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Visualizing the research on pervasive and ubiquitous computing

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Abstract The aim of this paper is to identify the research status quo on pervasive and ubiquitous computing via scientometric analysis. Information visualization and knowledge domain visualization techniques were adopted to determine how the study of pervasive and ubiquitous computing has evolved. A total of 5,914 papers published between 1995 and 2009 were retrieved from the Web of Science with a topic search of pervasive or ubiquitous computing. CiteSpace is a java application for analyzing and visualizing a wide range of networks from bibliographic data. By use of it, we generated the subject category network to identify the leading research fields, the research power network to find out the most productive countries and institutes, the journal co-citation map to identify the distribution of core journals, the author co-citation map to identify key scholars and their co-citation patterns, the document co-citation network to reveal the ground-breaking literature and detect the co-citation clusters on pervasive and ubiquitous computing, and depicted the hybrid network of keywords and noun phrases to explore research foci on pervasive and ubiquitous computing over the entire span 1995–2009.

Keywords Pervasive and ubiquitous computing · Document co-citation analysis · Co-citation cluster analysis · Research foci

Introduction

Pervasive and ubiquitous computing is an emerging field of research that brings in revolutionary paradigms for computing models in the twenty-first century. It is the third wave in computing after distributed systems and mobile computing. In effect, pervasive and

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ubiquitous computing is a post-desktop model of human–computer interaction in which information processing has been thoroughly integrated into everyday objects and activities.

Historically, pervasive computing has its roots in ideas first coined by the term ubiquitous computing. Ubiquitous computing (ubicomp) as envisioned by Weiser in his seminal paper is a computing environment where computing systems weave themselves in the fabric of everyday life and vanish into the background (Weiser 1991). Its initial incarnation is in the form of "tabs," "pads," and "boards" built at Xerox PARC, 1988–1994. The terms ubiquitous computing and pervasive computing are often used interchangeably (Saha and Mukherjee 2003), but they are conceptually different (Lyytinen and Yoo 2002). Ubiquitous computing combines the advances in mobile computing and pervasive computing to present a global computing environment to a human user as she/he moves from one location to another. Pervasive computing, on the other hand, aims to acquire context from the environment and dynamically build computing models dependent on context. It is invisible to human users and yet provides useful computing services. In this article, we treat them as two equivalent terms and pay no attention to their difference.

Pervasive and ubiquitous computing is a cross-disciplinary area with tremendous potential where new computing models and associated applications and usage scenarios have driven a broad set of research topics such as low power, integrated technologies, embedded systems, mobile devices, wireless and mobile networking, middleware, user interfaces, applications, services, security, privacy and so on. After many years' development, it has made rapid progress in theories and practical applications. Based on prior studies, however, there are few studies having examined the research status quo of pervasive and ubiquitous computing in a comprehensive and integrated approach, so it is necessary for us to carry out an analysis of papers on pervasive and ubiquitous computing from the WoS over the last 15 years in order to learn about its development process as a whole.

Background

The study of information visualization starts with computer graphics and its goal is to represent abstract information spaces intuitively and naturally. Domain visualization is one of the new research fronts resulted from the proliferation of information visualization, aiming to reveal the essence of a knowledge domain (Chen et al. 2000). The domain analysis is a functionalist approach, attempting to under the implicit and explicit functions of information and communication and to trace the mechanisms underlying informational behavioral from this insight (Hjørland and Albrechtsen 1995). The objects of domain visualization not only involve the entire science but also a specific discipline (Garfield 1998; White and McCain 1998).

The combination of information visualization techniques and co-citation analysis greatly accelerate the development of co-citation study. Co-citation analysis is taken as a measure of proximity between documents for the mapping of scientific specialties. It mainly includes the journal co-citation analysis, the author co-citation analysis and the document co-citation analysis. The journal co-citation analysis can be used to identify the core journal set. The author co-citation analysis offers a new technique that might contribute to the understanding of intellectual structure in the sciences (White and Griffith 1981) and the co-cited author maps can represent the intellectual structure of a field (McCain 1986). The document co-citation analysis can be used to map out in great detail the relationships between the key concepts, methods, or experiments in a field. It offers a more objective way of modeling the intellectual structure of scientific specialties (Small 1973). The co-citation cluster analysis of documents can display the macro-structural evolution of scientific knowledge (Small 1992).

In this article, we will present a systematic and visual domain analysis of the emerging interdisciplinary field-pervasive and ubiquitous computing-in terms of various co-citation networks in order to explore the intellectual structure evolution of this knowledge domain over time.

The objectives of this study are:

- to examine the distribution of subject categories involved in the research of pervasive and ubiquitous computing;
- to identify the most productive research work forces at the country, institute and individual levels;
- to identify the distribution of core journals related with pervasive and ubiquitous computing;
- to study the document co-citation network for identifying the ground-breaking papers and exploring the main research themes in the field of pervasive and ubiquitous computing;
- to detect the research hotspots in the field of pervasive and ubiquitous computing over the entire span 1995–2009.

Data and methodology

Data collection

The input data for CiteSpace were retrieved from SCI databases via the Web of Science based on a topic search for "pervasive or ubiquitous computing" papers published during the period of 1995–2009. The search was limited to articles and proceedings papers. The resultant dataset contains a total of 5,914 records. A bibliographic record in SCI contains fields such as author, title, abstract, and references.

Research tools

This paper chooses CiteSpace as the research method to assist analysis in this study. CiteSpace is a java application developed by Dr. Chaomei Chen for analyzing and visualizing emerging trends and changes in scientific literature. It can produce co-citation or c networks consisted of nodes and links. Created nodes may present institutions, articles, authors, terms, keywords and so on. Created links may represent co-citation or co-occurrence between them. We use it to carry out a multiple-perspective co-citation analysis with the purpose of highlighting the intellectual base and the research fronts of pervasive and ubiquitous computing and detecting its emerging trends and patterns.

The general procedure of visualization analysis with CiteSpace is outlined as follows: (1) identify a knowledge domain; (2) data collection; (3) extract noun phrases from titles, abstracts, descriptors and identifiers of citing articles in the dataset; (4) time slicing; (5) threshold selection; (6) pruning and merging; (7) select the layout styles; (8) visual inspection; (9) verify pivotal points; (10) reach the corresponding conclusions (Chen 2006).

