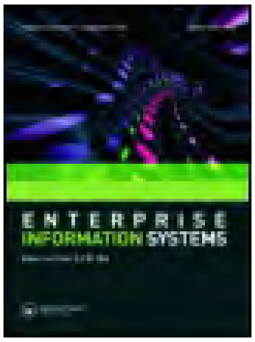

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A semantic similarity analysis of Internet of Things

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ARTICLE

A semantic similarity analysis of Internet of Things

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ABSTRACT

Internet of Things (IoT) has gradually become one of the most popular topics among both academia and industry, and it is considered as a crucial part of future Internet. However, very few objective and systematic review was conducted to address high-value articles and summarize the intellectual components from journals for examination and identification of the intellectual core and structure of IoT. Therefore, this study conducted a co-citation analysis for IoT by using 68 high-value articles retrieved within 1457 source papers from Web of Science online database. By using factor analysis, ten critical factors were identified, which includes (1) frameworks and challenges of IoT; (2) current situation of IoT in different applications; (3) interactions of IoT; (4) security issues of IoT; (5) application domains of IoT; (6) data management of IoT; (7) IoT in product lifecycle management; (8) enabling technologies of IoT; (9) IoT in smart cities; (10) IoT in recommender systems. Hierarchical Custer Analysis and Multidimensional Scaling were used to graphically illustrate the intellectual elements of IoT. In the current findings, fundamental elements of IoT including architectural framework, enabling technologies, network communication, data management, and IoT interactions were discussed with a series of challenges for wider and deeper IoT applications.

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Internet of things; IoT; citation; co-citation

1. Introduction

In the recent years, Information and Communication Technologies (ICTs) develop rapidly toward the directions of 'Smart' and 'Ubiquitous', more and more people no matter from academia or industry begin paying significant attention to Internet of Things (IoT). IoT refers to a global communication network interconnecting addressable physical and virtual objects through intelligent communication interfaces. (EPoSS 2008) It is initiated by the development of Radio-Frequency IDentification (RFID) and Electronic Product Code™ (EPC). Nowadays, IoT is generally associated with many modern technologies and concepts such as Big Data analytics, cloud computing (internet of services), Industry 4.0, ubiquitous computing and Machine to Machine (M2M). Therefore, IoT is believed in offering considerable potentials on researches and developments in various existing application domains such as logistics, healthcare, smart environment, personal and social domain, and even futuristic applications such as robot taxi and City Information Model (CIM). (Atzori, IERA, and Morabito 2010) According to a technology forecast report conducted by Gartner Inc., the number of IoT devices, which excludes PCs, tablets and smartphones, will reach 26 billion, and the generated incremental revenue will be over $300 billion in 2020 (Gartner 2013).

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Foreseeing this prospect, many IoT-based alliances have been established towards IoT's research and development, such as Alliance for Internet of Things Innovation (AIOTI), IoT European Research Cluster (IERC), Internet of Things Consortium, and Internet Protocol for Smart Object (IPSO) Alliance. This prospect also attracts various companies investing on different aspects of IoT. For example, Garageio, Xively and Pubnub develop their business on remote product management; Sigfox, Qulsar and Numerex focus on the business of wireless M2M network; Japster Technology, BaseN and Carriots provide solutions of cloud-based IoT platform; And, OpenPicus, SmartThings, SolidRun and Intel supply IoT related hardware. Besides different organizations, different countries and regions have also established strategies to respond the wave of IoT, such as the 'Smarter Planet' of United State, the 'Sensing China' of China, the 'IoT Strategic Research Roadmap' of European Union, the 'i-Japan' of Japan and the 'u-Korea' of South Korea (Zhang et al. 2015a).

As the same situation, IoT has become a popular and important research topic among scholars in the recent decade, numerous journals have been published to discuss with it. According to Google Scholar, which is a bibliographic web search database including 160 million documents in 2014 (Orduña-Malea et al. 2014), there are 9140 articles and books about IoT research, which substantial literature reviews, analyses and discussions on different dimensions of IoT have been conducted. However, the cited articles in previous studies are not clearly justified in terms of their selection criteria and the degree of impact in the field of IoT. This may weaken the objectivity of these studies and may lead to a result that some of main intellectual components of IoT cannot be revealed. Another issue is most of the studies may not cover all aspects of IoT or may not review some aspects in depth, which cause intellectual components from journals are scattered. As a result, researchers and practitioners are difficult to identify the panoramic view of intellectual structure of IoT and may not obtain expected results when implementing IoT through these studies. To address this gap, this research utilized a relatively objective, quantitative and systematic approaches for examination of the intellectual structure of IoT. Firstly, citation and co-citation analysis, which are the well-known statistical bibliometric analysis approaches for identification of intellectual structure in a specific academic field (Pilkington and Meredith 2009), were applied to extracted IoT related papers with high citation rate, which the citation threshold in this study is 16. These papers are considered as high-value papers in the field of IoT. In the next step, factor analysis, Hierarchical Cluster Analysis (HCA) and MultiDimensional Scaling (MDS) are used to address the dimensionalities of IoT using the high-value papers. Through analyses of the dimensionalities of IoT, the comprehensive intellectual structure of IoT can be clearly presented.

In this paper, sufficient number of influential IoT related journals were collected from Web of Science online database for identification of intellectual structure of IoT. Total 1457 articles and 7029 cited references were yielded from 2004 to 2015. Co-citation analysis was adopted to analyse the correlations among these collected articles and identify groups of articles, which address different intellectual core components of IoT works. The remainder of the paper is organized as follows. In Section 2, a literature review of IoT and citation and co-citation analysis is provided. The research methodology, which includes citation analysis, co-citation analysis, factor analysis, HCA and MDS is described in Section 3. Section 4 presents the research results and Section 5 provide the result discussions and findings. The conclusion is provided in Section 6 and the research limitation and further study are presented in Section 7.

2. Literature review

2.1 *Internet of things (IoT)*

The term Internet of Things (IoT) was firstly brought up in 1999 by Kevin Ashton, who was the cofounder of the Auto-ID Labs at MIT. He presented the concept about connecting the Internet and the physical things in the world through leveraging Radio-Frequency IDentification (RFID) and sensor technologies (Ashton 2009). In 2005, International Telecommunication Union (ITU) published an official report on IoT and expounded the vision of IoT, which is to connect everyday 'things' to communication networks at 'anytime, anywhere, by anyone and anything.' (ITU 2005) Later on, ITU issues the definition of IoT as 'A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.' (ITU-T 2012). The visions of IoT are categorized into three perspectives based on three different focuses. The name of IoT provides clues for the first two perspectives. 'Things oriented' visions focus on 'things' identification and integration, which includes RFID, Wireless Sensor and Actuator Networks (WSAN), Unique/Universal/Ubiquitous IDentifier (UID) (Sakamura 2006) and Smart Objects/Items. 'Internet oriented' visions including IP for Smart Objects (IPSO) (Dunkels and Vasseur 2008) e.g. 6LoWPAN (Hui, Culler, and Chakrabarti 2009), Internet 0 (Gershenfeld, Krikorian, and Cohen 2004) and Web of Things (Guinard and Vlad 2009) focus on devices networking, connection efficiency and IP simplification for devices with limited capacity. The last perspective, 'Semantic oriented', is about managing the numerous IoT devices and tremendous amount of information generated by such devices. These visions include semantic technologies, reasoning over data, and semantic execution environments (Atzori, Iera, and Morabito 2010). Another concrete definition of IoT is issued by the Cluster of European Research projects on the Internet of Things (CERP-IoT), which IoT is defined as 'a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.' The visions of IoT are specified to cover Pervasive Computing, Ubiquitous Computing and Ambient Intelligence, which allows 'people and things to be connected Anytime, Anyplace, with Anything and Anyone, ideally using Any path/network and Any service.' (Sundmaeker et al. 2010). The visions are further extended to cover Web 2.0, "Internet Protocol (IP), communication technology, embedded devices, its applications, the Internet of People or the Intranet/Extranet of Things." (Uckelmann, Harrison, and Michahelles 2011).

Towards the visions of IoT, the architecture of IoT should fulfil a series of high level and specific requirements. Since IoT interconnects heterogeneous and scattering 'things' in both physical and virtual world, the design of IoT architecture should consider the interoperability, flexibility, scalability, efficiency of real-time interaction and event-driven handling capability. Therefore, multi-layer Service Oriented Architecture (SOA) is considered as a feasible approach for IoT among the literature. A generic SOA of IoT consists of four major layers: sensing/perception/device layer, network/networking layer, service layer and interface/application layer. (Li, Xu, and Zhao 2015) In some literature, the service layer and interface/application layer are combined into one layer. (Domingo 2012) Sensing/perception/device layer contains numerous 'things' with unique identities. These 'things' are capable to provide their internal (i.e. the status of the smart objects) and external (i.e. the condition of the surrounding environment) sensors data, and capable to exchange data with each other through wire or wireless communication. Network/networking layer acts as a role to provide specific data transport of IoT related services, controls, and applications, network connectivity management and Quality of Service (QoS) management. In the service layer, there are some common components including service discovery, service composition, service repository and trustworthiness management for the operations of all service-oriented activities. Based on these components, various sets of application requirements, service Application Programming Interfaces (APIs) and protocols required applications and services could be found for performing various service requests and responses, such as information exchange, data management, 'things' monitoring and communication. IoT middleware is also integrated in this layer to provide efficient and flexible interfacing functionalities between IoT related hardware and software. Lastly, interface/application layer contains various interaction methods to allow different users and applications effectively interacting with IoT related services.

From the rise of the IoT concept to nowadays, realising IoT become more concrete and possible since many new technologies emerge and many existing technologies are developed to be mature. Some of these technologies are key enabling technologies, which the integration of them is driving the visions of IoT. These key enabling technologies can be divided into several categories: (1) Identification technologies including (but not limited to) RFID, Near Field Communication (NFC) and barcode system; (2) Sensing technology including (but not limited to) WSN and WSAN; (3) Communication technologies including (but not limited to) Ethernet, WiFi, Zigbee, Bluetooth, UWB, WiMax and Cellular Network;(4) Addressing scheme including (but not limited to) IPv6 and 6LoWPAN, (5) Cloud computing; (6) Big Data analytics. By integrating these key technologies, IoT possesses considerable potential for developing various innovative and intelligent applications in many different fields. Table 1 lists some examples of IoT applications in various fields.

2.2 *Co-citation analysis*

The general concept of co-citation was developed based on bibliographic coupling. Bibliographic coupling refers to two documents contain one or more same citation. It is the earliest citation analysis measure for document similarity, which is suggested by M.M. Kessler in 1963 (Kessler 1963). However, the biggest drawback of bibliographic coupling is the timeliness. Since the similarity relationship between journals is static and lies in the past, the coupling strength remains unchanged over time. In 1973, Henry Small (1973) introduced co-citation analysis, which is another semantic similarity measure of citation relationship between papers. Co-citation was defined as the frequency that two documents are cited together in the same document. Under the assumption that the co-citation rate reflects the actual influences of significant concepts and ideas in a specific field and the peer recognitions, co-citation can be adopted to identify the relationships among topics, journals, keywords and authors, as well as reveal the structures of these relationships in a specific field, thereby establish an intellectual core for that field (Small 1973). When new papers appear and old papers fade out continually, the co-citation patterns vary over time following the changes of scientific trend. Thus, co-citation measure is a more appropriate indicator for monitoring the development of various fields (Sullivan et al. 1980). There are three types of co-citation analysis, which includes document co-citation analysis, author co-citation analysis, and journal co-

Table 1. Examples of IoT applications in various fields.

Fields	Applications	Authors (year)
Health care	Remote human gait tracking	Luo et al. (2010)
	IoT-Based Information System for Emergency Medical Services	Xu et al. (2014)
Food supply chain	Value-centric food supply chain management	Pang et al. (2015)
Environmental monitoring	Tailings dam monitoring	Sun, Zhang, and Li (2012)
	Regional environmental monitoring	Fang et al. (2014)
Transportation and logistics	Urban Intelligent Transportation System	Zhou, Liu, and Wang (2012)
Smart home	Daily activities recognition and tracking	Rashidi et al. (2011)
	Smart thermostat	Lu et al. (2010)
Smart industry	Automated assembly modeling system	Wang, Bi, and Xu (2014)
	Real-time information of manufacturing resources capturing and integration	Zhang et al. (2015b)
Smart city	Smart parking system	Polycarpou, Lambrinos, and Protopapadakis (2013)
Smart grid	Smoothing household electrical loads	Ancillotti, Bruno, and Conti (2014)
	Load balancing and monitoring and control of distributed energy systems	Kleineidam, Krasser, and Reischböck (2016)
Agriculture and breeding	Crop Monitoring System	Zhao et al. (2011)
	Livestock tracking	Voulodimos et al. (2010)
Product lifecycle management	Configurable information service platform for product lifecycle Management	Cai et al. (2014)

citation analysis (Hsiao and Yang 2011). This study primarily focuses on document co-citation analysis since key concepts and ideas related to IoT are scattered in different journal papers written by various authors.

