Trends in Networking via Topic Modeling

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Abstract

Since the advent of the internet, networking has developed substantially. As the field has matured, the areas of inquiry have expanded and changed rapidly. How has the distribution of interest in various topics within the research community changed over the years? By leveraging tools from natural language processing, we attempt to formulate a data-informed answer to this question. In particular, we use latent Dirichlet allocation (LDA) on a corpus of titles, keywords, and abstracts extracted from the IEEE International Conference on Computer Communications (INFOCOM) conference from 1988 to 2018.

1 Introduction

Computer networking is a field with a long history spanning more than half a century. Over this time period, a large body of exciting research has been done to address the pressing needs of the times, develop new technologies, and lay the foundation for the future of the internet. Indeed, this body of work is now so large that the interaction of an individual researcher with it is limited to restricted parts thereof.

Systematically engaging with a large section of the networking literature might lead us to new insights into interesting questions, such as:

- How have computer networking conferences evolved over the past three decades?
- During what periods have the topics in a given paper been prominent in the past?
- How have classic papers affected the direction the field took around the time they were published?
- How similar or dissimilar are trends observed in various conferences?

While an expert deeply familiar with the field might attempt to answer these questions with some confidence, working towards a more systematic approach may lead to answers of superior reliability. To that end, we leverage topic models, [1] a tool from Machine Learning and natural language processing, to attempt to answer some of these questions. On a conceptual level, topic models are distributions where each topic represents a collection of related words. More precisely, it is a distribution over those words. The words in a document are thought to have arisen independently from a subset of these topics where each topic is weighed differently. In the reverse direction, given a new document, the model tries to assign weights to each candidate topic.

We will be using these models to investigate the proceedings IEEE International Conference on Computer Communications (INFOCOM) conference from 1988 to 2018.

2 Background

2.1 Related Work

Topic models have seen much use in analyzing scientific literature. These models have been used to gain insights into articles from the journal *Science*, the *Yale Law Review*, grant proposals to the American National Institute of Health, and other archives of documents in a variety of fields including history, literature, and physics. [1] [2] [3]

Of greater relevance to computer scientists is that topic models have been used in analyzing the trends in programming languages over the years. [4] Our work and methodology is indeed derived from such analyses.

2.2 Topic Models

We will be working with the latent Dirichlet allocation (LDA) model. [5] In this model, a topic is represented as a distribution over a fixed collection of words. The probability, or weight, of a given word represents how strongly the given word is related to the topic. For example, for a topic "Software Defined Networking", such words as "Openflow", "controller", and "data-plane" will probably be associated with it. A word like "TCP" may also be associated, but we would not expect it to have as high a weight. If there were a topic "Congestion Control", we would expect "TCP" to have a high weight in it, but we would not expect a high weight for "Openflow". Each topic is itself given a weight via a distribution which denotes how common a given topic is relative to the others in the corpus.

LDA treats each given document as a bag of words, i.e. the order is ignored and the document is treated as a collection of words where we keep track of duplicates (a multiset). A given document in the LDA model is produced by a multistage generative process.

Recall that each topic has a weight relative to the other topics in the corpus, and that each topic is a distribution over words. First, using the relative topic weights we randomly generate a mixture of topics. That is, we generate a list of numbers which denote how strongly each topic contributes to a document relative to all the other topics. Next, for each word we independently pick a topic and sample the word from that topic distribution. Therefore, for each document we produce a new random vector representing the relative proportions of each topic. Based on this the words are generated, implying different papers will likely have topics mixed in different proportions. The set of possible topics in a given LDA model is fixed.

In our problem, we begin with a corpus of documents and we want to infer what the "right set" of topics will be to produce the given corpus. This is not immediate from the given set. Concretely, we want to infer parameters for a set of distributions and proportions between them. An important problem in machine learning is to solve this problem in a principled fashion. Several methods exist to infer such a model, including expectation maximization and variational methods. [5]

3 Implementation

3.1 Dataset

We are working with data from the IEEE International Conference on Computer Communications (INFOCOM). We collected titles, keywords, and abstracts from the proceedings of INFOCOM from 1988 to 2018, giving us a dataset of 8,257 documents. This data is stored in the BibTex format, making it easily readable. In recent years the conference has had over 300 papers per proceeding, although 30 years ago the number was approximately half of that.

