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Towards truly sustainable IoT systems: the SUPERIOT project

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Abstract

This paper provides an overview of the SUPERIOT project, an EU SNS JU (Smart Networks and Services Joint Undertaking) initiative focused on developing truly sustainable IoT systems. The SUPERIOT concept is based on a unique holistic approach to sustainability, proactively developing sustainable solutions considering the design, implementation, usage and disposal/reuse stages. The concept exploits radio and optical technologies to provide dual-mode wireless connectivity and dual-mode energy harvesting as well as dual-mode IoT node positioning. The implementation of the IoT nodes or devices will maximize the use of sustainable printed electronics technologies, including printed components, conductive inks and substrates. The paper describes the SUPERIOT concept, covering the key technical approaches to be used, promising scenarios and applications, project goals and demonstrators which will be developed to the proof-of-concept stage. In addition, the paper briefly discusses some important visions on how this technology may be further developed in the future.

1. Introduction

Wireless and mobile communications have become the pillars of our connected world. These technologies derive from the 1990's concept of the integrated network of software and hardware elements that communicate over radio waves and infrared [1, 2]. Over the last few decades, a great array of technologies has been developed to provide untethered connectivity. Mobile communications were initially developed to provide personal communications, and today there are more than seven billion mobile services subscribers around the world. In recent years, there has been a growing interest in providing connectivity to entities other than users, such as computers, machines, and vehicles. The ultimate connectivity frontier is defined by the paradigm of the Internet of Things (IoT), aimed at connecting virtually any object. The name IoT itself began to be used in published works from the 2000s [3, 4], and it can now be seen as the final connectivity challenge, as billions and even up to trillions of entities could be connected, creating a huge new global market [5]. Today, there is a vast literature available on IoT focusing on technologies and applications. The role of IoT as a key enabling technology in current 5G and future 6G is discussed in recent publications

[6, 7]. Moreover, the importance of developing a green IoT is considered in [8], particularly from an energy efficiency standpoint. Most of the research on IoT has been carried our assuming wireless connectivity based on radio communications. However, ideas for wirelessly connecting sensors through optical communications have been considered in the past, as in the concept of smart dust [9]. In recent years, interest in light-based IoT has been growing, and one of the reasons for this is the prospect of reusing the solid-state illumination infrastructure [10, 11]. Radio- and light-based wireless connectivity are both attractive for IoT, and in fact, these two technologies are highly complementary. Lately, there has been a growing interest in hybrid optical-radio networks, aimed at combining their advantages to create highly capable and flexible wireless communication systems, as discussed in [12, 13].

Today, IoT research is yielding applications which are more sophisticated [14], lower power [15], and increasingly common [16]. The impact of IoT has been widely studied over the last decade, and the need for this technology to be sustainable has been clearly stressed. The World Economic Forum has identified IoT as a key technology to accelerate progress towards the sustainable development goals (SDGs) [17]. The roles of IoT and other technologies as solutions for climate change and their possible drawbacks have been recently discussed in [18].

However, IoT *itself* needs to be a sustainable technology. The requirements for sustainability become evident when one considers the degree of massiveness expected for IoT, for instance, the resources required to manufacture billions of IoT devices (e.g. energy, materials, etc.) and the fate of these devices after the end of their operative lives. The SUPERIOT project (pronounced 'super IoT'; Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies) will address the sustainability challenges of IoT systems by developing an IoT communications system that is sustainable in a wide sense, considering sustainability in a holistic manner. This paper provides an overview of this research initiative, which is aligned with recent EU sustainability policies and sustainable design-related directives. In fact, the EU has championed ecological design for sustainable products with the introduction of the Ecodesign Directives [19, 20] and the proposed ecodesign for sustainable products regulation as the cornerstone to more environmentally sustainable and circular products [21]. The development of a truly sustainable communications system requires the consideration of several aspects at the design and implementation levels. Sustainable design encompasses design for low and efficient energy usage, design for long life, design for recycling, design for upgrading, modular design, design for flexibility and adaptability, design for scalability and others [22]. The SUPERIOT concept considers dual-mode (optical-radio) wireless communications, as described in [12, 13], but applied to IoT systems. The concept also defines energy autonomous IoT nodes that harvest energy from the environment, as in the green IoT approach discussed in [8]. In this case, energy is harvested from the available optical and radio sources. IoT positioning using radio and optical signals is discussed in [23] and [24], respectively. The SUPERIOT project will consider both optical and radio signals for positioning of the IoT devices.

