# Ubiquitous Computing and Multi-agent Systems: Clarification of the Lexicon

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**Abstract.** Ambient computing and Internet of Things have reached a level of maturity and a dynamic activity of research and engineering actors. Their goal is to create interactions between a set of distributed devices in an environment, in order to assist human activities. Multi-agent system is an interesting tool for coordinating devices and services for this purpose, because of its adaptation, autonomy and decentralized specifications. However, it is sometimes difficult to understand and share the same idea when it comes to terms such as "Ubiquitous Computing," "Ambient Computing" or the "Internet of Things." As a result, it can be really difficult to browse the literature through research engines and to make a bibliographical study without missing important papers.
That is why we want to address this first problem by means of a glossary proposal, synthesizing and unifying the extensively cited definitions of the lexicon belonging to these domains. After this necessary step of clarification, we present usability and interest of multi-agent approach in the service of ubiquitous computing.

**Keywords:** Ambient Agents · Ubiquitous Computing · Multi-Agent Systems · Scientific Lexicon · Internet of Things .

## 1 Introduction

The democratization of devices with computational capabilities and their miniaturization have allowed the various actors of the research to imagine environments where such a set of devices, defined as "intelligent", would assist mankind in everyday life, in the most natural and intuitive way. The use of computers therefore go from a personal computer, used individually and exclusively, to the use of a multitude of devices that enroll the user in a transparent consumption of computing devices. We are talking about *ubiquitous computing*.

This strong dynamic has allowed the emergence of many applied solutions. MediaCups [1], the first connected cups, or more contemporary smartphones can be referred as examples among these. From such enthusiasm also results in the appearance of a large number of articles dealing with fields related to ubiquitous computing, such as robotics, home assistance or the study of human-machine interactions.

This is why section 2 of this article deals with the state of the art of the lexicon, sometimes inconstant, that we draw on this domain. Then, section 3 exposes a proposal for a glossary containing the main terms of the domain terminology.

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From that lexicon, we show the relationship between multi-agent system and ambient intelligence in section 4. Finally, section 5 consists of a conclusion of the work presented and proposals of raised prospects.

In addition, you can notice that we use the term "computer" to talk about any device with computational capabilities, such as a smartphone, a tablet, a laptop, etc.

Moreover, the state of the art, which is the subject of the next section, was constructed from a non-exhaustive selection of articles. To select them, we simply based on their referencing on the website *Google Scholar*.

## 2 State of the art of ubiquitous computing

### 2.1 From ubiquitous computing

In [2], Mark Weiser describes ubiquitous computing as the idea of integrating computers into everyday physical objects. He opposes this idea to the notion of "virtual reality," which places the user in an entirely virtual representation built by the computer. Whereas "augmented reality" can be seen as an intermediate stage where virtual representations enrich the real world. Later, Mark Weiser will point out that ubiquitous computing is a future world where users interact, in an invisible way, with a multitude of interconnected computers [6].

This idea is echoed by Lyytinen and Youngjin [4], who tell that "next step in this evolution involves the move toward ubiquitous computing, in which computers will be embedded in our natural movements and interactions with our environments." This vision of ubiquitous computing evokes here the fact of the evolution of a situation in time, and therefore a new state of computing to reach.

Later in 2010, Krumm [3] described ubiquitous computing as "the third era" of computing. This era, which represents the era in which we find ourselves, is characterized by the explosion of the use of embedded connected computers (such as smartphones) and thus by the use of several computers per person. The terms "Ubiquitous Computing" and "Pervasive Computing" are equivalent according to [3]. From this vision, it is possible to represent this era as we do on figure 1.

On figure 1, the first era depicts the birth of computers and begins in the 40s . Those mainframe computers, as the *Z1* created by Konrad Zuse or the *Atanasoff-Berry Computer*, were mainframe computers owned by an organization and shared by many users. The second era corresponds to the democratization of personal computers and starts in the 70s, with the first commercialization of personal computers based on transistors. Finally, the last era would be the era in which we find ourselves. This is an era where we all own and use a multitude of interconnected computers, like laptops, tablets, smart watches or smartphones.