3.2 Methods

The data was stored in the form of BibTex citations. It includes the text of each paper's title, keywords, and abstract. We used the open-source PyPi module bibtexparser[1] to read and process the BibTex citations. Some papers are missing their abstracts, keywords, or both; we included these partial entries regardless. To train the model, for each paper we append these three fields together and treat the result as a single document.

Before running LDA, we have to be careful to disregard words such as "the", "or", and "because", as they are be very common but do not provide any meaningful information about the topics represented in the documents. Words like these are collected in a list of "stopwords" to be eliminated. We used the list of English stopwords provided by the Natural Language Toolkit (NLTK) library [6]. We augmented NLTK's stoplist with additional entries such as "exist", "because", etc., which we felt did not provide much information. We also removed dashes and underscores, such that "data-plane", for example, becomes "dataplane". During preprocessing, we transform each abstract to a bag of words. We next eliminate punctuation, and then we remove all words appearing in the stoplist. The bag of words is represented as a set of tuples. Each tuple consists of a word and the number of times it appears. To ensure that different forms of the same root word, such

[1] https://github.com/sciunto-org/python-bibtexparser

as "router" and "routers", are treated as the same word, we use the NLTK library's stemming functionality. [6]

To train the LDA model we used the PyPi module gensim[7]. It is required that the number of topics that the LDA model is to represent be specified at the beginning of training. The model does not provide human-readable names for the topics, instead specifying a word distribution for each topic learned. Readable topic names must be assigned manually if they are desired. We decided to run our topic model with 30 topics for simplicity and to satisfy time constraints.

3.3 Code Repository

We have made our implementation publicly available as a GitHub repository, which can be found at `https://github.com/mpenza19/LatentDirichletAlloc`

4 Results

4.1 Topics Generated

After training the model over our 30-year corpus, we manually assigned names to the topic distributions generated. To achieve this, for each document we generated a distribution over the topics representing the most likely mixture of topics the document could be generated from. The probability of a topic can be interpreted as the weight given to that topic. The higher the weight, the greater the contribution that topic has to the given document. Then for each topic we took the top 10 documents which gave that topic the highest weight. We inspected these papers and gave them names to the best of our ability. We list them below with some example titles. In some cases there was some ambiguity, which we specify where applicable.

1) Congestion control and Connection Management: "JetMax: Scalable Max-Min Congestion Control for High-Speed Heterogeneous Networks" [8] and "Efficient Distributed Admission Control for Core-Stateless Networks" [9].

2) Flow measurements: "A Quasi-Likelihood Approach for Accurate Traffic Matrix Estimation in a High Speed Network" [10] and "Decentralizing network inference problems with Multiple-Description Fusion Estimation (MDFE)" [11].

3) Information retrieval: *In this topic (like a few others later) the connection between the papers is weaker. Most of the papers dealt with issues related to information retrieval like caching and error correction. There was a paper or two which exactly did not fit this paradigm.* "From Uncertain Photos to Certain Coverage: a Novel Photo Selection Approach to Mobile Crowdsensing" [12] and "Asymptotic Miss Ratio of LRU Caching with Consistent Hashing" [13].

4) Optical Networks: "Integrated Intermediate Waveband and Wavelength Switching for Optical WDM Mesh Networks" [14] and "A generalized framework for analyzing time-space switched optical networks" [15].

5) Routing (Packet Classification, table lookup): "A fast IP routing lookup scheme for gigabit switching routers" [16] and "CutSplit: A Decision-Tree Combining Cutting and Splitting for Scalable Packet Classification" [17].

6) Unclear 1: *A common theme for this topic is unclear. A number of these papers are related to transport protocols and TCP in particular. The remaining papers are related to different topics like network topology and email protocols.* "TCP Vegas revisited" [18] and "An analysis of Internet inter-domain topology and route stability" [19].

7) Data Centers (Multicasting): "A combined group/tree approach for scalable many-to-many reliable multicast" [20] and "How bad is reliable multicast without local recovery?" [21].