The key contributions of the paper are (a) the introduction of a holistic approach to sustainability and its application to the project, (b) a novel concept by which light and radio waves are used for wireless connectivity, energy harvesting and localization purposes in a reconfigurable IoT system, and (c) the use of printed electronics (PE) as a key sustainable technology for the implementation of the IoT nodes.

This paper is organized as follows: section 2 briefly describes the relationship between wireless communications systems and sustainability, section 3 describes the holistic approach to sustainability followed by the SUPERIOT project. An overview of the project is presented in section 4, including the descriptions of the concept, PE technologies, and energy harvesting methodologies as well as the project goals and demonstrators. Section 5 presents the project visions, and section 6 concludes the paper.

2. Wireless communications systems and sustainability

A wireless communications system, in the context of information and communications technology (ICT), is part of a connectivity infrastructure supporting a sustainable world, which has social, economic and environmental aspects. On the other hand, the wireless communications system itself as a whole needs to be a sustainable solution. As has been identified in recent studies, great interest is being shown by society and regulators, as well as an increasing level of commitment by manufacturers, towards the development of sustainable mobile and wireless communications networks [25, 26]. Consequently, sustainability plays a key role in the context of the current developments in 6G [27]. As 6G technology is currently being developed, the research community and industry are committed to creating wireless communications systems that are not only capable of fulfilling the requirements of different 6G services and applications, but also to use resources in a conscious manner. The sustainable provision of wireless services is one of the goals of 6 G, and a key objective of the SUPERIOT project, in the context of IoT communications.

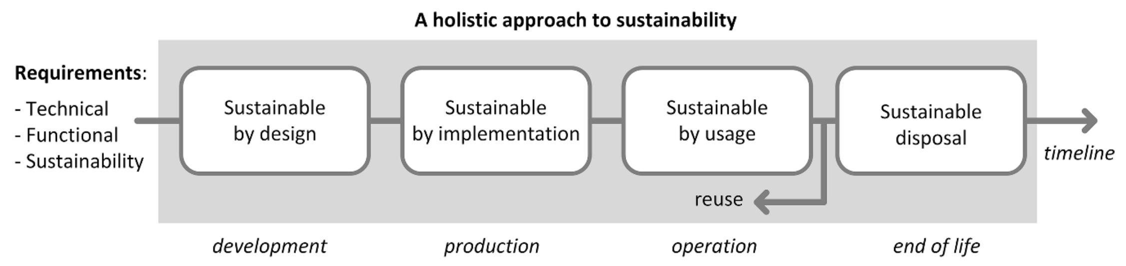

Figure 1. The holistic approach to sustainability followed by the SUPERIOT project.

3. A holistic approach to wireless communications systems

The project will exploit a unique holistic approach to sustainability, considering each of the main life stages of a wireless communications system, from conception to the end of its useful life. Figure 1 illustrates this holistic approach, where sustainability aspects are considered at the development, production, operation and end-of-life of a wireless communications system. IoT systems, typically characterized by low to moderate performance requirements and relatively simple implementation, are very well suited for this development method. Associated with the aforementioned four life stages, SUPERIOT will advocate the use of the rules: (1) sustainable by design, (2) sustainable by implementation, (3) sustainable by usage, and (4) sustainable disposal/reuse, as shown in figure 1. Creating a truly sustainable IoT system is the main driving force behind the SUPERIOT project.

The need for the creation of sustainable wireless communication systems has been widely identified and discussed over the last two decades. The concept of green communication networks was extensively studied during the last decade [28, 29]. In general, techniques for more efficient use of radio resources, particularly with respect to energy, were heavily investigated under this concept. This includes an array of highly relevant techniques described in the vast available literature, including energy aware protocols, low power solutions, energy autonomous systems, energy-aware hardware design, low energy operating modes, renewable energy usage, and many others. Other aspects of green communications have been also considered, but with much less weight, such as the carbon footprint impact of these systems, as studied in [30]. More recently, there has been a growing interest in developing sustainable IoT systems. However, sustainability is mostly approached from energy considerations [31, 32]. A study of sustainable IoT devices was recently presented, where sustainable manufacturing and recycling as well as green materials for device implementation were considered [33]. A life cycle assessment (LCA) of the proposed SUPERIOT concept will be carried out as a part of the project. This is a complex task, particularly when considering the multiple aspects of the problem. An example of an LCA for a mobile phone is presented in [34]. In this project, the term 'truly sustainable' is used to emphasize the wide and holistic approach to sustainability, accounting for both energy and sustainable production and disposal aspects discussed above, and even going beyond them to incorporate other aspects, such as those related to societal and economic sustainability.

