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Synthesizing Knowledge on Internet of Things (IoT): An Algorithmic Historiographical Approach

Research-in-Progress

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Abstract

Research on Internet of Things (IoT) has been booming for past couple of years due to technological advances and its potential for application. Nonetheless, the rapid growth of IoT articles as well as the heterogeneous nature of IoT pose challenges in synthesizing prior research on the phenomenon. Based on quantitative citation analysis, this Research-in-Progress (RIP) study seeks to tackle the abovementioned challenges by reviewing 1,065 IoT articles retrieved from ISI Web of Science. Specifically, we employed HistCite to generate a historiography of IoT research. In turn, the historiography yields a citation network that not only aids us in identifying main paths of codification and diffusion, but also helps in exploring the existence of path-dependent transitions within extant literature. This study hence contributes to both IoT research and practice by tracing the accumulation of knowledge on IoT and pinpointing the most influential ideas to-date on the topic.

Keywords: Algorithmic Historiography, Internet of Things, Citation Analysis, Main-Path Analysis, Path-Dependent Transitions

Introduction

The Internet of Things (IoT) is an emerging paradigm that aims to unify physical objects via the deployment of various network infrastructure, including ad-hoc networks and the Internet. IoT-related industries have thrived in the past few years, and their growth shows no sign of abating in the foreseeable future. According to Business Insider (BI) Intelligence Estimates, approximately 25 billion IoT devices will be installed across civic infrastructures, enterprise sectors and homes by 2020 (Moon, 2016). A number of noteworthy research firms have exhibited strong confidence in the prospective growth of IoT-related industries with IDC even predicting that the size of the global IoT market will reach 7 trillion US Dollars (Moon, 2016). The recent boom of the IoT industry can be largely attributed to ongoing IoT research ever since Schoenberger (2002) published his seminal article in Forbes about the possibility of creating an internet for things on the basis of the newly invented radio-frequency identification (RFID) chips, which allow the identification and tracking of a physical object via a unique electronic product code. The concept of the IoT is defined as "a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols" (Atzori et al., 2010, p. 2788).

The definition of IoT demonstrates the complexity and heterogeneity of this multi-disciplinary phenomenon. For instance, the IoT paradigm embodies three interconnected visions, namely the thing-oriented, internet-oriented and semantic-oriented vision. The thing-oriented vision accentuates the technologies that grant a physical object visibility, traceability, and computational capability (Atzori et al., 2010). The Internet-oriented vision emphasizes the technologies and protocols that enable ad-hoc network of physical objects as well as the addressability and reachability of these physical objects via Internet (Atzori et al., 2010). The third vision, semantic-oriented vision, is concerned with the means to represent, store, integrate, search, organize, and ultimately derive meaning from IoT-generated information (Atzori et al., 2010). Furthermore, the architecture that enables the IoT (i.e., SOA-based architecture) is also multi-layered. In general, the IoT architecture consists of three connected layers. The object layer represents the network of physical objects, including sensors and actuators, that identifies the objects in, collects information from, and shapes the real world (Atzori et al., 2010; Domingo, 2012; Gubbi et al., 2013; He et al., 2014; Xu et al., 2014). The middleware and network layer creates virtual representation of the physical objects, handles transfer of data and control command, as well as composes and manages services (Atzori et al., 2010; Domingo, 2012; Gubbi et al., 2013; He et al., 2014; Xu et al., 2014). Lastly, the application layer utilizes the functionalities of the middleware and acts as an interface between the available services and end users (Atzori et al., 2010; Domingo, 2012; Gubbi et al., 2013; He et al., 2014; Xu et al., 2014). In an ecosystem where things communicate, anything identifies, and everything interacts (Miorandi et al., 2012), IoT can be characterized as an imbrication between technology development (c.f., He et al., 2014) and managerial implication (c.f., Xu et al., 2014).

However, the growing popularity and heterogeneous nature of the IoT pose challenges to the synthesis of prior research on IoT. Particularly, IoT studies often come with divergent focus that hinders knowledge consolidation and integration. Moreover, the explosive growth of IoT research, due to its popularity, can exacerbate problems of heterogeneity, leading to an insurmountable barrier when conducting traditional narrative reviews of extant literature on the IoT phenomenon. In this Research-in-Progress (RIP), we attempt to address the abovementioned issues by performing a systematic review of prior IoT research through blending both qualitative and quantitative approaches.