8) RFID systems: "Season: Shelving interference and joint identification in large-scale RFID systems" [22] and "Tag size profiling in multiple reader RFID systems" [23].

9) Cognitive radio networks: "Utility-based cooperative spectrum sensing scheduling in cognitive radio networks" [24] and "Improved rendezvous algorithms for heterogeneous cognitive radio networks" [25].

10) Security (Authentication and Cryptography): "Cross-domain password-based authenticated key exchange revisited" [26] and "Checks and balances: A tripartite public key infrastructure for secure web-based connections" [27].

11) Graph Data Processing (Privacy, Machine Learning): "AppDNA: App Behavior Profiling via

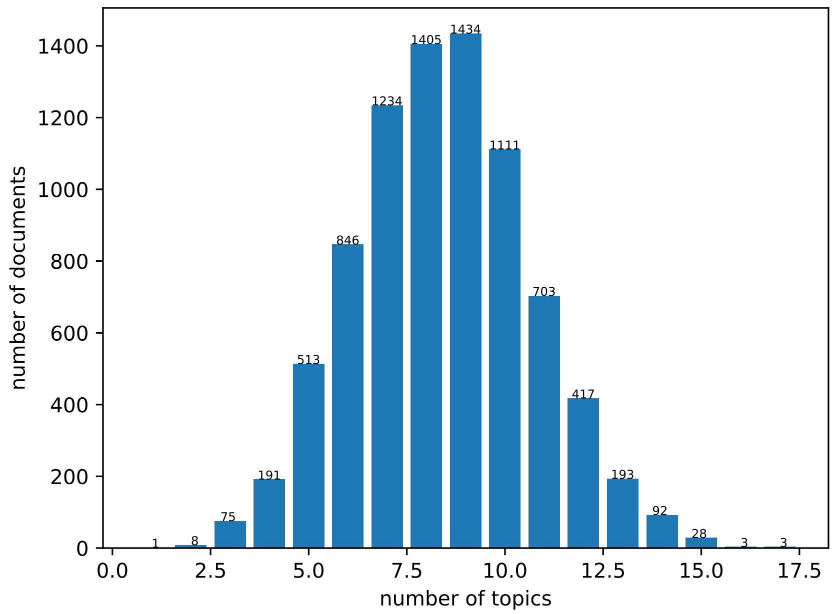


Figure 1: A histogram representing documents containing a given number of topics.

Graph-based Deep Learning" [28] and "Quantifying Graph Anonymity, Utility, and De-anonymity" [29].

12) Game Theory (online auctions and markets): "Truthful online double auctions for dynamic mobile crowdsourcing" [30] and "Flexauc: Serving dynamic demands in spectrum trading markets with flexible auction" [31].

13) Load Balancing / Network reliability: *There were two themes among high-weight documents for this topic distribution: load balancing and network reliability.* "An algorithm for capacity expansion of local access networks" [32] and "Optimizing Network Reliability via Best-First Search over Decision Diagrams" [33].

14) Network Security (Malware and Botnets): "Can we beat legitimate cyber behavior mimicking attacks from botnets?" [34] and "PeerClean: Unveiling peer-to-peer botnets through dynamic group behavior analysis" [35].

15) Queuing Analysis: "On stochastic recursive equations and infinite server queues" [36] and "A simple approximation for modeling nonstationary queues" [37].

16) Smart Grids: "Robust Multi-stage Power Grid Operations with Energy Storage" [38] and "Restricting Involuntary Extension of Failures in Smart Grids using Social Network Metrics" [39].

17) Task Scheduling: "Cluster fair queueing: Speeding up data-parallel jobs with delay guarantees" [40] and "Coupling task progress for MapReduce resource-aware scheduling" [41].

18) Algorithims (Graph / Optimization): "The k-Constrained Bipartite Matching Problem: Approximation Algorithms and Applications to Wireless Networks" [42] and "The online disjoint set cover problem and its applications" [43].

19) Video Streaming: "Statistical characteristics and multiplexing of MPEG streams" [44] and "Tracker-assisted rate adaptation for MPEG DASH live streaming" [45].