4. The SUPERIOT project: an overview

This section provides a general description of the SUPERIOT project, including the concept to be developed, PE technologies, the key goals of the project, scenarios and applications, and an overview of the project demonstrators.

4.1. The SUPERIOT concept

The SUPERIOT concept is based on the dual-use of light and radio technologies to create a reconfigurable IoT system that is highly flexible and adaptable, harnessing the advantages of these two very different spectral regions. In principle, the system can be used in a variety of scenarios and applications, including dynamic environments, e.g. fluctuating channel conditions, mobility, changes in requirements, security level, etc. Wireless connectivity will be provided by radio and optical communications, and the selection of the most suitable transmission technology will be decided based on the type of application and its functional and non-functional requirements, network availability, usage policies, user/service provider decisions, resource usage, etc. In some cases, the two technologies may be used in parallel, complementing each other. The IoT nodes will be designed as zero-energy devices, i.e. batteryless, whereby all the energy needed to operate the nodes will be determined using energy modeling and analysis techniques [35] so that the right amount of

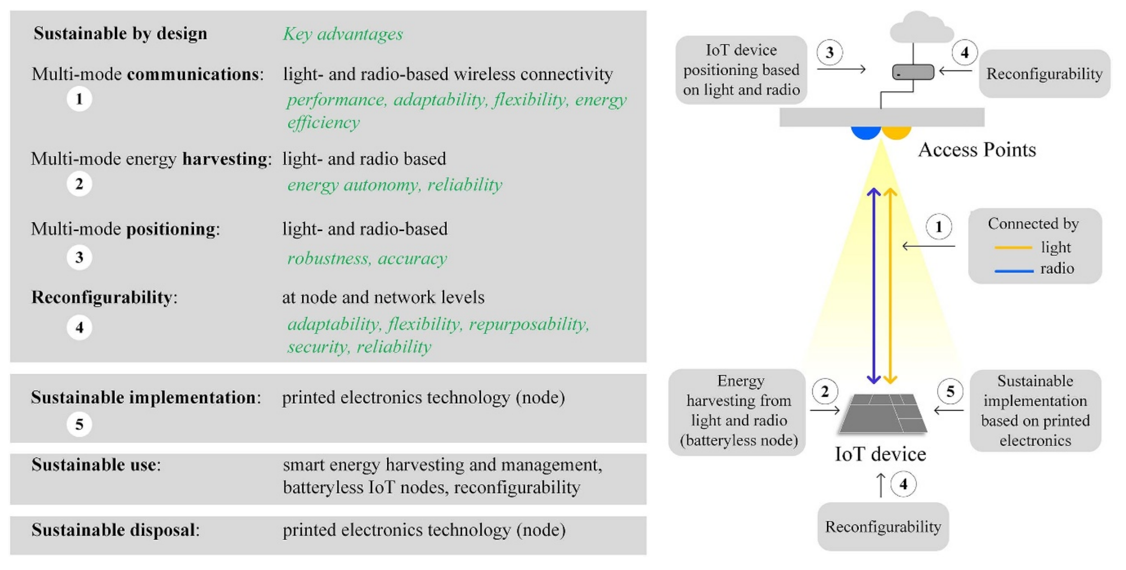

Figure 2. The SUPERIOT concept in a nutshell.

energy can be harvested from the light and radio sources and stored in the node. Light and radio signals will also be exploited to provide robust and accurate positioning services. Sustainable PE technology will be used as much as possible in the implementation of the IoT nodes. Connectivity-, energy harvesting-, and implementation-wise, the concept to be developed is an extension of the light-based IoT system presented in [36], but now considering both optical and radio signals. Figure 2 summarizes the SUPERIOT concept, highlighting some of the advantages of the joint exploitation of light and radio technologies. Reconfigurability at node and network levels is an essential characteristic of the concept.