Results

Analysis of publication output

Figure 1 depicts the distribution of bibliographic records from the WoS between 1995 and 2009. The first data curve represents the total publication output of pervasive and ubiquitous computing, the second data curve indicates the number of proceedings papers and the third data curve describes the number of articles. According to the document type statistics from the WoS, proceedings paper was the most-frequently used document type comprising 83% (4,907) of the total production, followed by article occupying 17% (1,007) in the total publication, suggesting that this research field has pained more attention to codify its scientific concerns and share its research fruits by use of conferences. Further analysis shows that the second data curve as a whole is on the rise during the period 1995–2009, while the third data curve is consistent with the first data curve in terms of the variation trend, suggesting that the total output on pervasive and ubiquitous computing mainly depends on the number of proceedings papers.

According to Fig. 1, during the period of 1995–2000, the number of papers on pervasive and ubiquitous computing increased slowly, in 1995, the number of papers was 1 and in 2000 the number was 75. During the year 2001–2007, the number of papers began to grow continuously with the speed of more than 100 papers per year and reached its peak in 2007, in 2001, the number of papers was 112 and in 2007 the number was 1,015, suggesting that the research had aroused more and more concern all over the world and a considerable amount of research achievements were published in the form of papers. Since 2007, the publication output began to decline greatly, mainly due to the reduction of proceedings paper output.

Analysis of subject category

CiteSpace can intuitively display the subject category distribution of papers. On the graphical user interface of CiteSpace, we selected the subject category as the type of network nodes. The time scaling value was set to 1, namely the entire time interval of

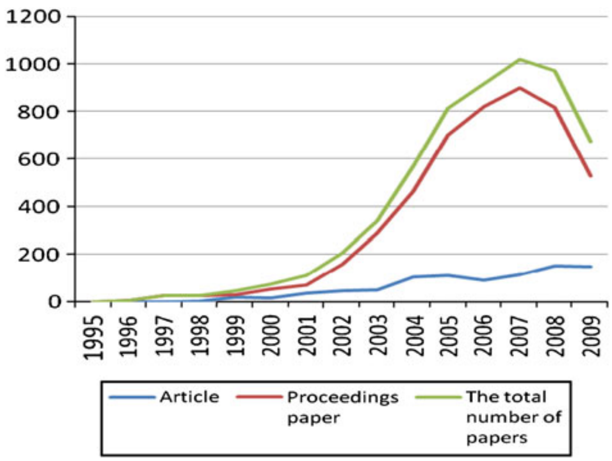

Fig. 1 Distribution of bibliographic records of pervasive and ubiquitous computing papers

1995–2009 was divided into fifteen 1-year slices for processing. In each time slice, the top 30 most cited or occurred items were selected out for constructing the co-citation or co-occurrence network. These individual networks led to an integrated network of multiple types of nodes and links.

Table 1 clearly specifies the top ranked research fields with the most publications. Figure 2 visually displays the distribution network of the subject category with 71 nodes and 101 links on pervasive and ubiquitous computing. Computer science is the leading subject category involved in the research of pervasive and ubiquitous computing. According to the subject category statistics from the WoS, papers mainly distribute in its six branches, including theory and methods, information systems, artificial intelligence, hardware and architecture, interdisciplinary application and cybernetics. Engineering is the second largest subject category having done a considerable amount of research on

Table 1 Publications of the top ranked subject categories

Frequency	Subject category	Frequency	Subject category
4,896	Computer Science	46	Health Care Sciences and Services
1,554	Engineering	44	Ergonomics
1,323	Telecommunications	40	Medical Informatics
197	Automation and Control Systems	38	Optics
84	Robotics	38	Operations Research and Management Science
68	Computer	37	Remote Sensing
66	Imaging Science and Photographic Technology	37	Business
59	Education and Educational Research	34	Imaging Science and Photographic Technology
53	Mathematics	30	Information Science and Library Science

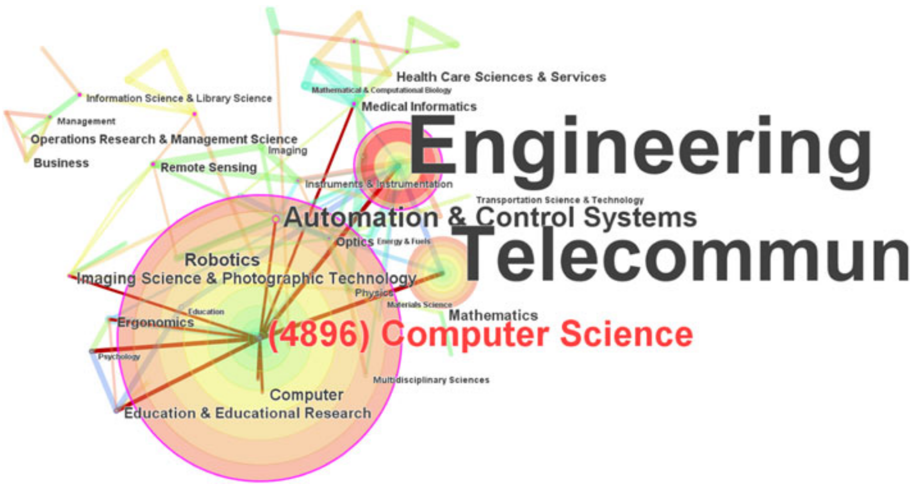

Fig. 2 A subject category network with 71 nodes and 101 links

pervasive and ubiquitous computing, and then followed by telecommunications ranking the third. Both of them contributed 1,554 and 1,323 papers respectively. Automation and control systems ranks fourth with 197 papers. Other subjects with publication frequencies varying from 30 to 84 also have made outstanding progress in this field, including robotics, computer, image science and photographic technology, education and educational research, mathematics, health care sciences and services, ergonomics, and medical informatics and so on. As is indicated from the results, there exist strong interdisciplinary relations and the rapid diffusing and sharing of scholarly knowledge within the research network. This might have been due to the characteristics of the field of pervasive and ubiquitous computing, which can be applied to various research fields and requires multidisciplinary capabilities from these areas to address various research challenges at the same time. Pervasive and ubiquitous computing will thus be the crucible in which many disjoint areas of research are fused.

Analysis of the research work forces

CiteSpace also can vividly show the distribution of papers among various countries. A comprehensive network consisting of nodes on behalf of the collaborating countries and institutes between 1995 and 2009 was shown in Fig. 3. If researchers from different countries coauthored published papers on pervasive and ubiquitous computing, these countries would be connected in the visualization map.

