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High-Capacity Ground-, Air-, and Space-based ICT Networks for Communications, Navigation, and Sensing Services in 2030

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Abstract

An integrated terrestrial-satellite system is proposed to provide the capabilities of communication, localization, and sensing for the innovative multidisciplinary services of the future pervasive Internet *Ecosystem.* They include services to enhance the quality of our everyday life as well as applications in critical situations and environments. Such a scenario requires the synergistic use of communication, localization, and sensing/monitoring techniques provided by a meshed heterogeneous architecture based on terrestrial and satellite segments to afford remarkable quality and performance to the future society based on the Internet of Things (IoT).

Keywords: Integrated terrestrial-satellite system, communications, localization, monitoring, sensing, cognitive networks, context awareness, internet of things.

4.1 Introduction

Recent technological and societal changes move our society toward a future where telecommunication platforms will be integrated with heterogeneous

Role of ICT for Multi-Disciplinary Applications in 2030, 77–94.

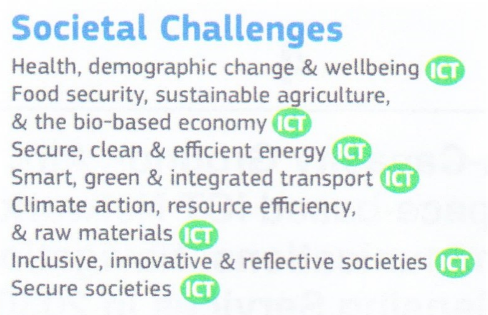

Figure 4.1 Guide on ICT-related activities in H2020 WP 2016-17.

Source: https://www.ideal-ist.eu/sites/default/files/Guide_to_ICT-related_activities_in_H2020WP2016-17_0.pdf

systems of localization and sensing capabilities, and intelligent objects will cooperate as in human social networks with the goal of providing multi-disciplinary services to the people and organizations at different levels of complexity, as foreseen in the paradigm of the Internet of Things (IoT) or even of the more challenging Internet of Everything (IoE). To achieve such a visionary scenario, each component has to be designed (and often redesigned) taking into account a remarkable level of generality and universality that characterizes the new system entities. New architectures and infrastructures have to be defined considering a plurality of services and applications with a low (ideally with no) reset effort. Such platform can support applications and services according to the objectives defined by the EU Horizon 2020 research and innovation program [1]. An interesting view of the possible ICT-related applications in societal challenges of everyday life of European citizens is shown in Figure 4.1.

The success of this strategy depends on a plurality of key factors that are briefly described in the following:

- The approach will have to be adopted for a very large set of possible future services, even if their requirements are rather diversified and even divergent;
- The proposed system will be characterized by distributed intelligence (sensing, learning, decision, and action), reconfigurability, adaptability, context awareness (physical, environmental, situational, and geographic), energy efficiency, and security; moreover, it will be able to exploit the benefits of clouds of users;

- The communications, both within the system and between the system and the external world, will have to be highly efficient and to deliver all the necessary information in due time, where needed, with required quality of service (QoS) and energy efficiency;

The reconfigurable heterogeneous infrastructure (the platform) that will be able to effectively cope with all these key issues will have to integrate localization and sensing/monitoring capabilities with terrestrial and satellite communication subsystems and intelligent objects and networks. As a result, the quality of life of the citizens and users will be improved in all scenarios of future IoE, such as for example but not limited to:

- Health, demographic change and wellbeing,
- Food security, sustainable agriculture, and bio-based economy,
- Secure, clean, and efficient energy,
- Smart, green, and integrated transport,
- Climate action, environment, resource efficiency, and raw materials,
- Europe in a changing world – Innovative, inclusive, and reflective societies,
- Secure societies – Protecting freedom and security of Europe and its citizens.

Moreover, the platform will be highly reconfigurable and adaptable to different application contexts: as an example, the system should be able to update the configuration parameter and the radio interface of a handheld device (e.g. a Smartphone) to provide the right information when and where needed.