In [5], for the author "ubiquitous computing" described an information system to access information or to perform tasks anywhere. This system offers an

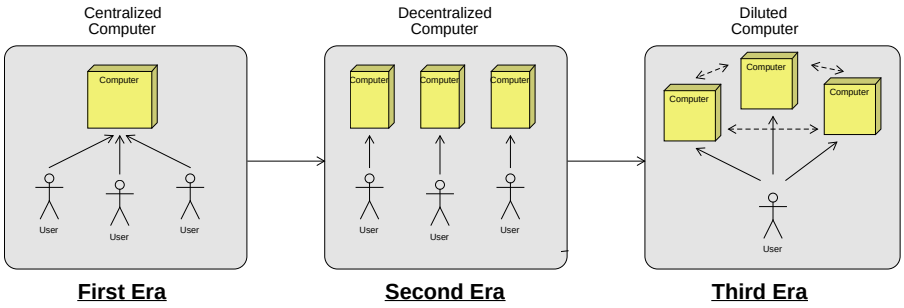


**Fig. 1.** Diagram of different eras of computing defined by Krumm [3]

intuitive use that seems invisible to the user. He defines several criteria for a system to be part of ubiquitous computing:

1. Computers need to be networked, distributed and transparently accessible.
2. Human-computer interaction needs to be hidden more.
3. Computers need to be context-aware in order to optimize their operation in their environment.
4. Computers can operate autonomously, without human intervention, be self-governed, in contrast to pure human-computer interaction.
5. Computers can handle a multiplicity of dynamic actions and interactions, governed by intelligent decision-making and intelligent organizational interaction.

These criteria would make a ubiquitous system that can operate intelligently based on interactions and organization. This is a conceptualization that we find interesting, but which we will return to in next section 2.2, dealing with ambient intelligence.

Indeed, we find that definitions, although they share a common idea, may slightly differ in terms of typologies. The authors lasts cited speaks of an information system, we propose to use the definitions of Krumm and that of Lyytien and Youngjin defining *Ubiquitous Computing* as a period or an era.
However, despite the explosion of the number of computing devices and the fact that we currently use a multitude of these devices (smartphone, laptop, tablet, etc.), remains the fact that our interactions with them are explicit and can not be defined as "invisible." This is why we propose to complete Krumm's [3] vision by distinguishing two phases, as shown in figure 2.
The first phase is transitory, where each user uses a multitude of computers by means of conventional Human-Computer interfaces. This is the era in which we find ourselves and is manifested by the many personal laptops, tablets or smartphones that we use daily through keyboard, mouse or touch screens.
In the second phase, the user utilizes his everyday objects, which have been endowed with computational abilities. However this makes the Human-Computer interactions "hidden." By way of an example, we can imagine that if a user falls

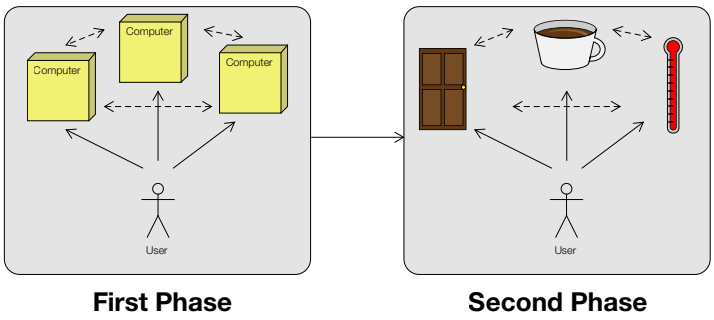


**Fig. 2.** Diagram of the phases of the third era described by Krumm [3]

asleep in his bed, the computer system present in his house will turn off all lights and adjust the temperature of his room consequently. This is the era to which we are moving toward.