Specifically, we will adopt citation analysis in the form of algorithmic historiography as our quantitative approach to conduct literature review (Lucio-Arias & Leydesdorff, 2008; Porch et al., 2015). Citations represent the historical dependency of scientific developments that underpin two types of relationships: *codification* and *diffusion* (Lucio-Arias & Leydesdorff, 2008). *Codification* is observed when a "citing" article draws inspiration from a body of knowledge codified in the form of references and represents a retrospective view of the citation history (Leydesdorff & Wouters, 1999). In contrast, *diffusion* refers to a dissemination of knowledge from the original article, which "is cited by" a more recent article. This recent article thus resembles a progressive view of the citation history (Lucio-Arias & Leydesdorff, 2008). By employing HistCite to generate a historiography capturing the network of citations among the 30 most essential IoT articles from a list of 1,060 IoT articles retrieved via ISI Web of Science, we seek to identify both *codification* and *diffusion* via *main-path analysis* (Lucio-Arias & Leydesdorff, 2008). In addition, we also explore possible *path-dependent transitions* that represent critical transitional articles, which exist outside the main paths of *codification* and *diffusion* (Lucio-Arias & Leydesdorff, 2008). On the basis of the results from our quantitative citation analysis, this RIP outlines a future plan to: (1) qualify the evolution of knowledge in the most essential IoT articles, and; (2) derive insights from the most recent cutting-edge IoT research that extends central IoT articles via *qualitative content analysis* (Porch et al., 2015).

We expect to answer the following research questions through an algorithmic historiography of extant literature on IoT: *What are the essential research articles in the field of IoT? What is the main path of evolution for the essential research articles in the field of IoT? How knowledge evolves in the field of IoT?*

Research Methodology

To ensure rigor in our literature review, we adhere to the four-stage process for systematic literature review that comprises planning, selection, extraction, and execution (Okoli & Schabram, 2010). We will describe our research approach under the guidance of this four-stage process in this section.

Planning

The planning stage requires the clarification of the purpose of review, the necessary protocol to be adopted and the training required for this endeavour (Okoli & Schabram, 2010). The purpose of this RIP is to uncover the citation structure and knowledge evolution in previous IoT literature regarding technical development and managerial implication. To achieve this purpose, we analysed citation history via HistCite, a software package for bibliometric analysis and visualization, and Pajek, a toolkit for network analysis and visualization. Established protocol for employing HistCite and Pajek was adapted from prior research to ensure quality in the analytical results (Lucio-Arias & Leydesdorff, 2008; Porch et al., 2015).

Selection

As Okoli and Schabram (2010) suggested, our selection stage consists of both literature search and screening. In order to ensure the comprehensiveness of our collection of IoT articles, we conducted our literature search in the ISI Web of Science database by applying the advanced search query: “TS=(internet of things OR IoT)”, meaning that we search for all articles pertaining to the topic of “internet of things” or “IoT”. This search query retrieved a relative large dataset of 2,685 IoT documents. Because of our focus is on the technological and managerial aspects of IoT, we filtered out articles in the research domain of *arts and humanities*, resulting in 2,635 IoT documents. We further exclude articles that are not written in English, obtaining a preliminary collection of 2,571 IoT articles.

Extraction

The extraction stage refers to the appraisal of the quality of retrieved documents as well as the extraction of relevant information (Okoli & Schabram, 2010). In order to ensure that every document in our data collection for literature review is centred on the IoT rather than mere reference to the term, we downloaded and read the abstracts of these 2,571 IoT documents. We eventually excluded 1,506 documents that are not directly related to the subject of IoT, thus yielding a final dataset of 1,065 documents for analysis. Figure 1 summarizes the annual publication counts as well as cumulative global citation scores from 1993 to 2016. As depicted in Figure 1, the IoT is an immature research field that only started to attract scholarly attention in 2009, but the number of publications has skyrocketed ever since. In 2015 alone, 434 IoT articles were published, a number deemed to be astronomical compared to that of 7 in 2009. This trend of publication is a testimony to the growing popularity of IoT within the academia.