20) Web Hosting: "Design and performance of a Web server accelerator" [46] and "DotSlash: handling Web hotspots at dynamic content Web sites" [47].

21) Virtualization: "The Impact of Virtualization on Network Performance of Amazon EC2 Data Center" [48] and "Consolidating complementary VMs with spatial/temporal-awareness in cloud datacenters" [49].

22) Sensor Networks: "On full-view coverage in camera sensor networks" and "Extending Network

Lifetime for Precision-Constrained Data Aggregation in Wireless Sensor Networks".

23) Unclear 2: *Here a decent chunk of papers were on crowdsourcing but the rest were on unrelated topics.* "Promela++: a language for constructing correct and efficient protocols" [50] and "Efficient and flexible crowdsourcing of specialized tasks with precedence constraints" [51].

24) Wireless Scheduling: "Delay Guarantees for Throughput-Optimal Wireless Link Scheduling" [52] and "Optimal delay bound for maximum weight scheduling policy in wireless networks" [53].

25) Mobile networking: "EnLoc: Energy-Efficient Localization for Mobile Phones" [54] and "Efficient location management based on moving location areas" [55].

26) Unclear 3: *Multiple themes seem to be represented, such as distributed computing, ad hoc networking, and graph algorithms.* "Localized low-weight graph and its applications in wireless ad hoc networks" [56] and "Optimal Construction of Redundant Multicast Trees in Directed Graphs" [57].

27) Wireless transmission: "CARA: Collision-Aware Rate Adaptation for IEEE 802.11 WLANs" [58] and "Decoding interfering signals with fewer receiving antennas" [59].

28) Machine Learning (Sensor data): "MV-Sports: A Motion and Vision Sensor Integration-Based Sports Analysis System"

29) Privacy (Sensor Data): "Data perturbation with state-dependent noise for participatory sensing" [60] and "Towards Privacy-Preserving Speech Data Publishing" [61].

30) ATM networks / Packet switching: "Queueing analysis for ATM switching of mixed continuous-bit-rate and bursty traffic" [62] and "Performance of a crosspoint buffered ATM switch fabric" [63].

We see that although it is fairly easy to assign a name to most topic distributions, some seem to be trying to capture multiple ideas at once. Also of note is that some broader ideas seem to be appear in multiple topics. For example, we have wireless scheduling and wireless transmission both under the umbrella of wireless networking. Interestingly, very specific topics like smart grids and RFID sensors have their own topics while a topic like software-defined networking (SDN) doesn't appear. This could be happening because SDN can be represented well by a mixture of a few topic distributions but topics like smart grids are not amenable to that.

4.2 Trends

For each document we produced a vector representing a mixture of topics which generated the document. For most documents will not use all possible topics. In figure 1 we see that that no document has more than 17 topics included in it. Most documents in fact have no more than ten topics included. We have also checked that each document gives some non trivial probability (more than 0.05) to at least one topic.

Figure 2 gives a bird's eye view of how each topic has varied in importance over the years. For each year, we look at the weights assigned to each topic among papers published that year. By grouping and normalizing them we get a measure of percentage contribution of a topic in a given year.

A number of interesting trends can be observed. Such topics as sensor networks, mobile networking, and virtualization have grown in prominence in recent years, which aligns well with our intuition. Topics like congestion control and ATM networks/packet switching account for fewer papers over the years. This is reasonable since, during the early years of the conference, problems like congestion control and connection management would have been immensely popular. As the complexity of the field has grown, more problems came into the limelight, leading these rudimentary topics to account for smaller and smaller proportion as the years went on.

We also plotted the data as individual line graphs for each topic in Figure 3 and 4 at the end. This helps us look at trends not as readily apparent in Figure 2. One of the things we observe is how cryptography and authentication (plot 10) had a dip in popularity but regained the ground it lost in recent years. Conversely, congestion control (plot 1) experienced a surge of popularity from c. 1995-2005, but has dropped off drastically ever since.