Figure 3 shows that papers on pervasive and ubiquitous computing were contributed by many countries spread over the entire globe, while the major contribution of the total output on pervasive and ubiquitous computing mainly came from eight countries. The frequency distribution of papers in Table 2 indicates that America is not only the original participating country but also the largest contributor publishing 1,083 papers in the field of pervasive and ubiquitous computing. Asian countries also are active in the research of pervasive and ubiquitous computing. South Korea's publication counts are 820 times and ranks second. The other two prominent nodes coming from Asian countries are China and Japan respectively with 626 and 450 times, ranking the third and fourth in terms of

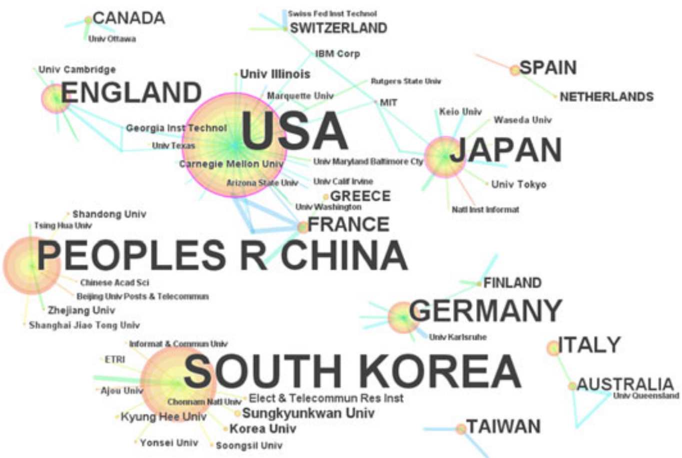

Fig. 3 A research power network of 135 nodes and 110 links over the past 15 years

Table 2 The top-8 most productive countries and institutes

Frequency	Country	Frequency	Institute
1,083	USA	77	Sungkyunkwan University
820	South Korea	59	Korea University
626	The People's Republic of China	57	University of Illinois
450	Japan	52	Kyunghee University
365	Germany	51	Electronics and Telecommunications Research Institute
335	England	47	University of Tokyo
189	Italy	45	Zhejiang University
157	France	42	Georgia Institute of Technology

publication counts. The contribution of European countries is very significant and its representative nodes mainly include Germany (365), England (335), Italy (189) and France (157). There are still other countries participating in the research of pervasive and ubiquitous computing, such as Canada, Switzerland, Spain, Italy, Australia, Taiwan and so on.

Figure 3 also identifies the distribution of institutes from the above countries. Institutes in the map are located in the straight lines connected with circular nodes representing their corresponding countries. Obviously, America, South Korea, China and Japan possess a stronger research power in the field of pervasive and ubiquitous computing than other countries. The important research institutes in America include IBM Corporation, University of Illinois, Georgia Institute of Technology, Carnegie Mellon University, Marquette University, University of Texas and so on; the prolific institutes in South Korea mainly include Sungkyunkwan University, Korea University, Kyunghee University, Electronics and Telecommunications Research Institute and so on; the research institutes in China include Zhejiang University, Shanghai Jiao Tong University, Beijing University of Posts and Telecommunications and Chinese Academy of Sciences; the representative research institutes in Japan include University of Tokyo, Keio University and Waseda University. Table 2 provides a list of the top 8 most productive institutes between 1995 and 2009. Among these institutes, Sungkyunkwan University, Korea University and University of Illinois rank top 3 in terms of publication frequency and they are important research work forces in their own countries. Thus, major universities worldwide have played an important role in the research activities of pervasive and ubiquitous computing, while other vibrant research communities also have accelerated the efforts of a rapidly growing of pervasive and ubiquitous computing.

Analysis of the cited journals

CiteSpace can plot the journal co-citation network of every subject domain. Figure 4 presents a time-zone view of the journal co-citation network of 192 nodes and 397 links in the field of pervasive and ubiquitous computing. The node size in the map represents the overall citation frequency of journals. The temporal distribution of journals with citations of over 100 times corresponds to three periods: (1) before 1995, (2) 1995–2000, (3) 2001–2005. The journals with most cited frequencies belong to the earliest period, which include *Lecture Notes in Computer Science* with a total of 1,119 citations, *Communications of the ACM* with 949 times (Table 3).

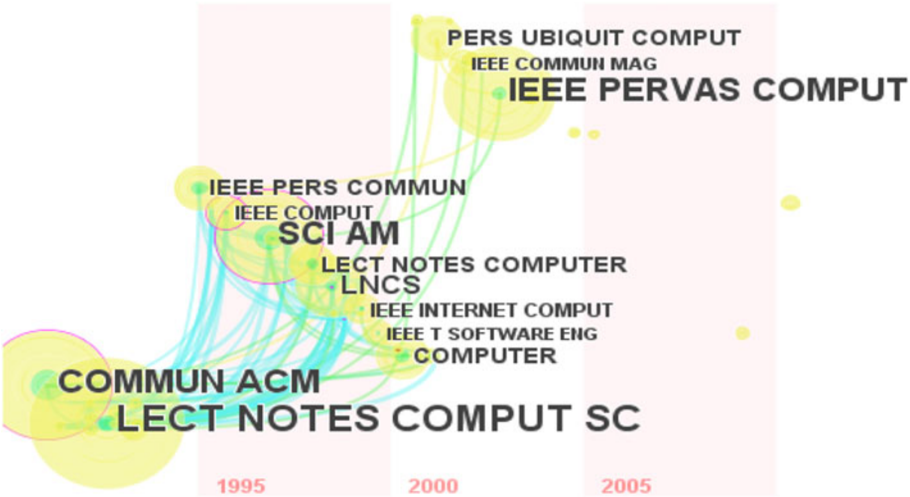

Fig. 4 A journal co-citation map of 192 nodes and 397 links on pervasive and ubiquitous computing

Table 3 Distribution of core journals on pervasive and ubiquitous computing

Frequency	Centrality	Journal title	Abbreviation	Year
1,119	0.07	Lecture Notes in Computer Science	Lect Notes Comput Sci	1994
949	0.39	Communications of the ACM	Commun ACM	1991
813	0.05	Scientific American	Sci Am	1993
813	0.08	IEEE Pervasive Computing	IEEE Pervas Comput	2002
545	0.04	Lecture Notes in Computer Science	LNCS	1997
434	0.17	IEEE Personal Communications	IEEE Pers Commun	1998
403	0.00	Computer	Computer	1997
398	0.05	Personal and Ubiquitous Computing	Pers Ubiquit Comput	2003
312	0.02	IEEE Computing	IEEE Comput	1996
299	0.00	IEEE Internet Computing	IEEE Internet Comput	1997
263	0.00	IEEE Transactions on Software Engineering	IEEE Trans Software Eng	1998
258	0.00	IEEE Communication Magazine	IEEE Commun Mag	2001

During the period of 1995–2000, the important journals include *Scientific American* ranking the third with 813 citations, *Lecture Notes in Computer Science* at the fifth place with 545 occurrences, *IEEE Personal Communications* with 434 times, *IEEE Computing* with 312 times, *IEEE Transactions on Software Engineering* with 263 times, *IEEE Internet Computing* with 299 times, and *Computer* with 403 times and so on.