This visionary objective demands the availability of a ubiquitous and flexible 5G infrastructure and of a complementary and seamlessly integrated terrestrial and satellite networks with very high capacity and great flexibility to meet the challenging requirements of the future Internet-of-Everything (IoE). In order to allow the implementation of such a system, the provision of a heterogeneous satellite-terrestrial architecture based on the paradigm of Software-Defined-Network/Network-Function-Virtualization (SDN/NFV) and the use of new Q/V and W bands for the satellite connections are an appropriate approach. The full reconfigurability of the heterogeneous network asks for frequency-agile transmission systems for capacity increase and defines the higher-layer network according to the new paradigms of access virtualization. This approach is in agreement with the recent trend of separation of the control plane from data transport in SDNs and with the progressive "softwarization" of all network layers, including the physical one. The migration toward NFV allows fine-grained definition of available services on a per-user basis, introducing new cross-tier interactions among information domains (user position, user context, user environment, etc.). Enabling NFV into satellite segment provides operators with suitable tools and interfaces in order to establish end-to-end fully operable virtualized satellite networks for third-party operators/service providers. SDN control center management is the flexible solution for non-proprietary adaptation to changing requirements and hardware products with ease upgradeability (in terms of both time and costs). The 5G terabit connectivity, achieved by integrating in seamless and cognitive manner 5G terrestrial and satellite network segments operating in the millimeter wave bandwidths, optimizes system resources and reduces the number of terrestrial hubs (whose development and management is the main system cost). The application of SDN/NFV paradigm to the HUB layer provides great benefit and simplifies the complex tasks to implement the Propagation Impairments Mitigation Techniques (PIMT) for the efficient use of EHF satellite links. "Smart gateways" (SGWs) are one of the most challenging PIMT, a spatial diversity scheme for the feeder link using a pool of synchronized GWs connected with terrestrial fiber network to route feeder link data traffic to counteract deep fades on one or more GWs. Virtualization technologies applied to the HUB layer will pave the way to an efficient implementation of these concepts for a "Virtual Smart Hub" where all resources will be virtualized.

We will propose a possible overall flexible system architecture for a high capacity ground-, air-, and space-based ICT networks for communications, navigation, and sensing services for future IoE.

This chapter is organized as follows. Section 4.2 is devoted to the description of the potential application scenarios of future integrated services and to the identification of the high-level requirements. Section 4.3 describes the flexible heterogeneous baseline architecture, highlighting the enabling technologies to support the provision of services for enhancing the quality of life. Section 4.4 presents some of the new paradigms and challenges for the development of advanced, highly reconfigurable, reliable, and secure systems. Finally, Section 4.5 concludes the chapter.

4.2 Toward Future Integrated Services

The objective of this section is to introduce future integrated services in some of the main ICT application sectors: starting from an overview of potential scenarios, the general requirements for the definition of a baseline system architecture are identified.

4.2.1 Potential Scenarios

A brief description of future potential integrated services is provided, focusing on the following application contexts:

- E-Health and Well-being,
- Public Safety,
- Mobility for Smart Cities,
- Entertainment.

4.2.1.1 e-Health and well-being

The main trend in the e-health sector is to empower patients in the management of their health, reducing the cost of medical assistance as well as coping with the increase in chronic diseases and the aging population. Smart devices with increased processing power, wearable technology, biosensors, and implantable devices combined with health application tools will enable the monitoring of a patient health status, remote diagnosis, and the self-control of chronic diseases. Anytime and everywhere (at home, in the hospital, in a rehabilitation structure, during a travel, outdoor, etc.), patient vital parameters can be monitored by smart objects interconnected with a medical assistance center. The user-transparent interactions among smart objects and the information exchange among the different entities (patient, doctors, family members) integrated with context-awareness (localization data) allow the provisioning of services ranging from well-being to chronic disease and emergency management.

Patients and caregivers (including specialists) are all part of a universal healthcare system: the former will be more responsible for their own health thanks to the active involvement in the management of their treatment and care, while the latter will act as a coordinator of treatment for patients. The processing of the collected data will automatically manage patients and request for specialist intervention as needed. Moreover, all the collected data will be used for the clinical studies, helping decision making and diagnosis.

4.2.1.2 Public safety

The development of new integrated system, including environmental monitoring, data transmission over satellite and terrestrial links, localization services based on advanced solutions for user-tracking, and innovative mechanisms for secure data exchange over wireless links, is leading rescue or safety team to adopt these technologies for guaranteeing public safety and security. In such a context, each user represents the destination of the alerting messages and the source of data coming from the interactions between the wearable/handled smart devices and the overall network and which transparently increase the contextual awareness of a particular event. In the next future, in order to help first responders to operate in critical contexts and to be guided by remote assistants (coordinator and control center), the transmission of the perceived reality (e.g. smell of burning substances, floor vibrations, etc.) will be one of the pursued innovative features, oriented to the achievement of an augmented reality.