To extract the citation structure among the 1,065 IoT documents, we import their citation file into HistCite. HistCite identified 30 most influential papers among all the imported documents in accordance with the Local Citation Score (LCS), which refers to the number of times a paper is cited by other papers in the local collection of papers (Garfield, 2004). In other words, these 30 articles are the most referenced articles in extant literature on IoT. By limiting our citation analysis to the 30 most influential papers, we can pinpoint the most highly cited articles that contribute significantly to the development of the research domain (Griffith et al., 1974), while at the same time, ensuring a legible visualization of the citation structure without the risk of overcrowding (Lucio-Arias & Leydesdorff, 2008). Table 1 demonstrates the

30 most influential articles elicited by HistCite. This set of articles is employed for further data extractions including: the generation of algorithmic historiography, the conduct of *main-path analysis*, the exploration of *path-dependent transitions*, and the performance of content analysis.

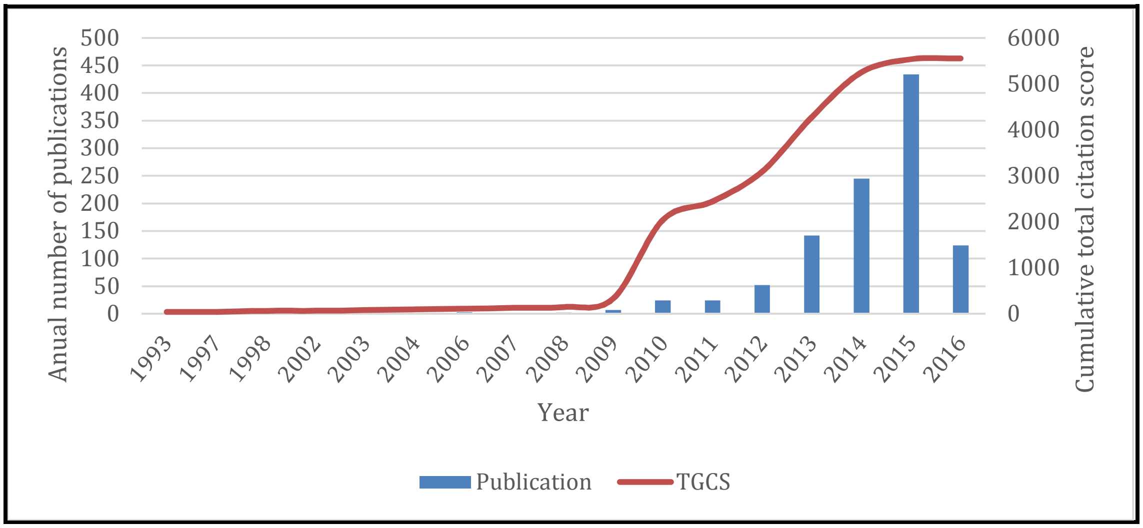

Figure 1. Annual Publication Count and Cumulative Global Citations of IoT Articles

Label No.	Authors & Year	Abbreviated Journal Title	LCS (Local Citation Score)
35	Atzori et al. (2010)	COMPUT NETW	232
103	Miorandi et al. (2012)	AD HOC NETW	73
226	Gubbi et al. (2013)	FUTURE GENER COMP SY	66
25	Kortuem et al. (2010)	IEEE INTERNET COMPUT	43
31	Guinard et al. (2010)	IEEE T SERV COMPUT	36
18	Welbourne et al. (2009)	IEEE INTERNET COMPUT	35
43	Zorzi et al. (2010)	IEEE WIREL COMMUN	34
250	Li et al. (2013)	IEEE T IND INFORM	32
61	Roman et al. (2011b)	COMPUTER	25
175	Li (2013)	BUS HORIZONS	23
116	Atzori et al. (2012)	COMPUT NETW	21
93	Domingo (2012)	J NETW COMPUT APPL	20
322	He and Xu (2014)	IEEE T IND INFORM	19
470	Xu et al. (2014)	IEEE T IND INFORM	19
49	Roman et al. (2011a)	COMPUT ELECTR ENG	16
383	He et al. (2014)	IEEE T IND INFORM	16
44	Shelby (2010)	IEEE WIREL COMMUN	15
378	Bi et al. (2014)	IEEE T IND INFORM	15
57	Zhou and Chao (2011)	IEEE NETWORK	14
73	Barnaghi et al. (2012)	INT J SEMANT WEB INF	14
381	Fan et al. (2014)	IEEE T IND INFORM	13
54	Jara et al. (2011)	PERS UBIQUIT COMPUT	12
91	Bormann et al. (2012)	IEEE INTERNET COMPUT	12
122	Palattella et al. (2013)	IEEE COMMUN SURV TUT	12
269	Perera et al. (2014)	IEEE COMMUN SURV TUT	12
42	Hong et al. (2010)	IEEE WIREL COMMUN	11
95	López et al. (2012)	PERS UBIQUIT COMPUT	11
20	Broll et al. (2009)	IEEE INTERNET COMPUT	10
366	Wang et al. (2014)	IEEE T IND INFORM	10
26	Kranz et al. (2010)	IEEE INTERNET COMPUT	9

