Self-Organizing Networks in the 6G Era: State-of-the-Art, Opportunities, Challenges, and Future Trends

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Abstract—Self-organizing networks (SONs) need to be endowed with self-coordination capabilities to manage the complex relations between their internal components and to avoid their destructive interactions. Existing communication technologies commonly implement responsive self-coordination mechanisms that can be very slow in run-time situations. The sixth generation (6G) networks, being in their early stages of research and standardization activities, open new opportunities to opt for a design-driven approach when developing self-coordination capabilities. This can be achieved through the use of hybrid weakly coupled SON designs. In this article, we review the history of SONs including the inherent self-coordination feature. We then delve into the concept of hybrid SONs (H-SONs), and we summarize the challenges, opportunities, and future trends for H-SON development. We provide a comprehensive collection of standardization activities and recommendations, discussing the key contributions and potential work to continue the evolution and push for a wide adoption of the H-SON paradigm. More importantly, we propose that H-SONs must be weakly coupled networks, i.e., the various feedback loops must be almost isolated from each other to improve the stability and to avoid chaotic situations. We finally conclude the paper with the key hints about the future landscape and the key drivers of 6G H-SONs.

Index Terms—6G; self-organization; self-coordination; conflict avoidance and resolution; weakly coupled system; hybrid self-organizing network (H-SON).

I. INTRODUCTION

The road to 6G networks has recently begun. It continues with the evolution of the capabilities of the network, with some emphasis on the convergence of fixed and wireless networks. A key problem is being able to manage and control networks, which are increasing in complexity and heterogeneity, and at the same time reducing the need for manual control. This problem is not totally new since it was already targeted during the development of 5G and its predecessors. Over the years, the standards that enable the design of functions for implementing self-* features, such as self-organization, self-configuration, self-diagnosis, self-repair, self-healing, self-optimization, self-awareness, self-adaptation, and other automated operations such as auto-discovery, have matured under the umbrella of self-managed systems and networks. Within them we find the inception of the well-known self-organizing networks (SONs), which brings all self-* features to the network.

Self-organization [1], [2] is a general term that covers any kind of autonomous restructuring of a system and is, therefore, the highest and most general in the hierarchy of all technical systems. Thus, the main objective of SONs in communication systems is to reduce capital expenditures (CAPEX) and operational expenditures (OPEX) through automating as many features as possible, spanning multiple network components and various engineering phases. SONs will therefore continue to empower future communication systems that must offer certain fundamental properties, i.e., functionality, stability, scalability, performance, dependability, security, cost-effectiveness, and resilience [3]. For instance, features such as densification or support of multiple radio access technology call for smoothly scalable SONs [3]. On the other hand, the SON architecture is decomposed into a set of smaller functional units referred to as SON functions (SONFs). Since 5G and beyond networks are characterized by high system dynamics, SONFs will be increasingly triggered and, consequently, they may interact either constructively or destructively. Thereby, advanced self-coordination capabilities are needed to ensure a conflict-free operation. Surprisingly, this feature has attracted very little research and standardization efforts. Most self-coordination principles are usually lightly covered [5], left open for future research attention [4] or not considered at the design phase of new communication systems [6].

To the best of our knowledge, the paper Bayazed et al. [6] is the first attempt to provide a detailed survey about the self-coordination functionality in cellular networks. It starts by providing an historical overview of SONs after the 2000s, i.e., starting from 3G networks. Then, it introduces a high-level comprehensive framework to categorize self-coordination logics into protective, reactive, and proactive. According to [6], protective methods that anticipate conflicts since the design stage are only valid for static situations whereas system dynamics call for proactive methods that can predict the potential conflicts at the execution time using artificial intelligence (AI) and machine learning (ML).

The present paper complements the work of Fourati et al. [2] and Bayazed et al. [6] by providing a comprehensive overview of the self-organization history from the late 1940s. We then emphasize the importance of hierarchy with different
time scales, decoupling of different hierarchy levels (i.e., time scale separation) or between subsystems at the same hierarchy level (i.e., separation using orthogonality), multiple degrees of centralization, and negotiation between various system parts as promising design paradigms to build the components of SONs and achieve a conflict-free behavior by design as opposed to reactive and proactive methods that can be too slow in dynamic situations. We particularly delve into the definition of the concept of weakly or loosely coupled systems referred to as Hybrid SONs (H-SONs) in [2] and [4], which are gaining importance within the current network landscape. From a standardization perspective, there has been insufficient interest in self-coordination aspects and the focus has been on the 3rd Generation Partnership Project (3GPP), the International Telecommunications Union–Telecommunication Standardization Sector (ITU-T), and the European Telecommunications Standards Institute (ETSI) activities [5], thus overlooking many initiatives driven by other standardization development organizations (SDOs).