Co-citation analysis has been one of the popular measures in different scientific fields for identification of knowledge. Many studies has been demonstrated the validity of this measure. For examples, Sircar, Nerur, and Mahapatra (2001) adopted co-citation analysis to compare the object-oriented and structured system development methods. Schildt, Zahra, and Sillanpää (2006) adopted co-citation analysis to examine the entrepreneurship research. Some researchers utilized the co-citation patterns of articles from different period to analysis development of a specific field in a specific period. Nerur, Rasheed, and Natarajan (2008) conducted co-citation analysis to find out the underlying structure in strategic management within 1980 – 2000 while Ferreira, Fernandes, and Ratten (2016) examine the period from 1971–2014. Furthermore, Tight (2008) adopted co-citation analysis in an education research. Pilkington and Meredith (2009) made a document co-citation analysis to explore operation management. Walter and Ribière (2013) examined 10 years of Knowledge Management (KM) theory and practices by using citation and co-citation analysis. Appio, Cesaroni, and Di Minin (2014) explored the underlying structure of the intellectual property management research by using document co-citation analysis. Wang et al. (2016) explored the research papers from 2004 to 2014 in Information System (IS) discipline for a citation and co-citation analysis on cloud computing. Shiau (2016) adopted co-citation analysis with factor analysis, MDS and cluster analysis to examine the intellectual core of enterprise information systems. In the same year, Shiau, Yan, and Kuo (2016) also adopted co-citation analysis to examine Human Computer Interaction (HCI) research.

3. Methodology

The source articles were collected from Web of Science/Web of Knowledge databases in order to guarantee the quality of raw data. Statistic methods namely citation, co-citation, factor, MDS and cluster analysis, were used to examine the intellectual structure of IoT studies. Figure 1 illustrates the flow of the research process used in this study. After retrieving related articles from Web of Science, the citation analysis was used for the identification of high-value articles and the record of citation growth. After screening out irrelevant articles, co-citation analysis was used to compile a co-citation matrix, which is an input for further statistical analyses, i.e. Factor analysis, HCA and MDS. These analyses were conducted to analyse and determine the intellectual structure of IoT studies.

3.1 *Data collection*

In this research, the representative research papers related to IoT were retrieved from Web of Science. Web of Science is a world's leading online platform connecting many high-reputation scientific databases for providing scientific paper search and discovery, and scientific citation indexing service. This platform covers over 12,500 high quality journals, 170,000 conference proceedings and 70,000 scholarly books from more than 250 disciples (Thomson Reuters 2016). It is trusted by approximately 7,000 worldwide scholarly institutions. More importantly, it provides a useful function to list the searching result sequentially based on citation counts. Such function enables user to sort out the highly cited articles efficiently. In the next step, a set of search keywords were defined. The main keywords to search IoT-related studies are 'internet of things' and 'IoT'. However, some papers without these two main keywords may include IoT-related content. For instance, before the raising of IoT paradigm, RFID and M2M related studies shaped the concept of IoT. When IoT emerges, cloud and NFC are two of the main components mentioned together with IoT in many studies. Consequently, the set of keywords is defined as **KEYWORDS** = {'internet of things', 'IoT', 'machine-to-machine', 'M2M', 'radio frequent

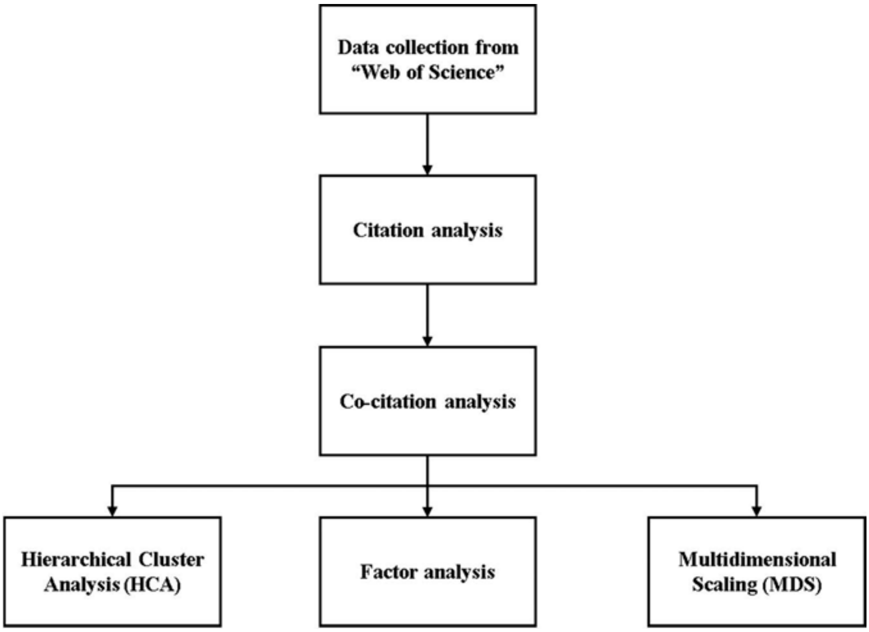

Figure 1. The flow chart of research process.

identification', 'RFID', 'near field communication', 'NFC', 'cloud'} after reviewing the development and components of IoT. By using these keywords, 1457 results and 7029 total number of citations to all the results could be yielded from 2004 to 1 November 2015 in Web of Science.

3.2 *Data analysis*

3.2.1 *Citation analysis*

Eugene Garfield, who is the 'father of citation indexing of academic literature' (Jacso 2010), mentioned the importance of citations: Citation is the explicit linkages between articles which contain similar specific contents together. Citation index is created to represent those linkages and it discloses the sources of citations. Because of the citation index, a literature search of an article can find how many and what documents have cited the article by providing the citation list (Garfield 1979). Citation analysis can list the citation sources of studies and record their citation growth continuously in a literature field. Citation index can be used to determine high-value papers because high citation index will be accumulated if a study is frequently cited, and thus researchers can make use of citation index to identify valuable articles. Citation analysis cannot be solely used to reveal the structure of a specific academic area because it ignores the linkage among topics and journals. Therefore, citation analysis was only conducted to screen out less influential articles for next stage, co-citation analysis.

3.2.2 *Co-citation analysis*

Co-citation analysis has been an illustrious structuring measure in bibliometrics (Borgman 1989). It counts the frequency of two papers that are cited together in the same article (Small 1973) and forms a co-citation frequency matrix. To form the matrix, two sets of documents should be obtained. One set contains highly cited papers which are representable in a research area while another set contains papers citing those highly cited papers (Hsiao and Yang 2011). Thus, following citation analysis process, a set of papers $\boldsymbol{P}$ related to a specific field or topic was obtained. Among $\boldsymbol{P}$, the set of high-value papers $\boldsymbol{P_h}$ can be identified, which $\boldsymbol{P_h} \subseteq \boldsymbol{P}$ and $\boldsymbol{P_h}$ contains the papers with a number of citations larger than a specific threshold. In the next step, every article in ***P*** was checked whether it cited more than one high-value paper in common. If a paper cited two high-value papers together, a co-citation frequency was generated for those two papers. Finally, an ***N*** x ***N*** co-citation matrix was formed, where ***N*** is the cardinality of $\boldsymbol{P_h}$. The co-citation matrix is a raw input for factor, hierarchical cluster and MDS analyses.

3.2.3 *Factor analysis*

Factor analysis is a well-known statistical measure to examine interrelationships between an enormous set of variables such as authors, journals or articles. This measure divides large set of variables into smaller group of factors and explains maximum amount of observations with minimum number of explanatory factors (Field 2013). There are two main types of factor analysis, which called confirmatory factor analysis (CFA) and exploratory factor analysis (EFA). Generally, CFA expects that the number of factors is confirmed before performing the analysis. In contrast, EFA does not have this assumption. In this study, 'factor' is the labelling of interrelated groups of variables performing data reduction and summarization among similar articles. Every factor is comprised of influential papers which are highly co-cited by other papers within a particular field (McCain 1990) and factor can also be treated as subfield in an academic area. Different factors provide the foundation of the subfields and they portray the intellectual core of an academic area. Therefore, the technique, factor analysis, used in this study is EFA and it is commonly used in document analysis such as co-citation analysis (Leydesdorff and Vaughan 2006).

3.2.4 *Hierarchical cluster analysis (HCA)*

Hierarchical Cluster Analysis (HCA) is a statistical method to cluster a group of data set into different sub-groups based on their unique characteristics. In the same sub-group, elements are more similar than those in other sub-groups. There are two strategies for HCA, namely agglomerative and divisive strategies (Rokach and Maimon 2005). Agglomerative HCA is a 'bottom-up' approach, which each observation is considered as a separate cluster and these clusters are combined while moving up the hierarchy until all clusters are merged into one cluster. Divisive HCA is a 'top-down' approach, which all observations are considered as one large cluster and this cluster divided into many sub-groups recursively while moving down the hierarchy. In this research, agglomerative HCA is adopted, which documents shared similar attributes are grouped in the clustering procedure. Thus, each group represents a subfield in an academic area (McCain 1990).

4. Results

In this research, total 1457 IoT related papers from 2004 to 1 November 2015 and 7029 total number of citations to all the results were obtained in Web of Science, as shown in Figure 2. The year analysis reveals that the number of published IoT-related articles has gradually increased since 2004. In order to ensure the influential papers, especially the newly added papers were included, the citation threshold was set as 16 citations (Shiau and Dwivedi 2013; Shiau 2016). As a result, total 84 articles within the 1457 IoT related papers were retrieved. The 84 papers were then reviewed manually to ensure all are highly related to IoT. Three criteria were established for screening irrelevant papers, which are (a) Limited counts of keywords 'Internet of things', 'IoT' or equivalent; (b) No paragraph related to IoT; (c) Gist is relevant to IoT, but in a small extent. Consequently, 68 papers, which are listed in Table 2, would be source documents for co-citation methods. Next, a 68 × 68 co-citation matrix were formed by these source documents. This co-citation matrix was then transformed into Pearson's R correlation matrix for further statistical analyses. The diagonal value of the correlation matrix is one because each observation should correlate with itself perfectly (Field 2013).

4.1 *Factor analysis*

The factor analysis was conducted by using SPSS software with the input of the Pearson's R correlation matrix. When factors are extracting, papers were determined to which factor they are

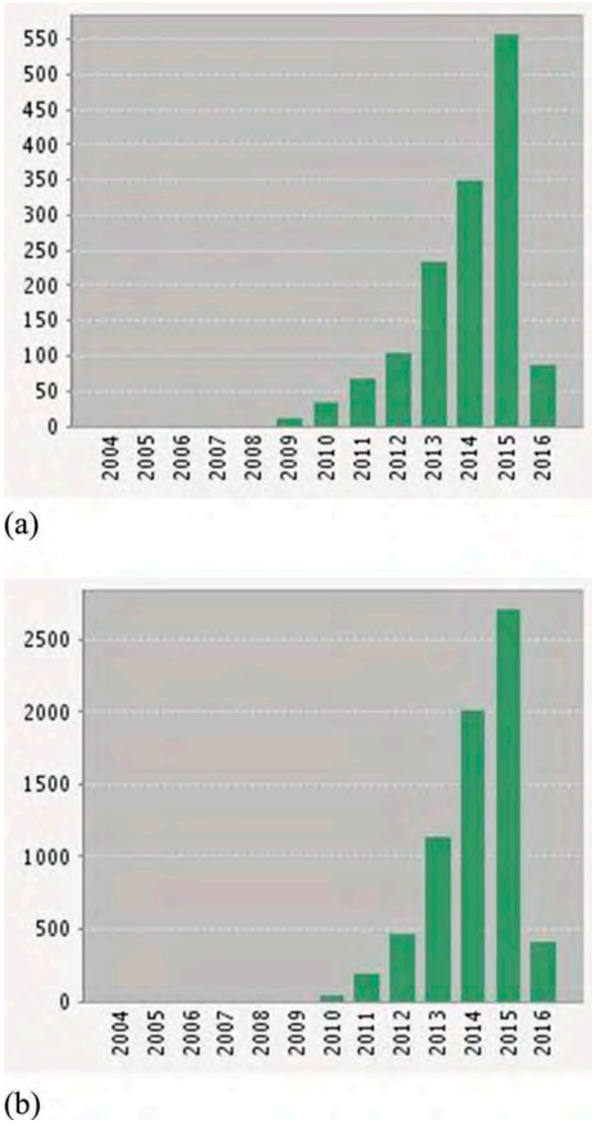

Figure 2. Citation report obtained from web of science. (a) Published articles of searching results. (b) Total number of cited references to all items in the searching result.

belonged to, by calculating the degree of variables load (or loading) on each factor. In general, most observations have high loadings on the most important factors but small loadings on remaining factors. In order to improve the interpretation of factor analysis, varimax rotation method was adopted, because varimax rotation maximizes the loadings dispersion within factors. Thus, the interpretation of factor analysis result will be more acceptable (Andrews 2003; Zhao and Strotmann 2008; Shiau 2016). To further reduce the number of factor, eigenvalue is set to be greater than one. This setting retains all qualified factors and excludes less influential factors (Kaiser 1960). For examining the appropriateness for conducting factor analysis in this research, Kaiser–Meyer–Olkin (KMO) test and Bartlett's test were applied. Since the input correlation matrix is not positive definite (PD), the test result cannot be obtained in SPSS. Therefore, the input correlation

Table 2. The 68 most frequently cited IoT related papers.