Table 1. Most Influential IoT Articles

Algorithmic Historiography

HistCite utilizes the reference lists of all these 30 articles to reconstruct a chronological network of citations. Since citations can reflect the propagation of information through a collection of articles

(Garfield, 1979; Ramos-Rodríguez & Ruíz-Navarro, 2004), the algorithmic historiography generated by HistCite serves as an instrument for us to identify patterns and temporal trends in IoT literature via qualitative and quantitative analyses. The algorithmic historiography is essentially a chronological network of citations in which each vertex represents an article and each edge indicates the directional relationship of citation (i.e., the priori article at the head of the arrow is cited by the posteriori article at the tail of the arrow). The number inside the vertex correlates to the label number in Table 1 whereas the size of the vertex reflects the local citation score of an article: the number of times a paper is cited by other articles in a local collection (i.e., a collection of 1,065 IoT articles).

Main-Path Analysis

Main-path analysis is employed to examine the dominant path, or edge, in an acyclic network that is time dependent by identifying the most representative vertices at different moments of time (Lucio-Arias & Leydesdorff, 2008). The representativeness of a vertex is reflected by its degree of centrality, which refers to the number of vertices that are connected to this particular vertex. In a citation network, the degree of centrality comprises both the number of citations an article receives (i.e., *indegree*) and the number of cited references in the documents (i.e., *outdegree*). (Lucio-Arias & Leydesdorff, 2008). A main path refers to a chain of citations that is reconstructed through those articles with high degree centrality until the path reaches an article that is no longer cited or one that contains no more references within the collection of literature (Batagelj, 2003).

Both paths of *codification* and *diffusion* can be identified via *main-path analysis*. The default citation network generated by HistCite can be utilized to illuminate the *codification* process because it shows the 'citing' relationship between articles, meaning that the direction of each edge goes from a more recent article to one of the earlier articles it cites (Lucio-Arias & Leydesdorff, 2008). Consequently, we can identify central articles with the highest outdegree and derive a chain of citations through these articles (i.e., path of *codification*). By transposing the matrix that denotes the citation network, we can uncover the 'cited by' relationship between articles and in turn, uncover the *diffusion* process (Lucio-Arias & Leydesdorff, 2008). By reversing the direction of each edge to go from an earlier article to a more recent one that cites it, we are able to identify central articles with the highest indegree instead. These central articles may reveal a different chain of citations (i.e., path of *diffusion*) when compared to the path of *codification*.

To conduct *main-path analysis*, we import both the 'citing' network and the 'be cited by' network into Rajek, and apply the main-path algorithm to leverage on each article's relative position in terms of 'citing' and 'be cited by' in order to unveil the underlying structural backbone of the collection of articles. According to the guideline in previous literature, we choose the search path link count algorithm (Lucio-Arias & Leydesdorff, 2008) that takes into account all plausible search paths through the network when estimating the main path (Hummon & Dereian, 1989).

Path-Dependent Transitions

Path-dependent transitions refers to critical documents that forge path dependencies or obligatory passing points (Callon, 1984). Specifically, a *path-dependent transition* can be conceived as an intermediate document between two directly connected documents (i.e., a *priori* document and a *posteriori* document that cites this priori document) such that the bridged path can better explain the transition between the priori document and the posteriori document, leading to a shortened information distance (Lucio-Arias & Leydesdorff, 2008). Exploring *path-dependent transitions* thus help us to identify critical intermediate article that is hidden on the periphery of main paths within a citation network.

To capture the information distance between two articles in terms of their bibliographies, we calculate the information value I (Kullback & Leibler, 1951) that a posteriori article contribute to the priori article in accordance with the formula below:

$$I(q:p) = \sum_{i=1}^{n} q_i \log_2 \left(\frac{q_i}{p_i}\right) \qquad (1)$$

In this formula, p_i refers to the occurrence of the ith reference in a priori article whereas q_i represents the occurrence of the ith reference in a posteriori article. The occurrence of a reference f_i is derived in accordance with the number of appearance of this reference among the 30 most influential articles and is normalized at the level of the article collection f_i/N (Lucio-Arias & Leydesdorff, 2008). To avoid encountering a zero denominator, all occurrences are increased by unity such that a zero occurrence becomes $1/N$ and so forth (de Solla Price, 1981; Elliott, 1971). I reflects the informational contribution in terms of bibliography made by a posteriori article to a priori article cited by the former (Lucio-Arias & Leydesdorff, 2008).