We also notice that there are no topics that could be described as stable. The vast majority show either a dip or peak as discussed immediately above, or else a clear decline or increase in interest over time, perhaps with a few sudden spikes upwards or downwards along the way. Optical networks (plot 4) and virtualization (plot 21) are prime examples of such

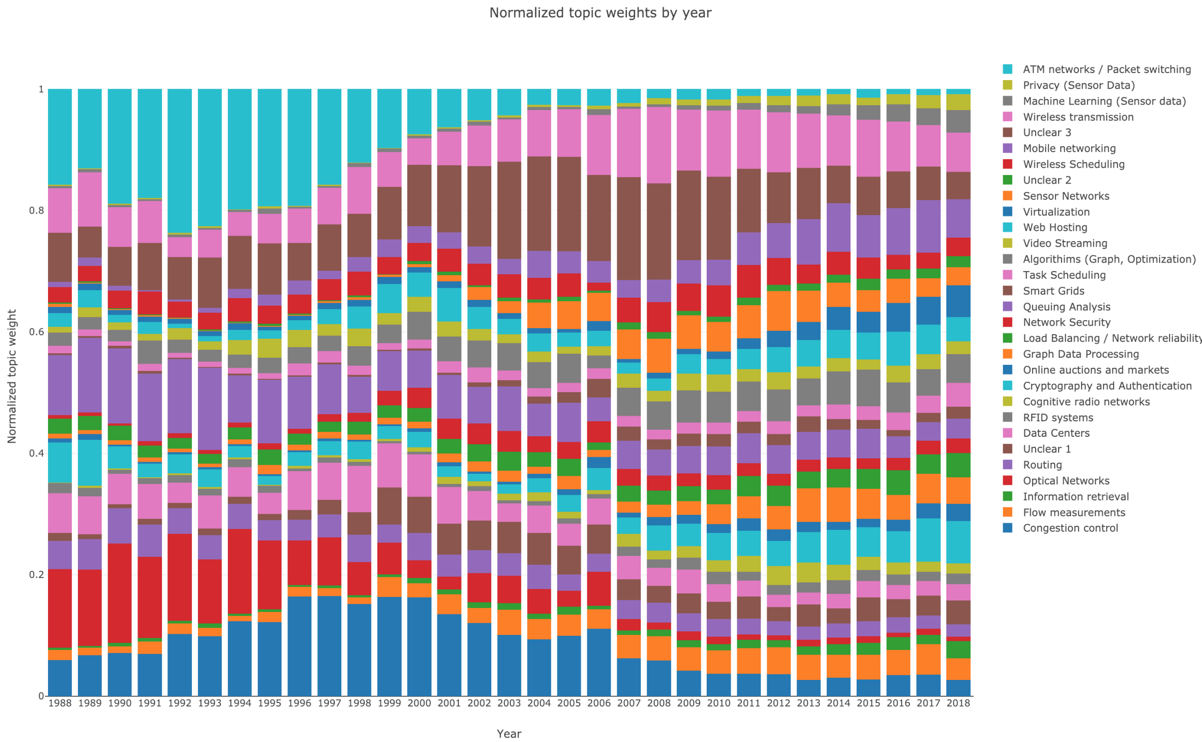


Figure 2: Normalized weights of each topic in the corpus over time.

decline and growth, respectively. The rest are mostly erratic, as exemplified by video streaming (plot 19) and wireless transmission (plot 27). The only topics that approach consistency over time are wireless scheduling (plot 24) and *unclear 1*, but only since c. 2010 in the latter case.

