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A Survey on the Use of P2P Technology for Network Management

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Abstract Network management has steadily evolved over recent years. Along with the growing need for advanced features in network management solutions, several distribution models were investigated, varying from centralized to fully distributed models. Despite the common agreement that some sort of distribution is really needed to execute management tasks, there seems to exist a permanent quest for the next distributed network management model. Among the distributed models, an interesting and emerging possibility is the use of P2P technology in network management, also known as P2P-Based Network Management (P2PBNM). Several investigations have shown that P2PBNM can be seen as an enabler for advanced network management features. However, due to the dispersion concerning the concepts and features related to these investigations, it is difficult to draw a comprehensive picture of the P2PBNM area. The purpose of this article is to look at literature on P2PBNM and to highlight initiatives regarding the use of P2P technology in network management. Furthermore, such initiatives are classified in respect to proposed review questions. Finally, future trends are discussed in order to predict what the future holds for P2PBNM.

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1 Introduction

The increasing complexity of computer networks requires sophisticated solutions to manage the underlying communication infrastructure and to help network human administrators in their daily tasks. Communication infrastructures consist of network devices from different vendors, using diverse technologies. In addition, computer networks carry traffic with different purposes and requirements (e.g. Web browsing, file transfer, e-mail messages, multimedia streaming). In this context, computer networks and the Internet have significantly evolved in terms of their capabilities. However, this evolution has not been accompanied by similar advancements in network management solutions [1].

Network management has become an important subject [2], with several solutions being proposed to respond to increasing management demands. Such solutions, for example, historically addressed the delegation of management tasks (e.g. Management by Delegation—MbD [3]), the support for high-level management goals (e.g. Policy-Based Network Management—PBNM [4]), the integration with recent business-related technologies (e.g. Web Services-based network management [5]), more proper support for configuration management (e.g. NETCONF [6] and its HTTP-based version RESTCONF), and self-*-based automation and optimization of management tasks (e.g. Autonomic Network Management [1]). In addition to these solutions, the employment of Peer-to-Peer (P2P) technology is also a possibility to further improve network management and is key to this survey article.

A P2P-Based Network Management (P2PBNM) system creates a management overlay over the managed network. In such an overlay, peers have a double role: besides acting as regular peers, they also perform management tasks [7]. P2PBNM holds the promise of incorporating beneficial key features of P2P technology into network management systems, such as highly-distributed processing and support for collaborative work. In addition, P2P technology deals with the idiosyncrasies of the Internet (e.g. broken network-layer end-to-end communication as the result of intermediate boxes like firewalls and NAT) more effectively in comparison with traditional network management technologies, since the latter have not been conceived taking current Internet peculiarities into account. This is because P2P systems emerged already operating considering the current patched architecture of the Internet. In this context, the success of distinct P2P applications and infrastructures in different areas paved the way for P2PBNM research initiatives.

At first, P2PBNM investigations carried out by the research community addressed aspects related to decentralized management including, for example, load balance of management peers [8] and self-organization of management overlays [9]. Afterwards, novel initiatives investigated the integration of P2PBNM with other management approaches such as autonomic management [10], cooperative management [11], and model-driven architectures [12]. Finally, complementary research efforts investigated other aspects related to P2PBNM, such as consistency maintenance of states of management data [13] and support for service coordination [14].

Since P2PBNM has received significant attention from the research community, it is relevant to have an organized view of the key P2PBNM research efforts, surveying the different initiatives carried out in recent years. That is the goal of this article. Our approach to organize such an overview begins by defining P2PBNM concepts and features. Then, we compile a research map on the use of P2P technologies for network management, presenting the initiatives according to an established network management taxonomy [15]. After reviewing the evolution of P2PBNM, we discuss what the future possibly holds for this research area.

The remainder of this article is organized as follows. In Sect. 2, we present an overview of P2P technology and P2PBNM concepts. In Sect. 3, we discuss the method employed to perform the literature review. The surveyed initiatives are highlighted in Sect. 4 and a comparison among such initiatives is described in Sect. 5. A discussion of current challenges and future research trends is presented in Sect. 6. Finally, Sect. 7 closes this article and features concluding remarks.

2 Background

In this section, we present state-of-the-art concepts on P2P technology and Peer-to-Peer (P2P)-Based Network Management (P2PBNM). P2P technology constructs application-specific overlay networks (i.e. a network that is built on top of other networks), usually running over the Internet as the underlay. In these overlays, resources distributed in several peers are used in order to implement applications (e.g. file sharing). This technology has been used to support diverse applications and services (e.g. file sharing, instant messaging, VoIP, collaborative work), often with varying conceptual definitions. In this section, we clarify the context and concepts behind the use of P2P technology, in addition to presenting an overview of P2PBNM concepts.

2.1 P2P Technology in a Nutshell

The term “Peer-to-Peer” (P2P) can be applied to several and distinct contexts. Usually, in computer science literature, P2P is followed by words such as system, application, infrastructure, overlay, and network. Steinmetz and Wehrle [16] defined a P2P system as a “self-organizing system of equal, autonomous entities (peers) which aims for the shared usage of distributed resources in a networked environment avoiding central services”. Androutsellis-Theotokis and Spinellis [17] stated that “it is fair to say that there is not a general agreement on what ’is’ and what ’is not’ peer-to-peer”, attributing such a lack of agreement to the fact that systems or applications are labeled “P2P” not because of their internal behavior, but because of their external appearance. Rodrigues and Druschel [18] reviewed P2P technology and stated three fundamental properties: (i) high degree of decentralization, since peers implement both client and server functionality; (ii) self-organization, thus, little (or no manual) configuration is needed to maintain the system after the introduction of peers; and (iii) multiple administrative domains, i.e. peers can be owned and controlled by different organizations or individuals.

P2P is employed in different contexts, associated with different levels of abstraction and interpreted in distinct manners. Androutsellis-Theotokis and Spinellis [17] grouped the use of such technology into P2P infrastructures and P2P applications. They define these groups considering only one kind of application, P2P content distribution, which was the most popular and developed technology at the time their article was published. However, over the years, other types of P2P technology usage emerged. We argue that it is possible to analyze and regroup the use of such technology at this moment, for example, into P2P infrastructures, P2P infrastructures for specific applications, and P2P applications. Examples related to each of these groups are presented below.

P2P infrastructures Infrastructures employed to deliver underlying conditions and services for applications. Examples include routing and location [19], reputation [20], topology management [21], performance [22], connectivity [23], and security [24]. Some well-known works related to P2P infrastructure are JXTA [25], Pastry [26], and Chord [27].

P2P applications Applications that make use of P2P infrastructures. This group consists of uses of P2P technology that present a very tight relationship between the P2P infrastructure and the application running on top of it. Androutsellis-Theotokis and Spinellis [17] also classified P2P applications into five categories based on the purposes associated with the applications: communication and collaboration [28], distributed computing [29], Internet service support [30], database systems [31], and content distribution [32].

Some major contributions from the P2P research community relate to the variety of applications that can be developed exploiting (i) the features introduced by the P2P infrastructure (e.g. scalability, robustness, and reliability), and (ii) the design concepts behind the P2P applications (e.g. distributed algorithms, collaboration to execute tasks, information sharing, decentralized decision-making). Encouraged by the features and design concepts introduced by P2P technology, the network management community started to explore this technology regarding its solutions.