ID	Authors (Year)	Source	Times cited	ID	Authors (Year)	Source	Times cited
1	Atzori, Iera, and Morabito (2010)	Computer networks	849	**35**	Li et al. (2011)	IEEE Communications Magazine	33
2	Gubbi et al. (2013)	Future Generation Computer Systems	177	**36**	Xu, He, and Li (2014)	IEEE Transactions on Industrial Informatics	32
3	Miorandi et al. (2012)	Ad Hoc Networks	170	**37**	Zhong et al. (2013)	The Journal of Supercomputing	32
4	Kortuem et al. (2010)	IEEE Internet Computing	153	**38**	Bormann, Castellani and Shelby (2012)	IEEE Internet Computing	32
5	Gershenfelo, Krikorian, and Cohen (2004)	Scientific American	132	**39**	Watteyne et al. (2012)	Transactions on Emerging Telecommunications Technologies	31
6	Guinard et al. (2010)	IEEE Transactions on Services Computing	117	**40**	Tozlu et al. (2012)	IEEE Communications Magazine	29
7	Welbourne et al. (2009)	IEEE Internet Computing	116	**41**	López et al. (2012)	Personal and Ubiquitous Computing	28
8	Ganti, Ye, and Lei (2011)	IEEE Communications Magazine	107	**42**	Sheng et al. (2013)	IEEE Wireless Communications	27
9	Bobadilla et al. (2013)	Knowledge-Based Systems	105	**43**	Hancke, Silva and Hancke (2013)	Sensors	27
10	Xu (2011)	International Journal of Production Research	98	**44**	Estrin (2010)	IEEE Internet Computing	26
11	Zorzi et al. (2010)	IEEE Wireless Communications	71	**45**	Perera et al. (2014b)	Transactions on Emerging Telecommunications Technologies	25
12	Bandyopadhyay and Sen (2011)	Wireless Personal Communications	63	**46**	Barnaghi et al. (2012)	International Journal on Semantic Web and Information Systems	25
13	Shelby (2010)	IEEE Wireless Communications	57	**47**	Roman, Zhou, and Lopez (2013)	Computer Networks	24
14	Li, Xu and Wang (2013)	IEEE Transactions on Industrial Informatics	56	**48**	Kelly, Suryadevara, and Mukhopadhyay (2013)	IEEE Sensors Journal	23
15	Kiritsis (2011)	Computer-Aided Design	54	**49**	Vlacheas et al. (2013)	IEEE Communications Magazine	23
16	Zhou and Chao (2011)	IEEE Network	54	**50**	Palattella et al. (2013)	IEEE Communications Surveys & Tutorials	22
17	Roman, Najera, and Lopez (2011)	Computer	53	**51**	Heer et al. (2011)	Wireless Personal Communications	22
18	Jara, Zamora, and Skarmeta (2011)	Personal and Ubiquitous Computing	50	**52**	Främling et al. (2007)	International Journal of Computer Integrated Manufacturing	21
19	Perera et al. (2014a)	IEEE Communications Surveys & Tutorials	48	**53**	Chen, Wan, and Li (2012)	KSII Transactions on Internet & Information Systems	20
20	Domingo (2012)	Journal of Network and Computer Applications	46	**54**	Jara, Zamora, and Skarmeta (2012)	Mobile Information Systems	20

(*Continued*)

Table 2. (Continued).

ID	Authors (Year)	Source	Times cited	ID	Authors (Year)	Source	Times cited
21	Oliveira, De Sousa, and Rodrigues (2011)	International Journal of Communication Systems	45	**55**	Gama, Touseau, and Donsez (2012)	Computer Communications	19
22	He and Da Xu (2014)	IEEE Transactions on Industrial Informatics	44	**56**	Ma (2011)	Journal of Computer science and Technology	19
23	Atzori et al. (2012)	Computer Networks	42	**57**	Yan, Zhang, and Vasilakos (2014)	Journal of network and computer applications	18
24	Kranz, Holleis, and Schmidt (2010)	IEEE Internet Computing	40	**58**	Bi, Xu, and Wang (2014)	IEEE Transactions on Industrial Informatics	18
25	Broll et al. (2009)	IEEE Internet Computing	40	**59**	He and Xu (2014)	IEEE Transactions on Industrial Informatics	18
26	Roman, et al. (2011)	Computers & Electrical Engineering	39	**60**	Huang et al. (2013)	The International Journal of Advanced Manufacturing Technology	18
27	Atzori, Iera, and Morabito (2011)	IEEE Communications Letters	37	**61**	Iera et al. (2010)	IEEE Wireless Communications	18
28	Gluhak et al. (2011)	IEEE Communications Magazine	37	**62**	Giner et al. (2010)	IEEE Pervasive Computing	18
29	Zuehlke (2010)	Annual Reviews in Control	37	**63**	Guo et al. (2013)	Journal of Network and Computer Applications	17
30	Chen, Mao, and Liu (2014)	Mobile Networks and Applications	36	**64**	Feki et al. (2013)	Computer	17
31	Hong et al. (2010)	IEEE Wireless Communications	36	**65**	Yu et al. (2013)	IEEE Network	16
32	Zhang et al. (2014)	Enterprise Information Systems	35	**66**	Zhang et al. (2012)	Computers & Mathematics with Applications	16
33	Ning and Wang (2011)	IEEE Communications Letters	35	**67**	Chen et al. (2011)	Computer Science and Information Systems	16
34	Sarma and Girão (2009)	Wireless personal communications	34	**68**	Cooper and James (2009)	IETE Technical Review	16

matrix is transformed into the nearest PD correlation matrix by using eigenvalue method (Rousseeuw and Molenberghs 1993). As shown in Table 3, the test results support to conduct factor analysis, since the KMO measure is 0.700 which is larger than the minimum acceptable value 0.5 (Kaiser 1974), and the significant level of Bartlett's test is $p = 0.000 < 0.001$, which is smaller than the value of 0.05 for rejection of the null hypothesis (Bartlett 1950). Consequently, total 10 factors could be extracted explaining nearly 80% of articles. Table 4 shows the summary of each factor and it summarizes the factor analysis result.

Factor 1 (frameworks and challenges of IoT), explains 25.737% of the calculated variance, which includes: IoT frameworks (Atzori, Iera, and Morabito 2011; Bandyopadhyay and Sen 2011; Atzori et al. 2012; Gubbi et al. 2013); IoT application frameworks for diabetes therapy management (Jara, Zamora, and Skarmeta 2011), people with disabilities (Domingo 2012), and home environment monitoring (Kelly, Suryadevara, and Mukhopadhyay 2013); IoT elements including smart objects (Kortuem et al. 2010; López et al. 2012; Tozlu et al. 2012), testbeds (Zuehlke 2010; Gluhak et al. 2011), mobile crowdsensing (Ganti, Ye, and Lei 2011), and context aware computing (Perera et al. 2014a); IoT network communication including network architecture (Gershenfelo, Krikorian, and Cohen 2004), IPv6 for IoT (Oliveira, De Sousa, and Rodrigues 2011; Jara, Zamora, and Skarmeta 2012) and communication protocol (Bormann, Castellani and Shelby 2012; Watteyne et al. 2012; Palattella et al. 2013); service oriented approach (Guinard et al. 2010; Shelby 2010; Gama, Touseau, and Donsez 2012; Perera et al. 2014a); IoT data management (Welbourne et al. 2009; Barnaghi et al. 2012); research and technology challenges (Zorzi et al. 2010; Ma 2011; Miorandi et al. 2012; Feki et al. 2013); IoT security requirements (Roman et al. 2011; Roman, Najera, and Lopez 2011).

Factor 2 (Current situation of IoT in different applications), explains 13.370% of the calculated variance, which includes: the current development status and challenges of IoT in supply chain quality management (Xu 2011), opportunistic IoT (Guo et al. 2013), modern manufacturing (Bi, Xu, and Wang 2014; Zhang et al. 2014), a data cloud platform for automotive industry (He, Yan and Xu 2014), distributed systems integration (He and Xu 2014), and various industrial applications (Xu, He, and Li 2014); a compressed sensing based data acquisition approach for resource-restricted devices (Li, Xu and Wang 2013); a cognitive management framework of IoT for supporting smart city development (Vlacheas et al. 2013); a topological construction approach for improving and enhancing the topology of WSNs (Zhang et al. 2012); database issues of IoT and a roadmap of technological solutions (Cooper and James 2009).

Factor 3 (Interactions of IoT), explains 11.062% of the calculated variance, which includes: Physical Mobile Interaction (PMI) and Multi-Tag Interaction (MTI) approaches (Broll et al. 2009); mobile and labelling technologies (Giner et al. 2010); IoT enabled Human-Computer Interaction (HCI) approaches (Kranz, Holleis, and Schmidt 2010); an IP based WSN protocol for smart things interactions (Hong et al. 2010); architectural models for interactions between IoT and physical world (Iera et al. 2010; Li et al. 2011; Ning and Wang 2011).

Factor 4 (Security issues of IoT), explains 6.928% of the calculated variance, which includes: challenges and opportunities of Internet Engineering Task Force (IETF) communication protocol suite for IoT (Sheng et al. 2013); security challenges in IoT with distributed architecture (Roman, Zhou, and Lopez 2013) and in IoT using standard Internet protocols (IP) (Heer et al. 2011); trust management approaches for IoT (Yan, Zhang, and Vasilakos 2014; Chen et al. 2011).

Table 3. Kaiser-Meyer-Olkin (KMO) and Bartlett's test.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.700
Bartlett's Test of Sphericity	Approx. Chi-Square	5593.566
	df	2278
	Sig.	0.000

Table 4. The results of factor analysis.

Factors	Articles (#*ID*)	Eigenvalue	Percent of variance explained (%)	Sum of percent of variance explained (%)
1. Frameworks and challenges of IoT (38 results)	• Gubbi et al. (2013) (#2) • Miorandi et al. (2012) (#3) • Kortuem et al. (2010) (#4) • Gershenfelo, Krikorian, and Cohen (2004) (#5) • Guinard et al. (2010) (#6) • Welbourne et al. (2009) (#7) • Ganti, Ye, and Lei (2011) (#8) • Zorzi et al. (2010) (#11) • Bandyopadhyay and Sen (2011) (#12) • Shelby (2010) (#13) • Roman, Najera, and Lopez (2011) (#17) • Jara, Zamora, and Skarmeta (2011) (#18) • Perera et al. (2014a) (#19) • Domingo (2012) (#20) • Atzori, Iera, and Morabito (2011) (#21) • Atzori et al. (2012) (#23) • Roman, et al. (2011) (#26) • Atzori, Iera, and Morabito (2011) (#27) • Gluhak et al. (2011) (#28) • Zuehlke (2010) (#29) • Bormann, Castellani and Shelby (2012) (#38) • Watteyne et al. (2012) (#39) • Tozlu et al. (2012) (#40) • López et al. (2012) (#41) • Perera et al. (2014a) (#45) • Barnaghi et al. (2012) (#46) • Kelly, Suryadevara, and Mukhopadhyay (2013) (#48) • Palattella et al. (2013) (#50) • Jara, Zamora, and Skarmeta (2012) (#54) • Gama, Touseau, and Donsez (2012) (#55) • Ma (2011) (#56) • Feki et al. (2013) (#64)	17.501	25.737	25.737
2. Current situation of IoT in different applications (11 results)	• Xu (2011) (#10) • Li, Xu, and Wang (2013) (#14) • He and Xu (2014) (#22) • Zhang et al. (2014) (#32) • Xu, He, and Li (2014) (#36) • Vlacheas et al. (2013) (#49) • Ferreira, Fernandes, and Ratten (2016) (#58) • Appio, Cesaroni, and Di Minin (2014) (#59) • Guo et al. (2013) (#63) • Zhang et al. (2012) (#66) • Cooper and James (2009) (#68)	9.092	13.370	39.107
3. Interactions of IoT (7 results)	• Kranz, Holleis, and Schmidt (2010) (#24) • Broll et al. (2009) (#25) • Hong et al. (2010) (#31) • Ning and Wang (2011) (#33) • Li et al. (2011) (#35) • Iera et al. (2010) (#61) • Giner et al. (2010) (#62)	7.522	11.062	50.169
4. Security issues of IoT (5 results)	• Sheng et al. (2013) (#42) • Roman, Zhou, and Lopez (2013) (#47) • Heer et al. (2011) (#51) • Yan, Zhang, and Vasilakos (2014) (#57) • Chen et al. (2011) (#67)	4.711	6.928	57.097
5. Application domains of IoT (2 results)	• Atzori, Iera, and Morabito (2010) (#1) • Estrin (2010) (#44)	3.137	4.613	61.710

(*Continued*)

Table 4. (Continued).