4.3 Finding similar papers

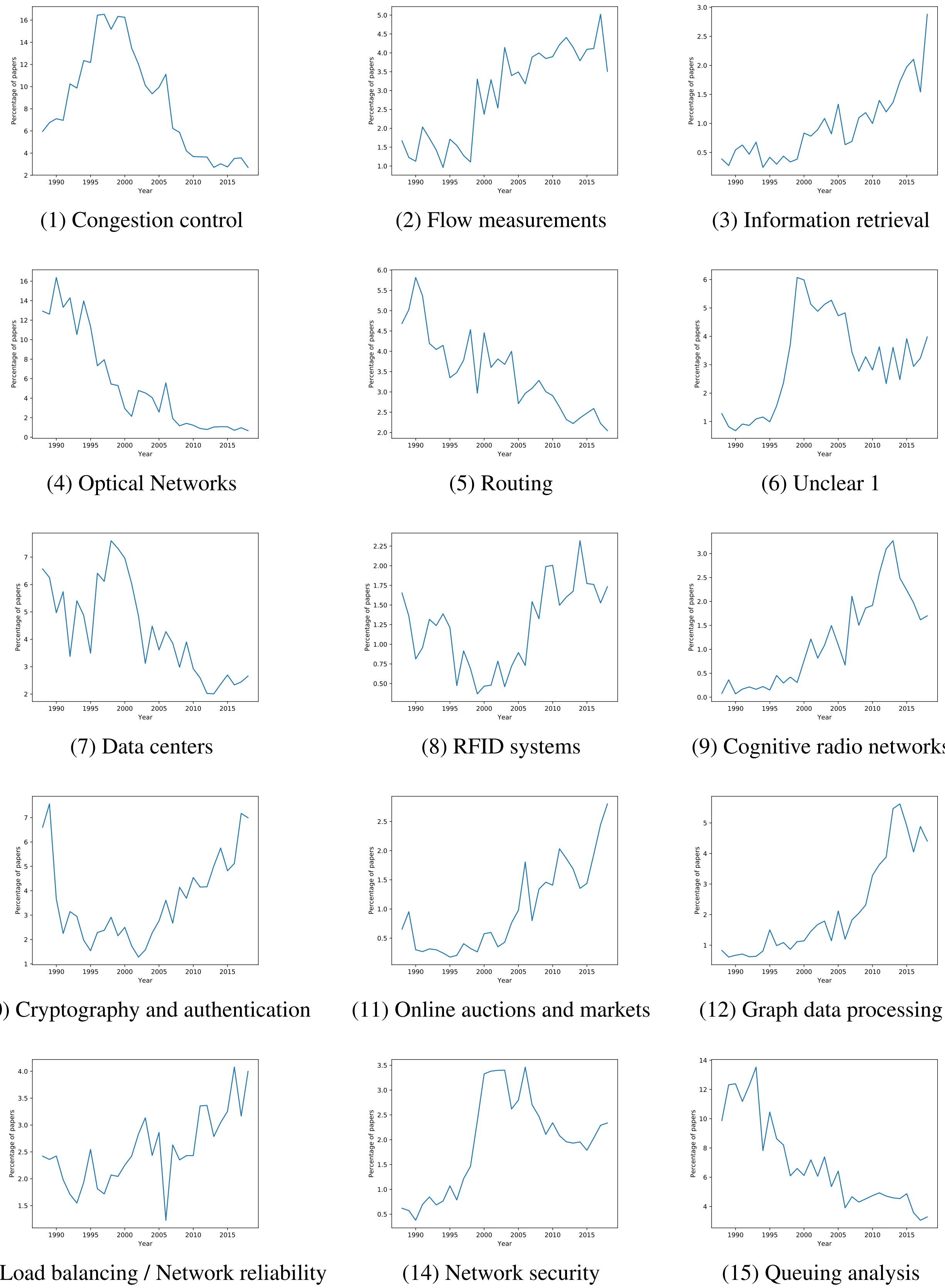
Now that we have a trained topic model, we can use it to compare documents. Given a document, the model can give a vector which contains each topic's weight. Now this weight vector can be used to compare it to the weight vectors of other documents. Given a paper from a different source, we can use this to find the most similar papers to the input paper.

We examined some papers from the 2016 SIGCOMM conference using our model. First we turned to the paper "Virtualized Congestion Control". [64] Upon examining the topic weight vector generated, we see the largest weight is assigned to the topic *congestion control* (0.37), followed by *virtualization* (0.13) and *task scheduling* (0.1), which appears to be reasonable for this particular paper. The three closest papers to it in the INFOCOM dataset are:

1. "Deadline-aware bandwidth sharing by allocating switch buffer in data center networks" [65],
2. "The cost of QoS support in edge devices an experimental study" [66], and
3. "New bandwidth sharing and pricing policies to achieve a win-win situation for cloud provider and tenants" [67].