2.2 Peer-to-Peer (P2P)-Based Network Management Concepts

Relevant solutions and technologies have been conceived to support network management. In this context, there is substantial research on models (we use the term “model” in the same sense that Pavlou [2] used for the Manager-Agent model) that address the structure of interactions required to execute network management tasks. In these models, various forms of distribution (i.e. decentralization) are used to produce, access, and store management data. In the traditional centralized model, a single management station typically controls the entire managed infrastructure.

Scalability issues arising from the centralized model motivated intense research on Distributed Network Management (DNM) alternatives.

DNM improves the execution of management tasks in respect to scalability, flexibility, and robustness [33]. Some work that emerged in the management literature classified the various flavors of DNM solutions (e.g. [2, 33–35]). Besides that, considering this literature, it is also possible to say that there is no widely accepted or adopted DNM solution. More than that, it is also safe to say that, although it has been widely recognized as a necessity [36], DNM evolved very poorly during the years because no solution has been undoubtedly definitive. As a consequence, DNM remains as an open problem. One of the possible approaches to decentralize the execution of management tasks is to employ P2P technology.

Since P2P technology is known to be successful regarding the support of different kinds of applications (as described in Sect. 2.1), it is plausible to infer that such technology could also be fruitful for DNM. A P2PBNM system, described in Definition 1 is a special case of a DNM system, and thus, it avoids the use of centralized management stations. Besides, considering the definition of Steinmetz and Wehrle [16] for general P2P systems, it is also necessary to highlight the autonomous features of the (management) peers and a focus on the shared usage of networked resources (for management purposes).

Definition 1 A P2PBNM system is a network management system that presents P2P properties, i.e. a high degree of decentralization, self-organization, and multiple administrative domains in the execution of most supported management tasks.

P2P technology is characterized by a high degree of decentralized decision making across network nodes. Distributed decision making has an advantage, in this context, over centralized decision making in the sense that a peer is not required to access information from all the other peers (to make a decision). In P2PBNM, most of the system states and tasks are directly and dynamically allocated among the peers. Thus, the bulk of the computation, bandwidth, and storage needed to operate P2PBNM systems is contributed by the management peers. The resulting decentralization also pushes the local autonomy of the peers, increasing the use of local data and logic to make management decisions.

Several investigations used an implicit P2PBNM model to explain how P2P technology is employed to perform management tasks. To the best of our knowledge, the only work that clearly describes a P2PBNM model is the one conducted by Granville et al. [7]. It describes P2PBNM as an extension of the Management by Delegation (MbD) model [3]. In MbD, managers delegate the execution of tasks to Mid-Level Managers (MLMs) located closer to agents (e.g. transferring management scripts), reducing network bandwidth consumption and decentralizing the execution of management tasks. The authors merged the services introduced by the P2P technology with the MbD model in order to define a P2PBNM model. Figure 1 presents a general view of the P2PBNM model proposed by Granville et al. [7]. The authors also used their P2PBNM model to highlight some possibilities of P2PBNM: human-based cooperative management, improved connectivity for message exchange, and management tasks load balancing.

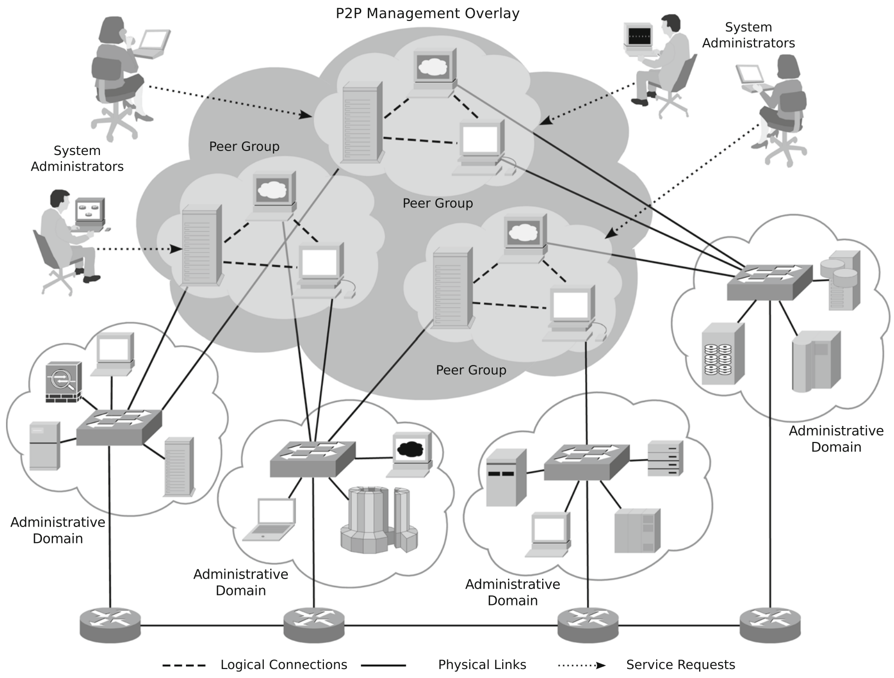

Fig. 1 P2P-based network management (P2PBNM) model

Figure 1 presents a P2P overlay in which resources are used to perform management tasks. P2P management overlays (described in the Definition 2), share some characteristics (e.g. overlay routing process, peer addressing) with the P2P protocol used to build such overlays. The choice of P2P protocols differs significantly between P2PBNM research initiatives. Some initiatives reuse well-established P2P protocols in order to exploit the properties of these protocols that were already described in the literature. The *Cyclon* protocol [37] is an example of P2P protocol used in management overlays [38]. The reuse of general P2P protocols eases the development of a P2PBNM system since the focus can remain on management components. On the other hand, some initiatives [39] build a P2P protocol from scratch focusing only on the required features/properties to make the management overlay operational. In this context, the efficiency of the P2PBNM system can increase since its overlay protocol does not need to address requirements of general purpose P2P systems.

Definition 2 A P2P management overlay is a P2P overlay network built specifically for the deployment of management components that implement management applications.

In a P2PBNM, peers have to perform management tasks and their related provisioning details (e.g. overlay organization). From the user perspective, however, the overlay provisioning details must be transparent, requiring no knowledge about the implementation or architectural organization of nodes in the overlay topology. Specially considering in-network (i.e. embedded) P2PBNM system, the decentralization of these systems makes their growth more "organic" since the addition of new devices can also follow the introduction of new management peers. Thus, P2PBNM systems can grow without requiring a fork-lift upgrade.

The approach to distribute management tasks also varies in P2PBNM investigations. One possibility is using Service-Oriented Architecture (SOA) [40] to perform management tasks through management services [8]. In this context, the result of these services is the execution of a management task. In general, these services are requested by system administrators (as shown in Fig. 1) or automation procedures, which can be hosted either inside the peers themselves or even in a centralized party. The software portion that is responsible for delivering management services is usually known as a management component. These components vary largely; e.g. from simple monitoring probes to complex autonomic policy interpreters.

Both the power of P2P systems and their features and properties relate intrinsically to the approach used by peers to communicate. P2PBNM systems usually employ some form of peer aggregation instead of using a flat overlay for message exchange. Figure 1 highlights the concept of peer groups that is described in Definition 3. Peer groups can support several desirable properties. For example, when aligned with replication of management components among different peers, peer groups can provide improved fault-tolerance and load balancing [8]. Besides, peer groups can also be used to decrease the number of exchanged management messages [13]. Some investigations also exploit the concept of epidemic communications to aggregate management information in a P2P approach, specially in monitoring tasks [39, 41].

