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Network of networks: A bibliometric analysis

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ABSTRACT

This study explores the evolving structure of the rising field of "network of networks" (NoN). Reviewing publications dating back to 1931, we describe the evolution of major NoN research themes in different scientific disciplines and the gradual emergence of an integrated field. We analyse the co-occurrence networks of keywords used in all 7818 scientific publications in Scopus database that mention NoN and other related terms (i.e., "interconnected networks", "multilayer networks", "multiplex networks", "interdependent networks", "multinetworks", "multilevel networks", and "multidimensional networks"). The results show that the NoN began to form as a field mainly in the 1990s around research on neural networks. Diverse aspects of NoN research, indicated by dominant keywords such as "interconnection", "multilayer", and "interdependence", gradually spread to computer and physical sciences. As of 2018, network interdependence – with its application in network resilience and prevention of cascading failure – seems to be one of the key topics attracting broad academic attention. Another noteworthy observation is the emergence of a distinct cluster of terms relevant to nanoscience and nanotechnology. It is envisaged from the analysis that NoN concepts will develop stronger ties with nanoscience with increasing understanding and data acquisition from the molecular, atomic, and subatomic levels.

1. Introduction

Networks are embodied features of nature's complex systems. Our bodies are composed of numerous interacting network systems ranging from proteins to genes, neurons, and blood circulatory systems. From birth, we also form social networks, starting with our family trees. The origins of network science go back to 1736 when Euler published a paper titled "Solution of a problem relating to the geometry of position" [1] about seven bridges of the Königsberg city [2]. Since then, the science of networks has been developed and has played a significant role in global socio-technical development. Over the last few decades, information technology has progressed hand in hand with virtual social connectivity and human mobility world-wide. Consequently, topics in network science related to interactions of multiple networks have received increasing attention, especially in relation to communication networks, energy grids and other cases of large and complex infrastructure. They have been also discussed from sustainability perspective [3].

Kivela et al. [4] classified the types of diverse formations of multiple networks (see Table 1 in [4]), using the term "multi-layer network" as the overarching keyword. We have identified eight terms used in the research of interactions between multiple networks that are increasing in use: "interconnected networks", "multilayer networks", "multiplex networks", "interdependent networks", "network of networks", "multinetworks", "multilevel networks" and "multidimensional networks". We refer to the concept represented by these terms as "network of networks" (NoN). The process of arriving at this list is explained in the data and methods section. Fig. 1 shows the annual trend of publications containing these eight terms in the Scopus database until the end of 2018. As evident, the first publication in the selection is from 1932. The rapid growth of the field, beginning in the 1990s and accelerating over the last two decades, is evident from the figure. This study explores the changes in the research into NoN in the last 88 years since the first publication appearance.

To gain a more in-depth view, Fig. 2 provides the annual publication profiles for each of these keywords. Here, we first look at the literature and investigate the original use of each of these keywords. We then conduct a detailed network analysis of the published literature containing these terms to assess the relations between the keywords used together and the evolutionary trends of this research field.

Interconnected network: As evident from Fig. 2, this term is the most common keyword among the eight discussed. There were over three thousand scientific articles about interconnected networks by the end of 2018 (see Fig. 2). The term was first used

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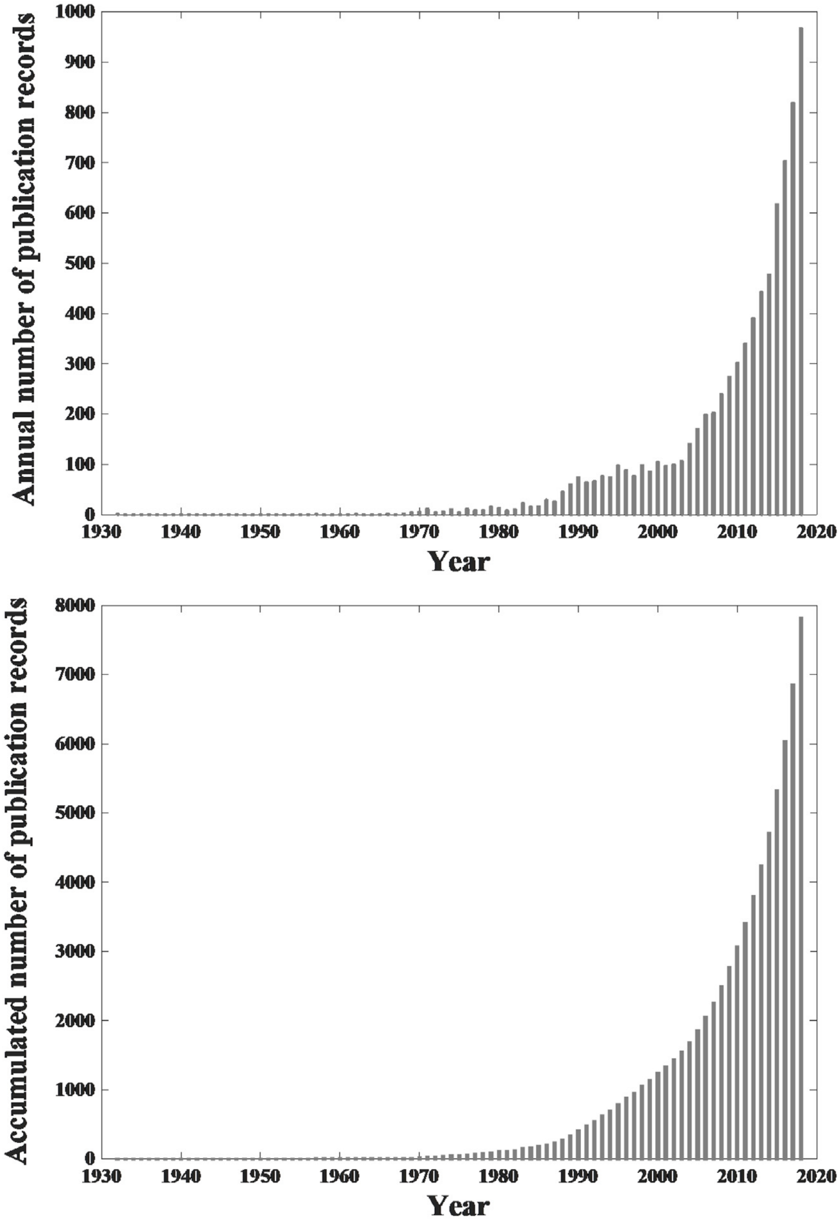