We note that the first and the third paper are similar, as they too deal with the problem of bandwidth allocation.

Next, we examined the paper "SNAP: Stateful Network-Wide Abstractions for Packet Processing" [68]. The key topic here is related to software-defined networking (SDN), which our model doesn't explicitly represent in a single distribution. However, we did observe some SDN-related papers among the high-weight papers while naming the topics. The topic weight vector has multiple topics with similar weight. The three closest papers to it in the INFOCOM dataset are:



(1) Congestion control (2) Flow measurements (3) Information retrieval

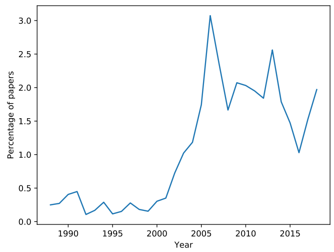
(4) Optical Networks (5) Routing (6) Unclear 1

(7) Data centers (8) RFID systems (9) Cognitive radio networks

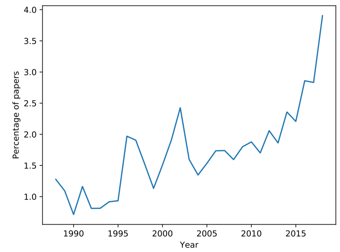
(10) Cryptography and authentication (11) Online auctions and markets (12) Graph data processing

(13) Load balancing / Network reliability (14) Network security (15) Queuing analysis

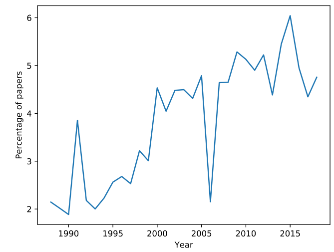
Figure 3: Individual trend lines plotting how the percentage of a topics contribution changes over the years



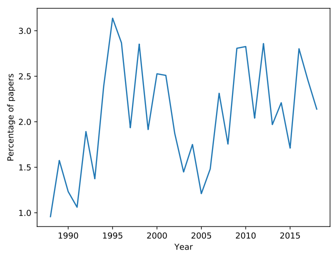
(16) Smart Grids



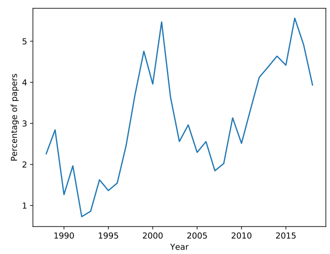
(17) Task Scheduling



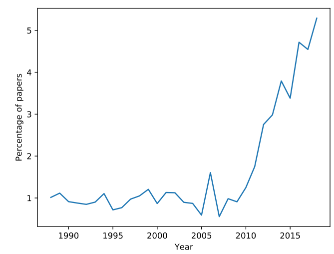
(18) Algorithms (Graph, Optimization)