4.2.1.3 Mobility for smart city

Environmental monitoring through roadside objects, traffic information based on a selected path in the navigator, establishment of relationships among the cars for useful information sharing (traffic, parking, accidents, etc.), and the trend of automated transport (self-driving cars) are some of the elements that will be part of the future system for mobility. Automotive manufacturers aim at the concept of a "connected vehicle" whose functions rely on underlying smart systems and networks for the information exchange, data analysis, and context aware solutions identification.

4.2.1.4 Entertainment and culture

Focusing on culture and entertainment contexts, and in particular, on the augmented reality technology in museums, the main trend is to interactively guide the visitor to a personalized cultural heritage experience through socio-personal interactions methodologies supported by multiple technologies. In the future, the possibility to recreate a full sensorial experience for a more effective perception of the artworks is foreseen thanks to the transmission of perceptions of all the five senses of a subject.

4.2.2 Requirements for Integrated Communications, Navigation, and Sensing Services

As highlighted in the description of the aforementioned scenarios, the seamless integration of the communication, navigation, and sensing features is one of the main objectives to be pursued for the development of advanced services.

The aim of this section is to identify a set of high-level requirements to be considered for the provisioning of such services. In details, due to the large variety of application contexts and the specific requirements for each service, the focus is on the definition of the general requirements for the design of a baseline architecture able to support a multiple services platform.

Aiming at translating the main users' needs to access the requested services into system requirements, the following features shall be considered:

- *Integration of heterogeneous technologies.* Existing technologies and systems shall be part of future architectures. User transparent integration of legacy and advanced systems is required for the exploitation of the different and complementary capabilities of each system and therefore for the development of personalized services based on user's specific needs.
- *Flexibility and scalability.* Future architectures shall be able to efficiently respond to unexpected events, which may affect the provisioning of services. Flexibility allows the system to self-adapt to the temporary context conditions in terms of network resources availability and environmental changes of specific location. Scalability can be seen as the system flexibility of the size of the users to be served.
- *Availability and reliability.* The users' increasing dependence on the ICT services asks for an always available network regardless of the user location. This allows users to access the desired data anytime and anywhere. Moreover, the continuous exchange of information and the big amount of data to be stored and processed in the cloud requires high reliable networks.
- *Reconfigurability.* The trend of providing highly customized services and the heterogeneity of the availability of network resources for the delivery of services (essentially based on the user location) requires the design of a high reconfigurable system. Reconfigurability shall be considered in terms of network resources allocation, network nodes functions, network access technologies usage, etc.
- *Security and Resilience.* Satisfying the user's mobility need means operating in an open access environment. Since multiple threats characterize the open wireless channel, the future architecture shall provide high security mechanisms for data transmission, distributed storage, and distributed access to personal data.

Future architectures shall be able to meet all the previous high-level requirements through the adoption of different technologies based on the specific service needs (e.g. 5G systems for high capacity networks, satellite communication for global coverage, higher availability, delay tolerant services, etc.). Moreover, the introduction of new paradigms (Software Defined Networking, Network Functions Virtualization, Cognition, Social Networking, Human

Bond Communications) in the design of the advanced systems will allow the development of innovative integrated services (Section 4.4).

4.3 Baseline System Architecture and Enabling Technologies

4.3.1 Baseline Architecture

As a matter of facts, the provision of innovative ICT services in the scenarios which have been described previously requires the integration of telecommunication entities and heterogeneous system architectures with localization and sensing capabilities and in which people and intelligent objects will cooperate as in social networks [2]. As a result, a pervasive communication *Ecosystem* is likely to be realized in the near future. In order to understand the features of the future heterogeneous networks, it is worth discussing the archetypical architecture, which is thoroughly described in Del Re et al. [2] (Figure 4.2).

In order to support the development of new advanced services also exploiting the multiple combination of the existing ones, the proposed system architecture is based on the integration of the aforementioned functionalities: localization, communication, and sensing/monitoring [3]. This flexible, scalable, and reliable heterogeneous architecture includes the satellite component as a key element. Satellite GNSS, communication, and monitoring systems are all parts of the proposed architecture together with different terrestrial components. This meshed architecture enables the cooperation among satellite systems and terrestrial ones with the goal to benefit from the capabilities of each system. In particular, the capabilities of each single subsystem can be improved by the exploitation of the features of the other ones, also in critical contexts. Moreover, a full interoperable architecture will be enabled by the distributed system intelligence and by suitable interfaces.