That is why we propose to define ubiquitous computing as :

**Ubiquitous Computing :**
**An era in which the democratization and miniaturization of computers make it possible to offer users a distributed, intuitive and possibly invisible use of computers.**

The terms "ubiquitous computing", "pervasive computing" and "diffuse computing" are equivalent.

### 2.2 To Ambient Intelligence

Before studying ambient intelligence, we propose to define what intelligence is. Thus, according to [7], intelligence is the fact to perform rational actions, that is to say, which aims to maximize a performance measure, based on evidence acquired during a perception and a priori integrated knowledge.

According to N. Olson and Al. [8], the concept of ambient intelligence was initiated at a conference organized by the research teams of Philips. Ambient intelligence has been described as the enrichment of an environment by technology (sensors, processors, actuators, etc.) in order to build a system for capturing and processing data, and for making decisions, to the benefit of users in this environment.

On another side, the authors of [14] declared that Ambient intelligence "deals with a new world of ubiquitous computing devices, where physical environments interact intelligently and unobtrusively with people." This proclaim is interesting because it is intuitive, but highlights the link between the term ubiquitous computing previously studied, and introduces the notion of intelligent or smart physical environment in interaction with users.

In 2001, the European Commission's Information Society Technologies Advisory Group introduced the concept of Ambient Intelligence [12] and stated that it "provides a vision of the Information Society where the emphasis is on greater user-friendliness, more efficient services support, user-empowerment, and support for human interactions. People are surrounded by intelligent intuitive interfaces that are embedded in all kinds of objects and an environment that is capable of recognizing and responding to the presence of different individuals in a seamless, unobtrusive and often invisible way." In addition, they proposed several scenarios of what ambient intelligence might look like in 2010. The purpose of these scenarios is also to anticipate its impact on society.

Later, in 2003, the European Commission's Information Society Technologies Advisory Group defined an *Ambient Intelligent Environment* as a situation where "humans will be surrounded by intelligent interfaces supported by computing and networking technology that is embedded in everyday objects such as furniture, clothes, vehicles, roads and smart materials."

The authors of the book[9] has stated that ambient intelligence is a concept with potential that aims at a specific goal : "technology will become invisible, embedded in our natural surroundings, present whenever we need it, enabled by simple and effortless interactions, attuned to all our senses, adaptive to users and context-sensitive, and autonomous."

Moreover, according to [11], the concept of Ambient Intelligence is based on a network of computers that is integrated in the environment of our daily lives. Human beings are surrounded by intelligent interfaces that are integrated into familiar objects through which the access to a number of services is made possible in a simple, comfortable and intuitive way.

Finally, according to Aarts and Wichert [15]: "Ambient Intelligence (AmI) is about sensitive, adaptive electronic environments that respond to the actions of persons and objects and cater for their needs. This approach includes the entire environment and associates it with human interaction." Also, they declared that in an environment supported by ambient intelligence, [15] "various devices embedded in the environment collectively use the distributed information and the intelligence inherent in this interconnected network."
These authors also determined 3 criteria for the implementation of ambient intelligence [15]:

- **Perception of the situation :** By combining the data collected by the distributed sensors, we can create semantic information to determine the environment and the user's context. It is context-awareness
- **Ubiquitous access :** Retrieval, transfer and reproduction mechanisms are necessary to ensure that digital media are available at any time, in any location and on any device.
- **Natural interaction :** Interactions with the system have to be as natural as possible. In other words, instead of issuing commands, the user defines objectives which are automatically interpreted and handled.