Definition 3 A peer group is a group of peers that share one or more properties, e.g. provided management services, autonomous system, management team, etc.

P2P technology may also be a valuable tool to enable inter-domain management [42]. P2PBNM systems usually use Application Layer Routing (ALR) as their main message passing resource, and ALR adapts more easily to the boundaries of administrative domains. In this context, logical connections among the peers are mapped into physical links. In Fig. 1, we illustrate a scenario where participating peers (of peer groups) spread over different administrative domains; logical connections among peers are represented by dashed lines. Management entities in traditional management rely on the IP routing to communicate with one another. Thus, if the default route is unavailable, alternative routes cannot be selected. Furthermore, boundary boxes (e.g. circuit gateways, packet filters) break the network layer logic. For example, P2PBNM is able to cope with Internet patches like NAPT (Network Address and Port Translation) as well as network-level firewalls. The use of ALR can overcome network layer issues or at least optimize connectivity using information from the network layer [43].

However, despite its known advantages, the employment of P2P technology in network management has some important limitations. First, considering structural aspects, some critical issues inherited from general purpose P2P systems, such as the importance of routing protocols (specially in non-hierarchical overlays), can be discussed. Second, it is necessary to put more effort on the investigation of P2P management algorithms to improve the exploitation of P2P features on management tasks (e.g. collaborative fault management [44]). Several proposals just transpose DNM infrastructures for P2P overlays without exploiting genuine P2P features. Finally, some papers state that there is a lack of implemented solutions for many functions required to perform management tasks such as support for coordination services [14] and consistency of states of management information [13].

In the following sections, we present the method employed to perform the literature review on P2PBNM and the surveyed initiatives. These initiatives are mapped and grouped in order to produce a consistent overview of the employment of P2P technology in network management research scenarios.

3 Method for the Literature Review

The management of computer networks concerns the control of various network components in order to reach a desired system state. Given the solutions that have been presented throughout the years in network management literature, it is clear that the materialization of DNM can be accomplished following different approaches and technologies. In this paper, we perform a literature review (considering the authors' best knowledge) of the current efforts on the employment of P2P technology on network management. To the best of our knowledge, a survey of such approaches has not been provided so far.

The remainder of this section presents the method used in this survey. First, we describe the objectives and the review questions. After that, we propose two main phases to gather, evaluate, and analyze the literature concerning the employment of P2P technology on network management: the planning and execution phases.

3.1 Objectives and Review Questions

The literature review aims to characterize the state of the art regarding P2PBNM approaches and exploration of future research on such approaches. In order to perform such characterizations, we used an existing and acknowledged network management taxonomy [15]. This taxonomy was based on the topics for paper classification that were used by network management conferences, such as the Network Operation and Management Symposium (NOMS) and International Symposium on Integrated Network Management (IM).

To achieve the objectives of the literature review, a subset of the network management taxonomy proposed by dos Santos et al. [15] could be employed. This subset identifies the important topics regarding P2P technology. In more detail, 3 first level topics of the this taxonomy were selected, topic 4 (functional areas), topic 5 (management approaches), and topic 7 (management methods). Thus, these topics are represented by the following review questions that this work aims to answer:

– What functional network management areas can be tackled by P2P technology?
– What network management approaches can be deployed using P2P technology?

– What management methods can be employed using P2P technology?
– What are the opportunities and challenges for the employment of P2P technology in network management?

We provide more details about the challenges related to these features in Sect. 6 as well as future research directions. In the following, we briefly describe the features we focus in this literature review.

The employment of P2P technology can be performed for management tasks related to different functional areas. In simple terms, considering the FCAPS model, such tasks can be classified as Fault Management, Configuration Management, Accounting Management, Performance Management, and Security Management. In particular, several P2PBNM initiatives address more than one area since it is usually difficult to effectively classify management tasks into strictly separate function areas. In this context, we focus on the areas explicitly regarded as the main ones by the authors.

Different management approaches can be used by P2PBNM. *A priori*, one can argue that P2PBNM is an example of Distributed Network Management (DNM). However, some form of centralization can be used for specific processes in a P2PBNM system (e.g. storage of management data). Besides, P2P technology can be used either in an *ad hoc* manner or in addition to concepts and entities found in well-established DNM models, such as Policy-based Network Management (PBNM). Finally, there are approaches related to the automatization of management tasks such as autonomic and self management, and pro-active management.

P2PBNM initiatives can use different management methods to perform their tasks. Some methods can use intrinsic properties of P2P technology (as described in Sect. 2) to enhance the applicability of the methods themselves. In the literature review, we find 11 main methods: control theories; optimization theories; economic theories; machine learning and genetic algorithms; logics; probabilistic, stochastic processes, queuing theory; simulation; experimental approach; design; monitoring & measurements; data mining and (big) data analytics.

3.2 Planning Phase

The planning phase of the present literature review explores the defined objectives and review questions about the employment of P2P technology in network management to produce search keywords and inclusion and exclusion criteria. The definition of such keywords and criteria was performed considering, as an initial review, the meta-analysis of literature reviews performed in the context of 3 M.Sc dissertations and 2 Ph.D. theses on different aspects of P2PBNM. After that, the review questions were answered regarding the papers in order to extract relevant information.

The keywords used in the search process are *P2P* and *network management*. The set of papers, which was retrieved using these keywords, was significant. In any case, such papers still needed to transcend the exclusion criteria. Furthermore, we also studied the initiatives referred by this set of papers and the ones that refer to them in order to finish the definition of the search keywords.

Inclusion and exclusion criteria were defined to adjust and calibrate the focus of the survey. Our aimed review topic is the employment of P2P technology in network management. These criteria are used to delineate the final set of papers regarding this topic. The inclusion criteria are basically the mention of at least one of the keywords in the keyword fields. On the other hand, we also defined exclusion criteria in order to omit papers whose content was not relevant to the present review. We were not interested in papers that addressed the management of P2P technology, e.g. controlling the network traffic load due to P2P applications in an infrastructure. Finally, the included works must describe some approach to evaluate their own proposals (experiments, case studies, etc).

3.3 Execution Phase

This section describes (in more detail) how the selection process of the present review was performed. Initially, keywords were used to collect possibly relevant papers on the survey topic. Secondly, the set of collected papers was processed to find and eliminate duplicates. After that, titles and abstracts were read to apply the exclusion criteria. Papers that did not fit the scope of this survey were excluded. Finally, with the complete list of relevant documents, information concerning the research questions was extracted.

The execution phase of the literature review explored queries about the survey topic in addition to the initiatives found during the meta-analysis performed on literature reviews. Such queries were executed considering papers from 2010 to 2015 on network management conferences supported by the Institute of Electrical and Electronics Engineers (IEEE) and the International Federation for Information Processing (IFIP): IEEE/IFIP Network Operations and Management Symposium (NOMS) and IEEE/IFIP International Symposium on Integrated Network Management (IM). Besides, we also considered initiatives from the International Conference on Network and Service Management (CNSM), which is recognized as the most competitive network management conference. Finally, we added papers from the IEEE International Conference on Peer-to-Peer Computing (P2P), the IEEE International Conference on Computer Communications (INFOCOM) (flagship IEEE networking conference) and the Association for Computing Machinery (ACM) conference of the Special Interest Group on Data Communication (SIGCOMM) (flagship ACM networking conference) in the queries. In order to search for the P2PBNM initiatives on the proceedings of these conferences, we used the following digital libraries: IFIP Digital Library, IEEE Xplore Library, and ACM Digital Library. We assumed that the digital libraries are reliable and that selected papers went under peer review, which served as a quality filter. The papers selected in the performed queries were the candidates to be included in the survey.