The core journals during the third period focus on *IEEE Pervasive Computing*, *IEEE Communication Magazine*, *and Personal and Ubiquitous Computing*. *IEEE Pervasive Computing* takes the third place with 813 citations in the network.

In addition, *Communications of the ACM* and *IEEE Personal Communications* had higher levels of centrality than other journals, suggesting that they serve as an intermediary or a broker bridging the adjoining journals in the cited journal network. *Communications of the ACM* is the leading print and online publication for the computing and information technology fields, encompassing the broad scope of computing such as artificial intelligence, computer applications, computer systems, communications and networking, human–computer interaction, personal computing and so on. *IEEE Personal Communications* was renamed as *IEEE Wireless Communications* in 2002 and it deals with all technical, policy and standard issues related to wireless communications in all media. Its papers highlight such topics as wireless or mobile communications, networking, computing and services.

Analysis of the author co-citation network

The author co-citation analysis focuses on authors' impact in terms of citations. It aims to provide a useful glimpse of the dynamic structure of the contributing research community. In every subject, authors with most citations tend to be those scholars carrying out the fundamental research tasks and these scholars have made a profound and fundamental impact on the development and evolution of this subject. Table 4 lists the most cited pioneers in the field of pervasive and ubiquitous computing.

Figure 5 shows an author co-citation map of 233 authors and 1,155 co-citation links. A line connecting two items in this visualization map represents a co-citation link. The thickness of a line is proportional to the strength of co-citation. The most prominent author in Fig. 5 is Weiser with 1,236 citations. He is widely considered to be the father of ubiquitous computing. Additional highly cited scholars include Dey (494), Satyanarayanan (307), Want (307), Abowd (281), Roman (244), Chen (226), Kindberg (207), Ranganathan (194), and Garlan (182) and so on. These names are usually associated with research on human–computer interaction, mobile and pervasive computing, context-aware computing, and ubiquitous computing spaces and so on.

Table 4 The top 10 most cited authors in the author co-citation network

Frequency	Author	Frequency	Author
1,236	Weiser	244	Roman
494	Dey	226	Chen
307	Satyanarayanan	207	Kindberg
307	Want	194	Ranganathan
281	Abowd	182	Garlan

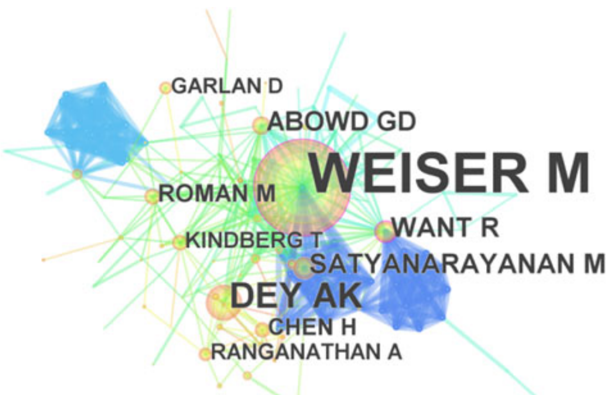

Fig. 5 A author co-citation map of 233 authors and 1,155 co-citation links (1995–2009)

Figure 6 depicts a minimum spanning tree derived from the author co-citation network and makes manifest the principal component of the author co-citation patterns. This network underlines the small-word phenomena as the six-degree association. Weiser had the direct co-citation relationship with many scholars such as Satyanarayanan, Norman, Kindberg, Roman, Dey, Abowd, Skillit, Hokimoto and so on; apart from Weiser, the other co-citation authors for Dey included Nakajima, Beigl, Ranganathan and Henricksen; while Satyanarayanan only had the co-citation relationship with two authors, namely Weiser and Garlan; the degree of the node for Want is 14, indicating that he and 14 other authors were once co-cited; Abowd, Chen, Kindberg, Ranganathan and Garlan were in the co-citation relationship with 14, 5, 10, 6, 4 authors respectively. In addition, the co-citation information about other nodes also can be obtained from Fig. 6.

Analysis of the document co-citation network

CiteSpace supports three complementary visualization views: cluster views, timeline views and time-zone views. Cluster views show networks as the commonly seen types of node-and-link diagrams, whereas timeline views and time-zone views arrange articles and terms in correspondence to the time of their publication or their peak time. The first two kinds of views were used for displaying the document co-citation network of 298 documents and 1,209 co-citation links.

Analysis of the most cited papers

The document co-citation analysis can help us find out not only the initial but also the highly cited and most influential research documents to learn about the intellectual base of each research domain. In Fig. 7, each node represents one cited document and has been