Fig. 1. Annual records for publications associated with "network of networks".

by Purcell and Powel [5,6]. Purcell, from Duquesne Light Co., and Powel, from Westinghouse Elec. & Mfg. Co., both companies in Pittsburgh, wrote a short letter titled "Interconnected Networks" to the Electrical Engineering journal in 1931 [5], describing the successful interconnection between the electricity networks of the two companies. In 1932, they wrote a full paper with the same title and provided details of their tie-line load regulators which facilitated the interconnection [6]. The term was not used in the scientific literature for the following 25 years until Matthaei [7] published a circuit analysis paper in 1957. He described a method for finding the characteristic polynomials of interconnected networks using the properties of their component networks. Again, we found no incidence of "interconnected network" usage for the following decade, until in 1966, Rieke, Karsten, and Bross [8] discussed the complexity of simulating the water network expansion of Berlin city due to the complex nature of the interconnected networks involved. This term has become increasingly used since that time, especially over the last decade (see Fig. 2).

Multilayer network: The term "multilayer network" seems to have been coined first by Weston in 1974 [9], describing an attempt to develop a multilayer neural network model of the auditory system for the study of lateral inhibition. A decade later, Coden [10] discussed the importance of multilayer networks versus disparate networks in the planning and design of fibre optic networks. In the late 1970s, the International Organization for Standardization (ISO) proposed the Open Systems Interconnection model (OSI model) as a conceptual model that characterizes and standardizes the communication functions of a telecommunication network. This was done in response to the growth of different networks that were developing from different equipment vendors and companies that were not originally compatible with each other, and appropriate common interfaces and standards had to be developed to interconnect them. The model partitions a communication system into seven layers of abstraction, where each layer serves the layer above it and is

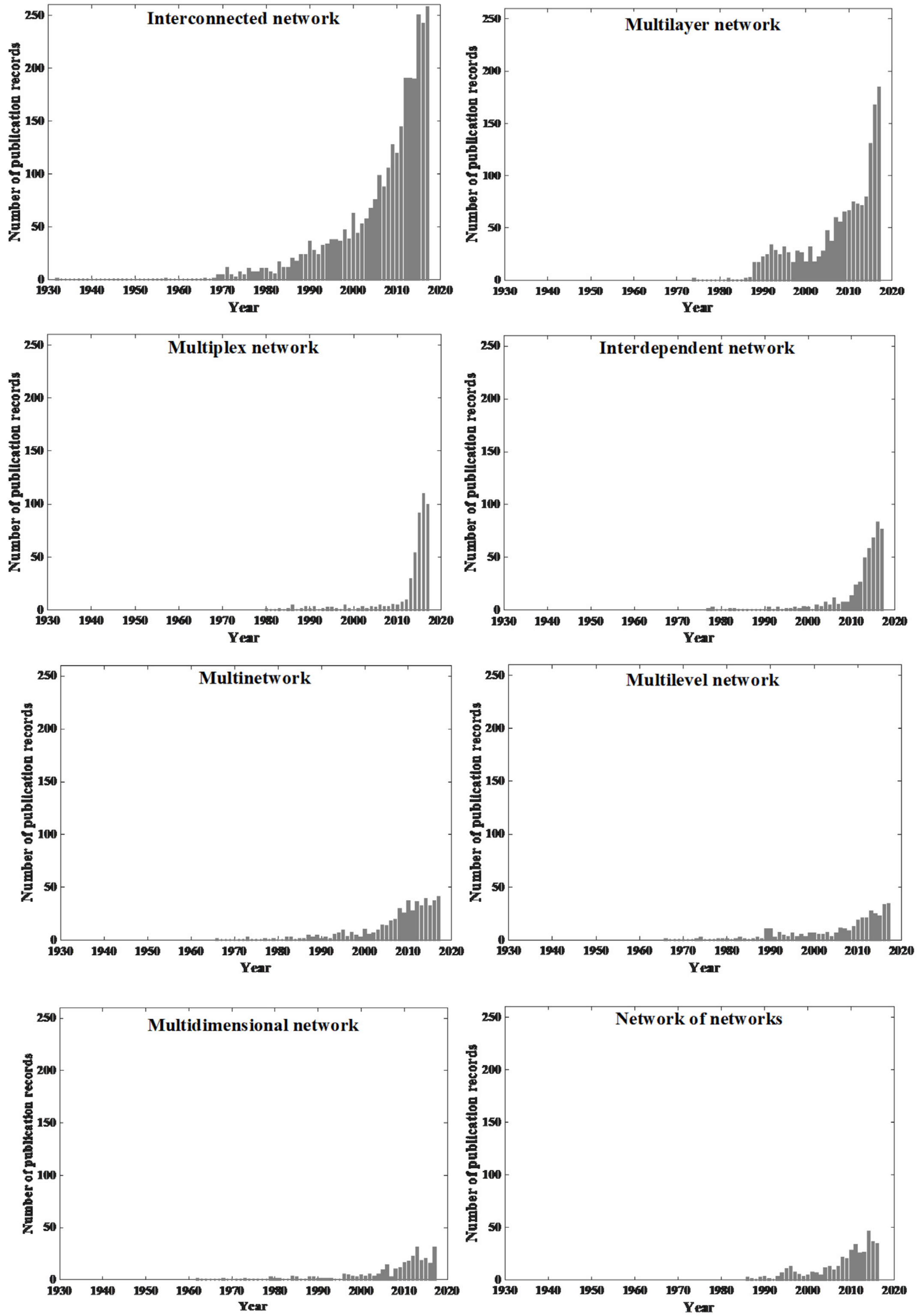


Fig. 2. Annual counts of publications including terms associated with networks of networks.

served by the layer below it. The OSI multilayer model was published in 1984 by both the ISO, as standard ISO 7498, and the CCITT (International Telegraph and Telephone Consultative Committee), as standard X.200 [11]. The TCP/IP (Transmission Control Protocol–Internet Protocol) protocol stack was developed in parallel for the same reason, in 1970s [12]. The use of the multilayer network term started to increase mainly from 1988, after which it grew gradually over the 1990s and 2000s. A steep increase in the use of this term has further been recorded since 2015 (see Fig. 2).