This last definition seems precise to us, while being in agreement with the definitions of the previous authors. Indeed, when the term "ambient intelligence" is

mentioned, we all have the intuition that it is indeed a thing that aims to improve human activities, in a non-intrusive way (i.e. to reach natural interactions), and this requires the need to perceive and interact in the physical space of the users (i.e. an environment). However, the typologies given by these authors are not evident. Thus, some speak of a "concept", or of what could be a field and most define it by its objective. This is why we propose to distinguish between the domain, the set of services and the environment through the following definitions, which are represented in figure 3 :

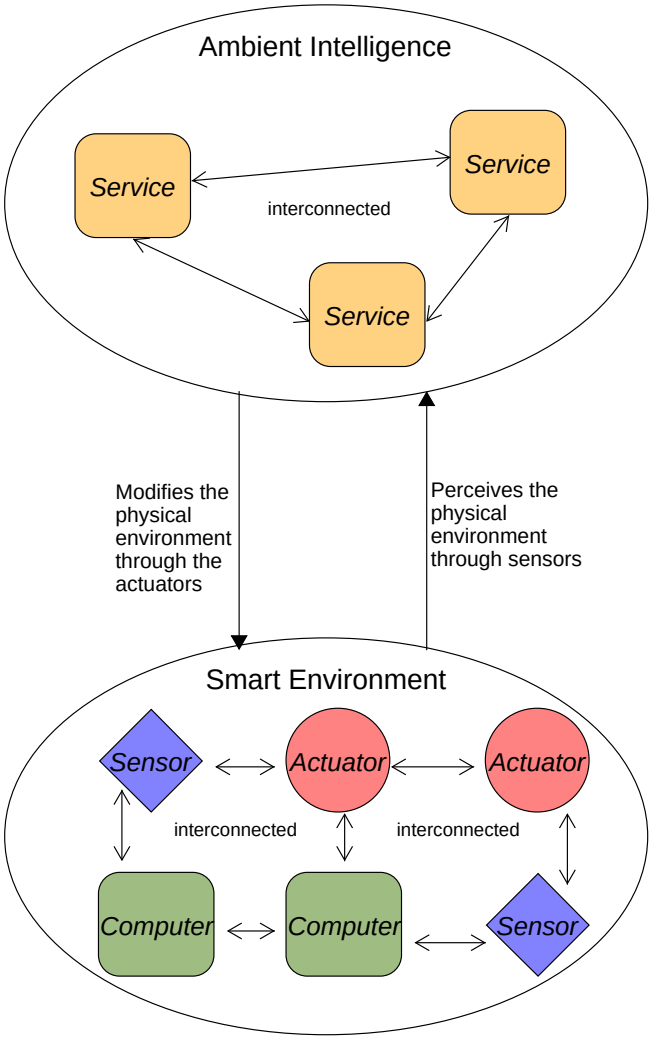


**Fig. 3.** Representation of ambient intelligence operating through a smart environment

**Ambient Intelligence :**
**A set of IT services which is interconnected, context-aware and naturally interactive and intelligent [7], in order to assist human activities. These services are based on a *smart environment.***

**Ambient Computing :**
**Emerging scientific domain of ubiquitous computing that aims to create ambient intelligence. This is an area touching many related fields such as: home assistance, robotics or artificial intelligence.**

**Smart Object :**
**Generally, an object whose original design has no direct link with computing, but which has been augmented with computational and communication capabilities. This is the basic block for building a *smart environment***

**Smart Environment :**
**A collection of interconnected objects, physically situated, that provide data capture, action and computing capabilities to a set of services.**

The set of services, if it does not meet the criteria of interconnection, context awareness and natural interaction, is not qualified as ambient intelligence.

Moreover, we can find the terms "smart environment," "responsive environment" and "intelligent environment" which are equivalent.

In the case where we want to communicate about the ambient intelligence and smart environment together, we propose to call it "ambient intelligence system". In this case, the definition is:

**Ambient Intelligence System :**
**A smart environment exploited by ambient intelligence which aims to assist human activities.**

### 2.3 Internet of Things

According to him [16], Kevin Ashton gave rise to the term "Internet of Things" in 1999. In this same article, he announces that "We need to empower computers with their own means of gathering information, so they can see, hear and smell the world for themselves, in all its random glory." This statement is interesting to put into perspective with the study of the terms ambient intelligence and intelligent environment made above. We find again the idea of having computational objects with the capacity to sense their environment and to treat, potentially in an intelligent way, the data raised by this perception. Although this statement does not tell of actuators, it is possible to feel these interactions(machine to physical environment) as a logical follow-up.