Referring to the holistic sustainability methodology of figure 1, the following list provides some examples of technical aspects or solutions to be taken into account at different stages in SUPERIOT:

(1) **Sustainable by design:** (a) system adaptability and flexibility by reconfigurability and modularity, based on the use of radio- and light-based connectivity, (b) energy-efficient modulation schemes, (c) optimized resource allocation mechanisms, (d) energy-efficient media access (MAC) protocols, (e) wireless energy transfer from light and radio harvesting, (f) smart/sustainable optical-radio network selection, (g) reuse of lighting infrastructure for optical communications, (h) wake-up techniques, etc.
(2) **Sustainable by implementation:** (a) IoT node designed to be implemented maximizing the use of energy- and material-efficient sustainable PE technologies based on sustainable materials [37, 38] and ecodesign to achieve more environmentally friendly products, (b) use of very low power solutions (e.g. microcontrollers, wireless communication), etc.
(3) **Sustainability by usage:** (a) zero-energy (batteryless) IoT nodes with maintenance-free operation, (b) remote reconfigurability, modifiability, updatability, etc.
(4) **Sustainable end-of-life management:** (a) use of PE results in circular economy-compatible devices (repair, reuse, repurpose etc.) through the use of circular and modular designs instead of contributing to electronic waste, (b) sustainable recycling through the use of recyclable and sustainable materials [38], (c) repurposeability (cradle-to-cradle approach).

4.2. PE technology

An important and novel aspect of SUPERIOT is the use of sustainable technologies for the implementation of reconfigurable IoT nodes, and a key goal of the project is to demonstrate and maximize the use of PE technologies. These can offer an environmentally friendly solution for manufacturing as they only produce low amounts of waste and can be based on safe, bio-based, renewable and abundant materials. These are enabled by additive printing processes, which help to avoid subtractive processes such as etching with toxic chemicals. Moreover, PE technologies can also help to avoid unnecessary use of energy and cost-intensive controlled environments, such as clean rooms, and complicated and expensive processes usually demanded by more conventional production methods (e.g. photo-lithography and vacuum deposition). In short, PE is based on the deposition of inks with different electronic functions, and on substrates using various printing technologies, such as inkjet, gravure, flexography, and screen printing. Post-processing such as drying and annealing is used to create multilayer structures directly on flexible substrates that act as a variety of passive and active components, sensors and actuators. The sustainable manufacturing methods of PE technology can allow cost reductions of more than 60% when compared with conventional electronic manufacturing methods [37]. As highlighted in [36–39], sustainability is related to many aspects of a product, including energy- and material-efficient manufacturing, use of materials from renewable sources, use of environmentally friendly materials, ecological design, use phase benefits, as well as support for recycling, reusing and repairing, among others.

Despite the fact that PE has advanced notably in the last decade and today a great range of components and even complete systems can be implemented with printed technologies, the current state-of-the-art of PE technology is not mature enough to allow the implementation of a fully-fledged IoT node as defined in the SUPERIOT concept, e.g. due to limited resolution and alignment accuracy, device yield and consistency. In general, printed components are characterized by a modest performance, compared with conventional silicon-based counterparts. In addition, they may suffer from stability, reliability, and repeatability problems [40–42], resulting in challenges when designing circuits for IoT devices. Furthermore, the achievable integration level today is much lower than that of conventional electronics. The project also faces a challenge related to the availability of PE components. Even though the project will develop some of the required PE components, not all promising printed components are commercially available. The dual-mode optical-radio concept poses challenges for a PE-based implementation, as the optical and radio chains would likely be based on different circuit solutions, and the availability of suitable components for both implementations could be limited. Because of the aforementioned issues, the project will employ a hybrid electronics approach combining state-of-the-art PE and silicon-based technologies (e.g. integrated circuits). It is envisaged that the following components based on PE could be used in SUPERIOT: printed photovoltaic cells, printed displays, antennas, supercapacitors, circuits based on thin-film transistors (TFTs), non-linear devices (e.g. memristors, diodes) and sensor components (e.g. photodiodes). As the materials, the ink formulations and the printed components further develop and their integration densities increase, the systems will become even more sustainable. Moreover, the development of biodegradable and compostable electronics will have a further impact on sustainability when other circularity schemes are not feasible. SUPERIOT will evaluate the sustainability of the proposed PE technology using LCA tools [43]. In the long term, PE will reach a high degree of maturity; thus, it is expected that in the 6G era advanced IoT nodes will be fully printed, resulting in a truly disruptive solution.