To contrast the information distance between the two paths, we apply the following formula to calculate the discrepancy in the two information value Is:

$$I(q:p) - I(q:p') = \sum_i q_i \log_2\left(\frac{q_i}{p_i}\right) - \sum_i q_i \log_2\left(\frac{q_i}{p'_i}\right) = \sum_i q_i \log_2\left(\frac{p'_i}{p_i}\right) \tag{2}$$

Formula (2) contains a new notation p'_i, which represents the occurrence of the ith reference in an intermediate article. Formula (2) allows us to validate the existence of *path-dependent transition* p' if $I(q:p) - I(q:p') > I(p':p)$ (Lucio-Arias & Leydesdorff, 2008). A confirmation of the above inequality equation bears distinct implication for *codification* and *diffusion*. For *codification*, a *path-dependent transition* resembles a chronologically closer approximation to a cited priori article (Lucio-Arias & Leydesdorff, 2008). Conversely, a *path-dependent transition* acts as an auxiliary transmitter that enhances the information dissemination from a priori article to a posteriori one in the case of *diffusion* (Lucio-Arias & Leydesdorff, 2008). The analysis for *path-dependent transitions*, which identifies transformative articles that disrupt the continuation of priori articles' influence on successive posteriori articles, is hence complementary to the *main-path analysis*, which is aimed at unearthing the continuous flow of knowledge in a body of literature (Lucio-Arias & Leydesdorff, 2008).

Execution

According to Okoli and Schabram (2010), the execution stage can be realized by conducting analysis of findings as well as presenting the review. To realize this stage, we conduct *main-path analysis* and the analysis of *path-dependent transitions* for both codification and diffusion conditions in accordance with the aforementioned procedures. Results from our analysis are presented in the sections below.

Results of Quantitative Analysis

Main-Path Analysis

The main paths for both *codification* and *diffusion* through the citation network of the 30 most influential IoT articles (i.e., articles with highest outdegree and indegree centrality in the citation network of IoT community) are generated by applying the search path link count algorithm implemented in Rajek. To better position the abovementioned two main paths into the citation network, we superimposed them unto the algorithmic historiography generated by HistCite (see Figure 2).

The main path for *codification* identifies focal articles that consolidate previous articles in the references and resembles a path, in which a later central article cites, or codifies, an earlier one (Lucio-Arias & Leydesdorff, 2008). According to the result, both Welbourne et al.'s (2009) work on RFID technology and Broll et al.'s (2009) work on Near Field Communication (NFC) and Physical Mobile Interaction (PMI) are the earliest influential IoT articles. Subsequently, there is a sequential codification through Atzori et al.'s (2010) review for IoT, Miorandi et al's (2012) highlights of the vision, applications and research challenges of IoT, and Xu et al.'s (2014) review of industrial IoT. Each of these three central articles resembles a codification of previous work in IoT field and is thus regarded as being influential in advancing IoT research.

By transposing the matrix of citation network, the main path for *diffusion* identifies central articles in terms of their influence on subsequent articles that cited them and represents a path, in which an earlier central article is cited by, or is diffused to, a later one (Lucio-Arias & Leydesdorff, 2008). Interestingly, the main path of *diffusion* diverges from that of *codification* after passing through Atzori et al.'s (2010) seminal work. Results indicate that Welbourne et al.'s (2009) insights into RFID and Broll et al.'s (2009) innovation of NFC and PMI sparked the initial ideas about IoT, which converge in Atzori et al.'s (2010) review. Beyond that, Atzori et al.'s (2010) vison and architecture of IoT diffused to both Domingo's (2012) proposed IoT application for people with disabilities and Gubbi et al.'s (2013) incorporation of cloud computing into IoT. This knowledge is further disseminated into three central articles: Bi et al.'s (2014) integration of IoT with Enterprise Systems (ESs) and modern manufacturing, Xu et al.'s (2014) review of industrial IoT, and He et al.'s (2014) vehicular data cloud service for auto-parking in IoT environment.