The authors of Gubbi and Al. [17], give us a more explicit definition of the Internet of Things as : "A radical evolution of the current Internet into a Network of

interconnected objects that not only harvests information from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, applications, and communications." This definition would allow us to assert that the Internet of Things is a network of objects that perceive and act in the physical world while offering services through Internet standards. Given the definition of a smart environment mentioned above, we can intuitively assume that the Internet of Things is a smart environment.

Otherwise, Zanella and Al. introduce : "Internet of Things is a recent communication paradigm that envisions a near future, in which the objects of everyday life will be equipped with micro-controllers, transceivers for digital communication, and suitable protocol stacks that will make them able to communicate with one another and with the users, becoming an integral part of the Internet." This vision is always in line with the previous proposal.

Finally, the authors, Atzori and Al. [19], are in agreement with what we are advancing in this article and note an "apparent fuzziness around the term Internet of Things." Indeed, they made the observation that this fuzziness comes from the fact of the different interests, finalities and backgrounds of the actors of the sector, whether they are from the world of research or the business world. Otherwise, they declare the semantic definition of the term as follows [19]: "A world-wide network of interconnected objects uniquely addressable, based on standard communication protocols."

In view of all these definitions of "Internet of Things", we propose the following definition, which is more adapted and fits into all the terms we have defined above:

**Internet of Things :**
**A world-wide *smart environment*, which aims to interconnect *smart objects* by means of the Internet standards of communication.**

In the same way, Guinard and Trifa [20] highlight the "need for a common language that can be understood" by all the heterogeneous objects of Internet of Things. Later they stated with Wilde [21] in 2010, that they : "propose to reuse and adapt patterns commonly used for the Web, and introduce an architecture for the Web of Things."

In 2011, according to the survey [22], the Web of Things can be defined as a reuse of existing Web technologies in order to build new applications and services with participation of Internet of Things.

We propose to define the Web of Things as follows:

**Web of Things :**
**Integration of Web standards and technologies to design web services based on interconnected smart objects belonging to Internet of Things.**

# 3 Clarification lexicon

## 3.1 Presentation

As mentioned above, definitions of terms related to ubiquitous computing may seem inconstant, especially in terms of typology.The purpose of our contribution is to do a synthetic analysis, and reformulation work that is as objective as possible. Our will is to consolidate the definitions outlined in the citations of the previous sections, to form a glossary of important terms related to ubiquitous computing, because we think that it is a necessary step to set out the link between ubiquitous computing and multi-agent systems.

We will conclude with a summary in the form of a diagram (figure 5) illustrating the different typologies and relationships between the main terms.

## 3.2 Main lexical proposition

*Smart object (Physical Object)* Generally, an object whose original design has no direct link with computing, but which has been augmented with computational and communication capabilities. This is the basic block for building a *smart environment*.

*Smart environment (Network)* A collection of interconnected objects, physically situated, that provide data capture, action and computing capabilities to a set of services.

*Internet of Things (Network)* A world-wide *smart environment*, which aims to interconnect *smart objects* by means of the Internet standards of communication.

*Web of Things (Standards)* Integration of Web standards and technologies to design web services based on interconnected smart objects belonging to Internet of Things.

*Ambient intelligence (Set of services)* A set of IT services which is interconnected, context-aware and naturally interactive and intelligent [7], in order to assist human activities. These services are based on a *smart environment.*

*Ambient Intelligence System (Network with services)* A smart environment exploited by ambient intelligence which aims to assist human activities.

*Ambient computing (Domain)* Emerging scientific domain of ubiquitous computing that aims to create ambient intelligence. This is an area touching many related fields such as: home assistance, robotics or artificial intelligence.

