Pervasive and Mobile Computing 5 (2009) 277–298

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Review

# Ambient intelligence: Technologies, applications, and opportunities

Diane J. Cook [a], Juan C. Augusto [b,*], Vikramaditya R. Jakkula [a]

[a] School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA, USA
[b] School of Computing and Mathematics, University of Ulster, UK

ARTICLE INFO

*Article history:*
Received 15 December 2008
Accepted 1 April 2009
Available online 15 April 2009

*Keywords:*
Ambient intelligence
Artificial intelligence
Sensors
Decision making
Context awareness
Privacy

ABSTRACT

Ambient intelligence is an emerging discipline that brings intelligence to our everyday environments and makes those environments sensitive to us. Ambient intelligence (AmI) research builds upon advances in sensors and sensor networks, pervasive computing, and artificial intelligence. Because these contributing fields have experienced tremendous growth in the last few years, AmI research has strengthened and expanded. Because AmI research is maturing, the resulting technologies promise to revolutionarize daily human life by making people's surroundings flexible and adaptive.

In this paper, we provide a survey of the technologies that comprise ambient intelligence and of the applications that are dramatically affected by it. In particular, we specifically focus on the research that makes AmI technologies "intelligent". We also highlight challenges and opportunities that AmI researchers will face in the coming years.



## 1. Introduction

Computer science is a relatively new branch of science and as such it has gone through rapid and yet important transformations during the first decades of its existence. Those transformations have produced a very interesting mix of available experiences, and expectations which are making possible the creation and deployment of technology to ultimately improve the way our environments help us. This technical possibility is being explored in an area called Ambient Intelligence. Here we survey the field of Ambient Intelligence. Specifically, we review the technologies that led to and that support research in AmI. We also provide an overview of current uses of AmI in practical settings, and present opportunities for continued AmI research.

### 1.1. Emergence of AmI

The European Commission first charted a path for AmI research in 2001 [1]. A significant factor in this birth of the field of AmI is the evolution of technology. Computers were initially very expensive as well as difficult to understand and use. Each computer was a rare and precious resource. A single computer would typically be used by many individuals (see Fig. 1). In the next evolutionary step, many users no longer needed to take turns to use a computer as many were able to access it simultaneously. The PC revolution in the 80s changed the ratio to one user per computer. As industry progressed and costs dropped, one user often was able to access more than one computer. The type of computational resources that we have at our disposal today is dramatically more varied than a few decades ago.

Today, access to multiple computers does not necessarily just mean owning both a PC and a laptop. Since the miniaturization of microprocessors, computing power is embedded in familiar objects such as home appliances (e.g., washing

* Corresponding author.
*E-mail addresses:* cook@eecs.wsu.edu (D.J. Cook), jc.augusto@ulster.ac.uk (J.C. Augusto), vjakkula@eecs.wsu.edu (V.R. Jakkula).

1574-1192/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.pmcj.2009.04.001

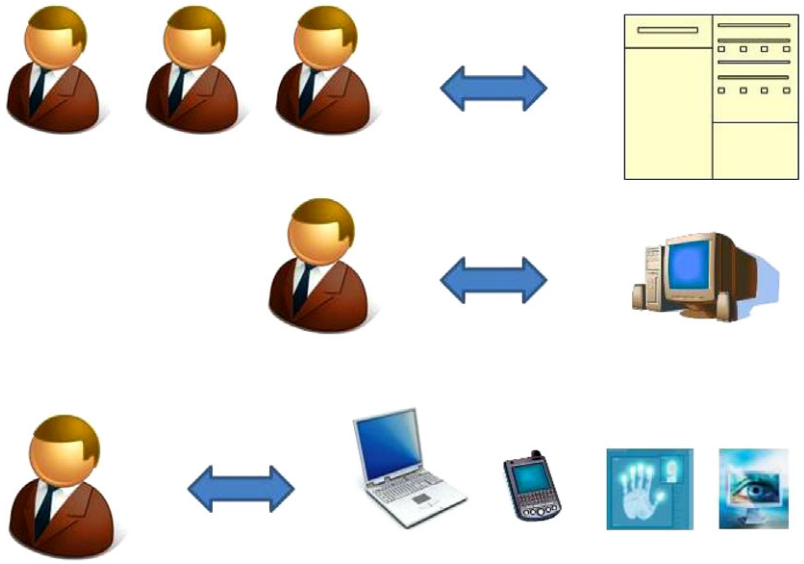

**Fig. 1.** A shift in people-computing power ratio.

machines, refrigerators, and microwave ovens), they travel with us outside the home (e.g., mobile phones and PDAs), and they help guide us to and from our home (e.g., cars and GPS navigation). Computers that perform faster computation with reduced power and tailor the computation to accomplish very specific tasks are gradually spreading through almost every level of our society. This widespread availability of resources sparked the realization of Ambient Intelligence.

Possessing the necessary supporting technology is not enough for an area of science to flourish. User's experiences with computers over recent decades have created an interesting context where expectations of these systems are growing and people's fear of using them has decreased. Concomitantly with this difference in the way society perceives technology there is also a change in the way services are handled. An important example of this is the decentralization of health care and development of health and social care assistive technologies. Because governments and health professionals are departing from the hospital-centric health care system, the way is paved for AmI systems to support caring for patients closer to home, within their communities. Developments, competencies and drivers are converging at the same time in history and all of the necessary components are in place: the need to distribute technology around us, the will to change the way our society interacts with technology, the available technological knowledge and all the elements to satisfy the demand.

The idea of Ambient Intelligence is not new, but what is new is that we can now seriously think about it as a reality and as a discipline with a unique set of contributions. Most of us have come across science fiction movies where doors opened when someone approached or computers were able to identify the interlocutor without their name being explicitly mentioned. Some of those features were far fetched for the technology available at the time, but gradually some features that indicate sensible autonomy on behalf of the system were targeted by industry, and AmI was born.

Technically, many of us today live in homes that were considered "smart" by 1960s standards, and for a very reasonable cost. Thermostats and movement sensors that control lighting are commonplace. Now the bar has moved much higher: even the ability to link movement sensors to a security alarm for detecting intruders will not impress a society which regularly interacts with such facilities.

Recent computational and electronic advances have increased the level of autonomous semi-intelligent behavior exhibited by systems like smart homes so much that new terms like *Ambient Intelligence* started to emerge [2,1,3]. The basic idea behind Ambient Intelligence (AmI) is that by enriching an environment with technology (e.g., sensors and devices interconnected through a network), a system can be built such that acts as an "electronic butler", which senses features of the users and their environment, then reasons about the accumulated data, and finally selects actions to take that will benefit the users in the environment.

### *1.2. What is AmI?*

Ambient Intelligence has been characterized by researchers in different ways. These definitions, summarized in Table 1, highlight the features that are expected in AmI technologies: sensitive, responsive, adaptive, transparent, ubiquitous, and intelligent.

From these definitions, and the features that we are using (summarized in Table 1) to characterize Ambient Intelligence, we can see how the discipline compares and contrasts with fields such as pervasive computing, ubiquitous computing, and artificial intelligence. The fact that AmI systems must be *sensitive*, *responsive*, and *adaptive* highlights the dependence that AmI research has on context-aware computing.