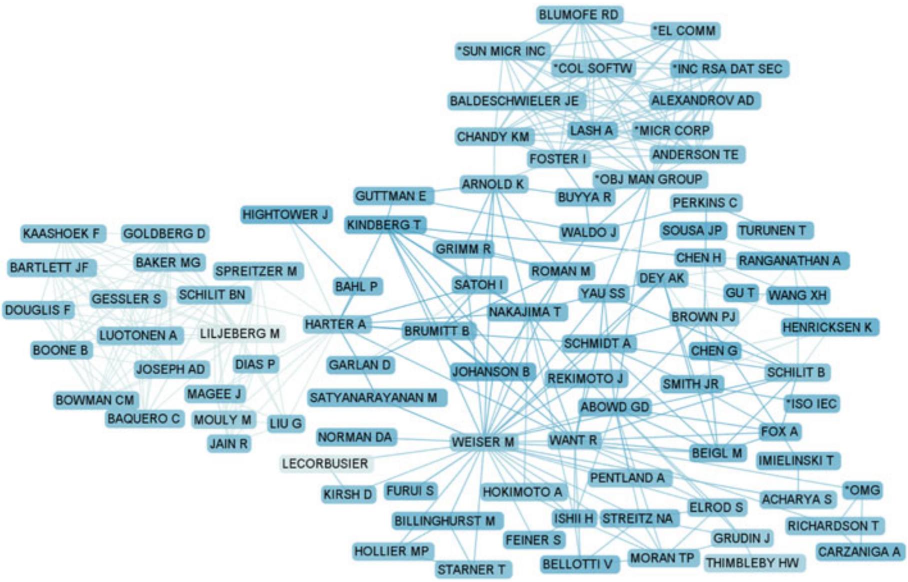

Fig. 6 A main component map of the author co-citation patterns

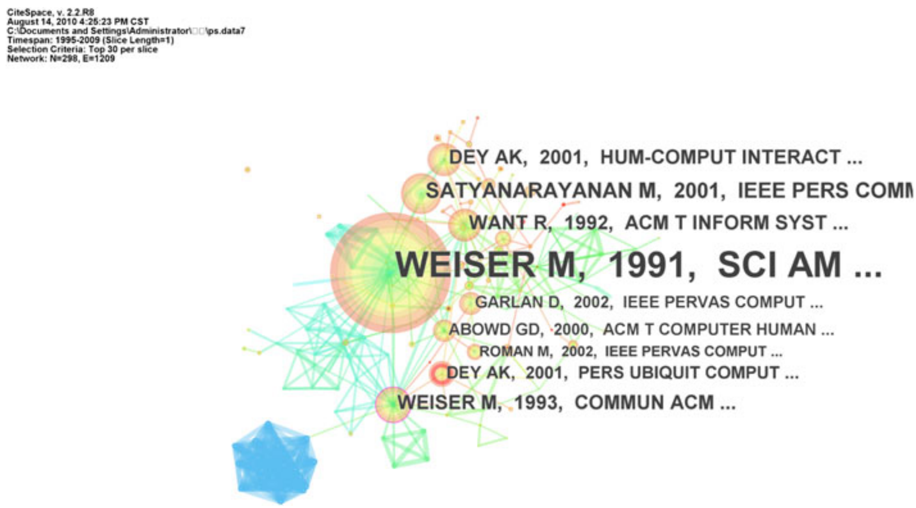

Fig. 7 A cluster view of the document co-citation network of 298 nodes and 1,209 links

Table 5 Top 9 highly cited papers with co-citation frequency of over 70 times

φ	τ	σ	Σ	Cited reference	Source
455	2.89	0.06	1.20	Weiser (1991)	Scientific American
158	–	0.01	1.00	Satyanarayanan (2001)	IEEE Personal Communications
142		0.18	1.00	Weiser (1993)	Communications of the ACM
136		0.10	1.00	Want's (1992)	ACM Transaction on Information System
133		0.03	1.00	Dey et al. (2001)	Human–Computer Interaction
104	8.31	0.01	1.13	Dey (2001)	Personal and ubiquitous computing
94	–	0.04	1.00	Abowd and Mynatt (2000)	ACM Transactions on Computer–Human Interaction
93	–	0.20	1.00	Garlan et al. (2002)	IEEE Pervasive Computing
73	–	0.00	1.00	Roman (2002)	IEEE Pervasive Computing

labeled with the representative author of the cited document, year of publication and publication magazine. Moreover, each node is depicted as circles filled with citation rings and the thickness of every ring is proportional to the amount of citations received in that time slice. Thus, a large-sized circle denotes a highly cited reference. The highly cited papers in the visualization are Weiser's (1991) paper, Satyanarayanan's (2001) paper, Weiser's (1993) paper, Want's (1992) paper, Dey's (2001) paper and so on.

Table 5 summarizes the top-9 most cited papers and their structural, temporal, and saliency metrics such as citation frequency (φ), citation burstness (τ), betweenness centrality (σ), and sigma (Σ). Citation frequency shows the counts of other papers citing to one paper, and Citation burstness determines whether the citation frequency of this paper has significant fluctuation during a short time interval within the overall time period. With regard to betweenness centrality, it measures the extent to which the node is in the middle of a path that connects other nodes in the network. Sigma is used for measuring the scientific novelty of one paper (Chen et al. 2010).

In terms of citation frequency, Weiser's (1991) paper takes the first place with the most citations of 455 times, suggesting that it is the most influential paper in the emerging field. Satyanarayanan's paper has been cited 158 times since its publication in 2001 and ranks second. Weiser's (1993) paper and Want's (1992) paper are at the third and fourth place respectively with 142 and 136 citations. Dey's two papers in 2001, Abowd and Mynatt's (2000) paper, Garlan et al.'s (2002) paper and Roman's (2002) paper are also the important documents and have made great contribution to the research on pervasive and ubiquitous computing. From the perspective of citation burstness (τ), Dey's (2001) paper and Weiser's (1991) paper separately gain the values of 8.31 and 2.89. According to their citation history shown in Fig. 8, the first paper's citation counts abruptly declined from 2008 to 2009, while the second paper had a stronger citation increase from 2003 to 2004. In addition, Weiser's (1993) paper and Want's (1992) paper have high betweenness centrality value of more than or equal to 0.1, suggesting that both of them are hub articles and occupy important positions in connecting different theme clusters on pervasive and ubiquitous computing. As seen from the novelty metric of highly cited papers, Weiser's (1991) paper and Dey's (2001) paper are the two articles with relatively higher innovational characteristic than others.

According to the publication time, the highly cited papers are listed as follows:

The opening paper is Weiser's (1991) paper in *Scientific American*. His article, entitled "The computer for the 21st century," introduced the area of ubiquitous computing and put forward a vision of integrating computers seamlessly into the natural human environment.

The second paper is Want's (1992) paper on the PARCTAB system serving as a preliminary testbed for ubiquitous computing. The third paper is entitled "Some computer science issues in ubiquitous computing." Weiser provided a valuable introduction to some computer science issues involved in this area in 1993.

The fourth paper took a prominent historical perspective in depicting the development of ubiquitous computing. Abowd and Mynatt's (2000) article is entitled "Charting past, present and future research in ubiquitous computing." They reviewed the research accomplishments on interaction themes and posited a new area of applications research: everyday computing.