Factors	Articles (#*ID*)	Eigenvalue	Percent of variance explained (%)	Sum of percent of variance explained (%)
6. Data management of IoT (4 results)	• Zhou and Chao (2011) (#16) • Sarma and Girão (2009) ((#34)) • Zhong et al. (2013) (#37) • Huang et al. (2013) (#60)	3.105	4.566	66.276
7. IoT in product lifecycle management (2 results)	• Kiritsis (2011) (#15) • Främling et al. (2007) (#52)	2.487	3.657	69.933
8. Enabling technologies of IoT (3 results)	• Chen, Mao, and Liu (2014) (#30) • Chen, Wan, and Li (2012) (#53) • Yu et al. (2013) (#65)	2.317	3.407	73.340
9. IoT in smart cities (1 result)	• Hancke, Silva and Hancke (2013) (#43)	1.783	2.623	75.963
10. IoT in recommender systems (1 result)	• Bobadilla et al. (2013) (#9)	1.464	2.153	78.115

Factor 5 (Application domains of IoT), explains 4.613% of the calculated variance, which includes: participatory-sensing applications (Estrin 2010); application domains of transportation and logistics, healthcare, smart environment, individual and society, and futuristic developments (Atzori, Iera, and Morabito 2010).

Factor 6 (Data management of IoT), explains 4.566% of the calculated variance, which includes: data management in a cloud manufacturing service platform (Huang et al. 2013); a data cycle system constructed based on IoT (Zhong et al. 2013); virtual identities and digital shadow approaches for data privacy issues (Sarma and Girão 2009); a multimedia traffic security framework for multimedia services in IoT (Zhou and Chao 2011).

Factor 7 (IoT in Product lifecycle management), explains 3.657% of the calculated variance, which includes: standards of product lifecycle management for smart products in IoT (Kiritsis 2011), different approaches for product lifecycle information management (Främling et al. 2007).

Factor 8 (Enabling technologies of IoT), explains 3.407% of the calculated variance, which includes: data generation, acquisition, storage, and analysis of big data (Chen, Mao, and Liu 2014); correlations and integrations of M2M, WSNs, CPS, and IoT (Chen, Wan, and Li 2012); cloud-based resources sharing among vehicles (Yu et al. 2013).

Factor 9 (IoT in smart cities), explains 2.623% of the calculated variance, which includes: the role of IoT for smart city development and the significance, technical and non-technical challenges of IoT for smart cities (Hancke and Hancke 2013).

Factor 10 (IoT in recommender systems), explains 2.153% of the calculated variance, which includes: recommender systems based on the information from IoT and other sources for providing predictions and recommendations (Bobadilla et al. 2013).

4.2 *Hierarchical cluster analysis (HCA) and multidimensional scaling (MDS)*

In this study, HCA and MDS are adopted to graphically classify the obtained papers into groups. Figure 3 is the Dendrogram obtained from the result of HCA with Ward's method. Figure 4 is the result of MDS, which the horizontal axis represents the chronological development of IoT ranging from visions and frameworks to advance applications (from right to left along the x-axis), and the vertical axis represents domains of IoT ranging from infrastructural domain to serviceable and analytical domain (from top to bottom along the y-axis). As a result, the papers were analysed and classified into six groups. The papers in each group of the results of HCA and MDS are equivalent

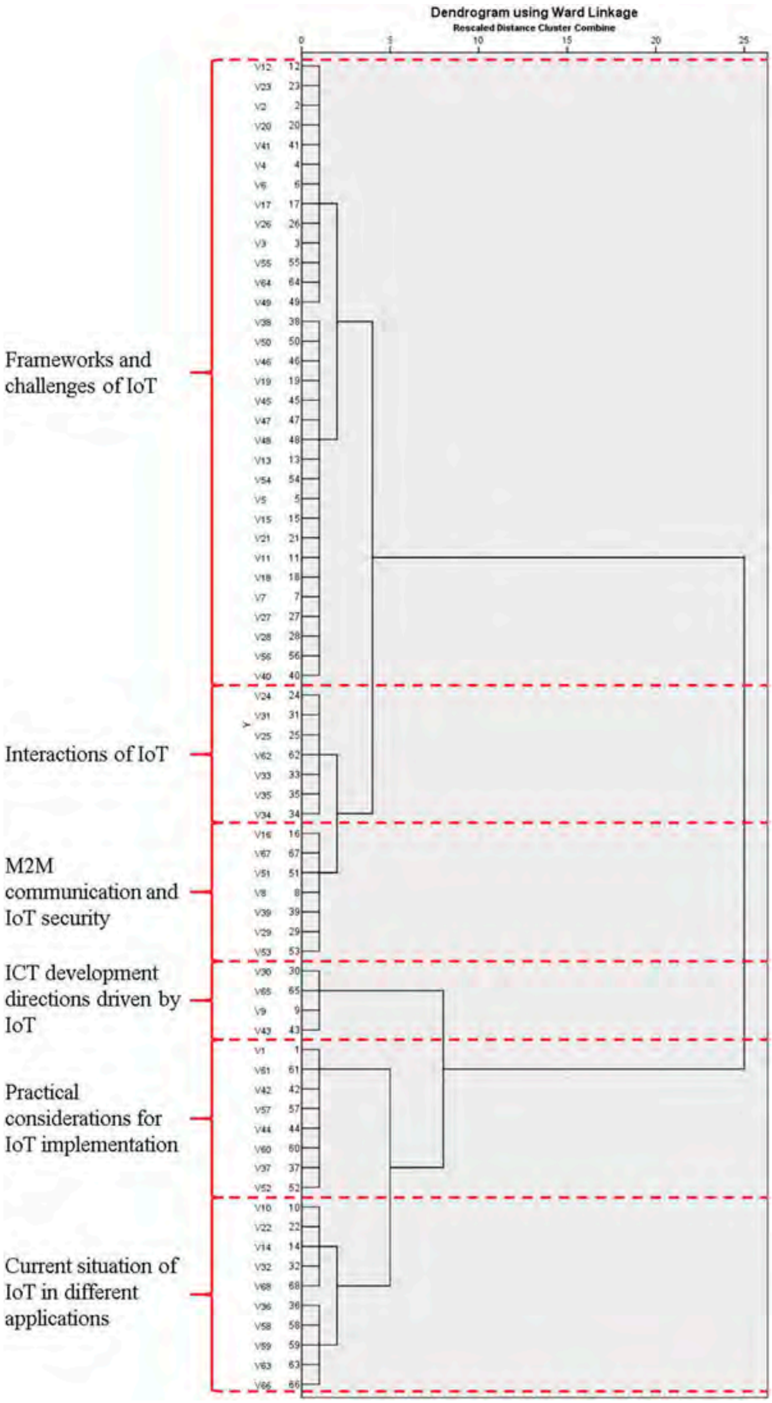

Figure 3. The results of hierarchical cluster analysis.

except the classification of paper 61, 'The Internet of Things' (Iera et al. 2010). The details of the results are describe in the following.

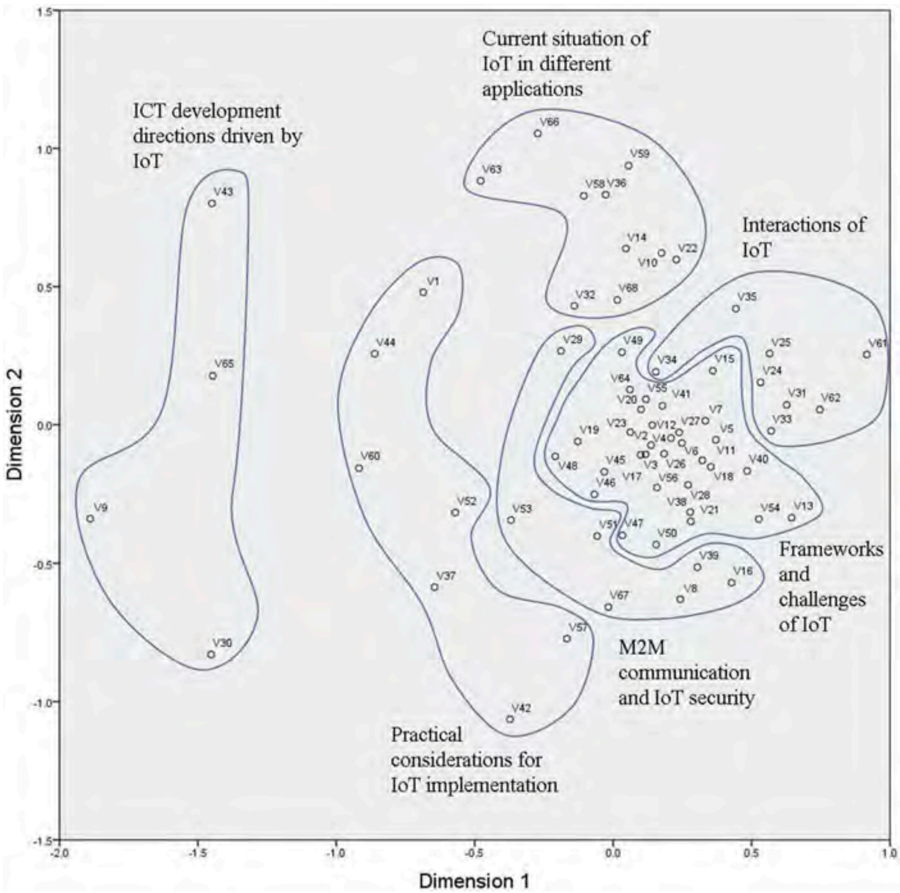

Figure 4. The results of multidimensional scaling analysis.

Group 1 (frameworks and challenges of IoT) included a IoT generic framework (Gubbi et al. 2013), extended frameworks integrating with social networks (Atzori et al. 2012; Atzori, Iera, and Morabito 2011) and IoT application frameworks specialized for diabetes therapy management (Jara, Zamora, and Skarmeta 2011), product life management (Kiritsis 2011), people with disabilities (Domingo 2012), home environment monitoring (Kelly, Suryadevara, and Mukhopadhyay 2013), and smart cities (Vlacheas et al. 2013). The group also comprised IoT elements including smart objects (Kortuem et al. 2010; López et al. 2012; Tozlu et al. 2012); testbeds (Gluhak et al. 2011) and context aware computing (Perera et al. 2014a); IoT network communication including network architecture (Gershenfelo, Krikorian, and Cohen 2004); IPv6 for IoT (Oliveira, De Sousa, and Rodrigues 2011; Jara, Zamora, and Skarmeta 2012); communication protocol (Bormann, Castellani and Shelby 2012; Palattella et al. 2013); service oriented approach (Guinard et al. 2010; Shelby 2010; Gama, Touseau, and Donsez 2012; Perera et al. 2014a); IoT data management (Welbourne et al. 2009; Barnaghi et al. 2012); research and technology challenges (Zorzi et al. 2010; Bandyopadhyay and Sen 2011; Ma 2011; Miorandi et al. 2012; Feki et al. 2013); IoT security requirements and challenges (Roman et al. 2011, Roman, Najera, and Lopez 2011; Roman, Zhou, and Lopez 2013).

Group 2 (interactions of IoT) included IoT enabled Human-Computer Interaction (HCI) approaches (Kranz, Holleis, and Schmidt 2010); physical mobile interaction (PMI) and multitag interaction (MTI) approaches with IoT for design of physical user interface (Broll et al. 2009); a IP based WSN protocol named SNAIL for smart things interactions in the network of IoT (Hong et al. 2010); architectural models for interactions between IoT and physical world (Ning and Wang 2011;

Li et al. 2011); smart workflows utilizing mobile and labelling technologies for reducing the gap between cyber and physical world (Giner et al. 2010); virtual identities management for future Internet which embedded with IoT (Sarma and Girão 2009).

Group 3 (M2M communication and IoT security) included architectures, standards and application domains of M2M communication (Chen, Wan, and Li 2012; Zuehlke 2010; Ganti, Ye, and Lei 2011); an open-source communication protocol for WSN (Watteyne et al. 2012); security challenges in IoT using standard Internet protocols (IP) (Heer et al. 2011); a trust management approach based on fuzzy reputation for IoT (Chen et al. 2011); a multimedia traffic security framework for multimedia services in IoT (Zhou and Chao 2011).

Group 4 (ICT development directions driven by IoT) included big data management and analytics for IoT(Chen, Mao, and Liu 2014); cloud-based vehicular networks for resources sharing among vehicles (Yu et al. 2013); the significance of IoT development for smart city development and the co-related technical and non-technical challenges (Hancke and Hancke 2013); recommender systems based on the information from IoT and other sources for providing predictions and recommendations (Bobadilla et al. 2013).