Path-Dependent Transitions

To explore *path-dependent transitions*, we isolated all intermediate articles as well as the priori and posteriori articles they bridge. Table 2 summarizes the results of our analysis for *path-dependent transitions*. Results attest to the non-existence of *critical transitions* in the citation network of 30 most influential IoT articles for both *codification* and *diffusion*. Accordingly, for *codification*, there is no alternative article that detracts from the main path whereas for *diffusion*, there is no auxiliary transmitter that facilitates the dissemination of ideas. Our findings thus point to the absence of a disruptive paradigm shift in IoT research at the moment, which is understandable for two reasons. First, IoT research is still in its infancy stage of development. Second, IoT research is still relatively diversified so much so that a dominant paradigm has yet to emerge, which could also be due to the heterogeneous nature of IoT. Nonetheless, since the citation network of IoT research is devoid of *path-dependent transitions*, it reinforces the robustness of the main paths of *codification* and *diffusion* as identified in this study.

Codification						Diffusion					
p	***p'***	***q***	***I(p':p)***	***I(q:p) - I(q:p')***	**Critical transition**	***p***	***p'***	***q***	***I(p':p)***	***I(q:p) - I(q:p')***	**Critical transition**
18	35	93	0.152	0.070	No	93	35	18	0.095	0.013	No
18	43	93	0.046	0.032	No	93	43	18	-0.025	-0.039	No
18	35	226	0.152	0.075	No	226	35	18	0.085	0.008	No
18	43	226	0.046	0.015	No	226	43	18	-0.014	-0.044	No
18	35	378	0.152	0.070	No	378	35	18	0.046	-0.036	No
18	43	378	0.046	0.018	No	378	43	18	-0.060	-0.089	No
25	119	470	0.086	0.061	No	470	119	25	-0.051	-0.076	No
31	103	220	0.255	0.126	No	220	103	31	0.229	0.101	No
31	220	470	0.032	0.029	No	470	220	31	-0.082	-0.084	No
31	103	470	0.255	0.131	No	470	103	31	0.140	0.016	No
31	322	470	0.196	0.112	No	470	322	31	0.068	-0.016	No
35	226	383	0.098	0.027	No	383	226	35	0.087	0.016	No
35	93	470	0.098	0.027	No	470	93	35	0.042	-0.029	No
35	103	470	0.208	0.091	No	470	103	35	0.140	0.023	No
35	116	470	0.035	0.003	No	470	116	35	-0.026	-0.058	No
35	174	470	-0.024	-0.026	No	470	174	35	-0.087	-0.088	No
35	226	470	0.098	0.036	No	470	226	35	0.042	-0.020	No
35	103	220	0.208	0.086	No	220	103	35	0.229	0.108	No
35	116	220	0.035	0.003	No	220	116	35	0.059	0.027	No

Table 2. Results of the Analysis for Path-Dependent Transitions

Conclusion and Future Study Plan

In this RIP, we subscribe to a quantitative citation analysis approach to identify 30 most influential research articles in the field of IoT and visualize the paths of citation through these 30 articles. Furthermore, we identified the main paths of both *codification* and *diffusion*. Whereas the path of codification demonstrates how central IoT articles synthesized findings from previous literature, the path of diffusion illustrates how central IoT articles disseminated their insights into subsequent research with diversified topics. The robustness of these two main paths can be further corroborated by the lack of *path-dependent transitions*, which in turn implies that IoT is still a young research field with no discernible sign of paradigm shift.

Guided by the algorithmic historiography generated by HistCite (see Figure 1) as well as the main paths identified by employing Rajek, we plan to conduct a qualitative content analysis on the findings of the 30 most influential IoT articles in a chronological order. Our content analysis focuses on infrastructures/overarching frameworks, enabling technologies, potential applications, and research challenges in the IoT context. For example, we are able to detail the progression of enabling technologies for IoT from Radio-Frequency IDentification (RFID) and Near Field Communication (NFC) through network infrastructures and protocols, such as Wireless Sensor and Actuator Networks (WSAN), to cloud computing and mobile devices. Since our literature review revolves around citation-based historiography generated by HistCite, the most recent IoT articles are often overlooked due to insufficient accumulative citations for these articles (Lucio-Arias & Leydesdorff, 2008). Therefore, we also plan to compensate for this shortcoming of citation-based historiography by including recently published articles between 2014 and 2016 that drew inspiration from the 30 focal articles into our qualitative content analysis.