The candidate papers were retrieved and organized in a list to allow duplicate elimination and to apply the exclusion criteria. A final validation was performed by 2 different people and the output was the final set of papers. After that, this set was scrutinized with research questions in order to extract the main characteristics of the employment of P2P technology in network management.

4 Surveyed Initiatives

The objectives of the present literature review is the characterization of the state of the art of the employment of P2P technology in network management. Thus, the complete list of relevant initiatives considering the selected keywords and inclusion and exclusion criteria are classified using the proposed review questions.

In Table 1, we provide the classification of the surveyed initiatives according to the review questions. It is important to emphasize that an initiative may address more than one feature in each question. Then, we describe such initiatives.

4.1 Pattern-Based Management Programs

Lim and Stadler [45] proposed Pattern-Based Management Programs as a novel approach for distributed management. This approach is based on the methodical use of distributed control schemes for large-scale, dynamic networks. Such programs can be viewed as a mobile code distribution considering a P2P management overlay. In fact, most pattern interactions are intrinsically P2P. The authors claimed that the use of patterns makes it easier to estimate the performance of management operations. Furthermore, these patterns could reduce the complexity of distributed management programs through the re-usability of key software components.

4.2 Doyen et al. [46]

The authors proposed a P2P hierarchical management architecture [46]. This architecture enables the distribution of management functions and avoids an excessive centralization of the manager role. Furthermore, the authors claimed that the proposed architecture fits the dynamics of the P2P model well. The evaluation is performed through an implementation in the Pastry framework, which collects management data in a network infrastructure.

4.3 Ambient Networks Management

Simon et al. [47] detailed the employment of a P2P approach to enable management composition for Ambient Networks (ANs) [74]. Kamienski et al. [48] proposed a P2P infrastructure to provide a better support on the management of policies, keeping the same hierarchical concept behind the PBNM model. However, instead of using a single Policy Decision Point (PDP), the authors replaced it using Policy Decision Nodes interconnected by a DHT network. Mathieu et al. [49] proposed the employment of P2P technology in the self-management of contexts associated to the overlays of ANs through the definition of Service-aware Adaptive Transport Overlays (SATOs).

Table 1 Classification of the proposals in literature

Proposal	References	Functional areas	Management approaches	Management methods
Pattern-based management programs	[45]	Performance	Mobile agents-based network Management	Control theories
Doyen et al.	[46]	Performance	Distributed	Data mining and data analytics
Ambient networks management	[47–49]	Configuration	Policy-based network management, autonomic and self-management	Logics
DNA	[9]	Fault, performance	Autonomic and Self-Management	Data mining and data analytics
Idhaw et al.	[50]	Configuration	Policy-based network management	Logics
S^3	[51, 52]	Performance	Distributed	Control theories, Optimization theories
ManP2P	[8, 10, 11, 38]	Fault, performance, security	Policy-based network management, autonomic and self-management	Control theories, logics
Fallon et al.	[12]	Configuration	Telecommunications management network	Control theories
P2P-CBR	[53]	Fault	Autonomic and self-management	Machine learning and genetic algorithms
SMC	[54, 55]	Configuration	Policy-based network management, autonomic and self-management	Control theories, logics
PRISm	[56]	Performance	Distributed	Probabilistic, stochastic processes, queuing theory
dos San-tos et al.	[57, 58]	Fault	Distributed	Probabilistic, stochastic processes, queuing theory
Barshan et al.	[59]	Security	Management by delegation	Probabilistic, stochastic processes, queuing theory
G-GAP	[39]	Performance	Distributed	Probabilistic, stochastic processes, queuing theory
Nobre and Granville	[13, 44]	Fault, configuration	Autonomic and self-management	Machine learning and genetic algorithms, probabilistic, stochastic processes, queuing theory
OMAN	[42, 60, 61]	Performance	Management by delegation	Probabilistic, stochastic processes, queuing theory

Table 1 continued

Proposal	References	Functional areas	Management approaches	Management methods
Cartographer	[62]	Fault	Distributed	Logics
DECON	[63]	Performance	Distributed	Optimization theories
SAAM	[64–67]	Performance	Autonomic and self-management	Probabilistic, stochastic processes, queuing theory
SMON	[68]	Configuration	Distributed	Probabilistic, stochastic processes, queuing theory
DITA	[69–71]	Performance	Distributed	Data mining and data analytics
Mobi-G	[72]	Performance	Distributed	Probabilistic, stochastic processes, queuing theory
Badis et al.	[73]	Security	Distributed	Probabilistic, stochastic processes, queuing theory

4.4 Distributed Network Agent (DNA)

Binzenhofer et al. [9] employed P2P overlays to address fault and performance management in a distributed and self-organized system that is based on DNAs [75]. The distributed infrastructure is achieved by employing overlays formed by structured P2P networks using Distributed Hash Tables (DHTs) on top of the monitored network infrastructure. In this sense, groups of DNAs composing a DHT are able to communicate to exchange monitoring information and ask for other DNAs to execute tests in order to find eventual network failures.

4.5 Idhaw et al. [50]

The authors proposed the utilization of P2P technology to improve policy distribution for an IP-based Airborne Network [50]. In this context, PDPs are implemented as peers of a P2P management overlay. The employment of P2P technology provides distributed services (e.g. discovery mechanisms) and is able to handle specific characteristics of this network, such as highly dynamic topology and bandwidth limitations.

4.6 S^3

Yalagandula et al. [51] proposed S^3, a Scalable Sensing Service (thus, the "S^3" acronym), using concepts from SDIMS (Scalable Distributed Information Management System) [76] and DHT algorithms. S^3 enables personalized monitoring of the environment as dictated by applications. Such monitoring is performed through the construction of network service overlays composed by web service enabled sensor pods (i.e.management peers) [52]. These pods connect to a sensing information backplane that provides a substrate to aggregate collected data.

4.7 ManP2P

Panisson et al. [8] proposed ManP2P, a P2PBNM framework based on JXTA [25]. This framework provides load balancing mechanisms for management applications through the use of peer groups. These management applications are developed through the composition of management services. The framework supports an MbD infrastructure composed of Mid-Level Managers (MLMs), Top-Level Managers (TLMs), and agents. Melchiors et al. [11] proposed a model that defines the ManP2P entities according to the different functions played by the management peers (e.g. network administrator interface, managed resources control) and an architecture that integrates distributed functionalities such as publish-subscribe notification and distributed storage services. Finally, Duarte et al. [38] proposed an extension to ManP2P (ManP2P-ng), focusing on materializing distributed self-healing features through the use of P2P management overlays and high-level descriptions called workplans.

4.8 Fallon et al. [12]

The authors proposed a P2P approach to autonomously form network management topologies in order to accomplish specific network management tasks [12]. Network Elements (NEs) are grouped into clusters, and these clusters form P2P overlays that can be arranged hierarchically according to the requirements of the management task to be executed. The self-forming property is associated with the process of preparing the network management infrastructure. Based on parameters associated with the NEs, the clusters are formed, maintained, and self-optimized in the presence of environment changes.