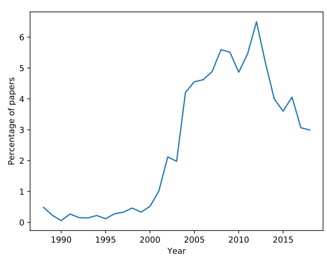
(19) Video streaming



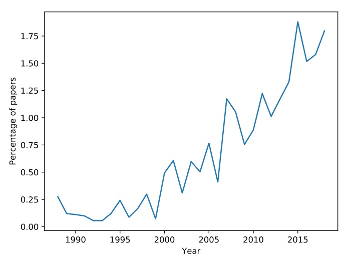
(20) Web hosting



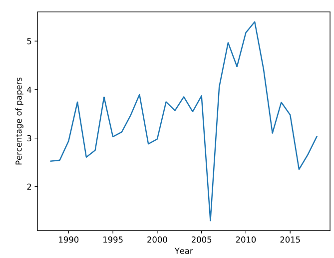
(21) Virtualization



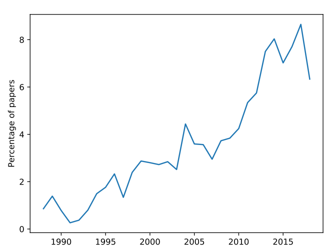
(22) Sensor networks



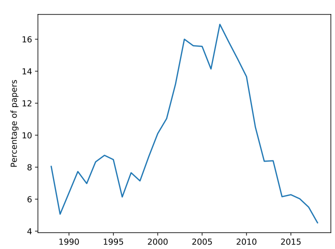
(23) Unclear 2



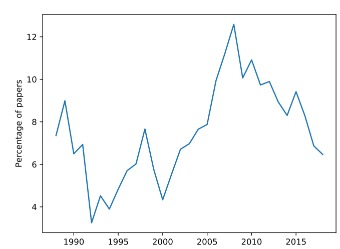
(24) Wireless scheduling



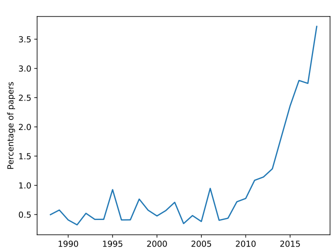
(25) Mobile networking



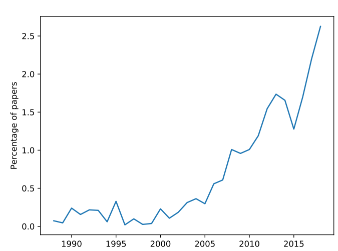
(26) Unclear 3



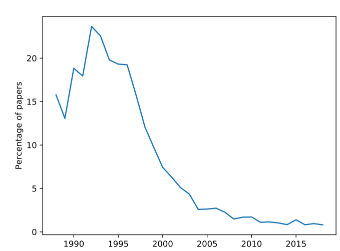
(27) Wireless transmission



(28) Machine learning (sensor data)



(29) Privacy (sensor data)



(30) ATM networks / Packet switching

Figure 4: Individual trend lines plotting how the percentage of a topics contribution changes over the years (continued from Figure 3)

1. "Network anti-spoofing with SDN data plane" [69],
2. "GMPLS Control Plane, Policy-Based Management, and Information Modeling" [70], and
3. "A distributed and robust SDN control plane for transactional network updates". [71]

Two of these are SDN-related papers. The second is also related, albeit less directly, as it deals with network management.

Finally, we examined the paper "The Deforestation of L2" [72]. This is another topic that did not appear in our topic list. The topic weight vector for this paper gave the highest weights to *unclear 1* and *unclear 3*. The closest 3 papers to it in the INFOCOMM dataset were:

1. "Flow labelled IP: a connectionless approach to ATM" [73],
2. "Switch-aided flooding operations in ATM networks" [74], and
3. "Analysis of point-to-point packet delay in an operational network" [75].

The second mentions link flooding and network spanning tree protocols, which are concepts related to the SIGCOMM paper in question.

5 Limitations and Future Work

From the list of topics generated we see that a lot of topics are mixed in a single one and there is ambiguity in some others. One way to deal with that is possibly to train the model with more topics allowed. Another is to use more sophisticated models. Latent Dirchlet Allocation (LDA) doesn't take into fact that some topics can be correlated to each other. To address that we can use Correlated Topic Models [76] and Pachinko Allocation Model [77].

It would also be interesting to compare results from different conferences or try to analyse them together. We did very simple experiments on papers from SIGCOMM which gave qualitative results. Training models on conferences like SIGCOMM and NSDI can allow us to compare trends between conferences. We could run the similarity experiment in both directions using multiple models. INFOCOM is a huge conference with a very broad scope. Working with a conference with a smaller scope may lead to more interesting results with simpler models. Instead of working on papers published in a conference, one can look at the papers published by an individual researcher and see how that has evolved over time.

Another possibility is to use dyanmic LDA [78] which allows us to model changes in topic contents. If we are working with multiple conferences it can help us observe if topics appearing in one conference influence other conferences.

6 Conclusion

We see that using LDA does give some interesting results and clearly shows broad trends in networking researchers' interests. We are able to see the attention paid to certain topics diminish to near zero despite having once been major focuses of the field, and others emerge from obscurity to take their place. This analysis has its place as a blunt instrument. For more refined results, however, the limitations addressed above ought to be dealt with, the more sensitive suggested models employed, and data from other conferences and journals analyzed.

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