Group 5 (practical considerations for IoT implementation) included some open issues of IoT such as standardization, addressing and networking, security and privacy, scalability, heterogeneity, mobility, energy efficiency, efficiency for system integration and development (Atzori, Iera, and Morabito 2010; IERA et al. 2010); challenges and opportunities of Internet Engineering Task Force (IETF) communication protocol suite for IoT (Sheng et al. 2013); trust management approaches for IoT (Yan, Zhang, and Vasilakos 2014); participatory-sensing applications for aspects of safety, sustainability, personal and public health (Estrin 2010); data management and exchange in a cloud manufacturing service platform (Huang et al. 2013); a data cycle system constructed based on IoT for managing data from social, physical, and cyber worlds (Zhong et al. 2013); requirements of unique identifiers for product lifecycle information management (Främling et al. 2007).

Group 6 (current situation of IoT in different application) included the current development status of IoT in supply chain management (Xu 2011), distributed systems integration (He and Xu 2014), modern manufacturing (Bi, Xu, and Wang 2014) and various industrial applications (Xu, He, and Li 2014); a compressed sensing based data acquisition approach for resource-restricted devices of IoT (Li, Xu, and Wang 2013); a cloud manufacturing paradigm leveraging IoT for advanced manufacturing in the near future (Zhang et al. 2014); a vehicular data cloud platform integrated with IoT (He, Yan and Xu 2014); an opportunistic IoT for connecting human and smart things (Guo et al. 2013); a topological construction approach based on weighted networks and local-world theory for improving and enhancing the topology of WSNs of IoT (Zhang et al. 2012); an summary and analysis of database issues of IoT and a roadmap of technological approaches for handling such issues (Cooper and James 2009).

5. Discussion

In this research, 68.highly cited (i.e. high-value) papers were identified from 1457 IoT related papers obtained in Web of Science.by using citation analysis. By using these high-value papers, ten factors were obtained from factor analysis, which are: (1) frameworks and challenges of IoT; (2) current situation of IoT in different applications; (3) interactions of IoT; (4) security issues of IoT; (5) application domains of IoT; (6) data management of IoT; (7) IoT in product lifecycle management; (8) enabling technologies of IoT; (9) IoT in smart cities; (10) IoT in recommender systems. Meanwhile, six groups are classified after conducting HCA and MDS. The six groups include: (1) frameworks and challenges of IoT; (2) interactions of IoT; (3) M2M communication and IoT security; (4) ICT development directions driven by IoT; (5) practical considerations for IoT implementation; (6) current situation of IoT in different applications. Comparing the results of HCA and MDS and the results of factor analysis, it is found that the six groups can be mapped to the ten factors. Figure 5 illustrates this mapping. Group 1 covers the same aspects of factor 1, and Group 2 covers the same aspects of factor 3. Group 3 covers some aspects of factor 1 about IoT communication and the aspects of factor 4 (security issues of IoT). Group 4 covers the aspects of factor 8, 9 and 10, which discussed some main development directions of ICT driven by IoT. These development

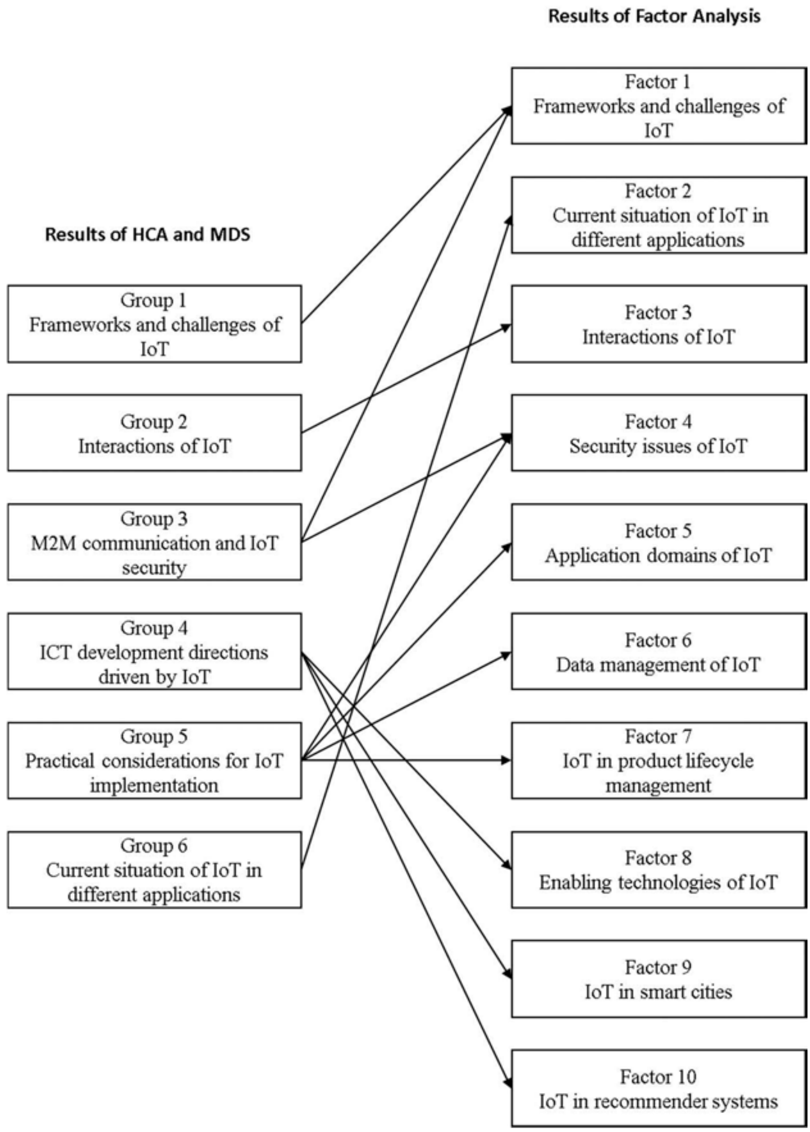

Figure 5. Mapping between results of HCA and MDS and results of factor analysis.

directions of ICT include big data technologies, pervasive cloud computing and its derived topics such as fog computing and edge intelligence, advance recommender systems and advance applications in smart cities. Group 5 is covers the aspects of factor 4, 5, 6 and 7, which is about the practical considerations such as security and trust management, communication protocols and data management for implementing IoT in different application domains such as product lifecycle information management, transportation and logistics, health care and environment monitoring. Lastly, Group 6 covers the same aspects of factor 2. As the two sets of results indicate the same intellectual components of IoT, the discussions of the intellectual core of IoT will focus on the ten factors only.

5.1 *Frameworks and challenges of IoT*

After ITU officially issued the visions of IoT in 2005, IoT became a popular topic of emerging technologies among different research and industrial areas and many research works related to IoT has been published.

5.1.1 *Frameworks*

Regarding the architectural framework of IoT, a three-layer architectural framework which includes sensing layer, network layer and application layer was brought up as a generic and fundamental framework for research and development (R&D) of IoT (Zheng et al. 2011). Following similar layered architecture, another four-layer IoT framework was proposed. The edge layer is equivalent to the sensing layer which consist of a series hardware such as sensor networks, RFID, embedded systems and mobile smart devices. The access gateway layer is equivalent to the network layer to perform networking functions such as message routing, object addressing, network integration and network resource management. The middleware layer works as an interface to manage the interactions between the upper application layer and the lower edge layer. At last, both the application layers in the two IoT frameworks provide various services to users as well as other applications in different application domains (Bandyopadhyay and Sen 2011 (#12)). To align with the current development of ICT, cloud computing and social network are considered as two constructive components in the architecture of IoT currently. Integrating with cloud computing, another three-layer architectural framework of IoT is proposed. The structure of these two versions of framework is similar. The bottom layer of the later version is equivalent to the combination of sensing layer and network layer in the former version, which is called 'Network of things'. Between the 'Network of things' layer and application layer, the middle layer named cloud computing layer is deployed to provide various services such as cloud storage, data mining and machine learning, for the other two layers (Gubbi et al. 2013 (#2)). Integrating with social networking, an IoT architectural framework named Social Internet of Things (SIoT) is proposed based on the three-layer framework without cloud computing. The SIoT contains three basic elements, which are SIoT Server, gateway and object. Gateway and object are constructed following the three-layer architecture except SIoT server while the SIoT server only contains network and application layer. The SIoT server also encompasses the main components of SIoT in its application layer. These main components include owner control, relationship management, service discovery, service composition, and trustworthiness management, which are used to implement four main SIoT processes for interconnection, interaction and management of various objects in SIoT. The four main processes are entrance of a new object, service discovery and composition, new object relationship establishment, and service provisioning. Through these four processes, different types of social relationships between SIoT servers, gateways and objects can be established, and the navigability and scalability of the SIoT can be enhanced by tuning the weights of the social relationships (Atzori, Iera, and Morabito 2011 (#27); Atzori et al. (2012) (#23)). As the above discussion indicated, the generic IoT architectural frameworks provide foundations for researchers and industrial practitioners for R&D of IoT, but the generic framework may not best fit for every application. Therefore, some IoT architectural frameworks, which specifically designed for certain application domains, emerged in the literature. Jara, Zamora, and Skarmeta (2011) (#18) proposed a three-layer IoT architecture based Ambient Assisted Living (AAL) information system to support blood glucose management and insulin therapy. In the sensing layer, a mobile node is designed to manage the sensors such as touch screen, glucometer and portable RFID reader. In the network layer, an AAL gateway works to manage networking and communication between the mobile nodes and backend system. Besides the backend system, there are some portals in the application layer for RFID management and access of Healthcare professionals such as physicians and nurses (Jara, Zamora, and Skarmeta 2011 (#18)). Similarly, a three-layer IoT architecture for people with disabilities is proposed. The three layers include a perception layer which is constructed by sensors, actuators, smart devices and RFID devices, a network layer for management of the network connecting different layers, and an application layer which contains various services operated by different application servers. The proposed architecture is also examined in several practical scenarios including scenario at shopping, at school and at home (Domingo 2012 (#20)). In a more concrete implementation, an IoT based domestic environment sensing system proposed by Kelly, Suryadevara, and Mukhopadhyay (2013) (#48), different up-to-date information technologies are adopted for system implementation. Firstly, a ZigBee WSN with temperature sensors, light intensity sensors and power sensors forms the sensing layer of the proposed system. The sensing data are then transformed from ZigBee data packets to IPv6 User Datagram Protocol (UDP) packets in the network layer by IoT application gateways and sent to a backend server. In the same layer, command data from the backend server can also be converted from UDP packets to ZigBee packets and sent to ZigBee sensor nodes. In the application layer, the collected sensing data are stored in a MySQL database and can be graphically display on a web portal by using PHP JSON functions and a JavaScript library called jQuery (Kelly, Suryadevara, and Mukhopadhyay 2013 (#48)).

Realization of IoT requires integration and innovations of a series of important enabling elements including automatic identification, sensing systems, embedded computing, cloud computing, context-aware computing, networking and Internet-based services. To be basic building blocks of IoT, smart objects are proposed and they are the enhancement of everyday objects integrating with modern technologies such as RFID, WSN, embedded technology and M2M communication. The aim of the design of smart objects is beyond the integration of hardware and software, rather than that, Human-Computer Interaction (HCI) of smart objects is considered as the ultimate aim for IoT realization (Kortuem et al. 2010 (#4)). Smart objects are defined to have some fundamental features including unique IDs, sensors, communication capability and decision making capability (López et al. 2012 (#41)). As a result of development of information technologies, some new concepts are considered for the design of smart objects. Firstly, low-power Wi-Fi has been considered as a competitive candidate to traditional energy efficient communication protocol such as ZigBee for network communications of smart objects. The low-power Wi-Fi shows promised performance on energy efficiency, anti-interference, communication range and ease of network integration due to the built-in IP network compatibility (Tozlu et al. 2012 (#40)). Secondly, sensors-rich mobile smart devices such as smart phones and smart tablets can be utilized as smart objects to perform mobile crowdsensing which the sensing and computing capability of individuals can be shared for sensor data collection, exchange, process and analysis (Ganti, Ye, and Lei 2011 (#8)). Thirdly, the sensor data generated from IoT are huge and increase in a high speed. To efficiently process and interpret these data, context-aware computing is adopted to tackle this challenge in IoT since it established links between sensor data and pre-defined context information, thereby making data interpretation and M2M communication easier (Perera et al. 2014a (#19)). Besides the development of smart object, the development of IoT experimental facilities is also growing. The main reason is that, a IoT solution usually involve many hardware and software integrations and interactions, thorough evaluations of the solution under a real-world condition is essential before the solution is launched. SmartFactory^{KL} is a research testbed towards to the perspective of factory-of-things, which is an IoT enabled future factory model. Through this testbed, researchers from both academia and industry can cooperate to develop and test existing and new technologies for the future factory in five dimensions including technical, architectural, planning, safety and security, and human dimension (Zuehlke 2010 (#29)). For the current and future IoT testbed development, Gluhak et al. (2011) (#28) raised out that while the development of IoT testbeds is towards promising solutions, developers should consider seven identified requirements including heterogeneity, federation, user involvement, repeatability, mobility, scale and concurrency (Gluhak et al. 2011 (#28)).