Although both the fifth and sixth papers were written by Dey (2001) and had connections to context, they addressed different topics. The former, entitled "Understanding and using context," developed the specific definition of context, whereas the latter, entitled "A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware

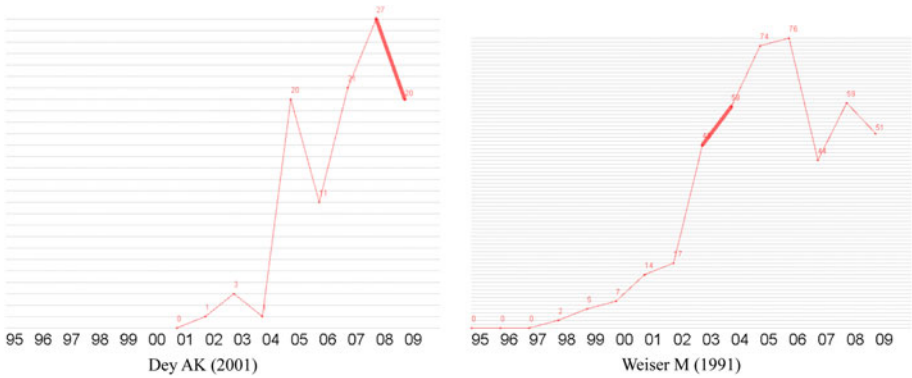

Fig. 8 The citation history maps from Dey's (2001) paper and Weiser's (1991) paper

applications," focused on designing a context toolkit for supporting the rapid development of a rich space of context-aware applications.

The title of the seventh paper is "Pervasive computing: vision and challenges." Satyanarayanan (2001) first examined the relationship of this new field with distributed systems and mobile computing, and then identified four new research topics and sketched a couple of hypothetical pervasive computing scenarios.

The eighth paper is Garlan et al.'s (2002) paper on Aura. The project Aura was specifically intended for creating an environment that adapts to the user's context and needs to minimize distractions on a user's attention. The ninth paper by Roman (2002) is associated with an experimental middleware called Gaia. Gaia provided the user-oriented interfaces for helping manage various computing resources distributed in physical spaces.

Through the detailed content analysis of the highly cited papers, it can be inferred from it that this collection of key documents constitute a solid research foundation for other scholars exploring such related themes continuously.

Analysis of co-citation clusters

Co-citation cluster analysis is one of the quantitive techniques. Co-citation cluster analysis for highly cited documents could reflect evolution process of scientific activity and reveal the underlying intellectual structure of a given scientific field. The interpretation of these clusters is augmented by automatic cluster labeling. CiteSpace provides three different algorithms to rank cluster labels, namely tf*idf, log-likelihood ratio tests and mutual information. This study chooses the tf*idf weighting algorithm to characterize the most salient aspect of each co-citation cluster.

Figure 9 shows a screenshot of the timeline visualization, in which 43 co-citation clusters are displayed horizontally alone timelines. In timeline visualization, the legend above the display area marks every 5 years. Cluster labels are automatically generated from title terms of citing papers of specific clusters and they are shown at the end of the cluster's timeline. In addition, this co-citation network's overall modularity score and mean silhouette score are 0.7966 and 0.8318 respectively, suggesting that this network is structured well and every cluster has a satisfactory partition from each other. The modularity Q measures the extent to which a network can be divided into independent blocks, while the silhouette metric tends to estimate the uncertainty involved in identifying the nature of every cluster.

Table 6 lists the six largest document co-citation clusters on pervasive and ubiquitous computing along with cluster ID, size, silhouette value and one of the most representative citing papers in each cluster (except from clusters without labels). Size measures the number of members contained in a given cluster. The citing papers in each cluster are representative of research front of this cluster.

Based on the analysis of Fig. 9 and Table 6, the largest cluster "location service" (#31) with 52 members is one of the most interesting research directions in the field of pervasive and ubiquitous computing. Its lower Silhouette value of 0.269 suggests that it has a much higher connectivity with other clusters because a diverse and complex range of research fronts may have drawn upon the knowledge of this cluster. Location service also is named "location-based service" and it mainly provide targeted information to individuals based on their geographic location in real or near-real time, typically through wireless communication networks and clients such as portable computers, personal digital assistants, mobile phones, and in-vehicle navigation systems. Leonhardt has a prominent role in the

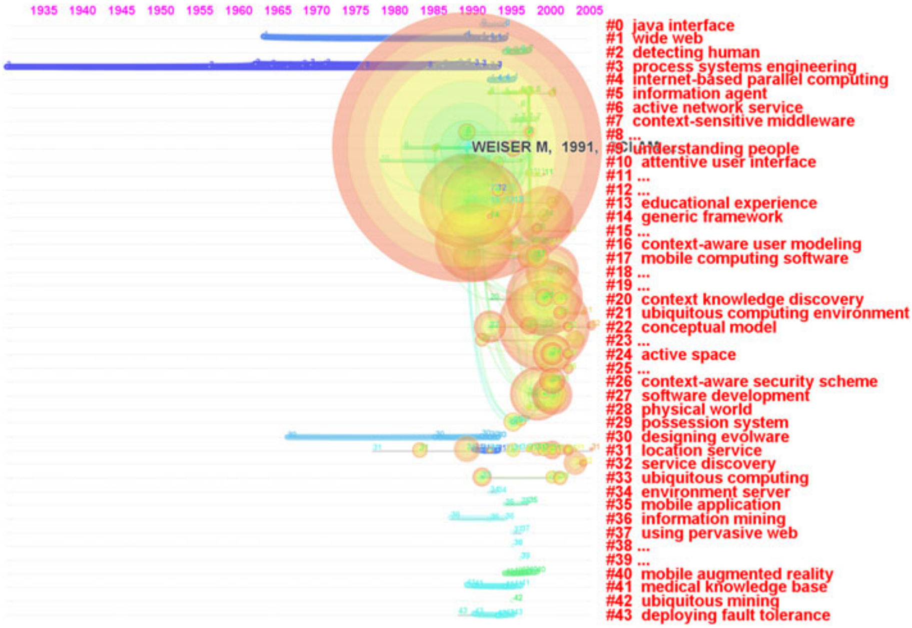

Fig. 9 A co-citation timeline visualization of 43 clusters (1995–2009, time slice length = 1 year, modularity = 0.7966, mean silhouette = 0.8318)

Table 6 The six largest document co-citation clusters on pervasive and ubiquitous computing

Cluster ID	Size	Silhouette	Label (tf*idf)	One of the most representative citing papers
#31	52	0.269	(16.59) location service; (16.18) mobile computing environment	(11) Leonhardt (1996)
#4	19	0.999	(16.59) internet-based parallel computing; (15.26) parallel computing	(12) Christiansen et al. (1997)
#1	16	1	(16.59) wide web; (16.59) connected access	(12) Schilit et al. (1996)
#13	12	0.578	(9.65)educational experience; (9.65) digital library; (8.06) making sharing	(4) Abowd et al. (2000)
#5	11	0.841	(6.85) information agent; (6.79) pervasive environment	(2) Finin et al. (2001)
#9	9	0.702	(9.99) understanding people; (8.62) augmented reality; (8.06) military environment; (6.12) interaction concept; (6.12) input device	(5) Schmalstieg et al. (2000)

research front of this cluster and he cited 11 references of the cluster in his paper named "location service in mobile computing environments."