4.9 P2P-CBR

Tran and Schonwalder [53] outlined a distributed Case-Based Reasoning (CBR) system for fault management based on P2P technology. The goal of this work is to assist operators in finding solutions for faults using various online knowledge sources and decentralized reasoning capabilities. The solution uses a self-organizing platform provided by a P2P management overlay. In this context, CBR engines propose fault-matching solutions using their local case databases and reasoning engines.

4.10 Self-Managed Cells (SMC)

Lupu et al. [54] proposed an architectural pattern for ubiquitous computing applications, aiming at different levels of scale. Each SMC is autonomous and uses policy-based techniques to drive adaptation decisions. In this context, each managed device is logically connected with only one SMC. Among different cross-SMC interactions, P2P interactions and federations are described [55]. SMC can be used for health monitoring applications, such as those related to body sensor networks.

4.11 PRecision-Integrated Scalable Monitoring (PRISm)

Jain et al. [56] proposed PRISm, a scalable monitoring service that makes imprecision an abstraction for its DHT-based aggregation service. PRISm introduces the notion of conditioned consistency that quantifies imprecision along a three-dimensional vector: arithmetic imprecision bounds numeric inaccuracy, temporal imprecision bounds update delays, and network imprecision bounds uncertainty due to network and node failures.

4.12 dos Santos et al. [57]

The authors developed a notification service to be used in P2PBNM solutions [57]. Such service is based on the publish/subscribe paradigm and implemented over a P2P management overlay that carries the notification messages using SOAP. The service uses MLMs to forward messages between a notification source and destination. Santos et al. [58] also evaluated the impact of using presence services in P2PBNM to provide ways to deliver presence information to interested parties.

4.13 Barshan et al. [59]

The authors proposed a 3-tier hierarchical architecture, aiming at fault tolerance features [59]. The layers that built this architecture are composed of Low-Level Managers (LLMs), MLMs, and TLMs. Redundancy is used in each layer of the architecture to increase the availability and decrease peer failure sensitivity concerning the P2P management overlay. This redundancy is implemented through the operation of some selected peers in different layers. In this context, peer groups are composed of peers from each layer.

4.14 Gossip-Based Generic Aggregation Protocol (G-GAP)

Wuhib et al. [39] proposed a protocol in order to investigate the use of gossip for continuous P2P monitoring of network-wide aggregates under crash failures. Monitoring tasks are computed from local management variables using aggregate functions such as sum, max, and average. This approach is similar to tree-based decentralized aggregation (e.g. GAP [77]), but using gossip-based aggregation. The authors claimed that G-GAP is robust against failures that are discontinuous in the sense that neighboring peers do not fail within a short period. Thus, G-GAP supports the correct contributions from peers that have failed in order to generate its aggregates.

4.15 Nobre and Granville [44]

The authors proposed the utilization of multi-agent truth maintenance features to bring consistency maintenance of the state of management data in P2P-based Autonomic Network Management (ANM) [44]. This is done in order to avoid centralized management entities for state consistency. Besides, the authors also addressed the consistency of policy states among autonomic management elements in general decentralized ANM [13].

4.16 OMAN

The authors proposed OMAN [60] to enhance connectivity among Mid-Level Managers (MLMs) and Top-Level Managers (TLMs), i.e. peers that react to human operator requests and communicate with other management entities to accomplish management tasks by investigating location issues of P2P infrastructures [42]. The authors also presented a performance evaluation in the context of the Aggregation Service (AgS), which is a P2P overlay-tier to aggregate the services and service components maintained by service providers [61].

4.17 Cartographer

Krupczak [62] proposed an approach to collect and process management data without relying on a centralized repository. Cartographer agents self-organize into P2P management overlays in order to exchange management information, software updates, and events. Such agents play the roles of managers and agents (in the sense used in the manager-agent approach). In this context, Cartographer agents communicate with one another to poll and store data, run distributed decision-making algorithms, and self-propagate.

4.18 DECON

di Pietro et al. [63] proposed a P2P coordination system aimed to assign passive monitoring probes. DECON architecture makes assignment decisions about the match between monitoring probes and the set of flows they monitor. This architecture aims to increase network coverage spreading the management load (due to monitoring probes) across different machines. This is done using a P2P overlay detached from the physical network. Authors claimed that DECON scales up to large numbers of flow records without requiring network topology information, traffic matrices, and packet marking.

4.19 Self-Adaptive Aggregation Mechanism (SAAM)

Makhloufi et al. [64–67] published several papers on the use of the autonomous adaptation of the management plane according to the underlying network operational state. In more detail, such papers focused on decentralized aggregation systems and deployment of network management information that operate in a P2P fashion.

4.20 Self-Managed Overlay Network (SMON)

Gao et al. [68] proposed SMON to support self-management capability to deploy and maintain the distributed application management system. This is important since the operation of the management system itself is one of the main issues of distributed management systems. SMON manages itself using an epidemic approach at runtime. SMON can automatically deploy itself to a set of machines and recovers failed peers securely. Moreover, SMON can also upgrade itself to new versions online.

4.21 Distributed IP Traffic Analysis (DITA)

Morariu and Stiller [69] proposed DITA as an approach to leverage different bottlenecks of traffic analysis (e.g. metering and exporting processes) using P2P technology. This is done through the distribution of IPFIX records to several management peers according to the rules required by an analysis application. DITA consists of two main mechanisms: Distributed Packet Capturing Architecture for High-Speed Network Links (DiCAP) [71] and Scalable Real-time IP Flow Record Analysis (SCRIPT) [70]. DITA management peers are organized in a Kademlia-based P2P overlay.

4.22 Mobi-G

Stingl et al. [72] proposed an approach to exchange information through flat gossiping and robust communication patterns. Mobi-G consists of a flexible protocol that relies on a time-based synchronization. Such protocol exploits the characteristics of wireless *ad hoc* communication and nodes' mobility. Thus, Mobi-G can cope with constantly changing network topologies and operate even in sparsely populated networks to provide accurate results at minimum cost.

4.23 Badis et al. [73]

The authors presented an approach to enable a collaborative egress detection of DDoS attacks leveraged by a botcloud [73]. Such an approach employs tree structures maintained through a DHT. These structures enable a collaborative source based detection. The use of a P2P management overlay in a cloud environment is motivated by the need for a scalable infrastructure, the need to address the churn, and the resilience of the detection system due to the absence of any central point.

In the following section, the presented initiatives are classified in order to produce an integrated perspective of such initiatives. The classification is performed considering the review questions. After that, opportunities and challenges in the employment of P2P technology in network management are described.

5 Comparison

Whereas, Sect. 4 surveys prominent research initiatives and their salient features, this section compares these initiatives using a set of qualitative metrics. In particular, we evaluate each proposal using the following three criteria: management functional areas, management approaches, and management methods. In the following subsections, we will provide a more detailed discussion for each review question proposed in Sect. 3 along with the evaluation of the surveyed initiatives.

5.1 The Employment of P2P Technology on Management Functional Areas

Network management tasks can be classified considering the executed management functions. Clearly, there is a noticeable diversity in such functions, and thus it is helpful to employ a model for this classification. The most accepted model that discuses management functions was proposed by the International Organisation for Standardisation (ISO) on the definition of a framework for network management, the Open System Interconnection (OSI) network management. Such a framework is divided into specific management functional areas: Fault Management, Configuration Management, Accounting Management, Performance Management, and Security Management. These functional areas are commonly referred to as the FCAPS model [78].