Based on the above introduction, the contributions of this article are three-fold. First, we concentrate on the potential and the promises of H-SONs for an improved design-driven self-coordination. Second, we provide an in-depth landscape analysis of past and current standardization activities related to SONs and the inherent self-coordination functionality within various SDOs to explore the harmonization possibilities. Broader standardization-related insights are presented in [7]. Finally, we summarize the challenges and the future technological trends for the development of SONs over the next decade.

The remainder of this paper is organized as follows. In Section II, we present the background and state-of-the-art of SONs. Then, Section III discusses the opportunities, use cases, technical hurdles, and standardization landscape of SONs. The challenges, trends as well as directions of research and standardization activities regarding SONs are identified in Section IV. Finally, Section V concludes the paper.

II. BACKGROUND AND STATE-OF-THE-ART

The historical development of SONs is presented in Fig. 1. To obtain intelligent behavior, usually a feedback loop is needed. Systems based on the feedback concept can be divided hierarchically into automatic, autonomous, and self-organizing systems, from bottom up [3]. A system may have regular inputs and control inputs. Regular inputs include any sensing information received from the environment, and control inputs are information given by an external controller to perform needed actions. Automatic systems are systems that do not need manual intervention. They can be divided into control and adaptive systems. They need a control input in the form of a set-point value or reference signal, respectively. Autonomous systems are automatic systems that do not need any control input during operation. Autonomous systems are learning systems, which are able to change their behavior based on earlier experience that is saved into a memory. Self-organizing systems are autonomous systems that are able to restructure themselves.

The general term self-organization was proposed by Ashby already in 1947. In communications, the first SON was the Internet that was originally called the Arpanet and is based on packet switching. The Transmission Control Protocol (TCP) and the Internet Protocol (IP) formed the present TCP/IP model, and the name of the Arpanet was changed to the Internet. At the same time, the generalized Open Systems Interconnection (OSI) model was developed.

Ad hoc or unstructured networks are multi-hop SONs without any fixed infrastructure. The history of ad hoc networks started from packet radio networks although the term "ad hoc networks" was only later officially adopted by an IEEE 802.11 subcommittee after which the term became popular. The interest in SONs rose in the 1980s and were originally defined to be distributed, thus having no centralized control. The 3GPP Rel. 8 (2008) divided SONs into three groups, including Centralized SON (C-SON), Distributed SON (D-SON), and H-SON, which is a combination of C-SON and D-SON. 3GPP Rel. 11 (2011) proposed the term self-coordination to avoid and resolve conflicts in SONs [4]. The research on coordination of conflicts in hierarchical systems started in the 1960s with Mesarovic’s pioneering work. In hierarchical systems, the conflicts were classified into inter- and intra-level conflicts which correspond to vertical and horizontal coupling. One of the methods suggested was interaction decoupling.

Independently of SONs, distributed computing was developed in computer science towards autonomic computing that is based on self-management. The term was later adopted also in communication networks. ETSI defined the Generic Autonomic Networking Architecture (GANA) reference model as the ETSI Technical Specification (TS) [9]. GANA describes the concept of "ownership" of managed entities (MEs) (i.e., system resources) that relay their configuration to specific functional entities called decision elements (DEs). They have a one-to-one relation to avoid that multiple DEs manipulate a DE at the same time, requiring DEs to negotiate with the DE that "owns" the ME. Among others, GANA defines multiple runtime techniques to synchronize policies among DEs, handling intents, and self-assessment of objective accomplishment.

The most important principles in system design include feedback, optimization and decision making, hierarchy, and degree of centralization [8]. Feedback is based on the sense-decide-act loop, which in modern AI forms the basis of an intelligent and rational agent, for example an SONE. The idea led to multi-agent systems (MASs), which form a hierarchy of interacting agents, a good basis for self-organization. Even before the AI theory was developed, the research on neural networks, pattern recognition, and game theory was started and finally merged to the MAS theory. Thus they were precursors of current AI.