4.3. Project goals

The main goal of SUPERIOT is to develop, demonstrate and advocate the concept of truly sustainable wireless communications systems, in particular, IoT systems. To accomplish this goal, the project will focus on the following technical targets: (a) demonstrate that dual-mode (light-radio) IoT communication is not only feasible but brings multiple unique advantages in performance, flexibility and adaptability; (b) demonstrate the efficiency of dual-mode energy harvesting and its suitability for the concept; (c) demonstrate dual-mode IoT node positioning; (d) demonstrate that PE is a key technology to implement sustainable IoT nodes, and finally, (e) create several demonstrators in which the concept will be validated for selected practical applications. Ultimately, SUPERIOT aims to serve as a motivating example demonstrating that wireless communications systems can be developed to be sustainable in a wide sense, i.e. beyond simply energy-related issues.

4.4. Scenarios and applications

SUPERIOT will identify a number of promising scenarios and associated applications to be used as references in the project. These will also define the technical and functional requirements of the IoT system to be developed. Three main scenarios suitable for the concept have already been defined, namely: (a) smart tags and labels for traceability and condition monitoring; (b) massive sensing and actuation; and (c) enhanced IoT communications in demanding environments. In the initial phase of the project, a few key applications will be considered, from which detailed requirements will be determined. These applications will be used as the reference for the development of the project demonstrators.

4.5. Project demonstrators

In the final phase of the project, four demonstrators will be implemented as proofs-of-concept of the developed technologies. Figure 3 depicts the key characteristics of the demonstrators. Demonstrator 1 will show the operation of a small form factor reconfigurable IoT node with all features defined in the SUPERIOT concept. In this case, the node will be implemented with hybrid technologies (a combination of printed- and silicon-based sub-systems). Demonstrator 2 will visualize the operation of a reconfigurable IoT network, particularly designed for medical ICT scenarios, where different resources distributed across a healthcare