The initiatives on P2PBNM address different management tasks in the same way as traditional network management initiatives. Thus, the FCAPS model can also be employed to classify management tasks performed using P2P technology. The surveyed initiatives are presented with respect to their primary focus and the management functions they perform. It is important to mention that neither of these initiatives was classified within the Accounting Management functional area.

5.1.1 Fault Management

Fault management is one of the main concerns of network administrators since it relates to the dependability of network infrastructures. Tran and Schonwalder [53] proposed the use of P2P CBR for fault management using on-line knowledge sources and decentralized reasoning capabilities. S^3 aims at scalable fault detection for large systems [51]. Cartographer [62] employs distributed root cause analysis and event correlation for fault detection. ManP2P [38] supports fault detection through the use of P2P management services. dos Santos et al. [57] developed a notification service to carry the event notification messages to use in P2PBNM solutions. Nobre and Granville [44] proposed the use of truth maintenance features for consistent detection of OAM Ethernet faults. Binzenhofer et al. [9] employed P2P overlays to provide the detection of connectivity faults.

5.1.2 Configuration Management

Configuration management concerns handling of configuration information in order to prepare, start, and enable the operation of networked services. Idhaw et al. [50]

proposed the use of a P2PBNM system to improve the distribution of network device configuration commands and policies for an airborne network. SMC also employs policy-based techniques in the context of health monitoring applications [54]. Nobre and Granville [13] proposed the use of truth maintenance features for the consistent configuration of distributed polices. Regarding Ambient Networks, Simon et al. [47] detailed the employment of a P2P approach to enable the composition of Ambient Networks, and Mathieu et al. [49] proposed the use of P2P technology to pool and share management information within and across heterogeneous composed networks. The Madeira platform uses P2P communication facilities to configure multiple customized network management topologies [12]. SMON proposed the use of P2P technology to support the deployment and maintenance of the distributed application management system as well as upgrade itself to new versions on-line [68]. RELOAD is a P2P signaling protocol to configure overlay network services and efficient message routing [79].

5.1.3 Performance Management

Performance management focuses on ensuring the effectiveness of networked services, which is usually done by collecting and analyzing data statistics. In the context of network traffic, DITA [69] aims to combine resources of multiple peers to perform P2P metering and analysis and DECON [63] matches the monitoring probes and the set of flows that increase network coverage. Alternatively, S^3 [51] and DNAs [9] are used for scalable SLA monitoring. Concerning large-scale monitoring, PRISm [56], ManP2P [11], Doyen et al. [46], and AgS [61] use P2P overlays to enable performance tools. Regarding the use of gossip for monitoring, G-GAP [39], Mobi-G [72], and SAAM [64] are employed for performance estimation. Finally, Pattern-Based Management Programs were also proposed to estimate the performance of management operations [45].

5.1.4 Security Management

Security management relates to the enforcement of security policies, including the control of security services and the distribution of security information. Badis et al. [73] proposed an approach to enable a collaborative egress detection of DDoS attacks in a cloud environment through a DHT. Barshan et al. [59] proposed a fault-tolerant hierarchical overlay that uses redundancy to increase the availability and decrease failure sensitivity (i.e. performability). ManP2P [38] supports fault-tolerant healing features through the use of peer groups.

5.2 The Employment of P2P Technology on Management Approaches

There is not a widely accepted taxonomy that defines and characterizes distribution aspects of network management approaches, but network management researchers usually consider distribution aspects that at least bring centralized and distributed approaches (e.g. [2, 33–35]). Some authors believe Distributed Network

Management (DNM) is essential to cope with current large-scale network infrastructures because DNM improves the execution of management tasks in respect to scalability and robustness [33]. P2PBNM is usually considered one of the DNM "flavors". In this context, we classified all initiatives described in this study as distributed management. Despite this, some P2PBNM initiatives employ some form of centralization. For example, Tran and Schonwalder [53] outlined a P2P CBR in which super peers bear CBR engines due to bandwidth and power processing capabilities.

Traditional DNM approaches are challenged in some environmental settings (e.g. cross-domain management tasks). The employment of P2P technology can be an interesting possibility to address these challenges. Management peers can play the role of the constitutive elements of traditional DNM models, executing their intrinsic management functions. The depicted initiatives are organized according to their support to the most common DNM models: Management by Delegation (MbD), Policy-based Network Management (PBNM), Telecommunications Management Network (TMN), and Network Management-Based on Mobile Agents (NMMA). A summary of such initiatives regarding the use of P2P technology to support traditional DNM models is described in Table 2. In this table, we present the aforementioned initiatives along with the used DNM model and the described management entities.

In the fairly recognized Management by Delegation (MbD) approach, Goldszmidt and Yemini [3] proposed the introduction of Mid-Level Managers (MLMs) in order to enable more flexible and scalable network management. In MbD, managers delegate the execution of management tasks to MLMs closer to the managed devices, thus decentralizing the execution of management actions. Delegation is used to move management functions (e.g. management scripts) towards the managed devices. However, even with MbD, network management systems may not provide important distributed features such as supporting the interaction among human operators located in multiple administrative domains.

P2P technology can be employed to overcome some limitations of the MbD model (e.g. flexibility). This seems to be the most common integration between P2P technology and DNM models. For instance, P2P technology can improve the connectivity for message exchange among management entities of an MbD system

Table 2 Initiatives on the use of P2P technology to support traditional network management approaches

Initiative	DNM model	Described entities
OMAN	MbD	MLM, TLM
ManP2P	MbD	MLM, TLM
Barshan et al. [59]	MbD	LLM, MLM, TLM
Ambient Networks Management	PBNM	PDP
Idhaw et al. [50]	PBNM	PDP
Fallon et al. [12]	TMN	NE
Pattern-based management programs	NMMA	MA

(e.g. MLMs) since P2P routing services are more flexible than those provided in IP networks. Some proposals focused on enhancing the connectivity among MLMs and introducing Top-Level Managers (TLMs), i.e. peers that reacting to human operator requests and communicate with other management entities to accomplish management tasks [8, 11, 42]. Barshan et al. [59] proposed a 3-tier hierarchical architecture using MLMs, TLMs, and introducing Low-Level Managers (LLMs).

Sloman [4] proposed the use of policies to meet a set of pre-specified high-level business objectives and goals through the Policy-Based Network Management (PBNM) approach. Although the original conception of PBNM did not enforce any specific architecture, one of the architectures often mentioned is the one defined by the Internet Engineering Task Force (IETF) [80] that consists of four main components: Policy Management Tool (PMT), Policy Repository, Policy Decision Point (PDP), and Policy Enforcement Point (PEP). The definition and placement of PBNM entities within a managed network can create distributed management systems [81].

P2P technology can be integrated with the PBNM model in order to improve its scalability and robustness. The functions of these entities can be implemented through management peers. Besides, the P2P management overlay can be used to support the distribution of updated policies. For example, different works proposed the distribution of PDP functions. This can be done by keeping the same hierarchical concept behind the PBNM model, but instead of using a single PDP, it is replaced by using PDPs implemented as peers of a P2P management overlay [48, 50]. Furthermore, Lupu et al. [54] proposed policy-based techniques to drive P2P adaptation decisions without relying on the traditional PBNM architecture.

The Telecommunications Management Network (TMN) is an architecture proposed by the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T) to manage telecommunication networks [82]. TMN is defined in the M series of ITU-T and uses Open System Interconnect (OSI) management specifications (ITU-T Recommendation series X.700). TMN introduces different levels of abstraction: element management, network management, service management, and business management. Managers at one layer are only aware of their subordinate Network Element (NE) in the next layer, and thus there is no communication between managers at the same level.