Optimization and decision making is a broad area with many different approaches. There are usually many conflicting objectives measuring the efficiency of the use of basic resources such as energy, time, and bandwidth. Optimization problems can be convex or nonconvex in nature. Different types of optima can exist for multiobjective optimization problems such as a global or a local optimum. A typical type of optimum that is targeted in such problems is called the Pareto optimum, valid for commensurate objectives, but it is not in general unique and therefore a final selection must be made based on subjective grounds, usually on fairness. Modern joint or
multiobjective optimization started already in the 1950s. Now multiobjective optimization is an essential part of the MAS theory. In practice the basic resources are incommensurate. In this case one can use evolutionary methods, and the result depends on the availability of the resources and their need according to the law of supply and demand. In this way the relative costs of the resources are defined when there is no objective basis for the definition of the costs.

The idea of hierarchy is to decompose a complex problem into a hierarchical set of simpler problems if there are different time scales in the changes in the system. This is also the basis for the TCP/IP and OSI models. The hierarchy also supports the stability of the system. Modern research on hierarchy and modularity started in the 1960s with the work by Simon and Mesarovic. It was noticed that biological systems are hierarchical and different subsystems or modules at the same hierarchy level are only weakly coupled. The hierarchies were classified into nested, multilayer, and dominance hierarchies. The layer and dominance hierarchies are common in communication networks. In a hierarchy, the basic idea is to use low speed, broad range, and low resolution at the higher levels such as in the network layer and high speed, narrow range, and high resolution at the lower levels such as in the physical layer. The speed should correspond to the rate of change of the relevant network parameters at each level. There is usually orders of magnitude difference in the speed at different levels. Range and resolution are defined in the amplitude, time, frequency, and space domains. In a hierarchical system, a form of joint optimization is cross-layer optimization, which can be loosely or tightly coupled. In the latter case the performance may be better, but the complexity is larger, and there may be stability problems.

According to the conventional degrees of centralization, systems are classified as centralized, decentralized, and distributed. Centralized systems are based on forced cooperation of agents in a hierarchy, decentralized systems are based on competition of autonomous agents without any hierarchy, and distributed systems are an intermediate form where the agents cooperate at least with their closest neighbors by exchanging information. An alternative intermediate form is a hybrid form that combines centralized and distributed control, as in the H-SON. A schematic view of this architecture is provided in Fig. 2, showing essentially a hierarchical weakly controlled set of almost autonomous agents. There is only a weak vertical and horizontal coupling or interaction between agents to improve stability so that the feedback loops are weakly coupled or almost isolated from each other. Using different degrees of coupling, the hybrid form can implement all other degrees of centralization as special cases. Self-organizing systems should have at least a weak centralized control to improve optimality, fairness, and stability so that the global behavior is predictable. Accordingly, the higher in the hierarchy we are, the more intelligence and complexity we have.

III. OPPORTUNITIES, USE CASES, TECHNICAL HURDLES, AND STANDARDIZATION LANDSCAPE

In this section we discuss some opportunities that may bring new possibilities, emerging use cases along with some biggest impediments identified in SONs, as well as the standardization issues and initiatives derived from them.

A. Opportunities

Rethinking system design is needed to resolve the currently weak coordination among SONFs. This will leverage the benefits of distributed systems and a pervasive approach through using advanced multi-tenant resource sharing. By coordinating SONFs, different performance metrics will be optimized, especially in dynamic situations.

In addition, some SONFs mostly focus on short term optimization as they mainly operate at the lower layers. With the aid of pervasive intelligence, SONFs will be able to process both external historical information gathered from previous experiences and internal contextual data to build solid long-term optimization and prediction, and thus will truly operate the network in a proactive and autonomous fashion.

On the other hand, a key opportunity is to work on the combined hierarchy and degrees of centralization to improve self-coordination. Hierarchy is used in SONs to manage the inherent complexity whereas different degrees of centralization
maintain SONs scalability. A hybrid form of hierarchy, i.e., H-SON (Fig. 2) is envisioned to avoid the weaknesses of pure centralized and distributed paradigms. Such hierarchical networks can be created statically in a structured manner or dynamically in an unstructured manner when needed. Structured network partitions can provide better support for AI/ML within and across network partitions.