Network communication is also an important basic element of IoT. At the early stage of the rise of IoT, some researchers has proposed a IP based network architecture named Internet 0 to connect ‘things’ in IoT. Internet 0 adapted a simplified IP stack to achieve ‘IP over anything’, which any object can be addressed and reached in any location by using IP (Gershenfelo, Krikorian, and Cohen 2004 (#5)). To accomplish the concept raised in Internet 0, a feasible communication architecture based on Open Systems Interconnection (OSI) model for supporting IoT has been shaped in recent years. For the lower layers of the architecture which encompass Physical (PHY) layer and Medium Access Control (MAC) layer, standard IEEE 802.15.4 is established. This standard have two main parts, which IEEE802.15.4–2006 PHY defines balanced specifications of communication range, data rate and energy-efficiency for low power radio hardware, while IEEE802.15.4e defines a MAC protocol for network scheduling, device to device synchronization, channel hopping and network formation (Palattella et al. 2013 (#50)). For the network layer, IPv6 over Low-power Wireless Personal Area Networks (6LoWPAN) has emerged as a potential IoT addressing scheme, since IPv6 provides large enough global addressing space, outstanding automatic configuration mechanisms and adequate mesh network support. 6LoWPAN also defines three different network architectures including Ad hoc LoWPAN, Simple LoWPAN and Extended LoWPAN for supporting routing and node mobility for different applications (Oliveira, De Sousa, and Rodrigues 2011 (#21)). However, a considerable amount of existing devices and systems are not likely to be compatible with IPv6 and 6LoWPAN. This issue becomes one of the big obstacles to the integration of existing and legacy systems with 6LoWPAN. Another concern of 6LoWPAN is the LoWPAN nodes may not have sufficient resources to process the relatively high communication payload of 6LoWPAN. To deal with these issues, Jara, Zamora, and Skarmeta (2012) (#54) proposed another addressing scheme named Glowbal IP. Glowbal IP contains an Access Address Identifier – IPv6 (AAID-IPv6) address translation mechanism to reduce the communication payload by converting the packet header in 6LoWPAN from 26–42 bytes to 5 bytes. As a result, this scheme allows existing and legacy systems to be extended to IPv6 through using the AAID-IPv6 translator (Jara, Zamora, and Skarmeta 2012 (#54)). For application layer, a relative new Web application transfer protocol named Constrained Application Protocol (CoAP) is designed for resource-constrained networks. CoAP works as a light-weight version of Hypertext Transfer Protocol (HTTP). Both protocols incorporates the useful Representational State Transfer (REST) approach for information exchange between networked applications via Uniform Resource Identifiers (URIs), but CoAP requires less network resources and code space while HTTP contains significant implementation overheads which cannot be afforded by most of resource-constrained devices. Another characteristic of CoAP is that it can easily interface with HTTP for integration with Web without any complex translation. Discovering such characteristics, CoAP is widely adopted in many IoT applications (Bormann, Castellani and Shelby 2012 (#38)). Based on the standard IEEE802.15.4e, 6LoWPAN and CoAP, (Watteyne et al. (2012) (#39) developed an open source implementation of a protocol stack named OpenWSN for IoT devices using the C programming language (Watteyne et al. 2012 (#39)).

To achieve interoperable communications among machines connected by Internet, web services are playing an indispensable important role. However, for IoT, the existing web service technologies such as HTTP, Simple Object Access Protocol (SOAP) and Extensible Markup Language (XML), cannot be adapted directly because of their unaffordable complexity and overhead. Tackling these issues, the emerging CoAP and Extensible XML Interchange (EXI) which is an efficient approach for payload compression and encoding are leveraged for realizing embedded web services with additional features such as resource discovery and publish-subscribe mechanism for realising a push model (Shelby 2010 (#13)). As a result, Service-Oriented Architecture (SOA) approaches are becoming applicable in IoT implementations. Guinard et al. (2010) (#6) proposed a SOA based approach to support dynamically discovery, query and selection of embedded web service at device level. This approach also introduces four requirements for SOA based IoT applications which includes minimal service overhead, minimal service registration effort, support for dynamic and contextual search, and support for on-demand service provisioning (Guinard et al. 2010 (#6)). The advantages of SOA for IoT are further exhibited in SOA based IoT middleware. The adoption of SOA adds a significant level of dynamicity and flexibility to IoT middleware, which smart devices can be added or removed at runtime of IoT system with minimal disruption, and a high level of decoupling between different machines, system layers and applications can be achieved (Gama, Touseau, and Donsez (2012) (#55)). Perera et al. (2014a) (#45) proposed a more applicational SOA based approach which is a sensing as a service model towards smart city. This model follows the concept of Everything as a Service (XaaS) introduced in cloud computing. There are four conceptual layers in the model. Sensor data generators and sensor data consumers form the two layers positioned at the two side of the model respectively. Between these two layers, a layer consisting of sensor publishers is set up for managing sensor services publishing and subscription. Following this layer, the last layer of the model is constructed for managing different sensor publishers and different extended service providers (Perera et al. 2014a (#45)).

Besides system architecture, composing elements and network formation, data management is another big topic for IoT to be discussed. For an IoT application, a huge amount of diverse data will be generated continually in a high speed. Data management becomes a basic and indispensable for IoT applications. Recently, big data analytics solutions integrated with cloud platforms have proven as effective methods for IoT data analysis, but data structuring, data annotation, integration and association with information, knowledge and intelligence in different domains are still challenging tasks for IoT data management. For example, Welbourne et al. (2009) (#7) proposed a small scale IoT application which is using RFID for human activities tracking and providing personal trending services in a building. The authors indicated that .one of biggest challenges of the project is how to create safe and meaningful associations between low level RFID tag reading data and a series personal, event related and service related metadata (Welbourne et al. 2009 (#7)). To deal with the raised challenges, semantic technologies are considered as effective solutions. Through these solutions, data collected from the sensing layer of an IoT application can be properly represented, automatically processed and seamlessly integrated with information and knowledge from both the same and other domains. Not only for data, components, resources, services and service interfaces in the IoT application can also be semantically annotated and associated for effective discovery, composition and access. The synergy created by semantic integration and association of different domain knowledge with other intelligent methods will finally facilitate inference of new knowledge (Barnaghi et al. 2012 (#46)).

5.1.2 *Challenges*

Starting from the early 21st century, the development of IoT is getting concrete to be realized nowadays, but there is still a significant distance to widely usage and acceptance due to challenges from scientific theory, engineering design, and user interactions (Feki et al. 2013 (#64)). For communication and computing aspects in IoT, a large number of challenges are come from resource constrained networks and devices. Since battery replacement and recharge are costly or nearly infeasible for these networks and devices, power consumption aware communication mechanisms such as active/sleep duty cycles are popular for power management of IoT devices. But the side effect is the increase of message latency, which finally causes communication and reaction performance drop. Thus, there is still no an optimized solution for balancing the trade-offs between energy efficiency and communication quality. The adoption of energy harvesting techniques is a relative new feasible approach to deal with the energy efficiency issue, but this approach still have some technological problems need to be solved. Considering the extra-large network scale, high level device heterogeneity, dynamic topology change, unreliable communication medium i.e. wireless communication, scaling issue will be a significant barrier to the IoT development. The current studies and researches on this issue are still inadequate although considerable literature can be found. (Zorzi et al. 2010 (#11)) Other challenges include deployment density issues of IoT devices and issues of IoT localization systems. For aspect of distributed systems, the design of networking is a key issue to be concerned. Effective routing protocols for large scale and dynamic networks, which consisted of heterogeneous IoT devices, and distributed data flow control approaches for controlling the huge amount of IoT data are the research directions of networking design in IoT (Ma 2011 (#56)). Issues related to system operation in IoT are also a renowned research topic. The research scope of this topic includes robustness and fault tolerance, clocks and task synchronization, middleware design and adaptive service models for large-scale IoT deployment. Another renowned issue is about establishment of a generic objects addressing standard for IoT. In the EPCglobal network architecture for RFID, Object Name Service (ONS) is an automated discovery services with similar working mechanism to the Domain Name System (DNS) for information discovery of RFID tagged objects. However, ONS cannot be adopted directly in IoT for seamlessly addressing a tagged object and a network node at present, thus, a more advance version of ONS may be needed to overcome the technical issues of a global-scale addressing standardization mechanism. For the aspect of distributed intelligence, data analysis and reasoning for the enormous amount of IoT data in distributed systems are considered as a challenging task and many research topics are proposed to cope with this task such as reusable IoT components and services, IoT applications with interoperability, and advance data mining and knowledge management. Research challenges also come from Artificial intelligence (AI) agents in IoT. The local interactions and cooperation strategies of AI agents have been raised the interest of many researchers. Researchers also start working on HCI, user-centric design and other research topics related to user experience in IoT (Miorandi et al. 2012 (#3)). As IoT is becoming concretely applicable, a critical set of challenges related to security and privacy unavoidably need to be handled. Traditional approaches used in computers and other machines with rich resource may be impossible to be accommodated for IoT devices. In the case of connecting a WSN to a cloud server through Internet, Roman et al. 2011 (#26) has studied four major existing frameworks of session key management system including key pool framework, mathematical framework, negotiation framework and public key framework for establishing secure client/server communication channels. The results indicated that the existing key management mechanisms may not be applied to create scalable and effective solutions for WSNs due to the limitations of sensor nodes (Roman et al. 2011 (#26)). The security issue also raise other problems in different areas such as cryptography, data management, identity and ownership management, trust management and privacy protection. Therefore, lightweight and simplified approaches based on existing protection mechanisms are not sufficient to cope with the IoT security issues. The feasible solution should be a total solution, which considers the problems from all other aspects, integrates all useful existing and newly designed security methods, and balances governance force and innovation approaches well (Roman, Najera, and Lopez 2011 (#17)). According to the results of factor analysis, more discussion about the IoT security issue will be presented in factor 4.

5.2 *Current situation of IoT in different applications*

Noticing the emerging trend and potentials of IoT, various industries start investing R&D resources to integrate IoT with other existing and new technologies for development of next-generation, advance and even future industrial applications. Although the development of IoT application is still in an infant stage, there are a growing number of IoT applications are being developed or developed in various application domains. In the development of supply chain quality management, researchers and developers identified a series of barriers such as lack of real-time collaboration and integration of different parties in supply chain, insufficient effective information management in term of information sharing, exchange and verification, and deficiency of automated system operations with appropriate information architecture for timely reaction and tracing on quality management. On the other hand, SOA, smart agent, workflow management and IoT are considered as the main technology enablers for real-time, streamlined and automated quality management and control. Currently, these enablers are not yet the mainstream technologies in supply chain quality management, but they are believed to perform essential and significant functions in the future (Xu 2011 (#10)). In modern manufacturing enterprise systems, there exists limitations in the current enterprise systems, which include unsatisfactory handling for changes and uncertainties, considerable gap between hardware and software flexibility, isolated information communication and sharing channels of different enterprise systems, sub-systems and devices, and uncertain system sustainability. IoT is believed to be capable to effectively support the establishment of next-generation manufacturing enterprise systems to resolve the limitations of current enterprise systems. For example, Zhang et al. (2014) (#32) introduced a cloud manufacturing service platform with prototype by integrating with cloud computing and IoT for solving the bottlenecks of existing manufacturing technologies and models (Zhang et al. 2014 (#32)). However, there is still a long way to the next-generation systems since researches and studies are required on IoT related topics such as modularization, semantics, standardization, safety, reliability, effective communication and decision-making (Bi, Xu, and Wang 2014 (#58)). For automotive domain, He, Yan and Xu (2014) (#59) proposed a vehicular data cloud platform to initiate effective sharing and application of transportation related information between different parties in the domain such as drivers, automakers safety authorities, and ultimately contribute to solving the increasing transportation issues. The platform is designed in a modular and multi-layered architecture while leveraging cloud computing and IoT. Three types of cloud service including Infrastructure as a Service (IaaS), Storage as a Service (SaaS) and Platform as a Service (PaaS) are supported by the platform to provide real-time and on-demand services for relevant parties, such as parking services for drivers and mining services of vehicle maintenance data for automotive and parts manufacturers. However, as stated by the authors, challenges such as security and privacy, scalability and quality of service, and issues of insufficient relevant researches and studies are still required to solve. Thus, systematic research and collaborations between academics and industrial practitioners are necessary for all the IoT applications (He, Yan and Xu 2014) (#59)). Similar situation can be found in different industries such as healthcare service industry, food supply chain, safe mining, transportation and logistics, and firefighting. More instances will be discussed in factor 5. For these industries, deployment of different systems and applications are becoming necessary, but integration of these distributed systems, applications and industrial devices produces many research challenges such as needs for guidelines, quality assurance and standard services and architecture of reusable and secure interaction approaches between heterogeneous devices, applications and systems, needs for scalable and easy-customizable middleware solutions and needs for optimized architecture of distributed applications which is capable of achieving effective data mining and IoT device control (He and Xu 2014 (#22)). Besides research challenges, some research trends are also identified, which involves integrating IoT applications with social networking, green technologies, context-aware computing techniques, AI techniques and cloud computing (Xu, He, and Li 2014 (#36)). Moreover, some researchers start discussing and studying the harmonious interaction between human and IoT. One of related studies is about opportunistic IoT, which is a niche research area of IoT. Different from general IoT applications, opportunistic IoT is established based on ad hoc opportunistic networks rather than infrastructure-based networking. Opportunistic networks are human-centric distributed networks using short-range communication techniques such as Wi-Fi and Bluetooth, and connection formation and information exchange rely on the contact nature of human. In this study, a conceptual framework are proposed to facilitate the development of opportunistic IoT applications while some research challenges brought by bi-directional effects between human behaviours and opportunistic IoT has been identified, such as data dissemination protocols considering human behaviours, collaboration of heterogeneous communities, security in opportunistic IoT and incentive mechanisms for user collaboration (Guo et al. 2013 (#63)).

