for virtualized resources within industrial networked computing environments. This effort encompasses methodological, architectural, modeling, and evaluation tasks to create best practices, mechanisms, and simple prototypes tailored for reconfigurable Industry 4.0 factories. JOULE focuses on the dynamic allocation, deployment, and configuration of compute, storage, and networking resources according to the QoS requirements of individual applications, such as time and reliability. JOULE's research will address (**i**) unified models and abstractions for managing distributed and diverse virtualized resources, to ensure the QoS requirements, (**ii**) definition of advanced algorithms for the dynamic reallocation and reconfiguration of virtualized (containerized) resources, and (**iii**) orchestration of industrial support/service components to optimize the use of virtualized compute, storage, and networking resources.