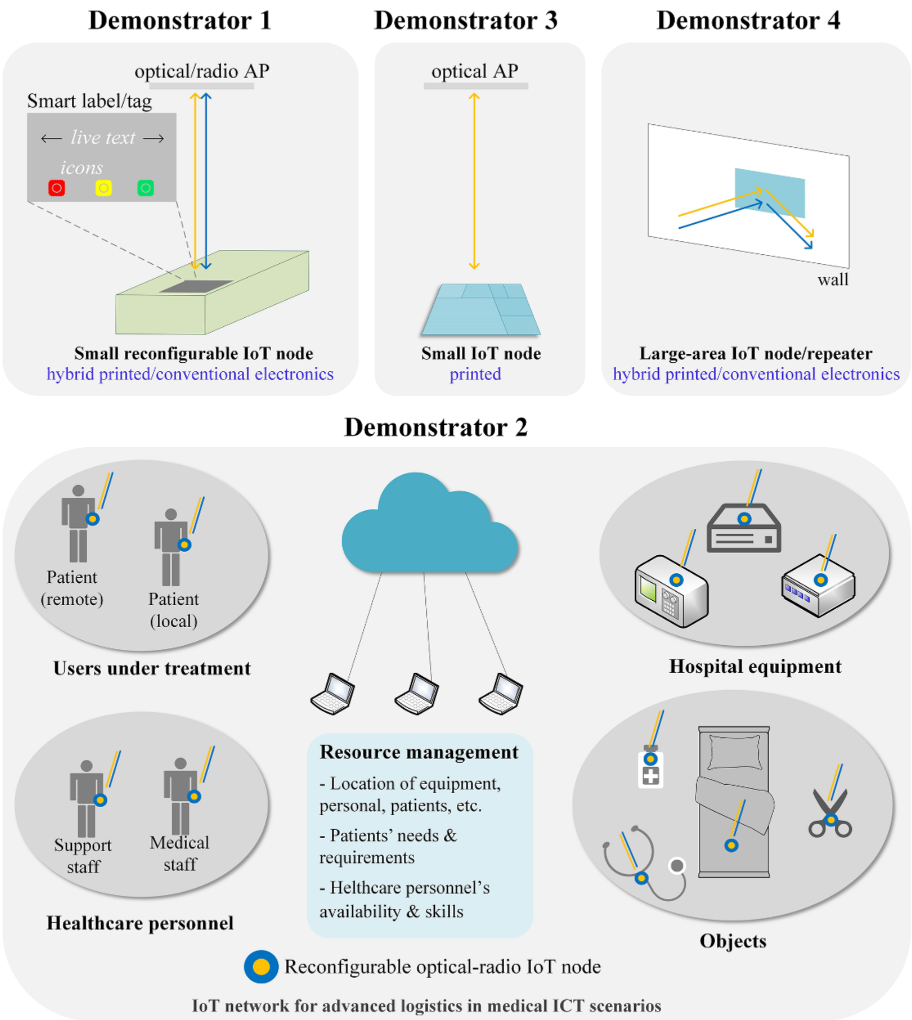

Figure 3. The four SUPERIOT demonstrators: (1) small reconfigurable IoT node; (2) IoT network for advanced logistics in medical ICT scenarios; (3) small IoT node and (4) large-area IoT node/repeater.

environment will be connected and managed. Demonstrator 3 will illustrate the implementation of a small form factor, very simple and reduced capability IoT node that is implemented with printed technologies only. Demonstrator 4 will focus on a large area implementation of a system supporting IoT communications, including such functions such as IoT nodes, repeaters and reconfigurable intelligent surfaces.

5. Project visions

SUPERIOT will develop a future-proof wireless concept, accelerating the development of sustainable communications systems where radio and optical communications will be combined based on the application and its requirements. PE is a fundamental enabling technology supporting the implementation of IoT nodes. The project will maximize the use of printed technologies, using state-of-the-art printed components, sustainable inks and substrates to implement the IoT devices. As a long-term vision, following advances in PE technologies, it is expected that a greater variety of printed components will become available, with better performance, extended operational life, and increased levels of integration. Such developments will pave the way to a myriad of novel applications resulting from the low cost, sustainable nature and high flexibility of a printed IoT node.

In the long-term, the project envisions the emergence of sticker-like energy-autonomous, highly capable IoT devices that can be based on PE technologies only. This will result in extremely low cost IoT solutions, making this technology attractive for widespread use. The development of electronics suitable for the circular economy, including compostable solutions, will make it possible that future IoT node disposal can be achieved in a truly environmentally friendly manner compatible with circular economy goals. Moreover, the prospect of such truly sustainable and very low cost IoT connectivity solutions will support the development of applications focused on massive sensing and actuation without major environmental concerns.

Applications in biodiversity and natural resources monitoring, agriculture, smart cities, industry, smart packaging and logistics are possible examples. Also, demanding communications scenarios such as underwater, in-body and mining could also benefit from this sustainable connectivity solution.

When considering the forecasted volumes for IoT technology [5], one cannot ignore the real environmental cost of manufacturing and eventually disposing of the billions of IoT devices needed in the future. The concepts proposed by the SUPERIOT project offer a realistic and impactful solution that is sustainable in a wide sense. The overall large-scale environmental impact of an IoT solution based on energy-autonomous nodes that are fully printed is expected to be huge. As PE technology further develops, IoT devices as well as many other connectivity, processing, sensing and actuation functionalities, will be embedded and distributed in the environment. The project outcomes can be seen as the initial steps towards a much more ambitious goal, namely the concept of living surfaces [10], i.e. the empowering of the surfaces around us with sustainably implemented functionalities to make our environments more efficient and our lives more pleasant.

6. Conclusion

This paper overviewed the SUPERIOT project, an EU initiative focused on developing a truly sustainable IoT communications system. The concept is based on the use of radio and optical technologies to create a flexible and adaptable reconfigurable IoT system. The IoT system exploits both radio and light to provide wireless connectivity, energy harvesting and positioning, resulting in a sustainable IoT solution based on PE technology that can be configured for use in different scenarios and applications, capable of adapting to the varying dynamics of the environment and responding to changing requirements. Following the holistic approach to sustainability considered by the project, PE technologies will be employed in the implementation of the reconfigurable IoT nodes and their sustainability will be evaluated through LCA. The paper also briefly discussed the key enabling technologies, goals, scenarios and applications, and project demonstrators. Finally, the paper shed some light on possible developments, novel uses and the future outlook. The fundamental goal of the SUPERIOT project is to demonstrate that wireless communications systems can be sustainable in a wide sense if proactively designed following a holistic sustainability methodology. This approach will pave the way to the development of truly sustainable and low cost wireless communications systems.

Data availability statement

No new data were created or analysed in this study.

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