Regarding some research challenges raised in IoT applications, researchers proposed some potential solutions and suggestions. For the data acquisition and sampling in WSN and IoT end nodes, the challenges may come from limited energy, computing and communication capabilities of these end nodes. Therefore, data compression is a common and effective approach. Li, Xu, and Wang (2013) (#14) proposed a data acquisition and compression tool based on compressed sensing theory and combined nonlinear reconstruction algorithm and random sampling. The performance of this approach was evaluated, which the requirements of resolution, sensitivity and reliability are fulfilled by low-cost data compression and storage, robust data transmission and accurate data reconstruction (Li, Xu, and Wang 2013 (#14)). For topology construction of WSNs in IoT applications, the main challenge is the balance between energy consumption and data transmission efficiency. Different from applying the unweighted small-world theory in some literature, Zhang et al. (2012) (#66) proposed a topology construction approach based on weighted networks and local-world theory. This approach does not only deal with the energy consumption issue by an uneven clustering weighted evolving model, but also enhance the robustness and fault tolerance of WSNs by decreasing the occurrence of successive node breakdowns while increasing network synchronization (Zhang et al. 2012 (#66)). For the challenges related to database management in IoT, Cooper and James (2009) (#68) suggested some technical priorities including process modelling, indexing, archiving, actuator control, transaction management, intelligent interoperability and agents for management of large volume data from heterogeneous systems in IoT. (Cooper and James (2009) (#68)). Focusing on some large-scale IoT applications, there are also some solutions for better usage of IoT. Heterogeneity and unreliable objects are two main challenges in IoT applications. The complexity of these challenges will be magnified in a smart city scenario due to the huge quantities of related objects. Vlacheas et al. (2013) (#49) presented a cognitive management framework to optimize the usage of IoT in smart city development. In this framework, virtual objects (VOs) are developed to represent real objects dynamically and the VOs can be aggregated to form composite VOs (CVOs) automatically. VOs and CVOs cooperate automatically and intelligently to complete the service requests following proximity and cognition mechanisms. This approach finally hide the complexity and heterogeneity, and enable the resilience of service provisions dynamically (Vlacheas et al. 2013 (#49)).

5.3 *Interactions of IoT*

As discussed above, full implementation of IoT requires overcoming a set of inevitable difficulties such as scalability, heterogeneity, energy efficiency, communication traffic handling and protocols design, security and privacy compatibility, and mobility management. It also requires enable effective bidirectional interactions in the levels of device-device, system-system, device-system, human-device and human-system (Iera et al. 2010 (#61)). Human-system and system-system interactions are mature areas to be studied and extensive applicable approaches can be found in the literature and existing Information Technology (IT) applications. For device-system interactions, as discussed in factor 1, an SOA based middleware can be an effective solution. Similarly, the concept of 'IP over anything' which is also discussed in factor 1 provides a concrete direction for enabling device-device interactions. Following this direction, 6LoWPAN emerges and many related research projects have been conducted. However, for applying 6LOWPAN in IoT, most of these projects focus on the implementation of a 6LoWPAN adaptation layer in IoT applications, only a few studies consider full implementation for entire framework of IoT. Hong et al. (2010) (#31) proposed a complete IP adapted WSN approach named Sensor Networks for an All-IP World (SNAIL). This approach not only develops a basic protocol for IPv6 adaptation, but also accomplishes four network protocols specific for WSN including mobility, web enablement, time synchronization, and security. Furthermore, this approach has been evaluated in terms of feasibility, interoperability and effectiveness on a testbed built in the Korea Advanced Research Network (KOREN) (Hong et al. 2010 (#31)). For human-device interactions, it can be classified as a sub category of human-computer interaction (HCI), preliminary application cases related to IoT can be found in the literature. Kranz, Holleis, and Schmidt (2010) (#24) developed four case studies of IoT enabled HCI objects including a case of context-aware kitchen utilities, a case of using capacitive touch input on clothes, a case of using non-standard input and output for gaming and sports, and a case of using small embedded objects for visualization of room occupation. From these four case studies, the authors derived a list of guidelines for design of IoT enabled HCI objects, such as appropriate information provision of HCI objects without user trigger, efficient task accomplishment by leveraging various IoT techniques, prevention of accidental use while handling the trade-off between feature indicators and product design, and preservation of original functions of IoT enabled objects (Kranz, Holleis, and Schmidt 2010 (#24)). Regarding IoT enabled HCI systems, Broll et al. (2009) (#25) proposed a framework named Pervasive Service Interaction (Perci) integrating Physical Mobile Interaction (PMI) and Multi-Tag Interaction (MTI) with Web services. A prototype of smart posters was developed as a case study of Perci, which this prototype allow users to use smart phone interacting with a multi-tagged movie poster for retrieval of associated movie information and services such as mobile ticketing (Broll et al. 2009 (#25)). Another example is a smart business process architecture leveraging smart phones with on-board camera and NFC. This architecture enables the participation of users and developers in business workflow under an IoT enabled environment, and it was verified by a case study of smart library (Giner et al. 2010 (#62)). Besides the five types of interactions in IoT discussed above, the interactions in hierarchical architecture of IoT can also be found in the literature. Ning and Wang (2011) (#33) discussed a possible architecture for future IoT, which the current IoT applications are believed only implementing some parts of the IoT visions. The proposed architecture introduces two concepts which are Unit IoT and Ubiquitous IoT. Unit IoT represents individual IoT systems built based on Man Like Neural network (MLN) model, which is also a version of the vision of next generation Internet model. Ubiquitous IoT represents global scale IoT systems integrating and managing more than one homogenous and heterogeneous Unit IoT as well as existing early-stage IoT systems. These systems are constructed following Social Organization Framework (SOF) model, which the interactions between Unit and Ubiquitous IoT resemble to individuals and social community. The Unit and Ubiquitous IoT contributes to shape the future IoT, but further research on compatibility, interconnection, intra-connection and standards formation still required (Ning and Wang 2011 (#33)). Similar concepts of the Unit and Ubiquitous IoT can also be found in some IoT applications. Li et al. (2011) (#35) proposed an IoT application named smart community. A smart community contains three domains. The home domain is individual smart home systems applying IoT. Different home domains in a local region interconnect and integrate together to form a community domain. The last domain is the service domain which is a public service provider for multiple neighbouring community domains. The authors further discussed two extended applications including neighbourhood watch and pervasive healthcare as well as some associated research challenges such as cooperative authentication, unreliable nodes detection and privacy protection (Li et al. 2011 (#35)).

5.4 *Security issues of IoT*

As mentioned in factor 1, security is a big issue for the development and widely application of IoT. Among the security issues, many of them come from the aspect of networking communication. Regarding to the IP based network communication architecture, which is the most feasible architecture for IoT, security challenges are still identified at different levels although different communication protocols such as physical layer, MAC layer, 6LowPAN, Low Power and Lossy Networks (RPL) protocols, and CoAP have been established for IoT (Sheng et al. 2013 (#42)). The major issues are related to the resource restriction of IoT objects and the different specifications of IoT. Consequently, IoT security solutions are developed without considerations of the interoperability with the Internet due to the specific requirements of IoT and finally fail to be directly integrated with the Internet. Similarly, the existing Internet security solutions are difficult to be adapted in the IoT because of limited resources of IoT objects for implementation of such solutions. To deal with these issues, researchers raised some design directions for IoT security solutions. Firstly, security solutions should contain lightweight security mechanisms for resource-restricted IoT objects. Secondly, security architecture should possess scalability for both small-scale and large-scale deployments. Thirdly, security protocols should possess flexibility for integration in heterogeneous communication models. In order to facilitate end-to-end communication security, the design of security protocols should support protocol translation at gateways and group security.

Furthermore, it is a difficult task for an IoT object to secure all the layers in the communication model individually. Therefore, security keys sharing and other common security mechanisms between layers should be taken into account in security solutions (Heer et al. 2011 (#51)). From the emerging of IoT, many IoT applications have been/being developed. Most of them are centralized approaches and others are distributed approaches. Currently, a growing number of distributed approaches have been established due to the notable advantages, which includes smaller risk of vendor lock-in, smaller risk of performance bottleneck, improved availability and improved scalability. These advantages are induced by the two construction principles of distributed IoT applications, which are edge intelligence and collaboration. However, the decentralized nature and increased heterogeneity lead to the development of more complex security mechanisms on cryptographic algorithms, security protocols, security key management, universal identity management, privacy handling, trust and governance, fault tolerance and recovery services (Roman, Zhou, and Lopez 2013 (#47)).

Trust Management (TM) is another important security topic in IoT. Trust not only relate to security and privacy, but also refer to other factors such as confidence, belief, strength, reliability, availability and ability. These factors contain both objective and subjective properties, thus, it is a complex and difficult task to implement TM in IoT. Trust can be assessed by reputation, which is obtained based on direct and indirect knowledge and experiences derived from former performance of entities in a system. Moreover, implementation of TM should cover all the layers and consider the whole IoT system. Implementing TM only at each layer of IoT individually is meaningless. For a detail review of TM in IoT, Yan, Zhang, and Vasilakos (2014) summaries ten objectives for achieving trustworthy IoT and discussed 15 existing open issues and challenges. The authors also proposed a research model for future research of TM in IoT on top of the three-layer IoT architectural framework (Yan, Zhang, and Vasilakos (2014) (#57)). Chen et al. (2011) (#67) proposed a trust and reputation model named TRM-IoT for IoT and Cyber Physical System (CPS). Through this model, a IoT object is able to identify a trustworthy route to request specific services provided by another IoT object. The proposed model contains an effective lightweight authentication mechanism, evaluation components of data processing and routing performance, and evaluation combination components for creating, updating and deleting trust and reputation degrees. The data processing and routing performance is related to the ratio of correct forwarded packets to the total number of forwarded packets in a fixed time window. The information of forwarded packets is collected by a neighbour monitoring process employed in each IoT object. The information then will be further processed by applying fuzzy set theory to evaluate direct and indirect trust and reputation degrees. (Chen et al. 2011 (#67)).

5.5 *Application domains of IoT*

From the vision of IoT, which is connecting everyday things at anytime, anywhere, by anyone and anything (ITU 2005), the great potentialities of IoT can be identified and tremendous possible applications in different areas can be established. Atzori, Iera, and Morabito (2010) suggest that five application domains for these possible applications can be formed based on the characteristics of applications, which refer to whether an application is direct applicable, human-habitudes related or futuristic. In transportation and logistics domain, applications include real-time monitoring and information collection in every link of the supply chain, environment monitoring for perishable products, assisted driving, augmented maps and mobile ticketing reaction. In healthcare domain, applications include real-time human position and motion tracking, real-time assets and materials tracking, identification and authentication of human and asset usage, real-time sensing in both in-patient and out-patient care, and automatic data collection and transfer. In smart environment domain, applications include smart home, smart industry, smart museum and smart gym. In personal and social domain, real-time and automatic update in social networking, query historical data and trends of objects and events, lost things searching and theft prevention. In addition, Estrin (2010) (#44) proposed a participatory-sensing system leveraging mobile phones and the corresponding infrastructure for individuals and communities to cope with a series of civic issues (Estrin 2010 (#44)). In futuristic domain, the applications are R&D projects expected to be established in the future and may not be ready for deployment at present, since these applications involve some developing new technologies or highly complex implementation processes. These applications include robot taxis, city information model and enhanced game room (Atzori, Iera, and Morabito 2010 (#1)).