*Ubiquitous computing (Period)* An era in which the democratization and miniaturization of computers make it possible to offer users a distributed, intuitive and possibly invisible use of computers.

### 3.3 Synthesis diagram

This last section takes up the different terms of the glossary in order to give them a graphic representation, figure 5, of their meaning and their relation to the other terms. Figure 4 represents the eras of computing in a timeline, with arbitrary annual landmarks.

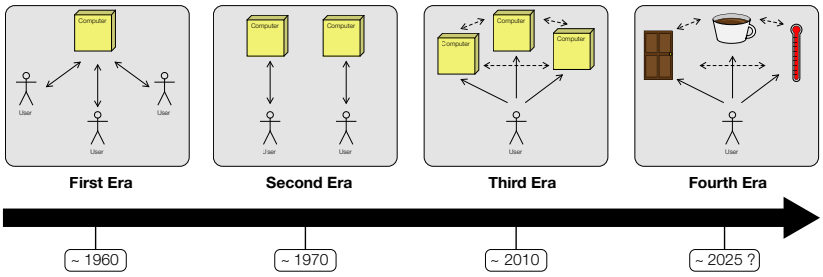


**Fig. 4.** Chronology of the eras of computing

As we now defined an explicitly categorized vocabulary and definitions of main keywords of ubiquitous computing, we can use it to clarify the relationship between ubiquitous computing and multi-agent systems. It is the subject of the next section.

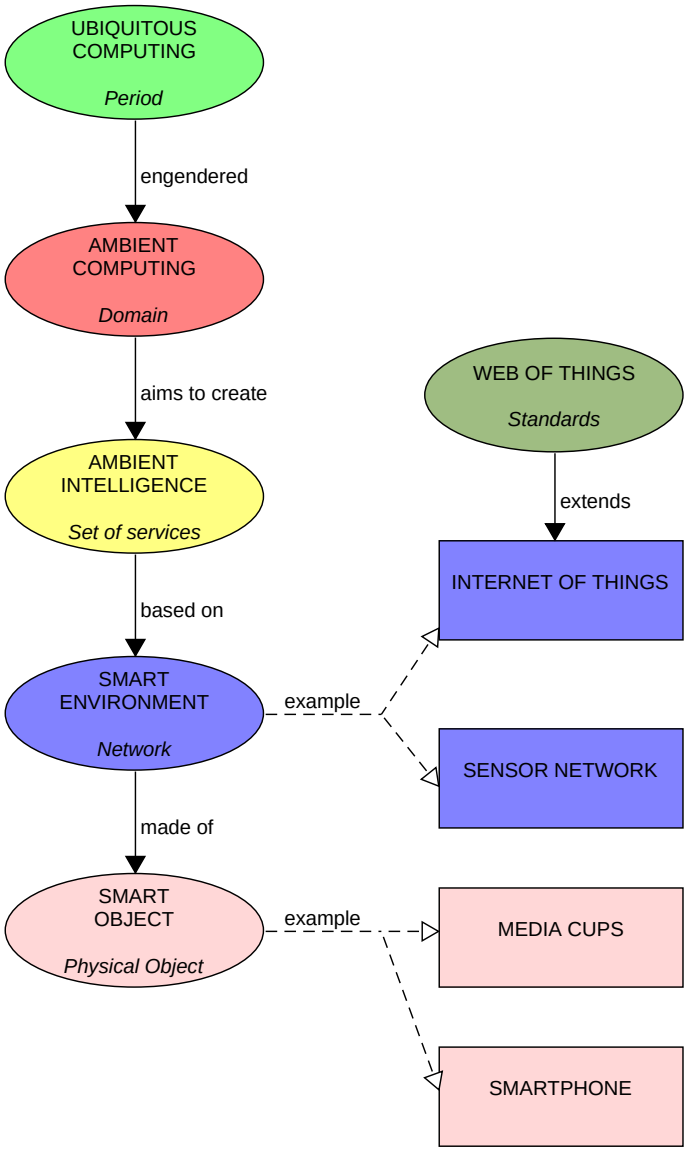


**Fig. 5.** Synthesis diagram to represent the terms and their relations with each other

## 4 Multi-agent systems

### 4.1 State of the art

Multi-agent systems have multiple applications such as multi-agent based simulation of complex phenomenons, collective robotics or problem solving. This

section is not intended to provide a glossary of terms belonging to the agent paradigm, but simply to ensure that we use common sense in the next section dealing with the interest of multi-agent system for ambient computing.