Multiplex network: This is a relatively newer term. It was initially used in 1980 by Ballinger [13] regarding high-frequency telecommunication cables and the use of frequency-division multiplex (FDM) networks to address the increasing traffic requirements of the time and the need of different users to share communication channels. FDM itself is a technique from the 1860s as harmonic telegraphy [14]. The initial use of multiplex network term was mostly for communication data multiplexing in various applications such as modem design [15], vehicle local area networks [16,17] or ATM networks [18]. However, the term did not become popular until recent years, and its use has displayed an accelerating pace from around 2012 (Fig. 2)

Interdependent network: The first recorded use of this term in the scientific literature is by Johnson [19] in 1977, discussing the benefits of interdependent networks of kin relationships in multicultural communities. However, the term was not used much until the late 2000s when it became more widely used. Its use has accelerated since 2010, but overall this term (together with "interdependence network") is less commonly used than multilayer or interconnected networks.

Multinetwork: This term seems to have been first used by Neubert [20], who in 1966 introduced a multinetwork for studying the elastic behaviour of anisotropic rubber by superposition of independent Gaussian networks. As evident from Fig. 2, this term was rarely used for the next two decades. Its common use began in the mid-2000s and is accelerating.

Multilevel network: The origin of this term has been attributed to Haring [21] in his introduction of multi-threshold threshold elements for electronics and computer networks in 1966. As displayed in Fig. 2, its regular use began in the late 1980s and accelerated from the late 2000s.

Multidimensional networks: This term seems to have been coined by Korn in 1962 [22] in his attempt to extend the model of a one-dimensional electrical network to multidimensional networks. The next record is again from Korn in 1966 [23] relating to multidimensional electrical networks. However, this term did not become popular until the last decade (see Fig. 2).

Network of networks: The term "network of networks" seems to have been coined by Wilson in 1986 in an article titled "Fiberway" [24]. He proposed Fiberway as a new digital broadband network which enabled simultaneous transportation of multiple independent protocols over the same fibre, calling it a network of networks [25]. In the following year, Coviello [26] introduced the "network of networks" concept for distributed communication across several communities as a network redundancy tool for survivability. Coviello argued that the establishment of a virtual network of networks utilizing user terminals as the switches and existing networks as the linkages could increase the resilience of the overall system compared to any of the constituent networks. The use of this term has grown steadily since then. The Internet itself is often described as a network of networks, each running its own protocols or having a different administrator, and interconnected at special nodes called gateways or routers, depending on the layer at which they are interconnected.

In this paper, we use the term "network of networks" (NoN) as an overarching term to address all related concepts including "interconnected networks", "multilayer networks", "multiplex networks", "interdependent networks", "multinetworks", "multilevel networks", and "multidimensional networks". We explore all available literature in Scopus database on these topics to the end of 2018 and longitudinally investigate the interactivity of related keywords in the development of the field.

2. Data and method

The publication dataset used in this study is built based on publication records extracted from Scopus.com. When conducting bibliometric studies, coverage (i.e., no bias towards covering publications from certain countries, languages or publishers) and accuracy (i.e., consistency in author name spelling and standardize journal titles and affiliations) of the chosen database are essential considerations [27,28]. As of January 2020, "Scopus contains over 51.3 million records post-1995 with references and 25.3 million records pre-1996, with the oldest record dating back to 1788 (76.8 million core records in total). Approximately 22% of titles in Scopus are published in languages other than English, adding up to 40 local languages (or published in both English and another language). In addition, more than half of Scopus content originates from outside North America representing various countries Europe, Latin America and the Asia Pacific regions" [29]. The scientific community has widely utilized the Scopus database due to its wide coverage and enhanced utility. However, it has received some criticism due to inconsistencies in the name of authors. Since our study is mostly focused on the keywords assigned to publications, the latter will not affect our results [28,30].

This bibliometric website was searched for publications which included in their titles, abstracts, or keywords the terms multinetwork, multi-network, interconnected network, inter-connected network, multidimensional network, multi-dimensional network, network of network, interdependent network, inter-dependent network, interdependence network, inter-dependence network, multilevel network, multi-level network, multilayer network, multi-layer network, multiplex network, or multi-plex network. The process of arriving at this set of keywords is as follows. We started the search with our own initial list of keywords. Then updated the list at two stages. The first step was expert opinion. We discussed the list with experts in the field and updated the list with their suggested keywords. In the second step, we searched and collected the literature based on the updated keywords list from the first step and conducted keyword analysis. From the analysis, we identified some similar keywords used in some disciplines which were not known to us earlier. We updated our keyword list and conducted another literature search followed by keyword analysis. We repeated this process until we became confident that we have a reasonably comprehensive list of related keywords. The search, conducted in February 2019, retrieved 7818 records in English published by the end of 2018 (see Fig. 1). Hence, here we explore the longitudinal dynamics in the research on NoN over the last 88 years.

The analysis mainly focuses on the co-occurrence of "keywords" in the retrieved publications. The keywords of scientific papers are carefully selected by their authors to describe the main topic and the research focus of the article. Exploring these keywords and identifying the frequency and structure of their co-occurrence in scientific articles can reveal the knowledge structure of discipline [31,32]. Word co-occurrence analysis is a technique that allows researchers to establish similarity relations between different keywords and, using these relations, construct a network of concepts and ideas in a corpus. Several studies have used this approach in fields such as renewable energy [31], service innovation [33], hydrogen energy and fuel cells [34], ecology [35], climate change [36], polymer chemistry [37], zoonotic disease propagation [38], simulation–optimization of supply chains [39], and information retrieval [40].

Assuming that two keywords are more related if they appear together in more scientific papers [31,41], we can construct valued keyword networks. Each keyword network consists of a set of nodes, each representing a keyword, and links indicating the number of papers in which two keywords appear together (weight of the links).