Through this RIP, we expect to contribute to both IoT research and practice. First, the finished study will serve as an example for future studies to conduct systematic literature review by combining quantitative citation analysis with qualitative content analysis. Second, the main paths of *codification* and *diffusion* in the algorithmic historiography accentuate the trajectory of knowledge progression in a body of literature. This trajectory in turn, translates into a more targeted and valid content analysis on pertinent central articles within a body of literature, such as that of IoT. Third, this study also seeks to offer publication strategies for positioning new studies in a body of research, such as how to stay in the main paths of *codification* and/or *diffusion* or how to disrupt main paths, which are well established. Lastly, the algorithmic historiography allows practitioners to extract core knowledge from central articles, including enabling technologies for IoT, previous example of IoT applications, and potential issues of adopting IoT.

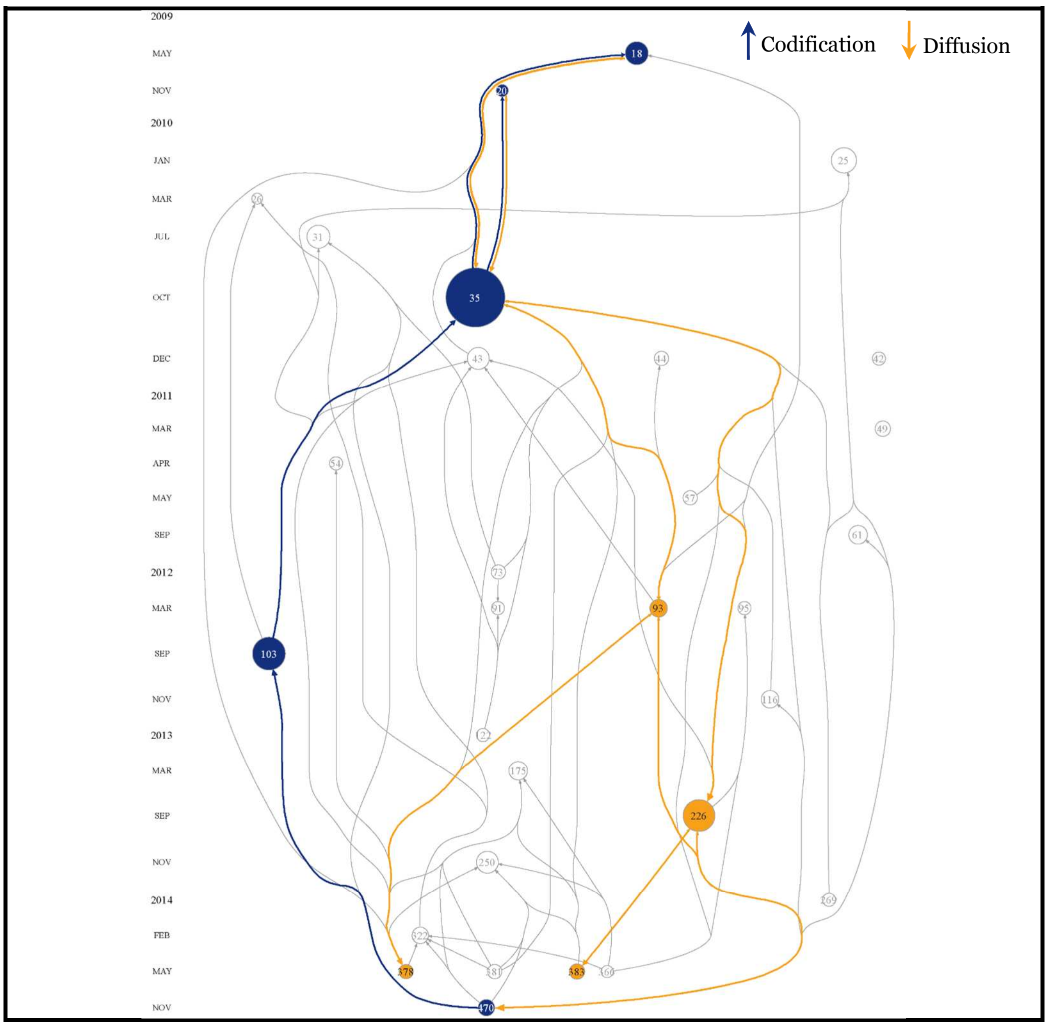

Figure 2. Main-Path Analysis Results and Algorithmic Historiography

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