5.6 *Data management of IoT*

As IoT data management leveraging semantic technologies has been discussed in factor 1, some more discussions on other aspects of this topic will be presented in this factor. In IoT, the huge volume of data generated by the things can be refined to contribute to not only context-aware intelligence, but also the development of Wisdom Web. Zhong et al. (2013) (#37) propose the paradigm of Wisdom Web of Things (W2T) constructed on top of IoT for realizing the harmonious symbiosis of the social world, the physical world, and the cyber world. The core of W2T is a data cycle system, which is utilized to drive the data transformation cycle through continuous processing and refinement of the data in IoT. The cycle starts from things to data, data to information, information to knowledge, knowledge to wisdom, wisdom to services, services to humans, humans then back to things. The data cycle system consists of two main parts for its operations. One is a data conversion mechanism integrating various technologies to transform and refine data at different levels including data, information, knowledge, wisdom and service level of the system. Another one is a data and service interface containing two middleware to enable the interaction between the data cycle system and the IoT (Zhong et al. 2013 (#37)). Similar concept of data refinement can be found in some other literature. Huang et al. (2013) (#60) proposed a cloud manufacturing service platform for small and medium sized enterprises. In this platform, different manufacturing related data are collected for knowledge aggregation and classification in order to establish manufacturing knowledge bases (Huang et al. 2013 (#60)). As the IoT is developing toward as a part of future Internet, two major problems are brought to data management. One problem is security and privacy handling, and another is how to achieve proper services assessment in overwhelming diverse services of future IoT. One possible solution is to utilize virtual identities and digital shadow. The virtual identities represent the end points of all communications, which these end points can be humans, devices or software. Consequently, it is easier to reach the communication end points and identify possible misbehaviours while hiding some privacy information of users such as the location and device type of user. The digital shadow contains usage and session information of each virtual identity and projects virtual identities onto logical nodes in the communication architecture. Thus, the communication network can be easily constructed, analysed and manipulated to deal with complex security and privacy requirements (Sarma and Girão 2009 (#34)). Regarding the security of data management and the characteristics of IoT, Zhou and Chao (2011) (#16) proposed a multimedia traffic security framework for various multimedia services in IoT. In this framework, four major security measures including key management, batch rekeying, authentication and watermarking were employed to effectively manage the multimedia traffic in terms of communication, computation and service (Zhou and Chao 2011 (#16)).

5.7 *IoT in product lifecycle management*

Product Lifecycle Management (PLM) is one of most significant IoT applications, in which contributed to distributed knowledge management, intelligent maintenance, effective and efficient product improvement, reuse and recycling, and proper product disposal. Before IoT and its enabling technologies emerge, the implementation of PLM is nearly impossible since the production information of a product during its lifetime especially at usage and disposal phases are difficult to be collected and managed. The difficulties mainly come from missing communication links of products after production. Possible solutions were discussed in the literature when IoT is emerging. One fundamental solution is to attach a Globally Unique Product Identifier (GUPI) to a product. Thus, the product can be identified in its lifecycle through using the GUPI to link to the corresponding product information and services in the backend systems. Currently, three existing approaches are considered as potential candidates to implement GUPI for PLM. These approaches include EPC network with ONS lookup system, ID@URI approach with DIALOG information system, and World Wide Article Information (WWAI) system (Främling et al. (2007) (#52)). For an advance approach, Kiritsis (2011) proposed the concept of closed-loop PLM by leveraging intelligent products named Product Embedded Information Devices (PEIDs). PEIDs process the capabilities of sensing, memory, processing, reasoning and communication, which bridge the gap of integration of RFID data and sensor data. As a result, PEIDs provide not only the product information, but also the environmental information during their product lifecycle for PLM. By integrating the information provided by PEIDs, the information loops across Beginning-of-Life (BOL), Middle-of-Life (MOL), and End-of-Life (EOL) of PEIDs can be closed. Therefore, the closed-loop PLM is able to address various industrial challenges such as mutable production requirements in terms of quantity, customization and lead time, complex product functions and design for X requirements, increasing enterprise collaboration, digital manufacturing and customer service management (Kiritsis 2011 (#15)).

5.8 *Enabling technologies of IoT*

As the development of IoT is still at infant stage, integration, collaboration and evolution of IoT enabling technologies are necessary for realizing the magnificent visions of IoT. In the context of these visions, RFID and WSNs are indentified as two key fundamental enabling technologies of IoT. RFID is adopted for ubiquitous identification of IoT objects. WSNs embody the basic and simplified form of IoT and mainly focus on environmental information perception. Similar to WSNs, M2M systems contain numerous nodes and gateways, and support interoperability, autonomous operation, and self-organization. The difference between WSN and M2M is M2M focuses on the communication between both wired and wireless machines without or with least human intervention, and which somehow reflects most of the present application patterns of IoT such as home networking, health care, and smart grid. For the further development, M2M is integrated with RFID, WSN, distributed real-time autonomous control, ambient intelligence, pervasive computing, and cloud computing to evolve into CPS. Thus, CPS is considered as a concrete technical form of IoT in the future (Chen, Wan, and Li 2012 (#53)). Accompanying the emerging of CPS, the development of big data technologies is emphasized for promoting the development of IoT. In IoT, enormous IoT objects are generating various kinds of data every second from everywhere. This huge volume of data with the characteristics of heterogeneity, variety, unstructured or semi-structured feature, noise and redundancy will finally become the most dominant part of big data. However, the development of data process and analytics is legged behind the development of data acquisition in IoT. This situation accelerates the development of big data technologies. On the other hand, the applications of big data technologies in IoT enable the continuous advancement of IoT research and business models. Thus, IoT and big data are considered as two inter-dependent technologies and jointly development are required in the future (Chen, Mao, and Liu 2014 (#30)). Besides big data, cloud computing is another technology which researchers and IoT practitioners believe it closely relate to the success of IoT. By integrating with IoT, pervasive cloud and efficient cloud resource management are consider as one of significant development directions of cloud computing. Yu et al. (2013) (#65) proposed a cloud based architecture for vehicular networks. In the architecture, three types of cloud are constructed to manage the cloud resources such as computation power, storage, and bandwidth, and enable resilient cloud services selection. Central clouds have rich cloud resources but high end-to-end communication latency, while roadside and vehicular clouds have limited resources but satisfactory communication quality. To manage these different clouds for providing efficient, continuous and reliable cloud sevices, the authors also proposed cloud resource allocation and virtual machine migration approaches for efficient resource management in the vehicular network. (Yu et al. 2013 (#65))

5.9 *IoT in smart cities*

In the recent decade, the notion of smart city representing intelligent, cyber and sustainable urban development is gaining increasing attentions from academia, industries and governments. Many smart city pilot projects have been established in many cities over the world such as Amsterdam and Groening in Netherlands, Barcelona, Malaga and Santander in Spain, Fujisawa Sustainable Smart Town (SST) in Japan, Norfolk in England, PlanIT Valley in Portugal, Songdo in Korea, and Vienna in Austria. In the development of smart city, IoT plays a crucial role in many aspects and is leveraged for the development and initiation of innovation solutions to improve the sustainability and completeness of a smart city as well as the quality of life of its citizens. The related applications in smart cities are various such as Structural Health Monitoring (SHM), water distribution, electricity distribution, smart buildings and home, Intelligent Transportation System (ITS), surveillance, healthcare, and environmental monitoring. However, at present, most of the applications are still at an early stage for widely implementation in smart cities since various challenges from both technical and social aspects are still needed to be handled properly. Some of the challenges include addressing and coordination of IoT objects, security and privacy, multi-disciplinary collaborations, social issues related to human-technology interaction and collaboration, centralized control, and costs for implementation of smart city. Therefore, a holistic multi-disciplinary IoT approach are required for solving such challenges and making a step forward of smart city (Hancke, Silva and Hancke (2013) (#43)).

5.10 *IoT in recommender systems*

Recommender System (RS) is one kind of information filtering system in which uses explicit and implicit information obtained from different sources for providing prediction of user preference and recommendations of user-interested items. In the era mixed Web 2.0 and Web 3.0 nowadays, RSs become increasingly popular and instances on different topics can be found among research and application areas. These instances include recommendations of movie, television, music, books and documents, e-learning, and e-commence. The popularity also facilitates the evolution of RS. In the first generation of RS, the data collection relies on tradition websites and three type of data can be collected which including content-based, demographic and memory-based data. As Web 2.0 is introduced, the second generation of RS is established by additionally utilizing the social information. The third generation of RS comes along with Web 3.0 and IoT. In this generation, geographic information, RFID data and real-time sensor data from mobile devices and IoT objects are considered in the RS, consequently, new and hybrid algorithms are developed for more accurate and sophisticated predictions and recommendation (Bobadilla et al. 2013 (#9)).

6 Conclusion

IoT is a paradigm of a global communication network with the vision of connecting everyday things at anytime, anywhere, by anyone and anything. From the term was firstly denominated in 1999, IoT has gain considerable attentions from both academia and different industries. Currently, IoT has become one of the most popular research topics in the ICT domain and it is considered as a crucial part of future Internet. In the literature, there are substantial reviews, analyses and discussions on different dimensions of IoT. However, no co-citation analysis was conducted to address high-value articles and summarize the intellectual components from journals for examination and identification of the intellectual core and structure of IoT. Therefore, this study conducted a very first citation and a co-citation analysis for the field of IoT by using 68 high-value articles retrieved within 1457 IoT related papers which were collected from Web of Science online database. By conducting factor analysis, HCA and MDS, ten knowledge structures were identified, which includes (1) frameworks and challenges of IoT; (2) current situation of IoT in different applications; (3) interactions of IoT; (4) security issues of IoT; (5) application domains of IoT; (6) data management of IoT; (7) IoT in product lifecycle management; (8) enabling technologies of IoT; (9) IoT in smart cities; (10) IoT in recommender systems. These ten intellectual components form a development roadmap of IoT. As a result, researchers, practitioners, consultants and policy makers are able to efficiently and effectively access the holistic and representative knowledge of IoT including the framework, enabling technologies, interactions, data management, application domains, security and challenges. This roadmap also indicates the research and development directions of IoT. For example, inspiring from the implication of factor 9, policy makers may consider investing on and leveraging IoT for driving the development of smart cities. When considering factor 10, researchers and practitioners may consider the integration of IoT, Web 3.0 and recommender system as one of the potential research trend. As a whole, this study established a basis and a guidance for future studies including investigation of IoT evolution and examination of the intellectual cores of other IoT related domains such as Web 3.0, big data, smart city, recommender system and pervasive cloud computing.

As this study focuses on employing co-citation analysis for examination of the intellectual structure of IoT, some common limitations of co-citation analysis are subjected. First, the source articles used in this study were collected from Web of Science online database. Web of Science is a reputable scientific database including millions of high-quality articles and this databased has been used by several co-citation analyses (McCain 1990; Nerur, Rasheed, and Natarajan 2008; Pilkington and Meredith 2009; Shiau 2016). However, high-quality articles existed in other excellent scientific journal such as 'Journal of Information Technology, Theory, and Application' and databases such as 'Scopus' were excluded. Therefore, one of the future studies is to incorporate influential IoT related papers from journals which are not included in Web of Science. Second, new papers published near and after the cut-off date of article collection were not considered in this study because of insufficient citations to be included in the set of source documents, even though some high-value papers will reach the citation criteria of 16 citations afterward. Thus, continuous review of the source documents in future study is useful for the refinement and verification of the intellectual core of IoT. In this study, the analysis results are generated by examining IoT related papers from 2004 to 2015. These results indicate that recommendation system integrated with IoT will be one of the potential research trend (factor 10). In post-study period (i.e. after 2015), a growing number of newly published papers related to recommendation systems or recommendation algorithm in IEEE Explore, one of the most famous scientific journal database, is observed. This growing may due to the tremendous cyber services and the rapid development of IoT and mobile technologies. In the near future, recommending appropriate services from tremendous number of existing cyber services to different users in different environments and situations is crucial, but it is also challenging. To deal with this difficulty, context-aware data acquired from IoT and mobile devices can be used to derive many effective solutions. As a result, this research topic attracts many researchers to study on it. For example, some researchers proposed a hyper-graph based recommendation algorithm to connect users, objects and services for effective IoT service recommendation (Mashal, Alsaryrah, and Chung 2016). Some researchers studied personalized recommendation system for mobile devices and provided a solution by using a Big-Data-processing based multi-agent system and contextual data from the IoT environment (Twardowski and Ryzko (2016)). Similarly, Forestiero (2017) proposed a decentralized and self-organizing multi-agent algorithm for a distributed recommendation system in order to effectively discover and recommend useful things in IoT environment (Forestiero 2017). Moreover, although this study presents an adequate analysis on the intellectual structure of IoT, only co-document analysis was conducted for the co-citation analysis. Other types of co-citation analysis such as co-author and co-journal analysis may yield different outcomes with new insightful perspectives. Future study may employ co-author and co-journal analysis to examine the intellectual structure of IoT.

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