We used MATLAB® 2018b to translate information from Scopus into a format useable by VOSviewer 1.5.4, which we used to visualize the keyword networks during different time intervals. The presented network maps are "distance-based", which

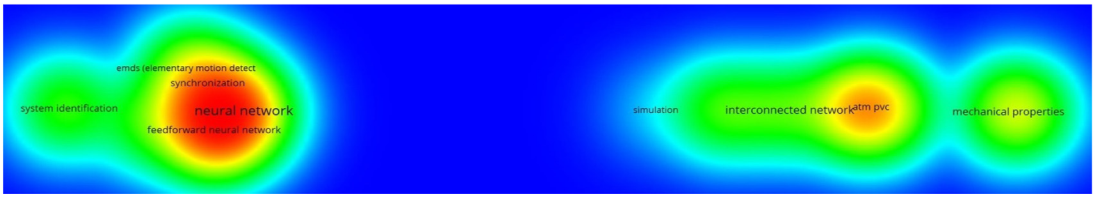


Fig. 3. Keywords network map (heat map) for all records up to 2000.

means that the location of nodes is algorithmically determined such that the distance between each pair of nodes (e.g., i and j) corresponds to the strength of the relationship between the nodes. The strength of the relationship (s_{ij}) is calculated as $s_{ij} = c_{ij}/\left(w_i w_j\right)$, where c_{ij} is the frequency of co-occurrence of keywords i and j; and w_i and w_j are the frequencies of keywords i and j, respectively. This mapping technique is referred to as visualization of similarities (VOS) proposed by [42]. They developed the technique as an alternative to multi-dimensional scaling techniques (MDS) [43] for visualizing bibliometric maps. While the two methods have some similarities in their underlying mathematical basis, the VOS method has been shown empirically to be more suitable for visualizing bibliometric data sets [42]. This disadvantage of the MDS approaches is the result of two artefacts. "One artefact is the tendency to locate the most important items in the centre of a map and less important items in the periphery. The other artefact is the tendency to locate items in a circular structure. Unlike the MDS approaches, the VOS approach does not seem to suffer from artefacts" [42].

In summary, to create a keyword network map, we identified the co-occurrence frequency of each pair of keywords in our data set for each time interval. This frequency is calculated based on the number of publication records in which the two keywords are both recorded in the article's keywords list. The co-occurrence frequencies matrix is then provided as input to the VOSviewer software. The relative distance of any pair of keywords in the maps created by the VOSviewer software approximately indicates the relatedness of the keywords as measured by co-occurrences [44]. Similar to MDS techniques, the x and y axes in these maps, do not have any special meaning, and the focus is on arranging the points in the two-dimensional space such that the pairwise distance between the points in the layout reflects the pairwise similarities as much as possible. Any rotation or flipping of the diagrams would not change the results.

We use two different views of keyword networks produced by VOSviewer. In the density view (heat map), colours show the distribution of the keywords (nodes) in the two-dimensional space underlying the visualization. The density view immediately identifies dense areas where many keywords are placed close to each other [44]. In this view, the background of the labels is displayed in colours ranging from red to blue. Background colours close to red represent a higher density of keywords, while colours close to blue demonstrate lower density. Density is defined based on the number of keywords in the area and their weights. This view can be used to identify important areas of a network [45,46].

In the label view, each node (keyword) is represented by a circle and its corresponding label. The sizes of the circles and labels vary, based on the weight of the nodes. The weight of a node is assigned as the total strength of all the links of the node. To avoid overlapping, not all labels are shown.

3. Results

Here, we present the keyword co-occurrence network maps (keyword network map for short) over three time-intervals chronologically. In each interval, using the heat and label maps, we describe the knowledge structure of the identified literature that arises as a result of the frequency and pattern of relations among keywords co-occurring in the publications.

3.1. Keyword network map up to 1990

From the annual publication profile (Fig. 1), it is observable that there was only a small number of NoN publications from the first instance in 1931 until the late 1980s. Before 1990, there was no systemic pattern of co-occurrence of keywords in the retrieved papers, which suggests that a coherent field of NoN research has not emerged before 1990.

3.2. Keyword network map up to 2000

As shown earlier, the topic of our study evinced an increasing pace from the late 1980s, and according to Fig. 1, by the year 2000, the total number of publication records reached 1122. The density map of the keywords network until 2000 (Fig. 3) shows two groups of keywords with high density (i.e., sets of keywords grouped together). The term "neural network" (see the high-density group on the left side of Fig. 3) is seen to have emerged as a new research field, followed by the term "interconnected network" (see the right side of Fig. 3). The large distance between these two groups of keywords also implies the relative independence of these two research fields.

Neural network cluster: Fig. 3 shows the rise of the field of [artificial] neural networks in the 1990s. Research in this field began with McCulloch and Pitts, who in 1943 introduced a logic-based computational model for neural networks [47]. Neural network research did not progress until the 1980s partly because of computational limitations [48]. Interest resumed in the 1980s for at least two reasons. The key reason was the introduction of the backpropagation algorithm by Werbos [49], which accelerated the training of multilayer neural networks. The other reason was the use of parallel distributed processing (itself inspired by neural networks) which further facilitated the simulation of computationally-intensive neural network problems, with methodologies elaborated by Rumelhart and McClelland [50]. Thus the field grew during the 1980s and became a research cluster in the 1990s, as evident from Fig. 3.

Interconnected network cluster: In the previous sections, we discussed that "interconnected network" is a popular term with the annual number of publication records exceeding 250 in recent years (see Fig. 2). Interestingly, as Fig. 3 shows, this term had not been developed as a research field until recently, and we notice only a small publication cluster related to interconnected networks by the beginning of this millennium.

Mechanical properties: On the right-hand side of Fig. 3, another small cluster developed around the topic of "mechanical properties" (see Fig. 4). Later we discuss the opportunity that the invention of electron microscopy provided in the late 20th century in imaging and identifying physical properties of materials (including biological). High-resolution imaging enabled characterization of atomic and molecular networks. This led to the birth of the fields of nanotechnology and modern biotechnology (system biology).

Fig. 4. Keywords network map (label view) up to 2000: focus on mechanical properties.

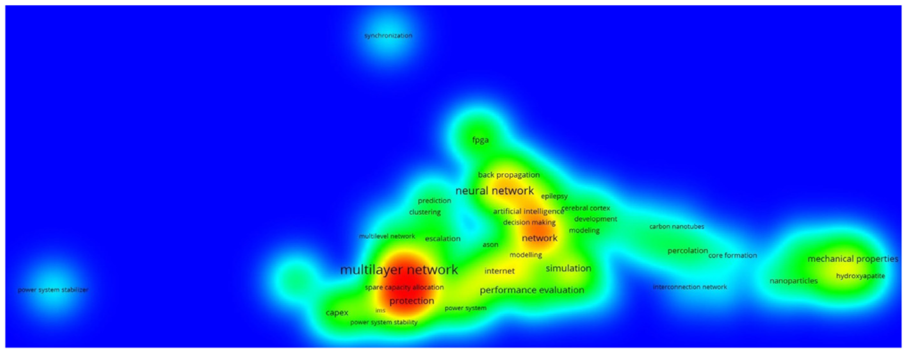


Fig. 5. Keywords network map (heat map) for all records up to 2010.