Cluster ID #4 is the second largest cluster with 19 members. It has a high silhouette value of 0.999, which represents a perfect differentiation from other clusters in the network. Its labeling term is called "internet-based parallel computing." One of its citing papers called "Javelin: internet-based parallel computing using java" written by Christiansen et al. (1997), mainly used java to construct the internet-based parallel computing and complete application service.

The third largest cluster (#1), with 16 members, is labeled as “wide web” and one of its active citers designed a system called “teleweb” for people to have access to the World Wide Web anytime and anywhere with the purpose of getting work done. “Educational experience” (#13) consisting of 12 members, is about researching the application of ubiquitous computing technology to support the automatic capture of live university lectures. Cluster ID #5 contains 11 members with emphasis on information agent in the pervasive environment. Cluster ID #9 focuses on “understanding people” and its other candidate labels for this cluster include augmented reality, military environment, interaction concept and input device. Augmented reality as the second candidate label is a combination of context-aware and natural interaction. So this cluster is also concerned with context. The detailed information about the remaining clusters is shown in Table 6.

An examination of the mean year suggests the temporal distribution of the co-citation clusters (Table 7). The mean year is an estimation of the time the cluster was formed according to the average age of co-citation papers in every cluster. It ranges from 1988 to 2005. The earliest cluster formed in 1988 is labeled as “designing evolware” or “cellular programming” (#30) and it reveals the fact that researchers brought in the idea of the cellular programming algorithm to perform useful computations.

The clusters over the period of 1991–1995 include attentive user interface (#10), wide web (#1), information mining (#36), understanding people (#9), deploying fault tolerance (#43), environment server (#34), medical knowledge base (#41), internet-based parallel computing (#4), Educational experience (#13), java interface (#0).

There are 15 clusters formed during the time span of 1996–2000. They are: location service (#31), detecting human (#2), possession system (#29), generic framework (#14),

Table 7 The document co-citation clusters sorted by the mean year

Mean year	Cluster ID	Cluster labels	Mean year	Cluster ID	Cluster labels
1988	#30	Designing evolware	1997	#37	Using pervasive web
1991	#10	Attentive user interface	1998	#5	Information agent
1992	#1	Wide web	1998	#17	Mobile computing software
1993	#36	Information mining	1998	#16	Context-aware user modeling
1994	#9	Understanding people	1998	#35	Mobile application;
1994	#43	Deploying fault tolerance	1998	#40	Mobile augmented reality
1994	#34	Environment server	1998	#6	Active network service
1995	#41	Medical knowledge base	1998	#7	Context-sensitive middleware
1995	#4	Internet-based parallel computing	2000	#20	Context knowledge discovery
1995	#13	Educational experience	2000	#28	Physical world
1995	#0	Java interface	2001	#27	Software development
1997	#31	Location service	2001	#22	Conceptual model
1997	#2	Detecting human	2002	#26	Context-aware security scheme
1997	#29	Possession system	2002	#24	Active space
1997	#14	Generic framework	2004	#21	Ubiquitous computing environment
1997	#42	Ubiquitous mining	2005	#32	Service discovery

ubiquitous mining (#42), using pervasive web (#37), information agent (#5), mobile computing software (#17), context-aware user modeling (#16), mobile application (#35), mobile augmented reality (#40), active network service (#6), context-sensitive middleware (#7), context knowledge discovery (#20) and physical world (#28).

The research clusters during the time interval of 2001–2005 include software development for ubiquitous computing environments (#27), conceptual model for context-aware adaptive services (#22), context-aware security scheme (#26), active space (#24), ubiquitous computing environment (#21) and service discovery (#32).

In summary, the formation process of clusters suggests that the research tasks on pervasive and ubiquitous computing have gone towards from the fundamental theory exploration to technical implementation to practical application and service. Moreover, the scope of the research topics has become more and more widespread, yet more and more deeply.

Analysis of research foci

An analysis of terms such as keywords can help us identify hot topics of pervasive and ubiquitous computing research. Figure 10 shows a hybrid network of keywords and noun phrases with 241 nodes and 988 links. Keywords are shown as triangles, whereas noun phrases are shown as circles. Triangle shapes in the map indicate fast-rising terms in titles and abstracts. Table 8 lists the top 26 terms with co-occurrence frequency of over 60 times. From Fig. 10 and Table 8, we can clearly see that the most-frequently used terms are ubiquitous computing with 1,306 times and pervasive computing with 906 times. Ubiquitous computing environment and pervasive computing environment are the second largest hotspot in pervasive and ubiquitous computing and appear 710 and 494 times respectively. So it can be learned that with the advent of ubiquitous computing, most researchers have focused on the study of ubiquitous computing environment. Pervasive and ubiquitous computing aims to create smart environments that embed computation and communication in a manner that contextually interacts with users to ease their daily life. Ubicomp environment involves the interaction, coordination, and cooperation of numerous, casually accessible, and often invisible computing devices.