The intrinsic priorities of hierarchical systems are a very powerful mechanism to resolve conflicts in SONs. Sensing information propagates upwards and control information downwards in the hierarchy so that higher levels will detect the conflict and act by preempting the lower levels where decisions are usually made because they are faster. This hierarchy will prevent a conflict from lasting for a long time causing system performance degradation. However, hierarchical systems may need a delay to detect, analyze, and trigger the best countermeasure commensurate with the number of the hierarchy levels.

**B. Use cases**

The open radio access network (O-RAN) architecture has been deliberately designed with flexibility to deploy SON functions at the core, metro or edge depending on the control loop latency requirements, using the non real-time (Non-RT) RAN Interface Controller (RIC), near real-time (Near-RT) RIC and potential use of edge platforms hosting virtual network functions (VNFs) as hosts for AI/ML applications as well (Fig. 3).

Development of third-party SON software realized as rApps and xApps will be made easier by the definition of reference designs for the supporting platforms’ hardware (e.g., commercial off-the-shelf (COTS) equipment) and software and through the definition of interface standards for the sensing input and action output of SONFs at different levels (e.g., O1 and E2 interfaces).

O-RAN design envisions the use of the H-SON concept where there is interaction between SONFs at different positions in the network. The definition of the A1 interface, in particular, allows a higher-level SON in the Non-RT RIC to access information from the Near-RT RIC and to exert policy controls over the Near-RT RIC. Support of integrated SONFs has been adopted as one of the use cases of interest within O-RAN. The key high-level O-RAN functions are depicted in Fig. 3 allowing for a multitude of more specialized use cases ranging from RAN sharing to unmanned aerial vehicles (UAVs) radio resource allocation using a weakly coupled design.

**C. Technical hurdles**

Optimization and decision making in SONs are facing several hurdles. The reason is that the complexity of optimization problems depends exponentially on the size of the system to be optimized. Therefore in practice, an exhaustive search cannot be used and various heuristic methods have been developed. In general, optimization methods can be divided into top-down deductive methods using parametric models and bottom-up inductive methods based on pattern recognition. The method based on parametric models is usually simple and it converges fast since only the parameters of the model must be identified, but it may fail if there is high uncertainty about what kind of models should be used. In pattern recognition, also called structural identification, the model is formed from scratch, for example using neural networks or evolutionary methods (e.g., genetic algorithms and game theoretical principles). Such methods are in general complex and they converge slowly, but they may work even in uncertain environments if the changes are not too fast. A combination of the two approaches is known as hybrid intelligent systems.

On the other hand, an additional technical impediment is to find mechanisms that are optimized to enforce changes
required by adapting SONs as soon as they can be enforced, considering the next steps in optimization to avoid unneeded changes but do not wait until all changes are definite. We must balance the cost of a suboptimal network and the cost of making the required changes to optimize it. Incremental improvements towards the objective need to be made. This is still an open research topic.

D. Standardization landscape

SONs are a key target of SDOs [5], [10]. They are included in the key framework of the ITU-T (Rec. ITU-T Y.3324) as a target for Long Term Evolution (LTE) and beyond, thus SON becomes a source of standardization efforts for 4G successors. Some features of SONs have been envisioned for the overall standardization landscape for network management. For instance, as argued in [11], a solution for a network to self-adapt to changes in its environment is aligned with ETSI Network Function Virtualization (NFV) Management & Orchestration (MANO) and assumed by the Internet Engineering Task Force (IETF) as part of the Network Management Research Group (NMRG) and the Anima WG. In this sense, standardizing self-organization and intelligent reasoning procedures becomes a key for the correct evolution of the network. It is agreed that all components, hardware and software must be assessed, both in terms of their SON capabilities (i.e., auto-*, self-*), as well as their overall adequacy and quality, thus the tenant of the network can have a high degree of certainty that the network will work as desired and expected.

In addition, the evolution within ETSI for designing SONs is taking part as Zero Touch Network and Service Management (ZSM), Experiential Network Intelligence (ENI) [5], and GANA [9]. They provide underlying mechanisms to build SONs. However, there are many topics to work on, as defined by ETSI in TS 128 313, in order to standardize the mechanisms needed to build a SON, either distributed or centralized. More specifically, they tend to cover optimization issues and configuration management. However, there are open questions regarding the cross interaction among ETSI, ITU-T, and IETF views, such as the interface compatibility and adaptation, the function definition for consistency, and the consolidation of architecture components for allowing multi-vendor deployments. These are required in the near future to define a stable framework for SONs [7].