3.3. Keywords network map up to 2010

In the subsequent decade, the number of NoN publications more than doubled, reaching 2738 by 2010 (see Fig. 1). The density map of the keyword network up to 2010 (Fig. 5) clearly shows the development of an intensely integrated research field under which neural network further developed and found widespread use in different disciplines (see the centre of Fig. 5). During this period, a new NoN research cluster emerged and took over the neural network cluster in terms of size. This result came from comparing Fig. 5 from this period (up to 2010) and Fig. 3 from the previous period (up to 2000) and we saw specifically this new cluster was centred around multilayer networks, a term first used by Weston in 1974 [9] in application to neural networks. The term later found wider applications after the proposal of the 7-layer OSI model (and later of the TCP/IP model) for the organization of telecommunication networks and the subsequent evolution of other sub-disciplines such as routing, optical networks, network resilience, network planning and capacity allocation. Fig. 6 shows the strong clusters in this period.

As in the preceding decade, in the decade to 2010 “mechanical property” shows a weak but growing cluster (compare the right sides of Figs. 3 and 5). It is observable from the right side of Fig. 5 that the “mechanical properties” cluster grew by 2010 and was linked with more keywords such as “nanoparticles” and “hydroxyapatite”. Hydroxyapatite, also called bone mineral, is a monocrystalline material which builds around 50%–70% of human bone [51]. In tissue engineering, the scaffolding material structure (network) plays a key role in the functionality of the synthesized tissues. The invention of the scanning probe microscope (SPM) in the 1980s [52] also led to significant developments in tissue engineering, as it was now possible to build tissue scaffolds from the bottom up with constituent materials while controlling the network structure and properties with accurate imaging [53]. In network language, we can assume the nanoparticle as one node where physico-chemical connections between particles in various topologies lead to diverse networks (products) with unique properties. A high-resolution view of the mechanical properties cluster of Fig. 5 is provided in Fig. 7. The figure clearly shows the emergence of keywords related to nanotechnology and system biology. In Section 4, we elaborate on this cluster.

3.4. Keywords network map up to 2018

In less than a decade, since 2010, the number of NoN publication records increased by almost three-fold, reaching 7818 by the end of 2018. Although these numbers are still small compared to many fields of research, the tripling represents the rapid growth of an important new field. The density map of the keywords network up to 2018 (Fig. 8) clearly shows the development of an intensely integrated research field under which multilayer networks further developed and found widespread use in further new disciplines such as communication networks, social networks and energy efficiency (see Fig. 9). The relationship with the neural network as discussed in the previous sections continues to grow in this decade as well. We also observe the emergence of keywords such as “deep learning”, “learning”, and “supervised learning” in this decade indicating the recent developments in the field of neural networks [54]. The term multilayer is often used in communication networks to separate them into different hierarchical layers of different functionality and agreed upon interfaces, so that the designer can focus on and improve on each of them individually, thus increasing modularity, conceptual simplicity, and interchangeability. During this period, however, the terms “interdependent network” and “multiplex network” became the most strongly connected keyword, developing a strong cluster in connection with “cascading failure”.

As evident from the right side of Fig. 8, by 2018, the former “physical properties” cluster yielded its place to graphene (first characterized in 2004 [55]; in 2010 bringing the Nobel prize to the discovery team [56]). As shown in Fig. 10, graphene is now the main cluster, and is integrated with the two clusters “mechanical properties” and “carbon nanotubes”. All these new emerging keywords have single- or multilayer network structures which are developing slowly over time and will eventually form strong connections with network theory and the NoN concept. We elaborate on this in Section 4.

In Table 1 we list the top 40 keywords which had emerged by the end of 2018. Further to our earlier discussion, it is evident that network resilience is receiving more attention, represented by keywords such as “cascading failure”, “robustness”, “resilience”, “reliability”, and “security”. The use of NoN theory in classification problems is another observation from the list of keywords which contain “community detection”, “clustering”, and “classification”.