P2P technology can be integrated with TMN in order to improve its flexibility and robustness. Since TMN uses a highly coupled hierarchy model that only allows vertical interactions, P2P technology can be used to improve the interaction model to allow more complex management tasks (e.g. service composition). Fallon et al. [12] employed a P2P approach to autonomously form network management topologies in order to accomplish specific network management tasks. The NEs are grouped into clusters, and these clusters form P2P overlays that can be arranged hierarchically according to the requirements of the management task to be executed.

Mobile Agents (MAs) were proposed regarding different application areas. One of these areas is network management. An MA is a software agent able to move between locations, according to a life-cycle model, a computational model, a security model, a communication model, and a navigation model. Mobile agents can be implemented using one of two fundamental technologies: mobile code (e.g.

AgentTCL and Telescript) or remote objects (e.g. Aglets). Several MA mechanisms were adapted for DNM, also known as Network Management-Based on Mobile Agents (NMMA), and a comprehensive review of them is available on network management literature [83].

MAs' approaches can be integrated with P2P technology in order to perform management tasks. A P2P management overlay can be used to ease the support of code mobility, i.e. hosting MAs. Since P2P technology is known to better support code updates, they offer the flexibility required to enable movement among different network locations. Besides, since some mechanisms related to MAs were already adapted for DNM (e.g. remote objects), such mechanisms can also be deployed in the P2PBNM system. An example of a joint use of MAs and P2P technology is the Pattern-Based Management Programs [45] that employs the distribution of mobile code considering a P2P management overlay.

The utilization of P2P technology can be a better alternative to traditional distributed technologies in autonomic and self-management. P2P systems have good performance in overcoming challenges related to dynamic systems, specially in large-scale, ubiquitous, or mobile environments [84]. In addition, some approaches to autonomous features in network management seem to require that management data be maintained in a distributed way. For example, SAAM provides an autonomous adaptation of the management plane according to dynamic network states [64]. These features usually aim to achieve lower management costs and reaction times [1].

Some works explore P2P technology and self-management as a whole. On the one hand, this can be done considering a specific and well-defined environment that eases self-management features. For example, some authors proposed P2P technology in the self-management of contexts associated with overlays of Ambient Networks [49, 74]. On the other hand, some works employ distributed autonomous entities, and these entities present P2P interactions. In this context, Lupu et al. [54] proposed Self-Managed Cells (SMC) as an architectural pattern for ubiquitous computing applications, and Binzenhofer et al. [9] described an archsitecture aimed to provide generic connectivity tests and Quality of Service (QoS) monitoring.

P2P technology can be used to enable some autonomic properties in network management systems. Nobre and Granville [13] proposed the use of Multi-Agent Truth Maintenance for the self-configuration of consistent management information. Self-healing features are described in the ManP2P system through the use of peer groups that consist of cooperative management peers [38]. Self-optimization is also proposed in some initiatives. For example, Fallon et al. [12] employed a P2P approach to self-optimize network management topologies in the presence of environment changes. In addition, Tran and Schonwalder [53] outlined a distributed CBR that uses a self-optimized platform provided by a P2P management overlay.

5.3 The Employment of P2P Technology with Management Methods

Network management tasks can be performed using several methods. Such methods are used to support features in management systems, such as task distribution, self-organization, and fault tolerance. In this context, the employment of P2P technology enhances the dynamic deployment of management methods. This deployment can use the flexibility of P2PBNM to distribute the computation due to management methods. For example, P2P management could be used to update the management peers' software in order to adjust management methods to different network environments.

The composition of P2P technology and network management methods allows the introduction of different characteristics in P2PBNM. The methods used to classify the initiatives surveyed in the literature review are control theories; optimization theories; logics; machine learning and genetic algorithms; probabilistic, stochastic processes, queuing theory; and data mining and data analytics. A summary of the classification described in the present section is described in Table 3.

5.3.1 Control Theories

Distributed management services can address tasks using methods from control theories. Lim and Stadler [45] proposed Pattern-Based Management Programs that are P2P control schemes that determine the degree of parallelism and internal synchronization of a distributed management operation through mobile code. SMC employs a closed-loop system where changes of state in the resources trigger adaptation, which in turn affects the state of the system [54]. S^3 uses an adaptive placement based on observed performance by the sensor pods for the inference and operation of control services [51]. Fallon et al. [12] proposed Adaptive Management Components (AMCs) that are containers in Network Elements (NEs) that run management software entities and communicate with entities running in other NEs. ManP2P employs autonomic control loops to support self-* properties, such as self-healing [38].

5.3.2 Machine Learning and Genetic Algorithms

Some studies proposed embedding methods related to machine learning and genetic algorithm features into P2PBNM solutions. Nobre and Granville [44] introduced multi-agent truth maintenance features into P2PBNM to improve the consistency of states of management data considering autonomic management environments. Such consistency is necessary since each management peer can be viewed as an intelligent agent in P2P-Based Autonomic Network Management (ANM). P2P-CBR employs CBR engines in a P2P management overlay, thus considering a distributed CBR solution [53]. Such engines are deployed in super peers since these peers bear more computational resources than regular peers.

5.3.3 Optimization Theories

Distributed management approaches, such as P2PBNM, can optimize management tasks considering dynamic and localized characteristics of network environments. In this context, management peers can implement methods from optimization theories

Table 3 Classification of P2PBNM initiatives in respect to management methods

Initiative	Control theories	Optimization theories	Logics	Machine learning and genetic algorithms	Probabilistic, stochastic processes, queuing theory	Data mining and data analytics
Pattern-based management programs	X					
Doyen et al. [46]						X
Ambient networks management			X			
DNA						X
Idhaw et al. [50]			X			
S^3	X	X				
ManP2P	X		X			
Fallon et al. [12]	X					
P2P-CBR				X		
SMC	X		X			
PRISm					X	
dos Santos et al. [57]					X	
Barshan et al. [59]					X	
G-GAP					X	
Nobre and Granville [44]				X	X	
OMAN					X	
Cartographer			X			
DECON		X				
SAAM					X	
SMON					X	
DITA						X
Mobi-G					X	
Badis et al. [73]					X	

in order to improve such tasks. DECON uses batch optimization to reduce messaging overhead in monitoring reports and response messages directed to a monitoring probe [63]. S^3 employs a near-optimal dynamic service placement for resource provisioning using information about different aspects of the environment [51].

5.3.4 Data Mining and Data Analytics

There are proposals concerning the employment of data mining and data analytics in P2PBNM. In this context, such proposals support the dissemination of management data in an overlay. DITA computes a routing hash value for each processed flow record using a routing function [69]. This is done to determine the forwarding of such records to different nodes (i.e. management peers). DNA uses the hash value to provision the P2P management overlay, i.e. to keep the DNAs connected in one logical network and to enable a single DNA to find another DNA in reasonable time [9]. Doyen et al. [46] proposed the distribution of management data collected in an infrastructure through the use of hash values.