SDOs are leveraging the power of digital twins to implement the capabilities required by SONs. They heavily rely on telemetry. Thus, the procedures, tools, and protocols for telemetry collection, transmission, and processing are being worked on for standardization by SDOs. For instance, the IETF has begun the initial steps for this task by the adoption of the Network Telemetry Framework (NTF) as the foundation of a future set of standards for this purpose. In addition, standardizing the mechanisms required for leveraging the information provided by a digital twin of a SON is an open issue for SDOs. A key is to extend the current abilities of SONs by eliminating some elements or actors from distributed coordination in response to models obtained by “simulating” possible scenarios, as the main purpose of digital twins.

Table I summarizes current and future SDO activities [7]. Obviously, most of those ongoing standardization initiatives are either inspired by or converge toward the reference GANA model, while the latter adheres to the H-SON paradigm guidelines.

IV. CHALLENGES, TRENDS, AND RESEARCH/STANDARD DIRECTIONS

In this section, we enumerate the fundamental challenges to be addressed for providing conflict-free SONs, and propose

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Fig. 3: Open RAN use case control loops hierarchy.
| SDO or Forum | WG or Framework | Standardization Activities | Activities Type and Maturity | Launch |
|-------------|----------------|----------------------------|-----------------------------|--------|
| IEEE | NGSON WG (P1903 standards) | Service overlay networks as the main abstraction level for autonomies via embracing context awareness and self-organization capabilities. | Regular track | 2013 |
| | INGR SysOpt WG (7) | Outlines standardization items and approach for enhancing standards on autonomies in other SDOs/fora. | Plans for standardization | 2019 |
| IETF | ANIMA (e.g., RFC 8993) | Defines a reduced-scope Autonomic Networking (AN) (which is a reference model to describe node behavior and self-management properties) with progressive introduction of autonomic functions (AFs). No implementation specifications for coordination among AFs. | Partly-mature standardization track, inspired and aligned to ETSI GANA. | 2014 |
| | NTF | Architectural framework for network telemetry. Protocols to gather accurate granular network data for full visibility. | Extend network management beyond conventional OAM. | 2018 |
| ETSI | TC NTECH/AFI WG and TC INT/AFI WG (e.g., ETSI TS 103 195-2 and White Paper No. 16) | GANA model and its instantiations onto various types of fixed, mobile and wireless networks. Running a 5G PoC program to implement some GANA aspects. | Regular Standardization track for technical standards and detailed specifications. | 2009 |
| | ENI ISG | Defines an AI-based architecture to help external systems improve their environmental awareness and adapt accordingly. Envisions the translation of input data as well as output recommendations/commands. | Pre-standardization track. | 2017 |
| | ZSM ISG | Reuses existing standards and frameworks into a holistic design to achieve E2E automation in multi-vendor environments using AI-based data collection and closed-loop control. | Pre-standardization track. | 2017 |
| ITU | SG13 | 1. Rec. ITU-T Y.3324: defines the functional and architectural requirements of autonomic management and control (AMC) for IMT-2020 networks. | Regular standardization track. | 2018 |
| | | 2. Rec. ITU-T Y.3177: specifies a high-level architecture of AI-based network automation for resource and fault management for future networks including IMT-2020. | Regular standardization track. | 2021 |
| | | 3. FG-AN: support standardisation activities of autonomous networks via building upon the existing standards’ gaps. | Pre-standardization track. | 2020 |
| 3GPP | Release 8 (e.g., TS 32.500) | Basics of LTE-SON. | Mature regular standard. | 2008 |
| | Release 10 (e.g., TS 32.522) | Self-coordination. | Mature regular standard. | 2011 |
| | Release 16 (e.g., TR 28.861) | Introduction to 5G NR-SON. | Mature regular standard. | 2018 |
| NGMN | 5G E2E architecture framework v3.0.8 | Describes a high-level vision of architecture principles and requirements to guide other SDOs/Fora and promote interoperability. Its automation capabilities of the network and services are based on the ETSI GANA model. | Requirements matured as inputs to standards. | 2019 |
| ONAP | Istanbul Release | Open source model-driven framework that brings orchestration and automation capabilities to physical and virtual network components. | Regular standardization track. | 2017 |
| BBF | AIM | Builds on ETSI GANA and ITU Recs. to define AFs for fixed access and E2E converged fixed/mobile networks. | Regular standards, mature. | 2018 |
| TMF | ODA (e.g., IG1167 and IG1177) | Mapping of the ETSI GANA framework to the ODA intelligence management model. | Standardized frameworks, mature. | 2018 |