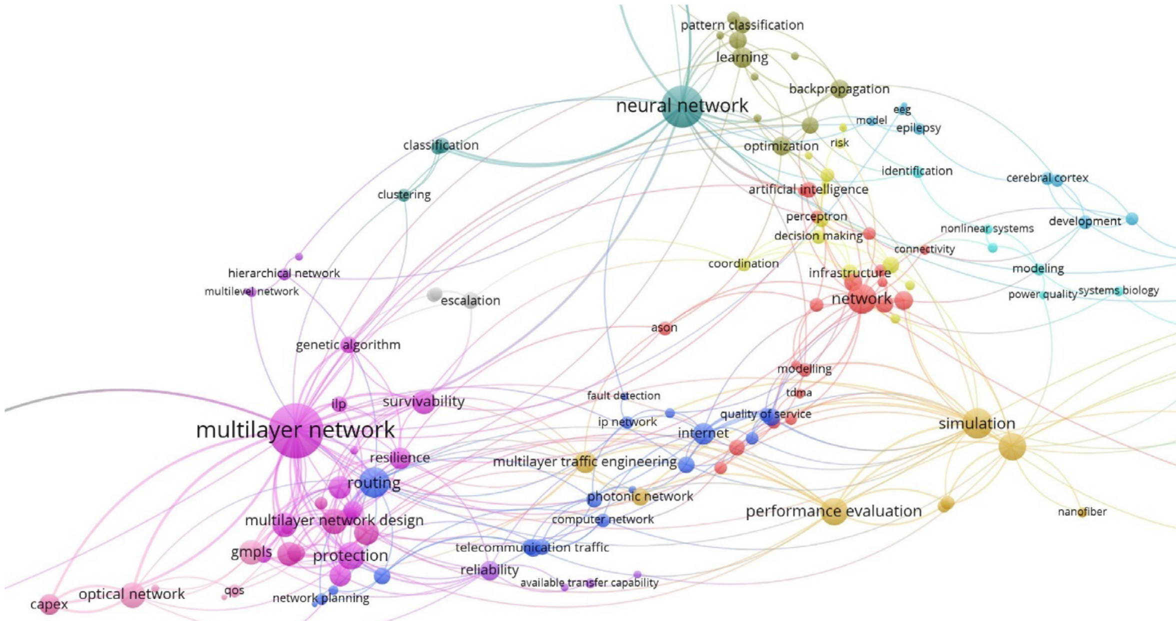
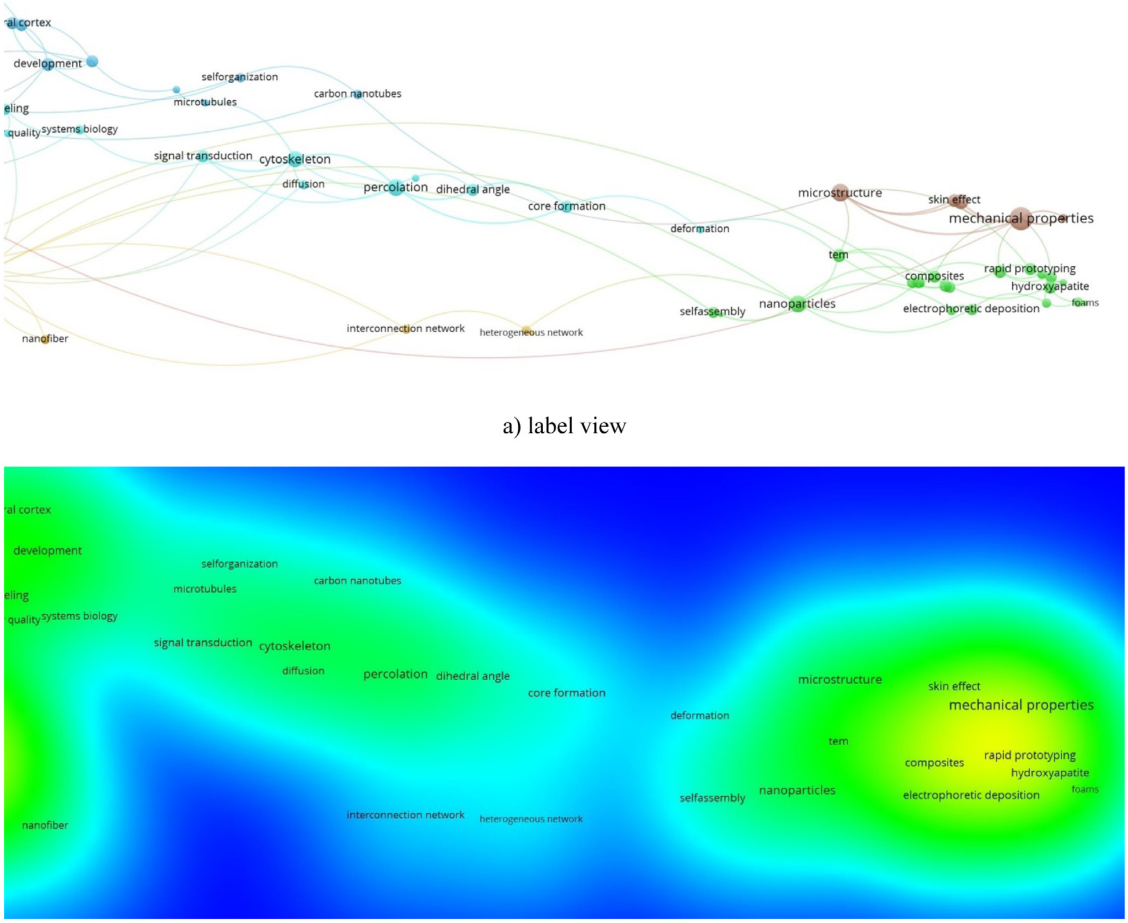


Fig. 6. Keywords network map (label view) up to 2010: focus on strong clusters.



a) label view

b) heat map

Fig. 7. Keywords network map up to 2010: focus on mechanical properties (nanoscience and nanotechnology).