If we reread Russell and Norvig's book [7] about agents, it simply states that : "An agent is something that perceives and acts in an environment." According to this definition, we can presume that a multi-agent system is a system composed of several of these agents, and which possibly have social interactions between them.

The authors of [23] have highlighted the fact that the term "agent" could have fluctuating definitions, but overall an agent would be a "a special software component that has autonomy that provides an interoperable interface to an arbitrary system and/or behaves like a human agent, working for some clients in pursuit of its own agenda." Although an agent can solitary operate, the authors state the fact that generally multiple agents are used. They interact directly or indirectly between them, and often for the purpose of modeling complex systems. The authors outline the following criteria to characterize an agent[23]:

- **autonomous**: it operates without the direct intervention of humans and has control over its actions and internal state.
- **social**: it cooperates with other agents.
- **reactive**: it perceives its environment and responds in a timely fashion to modify the environment.
- **proactive**: it is able to exhibit goal-directed behavior by taking initiative in addition to its perceives of its environment.

On the other side, from Ferber's point of view [24], "an agent can be a physical or virtual entity that can act, perceive its environment (in a partial way) and communicate with others, is autonomous and has skills to achieve its goals and tendencies." In the same way, he concludes that a multi-agent system: "contains an environment, objects and agents (the agents being the only ones to act), relations between all the entities, a set of operations that can be performed by the entities and the changes of the universe in time and due to these actions."

According to these definitions, relations in a very simple multi-agent system can be schematically represented as follows in figure 6.

### 4.2 Relation between Multi-agent systems and ambient intelligence

Firstly, in view of figures of Ambient Intelligence (**fig** 3) and a Multi-Agent System (**fig** 6), we can suppose that an ambient intelligence system is a kind of multi-agent system. In this case, we can make the following comparisons about ambient intelligence services:

- Ambient intelligence services are autonomous, because they can operate without the direct intervention of humans.
- Ambient intelligence is social, because the services that compose it are interconnected.