Even if the integration of services is currently possible only at client level (i.e. smart-phones, car computers, navigation devices) with a heavy limitation of the potentials of the services, a deeper level of integration will be afforded in the near future, also of the satellite component, so allowing to move services over networks, rather than moving clients over services and with a deeper level of integration. This objective could be afforded by the resorting to the separation of the control plane from data transport as in Software Defined Networks (SDN).

Nonetheless, since the implementation of applications is currently bound to the available access technology for each specific context, in the following

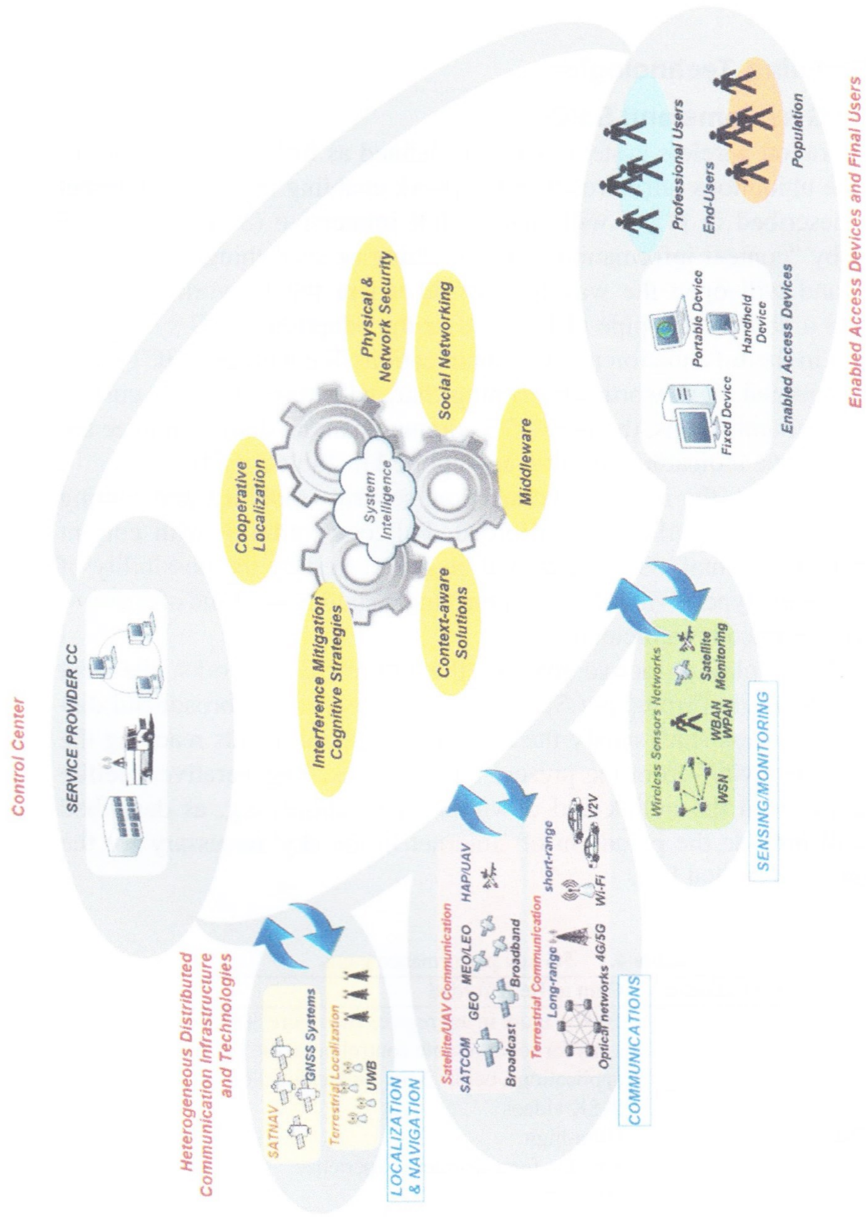

Figure 4.2 Baseline architecture proposed in Del Re et al. [2].