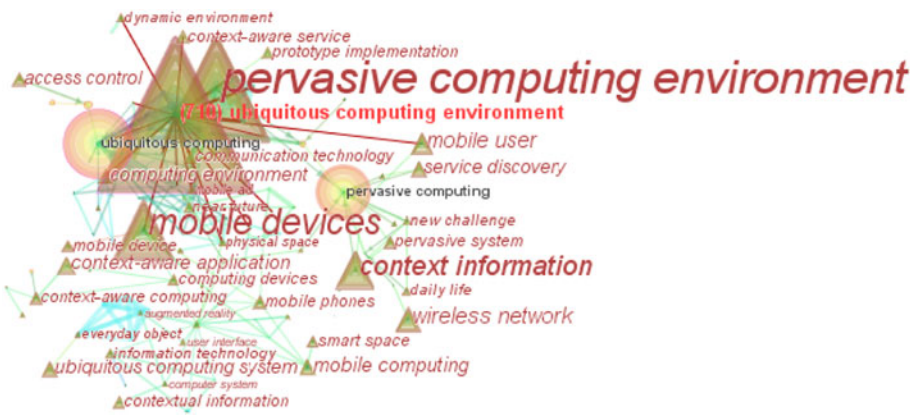

Fig. 10 A hybrid network of the high-frequency keywords and noun phrases

Table 8 Keywords\noun phrases with frequency more than 60 times in pervasive and ubiquitous computing documents

Frequency	Keywords\noun phrases	Frequency	Keywords\noun phrases
1,306	Ubiquitous computing	95	Context-aware application
906	Pervasive computing	91	Mobile computing
710	Ubiquitous computing environment	88	Pervasive computing system
494	Pervasive computing environment	86	Ubiquitous computing system
287	Mobile devices	84	Service discovery
196	Ubiquitous environment	76	Mobile agent
183	Context information	71	Smart space
154	Pervasive environment	70	Context-aware service
133	Wireless network	69	Mobile device
118	Web service	67	Grid computing
116	Mobile user	66	Prototype implementation
105	Ubiquitous computing technology	65	Context-aware computing
102	Ubiquitous computing application	64	Pervasive system
99	Ambient intelligence	63	Computing devices

The term “mobile devices” is the third largest hotspot with 287 occurrences. Mobile devices make up the personal pervasive computing environments and are playing an important role in our daily lives. The other similar high-frequency terms include mobile user, mobile agent and mobile computing. In Ubicomp, a mobile user is the center of computing, and services need to be delivered to the user adaptively according to the variation of context. Mobile agents are programs that can freely migrate from node to node in a network, acting on behalf of their users to employ knowledge and reasoning to understand the local context and share this information in support of intelligent applications and interfaces. Mobile computing is one of the two distinct earlier steps in the evolution process of pervasive and ubiquitous computing, whereas, pervasive and ubiquitous computing helps kick off the recent boom in mobile computing research.

Context information is the fourth active topic of research and its occurrence is 183 times. Other related hot topics on “context” in Table 8 include context-aware application, context-aware service and context-aware computing. These related terms originated in the first introduction of “context aware” by Schilit and Theimer (1994) to address the ability of systems to discover and react to changes in the environment. Context-aware computing actually intends to make computers more aware of the physical and social worlds we live in. Since the introduction of context-aware computing, many studies have been carried out and many researchers have attempted to define the term “context.” An accepted definition is proposed by Abowd et al. (1999) and so-called “context” meant any information that can be used to characterize the situation of an entity. The research themes about it have been expanding, including context-aware access control model, context reasoning, intelligent context-aware system, and context-aware active task discovery and so on.

The high-frequency keywords also show other hotspots on pervasive and ubiquitous computing, including wireless network, ubiquitous computing technology, ubiquitous computing application, ambient intelligence, ubiquitous computing system, service discovery, smart space, grid computing, prototype implementation, pervasive system, computing devices and so on.

Among these hot spots, ambient intelligence is a recent paradigm in information technology. It can be defined as the merger of two important visions and trends: ubiquitous computing and social user interfaces. It place strong emphasis on the fact that interaction takes place through natural interfaces, in such a way that people can perceive the presence of smart objects only when needed.

Service discovery aims to efficiently leverage the computational resources available of mobile devices. It covers many hot topics such as service discovery mechanisms, service discover models, service discover system and protocols, web service discovery, semantic web service discovery, grid service discovery and so on.

Smart space is an important research area which integrates the physical world and the information space. A smart space is a smart environment that has commuting embedded into it and can provide information that can be used to model the real world into the virtual computing world. In order to help users accomplish tasks in a highly effective manner,it places emphases on natural human computer interaction,and adapts well to the dynamitic evolvement of users and devices. The several practical examples on it include Smart Space by National Institute of Standards and Technology, Aware Home by Georgia Institute of Technology, Intelligent space by the University of Tokyo.

The term "grid computing" was coined in the middle 1990s to denote a proposed distributed computing infrastructure for advanced science and engineering (Foster et al. 2001). The essential of grid computing is coordinating heterogeneous computing resources across a networked environment and complete tremendous computational task. The SETI@home may be the best known grid computing project. Actually there are at least five categories of grid computing applications, namely distributed supercomputing, high throughput computing, on-demand computing, data intensive computing and collaborative computing.

Conclusion

This paper takes advantage of CiteSpace to conduct a comprehensive analysis of pervasive and ubiquitous computing. CiteSpace is a powerful information visualization tool to help us uncover the structural and temporal patterns of various co-citation networks. For pervasive and ubiquitous computing, yearly publications sustained a notable growth as a whole from 1995 to 2007 and then showed the ascending trend in recent 2 years. Pervasive and ubiquitous computing is developed from Computer Science and Computer Science remains its major research area. Such subjects as Engineering and Telecommunications also are engaged in research activities related to it. The contributing research community to pervasive and ubiquitous computing distribute over various countries and USA, South Korea, People's of China and Japan are the most productive countries. *Lecture Notes in Computer Science, Communications of the ACM, Scientific American* and *IEEE Pervasive Computing* are the representative journals in the field of pervasive and ubiquitous computing. The most influential scholars include Weiser, Dey, Satyanarayanan, Want, Abowd, Roman, Chen, Kindberg, Ranganathan and Garlan. The co-citation cluster analysis for highly cited documents in terms of the mean year reveals the evolution pattern of research themes over the past 15 years. Furthermore, our analysis has identified a diverse and dynamic landscape of research foci that peaked in the past, such as ubiquitous computing environment, mobile devices, context, wireless network and ambient intelligence.

As an exploratory study, this research has limitations. We have only collected bibliographic records on pervasive and ubiquitous computing from one database—the WoS. Also, the WoS did not begin to collect papers on pervasive and ubiquitous computing until

1995, so the research missed a small amount of papers that had been published before 1995. The two cases described above could result in the number limitation of papers on pervasive and ubiquitous computing. Future studies may carry out a broader study based on other databases to complement the preliminary results with the current study. In addition, it is necessary for us to analyze important domestic and international conferences and large-scale projects from every country involved in this field. Qualitative methods also should be used in the future for in-depth examination with other aspects such as the collaboration patterns of researchers in the field of pervasive and ubiquitous computing.

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