5.3.5 Probabilistic, Stochastic Processes, Queuing Theory

P2PBNM systems often use non-deterministic methods due to different aspects. For example, such methods can be more efficient than deterministic methods for a given scenario (e.g. large network infrastructures). Badis et al. [73] employed a detection algorithm based on Principal Component Analysis (PCA) for data normalization. Barshan et al. [59] employed redundancy in management roles to increase availability. PRISm uses the concept of conditioned consistency using network imprecision to address the distortion of monitoring results by network churn [56]. dos Santos et al. [57] employed queue theory to support scheduling policies at management peers for the exchange of notification messages over a P2P management overlay. Epidemic protocols aim at robustness and resilience. For example, Nobre and Granville [44] proposed eventual consistency of states of management data using biology-inspired processes (e.g. replication) as a P2P communication strategy, and SMON used an epidemic algorithm to monitor and maintain the management peers themselves, i.e. the P2P management overlay [68]. In addition, gossip protocols (a special case of epidemic protocols) were also used in P2PBNM to spread management information in G-GAP [39] and Mobi-G [72]. Finally, aggregation is employed for P2P service searching [61] and autonomous distribution of management data [64].

5.3.6 Logics

Different approaches can be used to integrate logics and the employment of P2P technology in network management. Cartographer enables distributed root cause analysis and event correlation [62]. Regarding the use of polices, Idhaw et al. [50] applied PBNM to manage airborne networks, Kamienski et al. [48] distributed the functions of some PBNM entities to manage ambient networks, Lupu et al. [54] used policies in SMCs to specify which adaptation should occur in response to environmental changes, and ManP2P supports autonomic features using the concept of workplan (a form of policy).

6 Trends and Analysis of Future Research Directions

The network management area has evolved into an important scientific field due to the increasing complexity of computer networks. Some authors even claim that the management of current and emerging network technologies is becoming the main bottleneck to any further advancements [1]. Thus, it is important to investigate approaches that improve the performance of network management systems concerning several challenges (e.g. scalability, robustness, and broadness). In this context, the employment of P2P technology in the network management field is a strong alternative to enhance the solutions in this field.

As the survey described in this article points out, the research relating P2P systems and network management tends to spread over several directions at the present moment. The benefits of enlarging the spectrum of research on P2P-Based Network Management (P2PBNM) can increase the chances of finding revolutionary mechanisms and techniques for network management as a whole. However, this tendency also often leads to unclear definitions of terms and borders among different research initiatives. For example, some authors in the network management community do not explicitly use the term “P2P”, despite the use of this type of interaction in their solutions, which makes it more difficult to fully understand the employment of P2P technology across the network management research area. Moreover, some P2PBNM ideas were included into other management topics (e.g. Autonomic Network Management and Machine-to-Machine Network Management), which also happened in general P2P systems [16].

Despite the adversities on delineating the employment of P2P technology into network management solutions, it is safe to state that more advances in the joint use of P2P and network management can further contribute to the design of distributed network management systems. In this context, it is also safe to say that although DNM has been widely recognized as a necessity, there is no definitive solution for technology employed to develop DNM systems. Some examples of potential scenarios that could be explored as future work under the P2PBNM approach are: networking devices with increasing processing capacity, new network environments, and autonomic and self-* network management.

Current network equipment vendors provide an increasing level of processing power and programmability in their networking devices, differing significantly from the beginning of the development of the network management field. This programmability capability is already used to enable traditional management software (e.g. management agents). Thus, by following the same path, it is possible to use such capability to embed management peers inside these network devices. Therefore, in-network P2P management overlays can be formed to offer management services, thus dispensing additional hardware to host the management peers. Research initiatives could compare the introduction of management peers inside network devices and in additional hardware regarding several metrics such as energy cost and management efficiency.

New network environments are interesting contexts where P2PBNM can show its strength, e.g. robustness in message exchange, high-distributed processing, and support for collaborative work. Some examples of these environments are the ones that expose different connectivity features such as unstructured Personal Communication Systems (PCS), Home Networking (HOMENET), Internet of Things (IoT), Vehicular Networking (VN), and Delay/Disruption-Tolerant Networking (DTNs). Indeed, some authors proposed the utilization of traditional DNM approaches in some of these environments [85]. In this context, general purpose P2P systems have already demonstrated that they cope graciously with new network environments [86]. Therefore, the characteristics of P2PBNM solutions can be a natural alternative to manage these environments.

P2P technology can be used to enable autonomous features on network management systems. Several autonomous features found on network management systems are based on distribution features, usually supported by technology from traditional distributed systems. For instance, autonomic and self-* network management systems are excellent candidates to be integrated into P2PBNM since they require that management data must be distributed to fully enable autonomous features [87]. These features usually aim at to achieve lower management costs and reaction times [1]. In this context, the need for cooperation among autonomic entities could be expressed by decision-making processes performed by management peers. Besides, an autonomic knowledge plane, which is a core aspect of autonomic systems, could also be deployed as decentralized network management information in a P2PBNM fashion.

Several challenges could be highlighted for the P2PBNM field. The predominant feature in the papers analyzed in this survey is the employment of P2P infrastructures to enhance the underlying connectivity of decentralized network management systems. Very few proposals use the concepts behind the P2P applications in order to enhance the execution of the network management task itself. During the analysis of the works described in this article, the cooperation among the peers of the P2PBNM infrastructure was repeatedly mentioned. However, it is usually unclear what the authors exactly meant by the term “cooperation”. In most of the cases, this term indicated a connectivity relation between the peers rather than a joint operation to solve a management problem. Indeed, the literature shows that P2P infrastructures are being well explored to build network management infrastructures. Nevertheless, management applications keep on being developed following traditional hierarchical network management approaches, and this scenario presents many opportunities for developing revolutionary management algorithms based on the distributed and cooperative capabilities of P2P technology.

New networking enablers, such as Software-Defined Networking (SDN) and Network Function Virtualization (NFV), challenge the deployment of the P2PBNM system. This is because these enablers are supported by centralization features (e.g. the use of SDN controllers) and P2PBNM systems have been designed as intrinsic distributed systems. However, P2P technology can still be valuable for network management in such networks. For instance, P2PBNM applications could be used to enable sharing and resource access for groups of SDN controllers, possibly in different administrative domains. Besides, distributed virtualized network functions (VNF) can employ P2P interactions for communication or information indexing/storage purposes.

7 Final Remarks

The support of new demands faced by traditional network management is a key research issue in the network management area. Distributed Network Management (DNM) has been proven to be a feasible approach for these demands. Indeed, the research community understands that it is common sense that distributed solutions are more suitable to handle the current scenarios where network management is employed. Despite the existence of such a sense, there is not a consolidated and wide accepted consensus on how to provide the proper infrastructure for DNM systems. One alternative that has been attracting attention in recent years is the employment of P2P technology for network management, also known as P2P-Based Network Management (P2PBNM).

In this article, we presented a comprehensive review of the state of art P2PBNM. First, we presented a review of the definitions associated with P2P systems and P2PBNM approaches. Then, the method used in the literature review was introduced. Subsequently, the main initiatives to employ P2P technology in network management were presented. After that, a comparison of the initiatives considering the review question was described. This article ends with the discussion about future trends and analysis of future research directions for P2PBNM.

Based on our analysis, we could verify the remarkable diversity of contexts and areas where P2PBNM solutions are employed. The main conclusions of our analysis are twofold. First, we identified that regardless of the context or area, there is a predominant employment of P2P infrastructures to enhance the underlying conditions of DNM systems. In this context, very few initiatives use the concepts behind P2P technology in order to enhance the execution of management tasks themselves. Second, the research on the employment of P2P technology in network management can contribute to the DNM area as a whole. Furthermore, the use of P2PBNM concepts can lead to the development of better DNM systems.

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