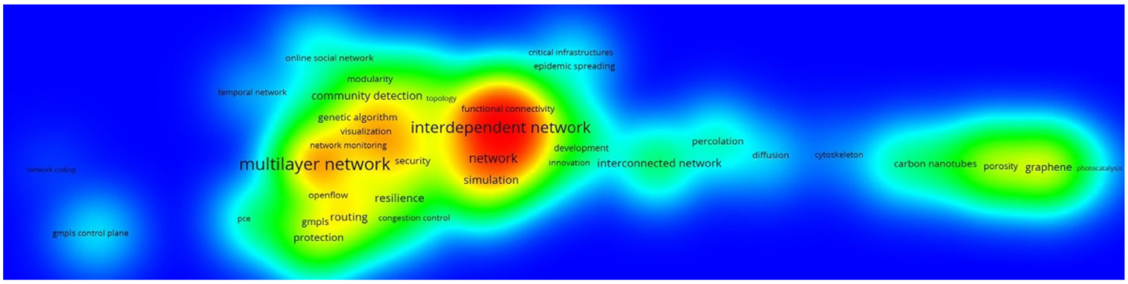
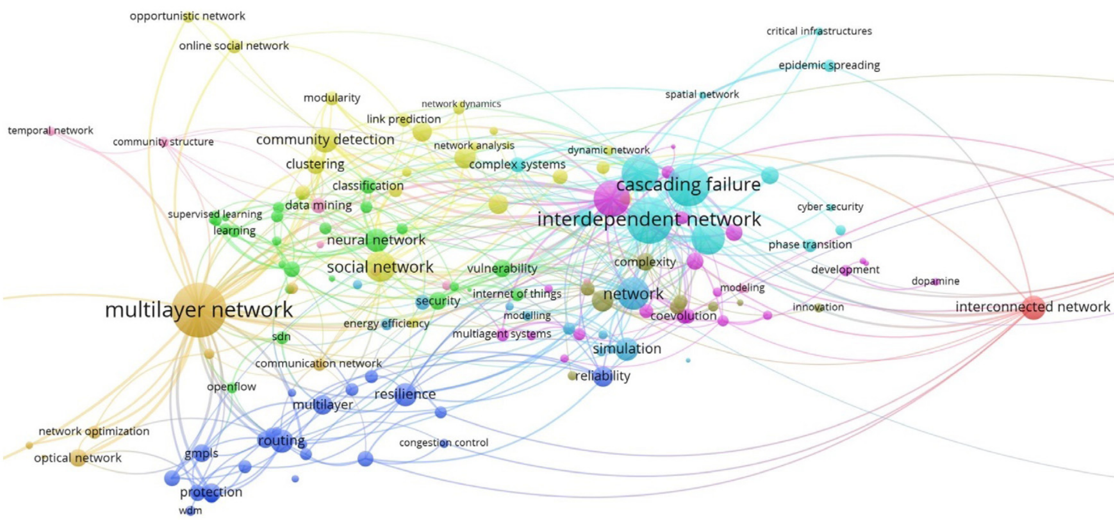
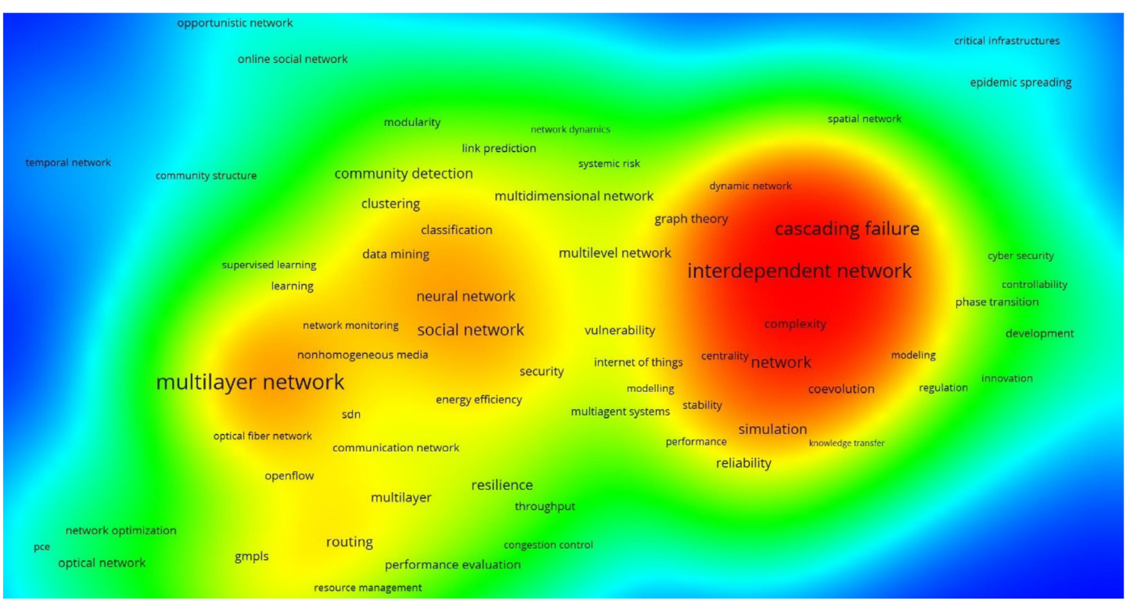


Fig. 8. Keywords network map (heat map) for all the records up to 2018.



a) label view



b) heat map

Fig. 9. Keywords network map till 2018: focus on strong clusters.

4. Discussion: the congruence of network theory and nanoscience

The study so far has revealed that in the 1990s, the NoN began to form as a field around neural networks research and gradually research clusters "interconnection", "multilayer", and "interdependence" were emerged dominantly in the disciplines of computer and physical sciences.

We also observed that a small cluster emerged in the 1990s around physical properties (Fig. 3 right side), and gradually developed (Fig. 5 as of 2010 and Fig. 8 as of 2018) into a rich cluster overarched by the term "graphene". Here we would like

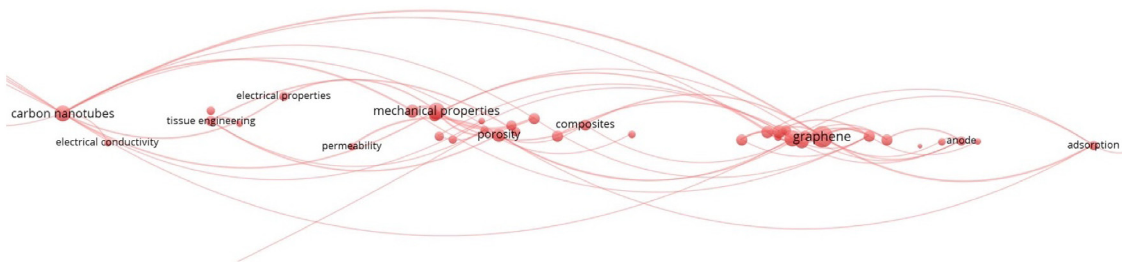


Fig. 10. Keywords network map (label view) up to 2018: focus on mechanical properties (nanoscience and nanotechnology).

Table 1
List of most frequently occurring keywords up to 2018.

Keyword	No. occurrence	Keyword	No. occurrence
multilayer network	385	smart grid	37
multiplex network	206	artificial neural network	35
interdependent network	166	optimization	33
complex network	134	routing	31
cascading failure	116	epidemic spreading	29
network	113	resilience	28
neural network	101	reliability	28
interconnected network	74	percolation	27
robustness	71	multinetwork	27
social network	69	clustering	27
multilevel network	50	complex system	27
multidimensional network	47	carbon nanotubes	26
simulation	46	security	26
internet of things (IoT)	45	multiagent system	25
community detection	45	gmpls	25
network of networks	45	network analysis	24
social network analysis	44	multilayer	24
mechanical properties	42	supercapacitor	24
synchronization	40	multilayer network design	24
graphene	40	cooperation	23

to discuss the possible reasons for the emergence of this cluster within a commonly perceived field of computer science. For this, we need to review the timeline of the nanoscience and graphene revolution.

Until the late 19th century, discoveries finer than micro scale were not possible due to a combination of reasons, including the maximum achievable magnification ratio of 300:1 and also the challenge of sample illumination [57]. The invention of electric bulbs in the late 19th century, together with Kohler's illumination theory [58], led to some improvement in imaging quality during the early 20th century. However, a huge technological step occurred when the transmission electron microscope (TEM) (see the right side of Fig. 7) was invented by Ruska and Knoll in 1931 and was further improved to the scanning TEM (STEM) by 1935 [59]. The critical advantage of TEM for optical microscopes was the use of electrons instead of light, which enabled imaging with much finer resolution.