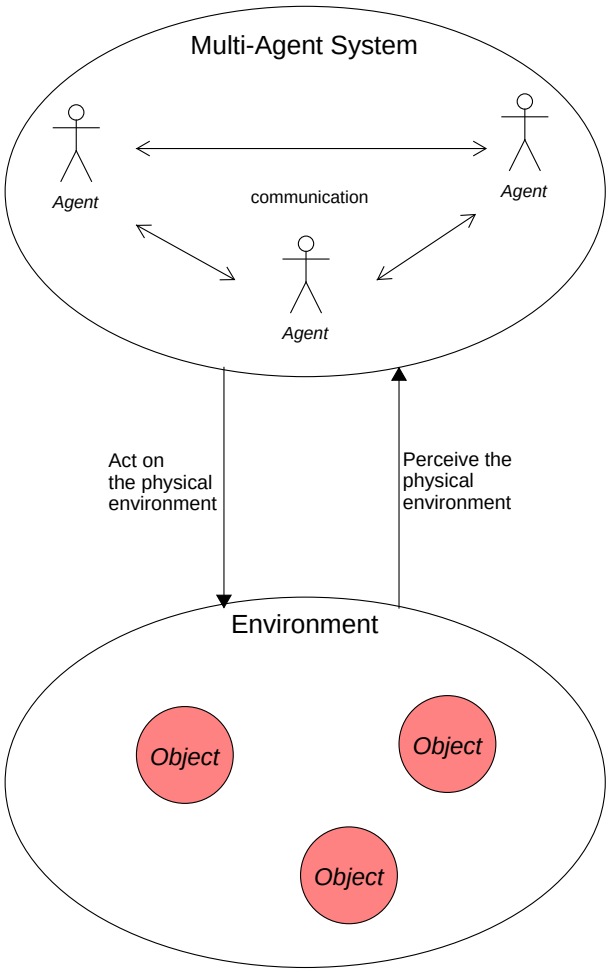


**Fig. 6.** Diagram of a simple multi-agent system

– These services act and perceive their environment through actuators and sensors devices in real time, so they are reactive.
– They are proactive because these services aim to accomplish a goal.

Moreover, this ambient intelligence system is composed by agents (the services) that operate in an environment (composed by smart objects). So we come to the conclusions that an ambient intelligence system is a case of multi-agent system. It is possible to take into account the users into the system. They are considered as agents, components of the system.

Secondly, many articles prove the interest of the multi-agent paradigm for ambient computing.

Authors of the handbook [26] made a state of multi-agent systems in the service of ambient intelligence. On this topic, they announce: "To provide useful functionality in the environments, we have to implement some autonomously functioning software into devices embedded in the environment. Agent technologies are useful in creating such functions." In this book [26], they describe multiple use case :

1. Mobile Agents
2. Multi-Agent Social Simulation
3. Multi-Agent Strategic Modeling in a Specific Environment
4. Learning Activity Models for Multiple Agents in a Smart Space

Most of them use multi-agent paradigm in order to design ambient intelligence systems. For example, Piette and Al. [25] proposed to use multi-agent approach for the deployment of services in a smart environment. On this topic, they affirmed "In real systems, privacy, autonomy, robustness and scalability are essential. That is why we identified MAS as a suitable solution."

In the same way, Satoh [27] submitted his framework which aims to construct distributed, large-scale, mobile application thanks to dynamics agents. These agents can migrate through computers of a network, so they are defined as "mobile agents". The flexibility brought by this system makes it suitable to manage smart environments and to ambient intelligence.

The article from Calvaresi and Al. [28] is an implementation of the multi-agent approach in a concrete framework of ambient intelligence. The context of this implementation is telereahibilitation of older adults, using these technologies to assist them.

Moreover, they are many articles, as evidence, that discuss about implementation of multi-agent approach to Internet of Things. The authors of [29] proposed to integrate agent-based approach and cloud computing to Internet of things, in order to deal with heterogeneity and scalability problem. Kwan and Al. [30] discuss about an agentified Internet of Things, where agents expose their functionalities and the smart object capacities with each other. Another way, Khalfi and Al. [31] proposed to use an avatar-based approach to abstract physical objects used by autonomous agents which operates through the Web of Things to design ambient intelligence systems.

Finally, another use of multi-agent system serving ambient intelligence is the simulation of this kind of system. Jamont and Occello proposed this kind of approach. In [32], they introduce a hardware/software hybrid multi-agent based simulation in order to design embedded agent societies exploit smart environments.

## 5 Conclusion and prospect

After an overview of the different terms related to ubiquitous computing, we showed a scattering in terms of interpretations. This phenomenon of scattering makes it more difficult to build the state of the art, particularly because of

the difficulty to bring out all the articles with different key words, despite the implementation of similar concepts.

This moved us towards the construction of a lexicon synthesizing and aggregating the definitions outlined in the citations of the previous sections.

From there, we showed the interest of this clarification by emphasizing the relationship between multi-agent system and ambient intelligence. This enabled us to determine that ambient intelligence is a particular case of multi-agent system.

Among the possible prospects, it seems interesting to strengthen the link between multi-agent systems and ambient intelligence, in particular by the proposal of meta-models and meta-languages describing smart environments to optimize the exploitation of these, which also goes through a more in-depth study of human/computer interactions. It also leads us to anticipate and prepare more about Cyber-Physical Convergence (i.e. CPW) and about its ethics and security issues.

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