These advances led to the discovery of the atomic and subatomic worlds in the early 20th century, which generated scientific motivations to manipulate atoms and molecules for the design of desired compounds [60,61]. This ambition became achievable in the early 1980s with the invention of scanning tunnelling microscope (STM) and the atomic force microscope (AFM) with resolutions in the order of 0.1 nm [52]. This invention should be considered the real enabler of the birth of the field of nanotechnology, i.e., the manipulation of matter on an atomic, molecular, and supramolecular scale. This enabled characterization of atomic-scale properties as well as new product developments. These are reflected in the NoN maps as well.

Physical properties: The possibility of imaging atomic and molecular structures at fine scales facilitated assessing the physico-chemical properties of the scanned samples. That is why in Fig. 3, we observe that from the 1990s, a weak cluster named "physical properties" emerges with strong connections with "cell". The facility of fine imaging has enabled molecular biologists to investigate the function of the extracellular matrix (ECM) as a network. An ECM is a collection of extracellular molecules that is secreted by cells to provide both structural and biochemical support to surrounding cells. Each cell is a network, and then their interactivity with neighbour networks (cells) develops an NoN with fixed features such as cell adhesion, cell-to-cell communication, and differentiation. As such, in the networks of 2010 and 2018, we observe the emergence of "system biology", "tissue engineering", and "cytoskeleton" (e.g., Fig. 7) all of which have a network structure. We further observe the link between "system biology" with keywords such as "network" and "modelling". It is worth mentioning the importance of complex system research in the development of the system biology field or more precisely "complex systems biology" as comprehensively reviewed in [62]. We can expect that, over time, the NoN concept will develop stronger ties with system biology, with increasing understanding and data acquisition from the molecular levels.

Graphene: Carbon nanomaterials are probably the subjects with most bridges to network theory. There is currently significant research around single-layer and multilayer carbon networks which have found extensive use in nanoscale electronics and devices. Even some network theories, such as site percolation, are commonly used in carbon networks [63]. Graphene is defined as a single-layer network of carbon, the existence of which was theorized in the 1960s. However, it was characterized only in 2004 [55] for which Geim and Novoselov were awarded the Nobel prize in 2010 [56]. Graphene has exceptional physical properties, such as being the strongest material ever tested. These properties have made it the basic structural element of many other carbon fibres and offered it a central role in the field of nanotechnology over the last decade. This history also shows itself in our network maps as we observe from Fig. 8 that by the year 2018, the "physical property" cluster has changed to a group this time flagged by "graphene".

In summary, thanks to the significant role of atomic microscopy in the last few decades, scientists are now able to discover and synthesize new NoN in the bio and nano worlds which integrate with the network theory of computer science. We can expect that, over time, the relatively weak graphene cluster will grow and develop stronger ties with the other clusters in Fig. 8.

5. Limitations and future research directions

It is worth mentioning the constraints and limitations of the analysis presented in this research. First, we acknowledge that the method to arrive at the final list of keywords to search for relevant literature could be biased towards the initial set and expert judgements, although we attempted to minimize it in the second step of developing the list of keywords. Second, the focus of this research was on the network of networks research that appeared in English-language publications and did not include any potential parallel developments in non-English language literature. The search relied on authors' keywords to visualize the development of the network of networks field overtime and its connection with other disciplines. Future research can explore the field further by investigating the whole corpus of available literature using topic modelling methods such as Latent Dirichlet Allocation [64].

6. Conclusion

The purpose of the present bibliometric analysis was to investigate the evolution of the field of NoN. Rather than producing new "scientific results", this paper attempted to rigorously integrate and map out the interconnections among previously produced scientific research to show the bigger picture of the emerging field of Network of Networks. A common issue in science is that generic terms often take on very narrow, specific meanings, which are used in different ways in different fields. Moreover, different terms can be used for the same concepts based on different disciplinary traditions. The presented approach helps to map how the usage of NoN-related concepts and terms evolved across diverse fields of science and how these terms have become widely adopted across a range of relatively independent disciplines.

Our analyses reveal that the field of NoN was conceived mainly from the 1990s as a coherent discipline primarily around neural networks. But over the following decades, other aspects of NoN, such as "interconnection", "multilayer" and "interdependence" became popular. Most recently, network interdependence and its application in cascading failure seem to be among the main topics attracting more academic attention.

Another interesting observation is the congruence of the NoN field and nanoscience. The invention of high-resolution scanning probe microscopes in the 1980s enabled scientists to become involved in the manipulation of matter on atomic, molecular, and supramolecular scales and in building complex molecular networks with desired biological, chemical and mechanical properties. Our analyses show that new NoN development in this scientific space is now a growing cluster and it can be expected to build a strong tie with the NoN of computer science in the coming decade(s).

Abbreviation

Al_2O_3	Aluminium oxide
ASON	Automatically switched optical network
AFM	Atomic force microscope
ATM	Automated teller machine
Capex	Capital expenditure
CCITT	International telegraph and telephone consultative committee
ECM	Extracellular matrix
EEG	Electroencephalogram
FDM	Frequency-division multiplex
FDMA	Frequency-division multiple access
FPGA	Field programmable gate array
GMPLS	Generalized multi-protocol label switching
ISO	International Organization for Standardization
MDS	Multi-dimensional scaling techniques
NoN	Network of networks
OSI	Open systems interconnection
PCE	Path computation element
PVC	Polyvinyl chloride
QoS	Quality-of-Service
SDN	Software-defined networking
SPM	Scanning probe microscope
STEM	Scanning TEM
STM	Scanning tunnelling microscope
TCP/IP	Transmission control Protocol–Internet protocol
TDMA	Time-division multiple access
TEM	Transmission electron microscope
VOS	Visualization of similarities

CRediT authorship contribution statement

Faezeh Karimi: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **David Green:** Conceptualization, Writing - review & editing. **Petr Matous:** Methodology, Writing - review & editing. **Manos Varvarigos:** Conceptualization, Writing - review & editing. **Kaveh R. Khalilpour:** Conceptualization, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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