AFI = Autonomic network engineering for the self-managing Future Internet; AIM = Automated Intelligent Management; ANIMA = Autonomic Networking Integrated Model and Approach; BBF = Broadband Forum; ENI = Experiential Networked Intelligence; FG-AN = Focus Group on Autonomic Networks; IMT-2020 = International Mobile Telecommunications-2020; INGR = IEEE International Network Generations Roadmap; INT = Core Network and Interoperability Testing; ISG = Industry Specification Group; NGSON = Next Generation Service Overlay Network; NR = New Radio; NTECH = Network Technologies; NTF = Network Telemetry Framework; ODA = Open Digital Architecture; ONAP = Open Network Automation Platform; PoC = Proof Of Concept; Rec. = Recommendation; RFC = Request for Comment; SG = Study Group; SysOpt = Systems Optimization; TC = Technical Committee; TMF = TeleManagement Forum; TR = Technical Report; WG = Working Group; ZSM = Zero touch network & Service Management.

A summary of those SON-specific challenges, potential solutions and open research questions is presented in Table II.
A. Challenges

Nowadays, the development and standardization activities of true SON solutions are still facing some key challenges. Notably, future communication systems are becoming increasingly complex as a result of supporting new ecosystems with huge information flow. Another challenge is that communication systems, as machines, do not have self-consciousness and they may act chaotically in unexpected situations. A classical example is the semantics, particularly the translation of homonyms. This increases the risk of control loss. Advancing self-organization capabilities will also need to deal with the interoperability issues. Despite the uptake of new communication systems, some fundamental services will continue to rely on legacy technologies as the case of voice services. For this reason, forthcoming sophisticated SONFs need to be backward compatible with the older ones. It is also noteworthy that self-organization is a process that spans various components and functions in the end-to-end mobile architecture. This makes it very difficult to design a holistic and turnkey SON solution. Finally, the full potential of SONs will only be achieved if they can continuously manage computationally expensive optimizations because future systems must provide quasi-instantaneous responsiveness.

B. Future Research Directions

The self-organization paradigm is expected to leverage the power of H-SON with its enabling technologies that will emerge within the next decade, as listed below.

Evolved H-SONs. Future communication systems call for a more seamless and adaptive H-SON to better balance the SONFs between the higher and lower levels. The conceptual fixed levels of self-organization functionality can be made more flexible during the run-time phase depending on the application being considered. Departing from the predefined levels at the design stage (e.g., the four abstraction levels of GANA [9]), real-time self-organization can scale up and down adaptively on the transmission time interval (TTI) timescale based on service needs to enable an efficient reactive self-coordination. More reference levels can be initially defined to include more use cases and enable cross-layer interactions. This tactical layers elasticity will reduce SON signaling, and can guarantee backward compatibility with legacy SONFs that have their own management levels even in run-time situations and immediate demands. Below, we share some enabling technologies that may deliver the flexibility needed in evolved H-SONs.

Virtualized, containerized, and multi-tenant architectures. Virtualization, containerization and multi-tenancy approaches are expected to be largely adopted. Accordingly, the use of COTS equipment from any vendor will potentially facilitate self-coordination capabilities because the network control parameters (NCPs) will be similar among various network elements. This can also reduce the parameter types to be controlled, and alleviate multi-vendor compatibility issues [12]. On the downside, different SONFs can access the same database and consequently compromise each other’s security.

Quantum technology. Self-coordination usually needs to solve complex optimization problems, which can be resolved with quantum computing (QC). QC techniques exploit the superposition of quantum states to concurrently explore different possibilities to quickly arrive at an optimal solution. In this perspective, QC will reduce computation cost (e.g., complex calculations) and the overall latency of the network (e.g., overheads of various layers) especially in virtualized and cloudified networks [13]. This can enhance both proactive and reactive coordination algorithms in extremely dynamic environments. However, quantum devices need to run under cryogenic temperatures or very high pressures. They are still in early development stages. On the other hand, quantum communication techniques use entanglement for quantum key distribution to support secure information exchange in emerging networks. Such techniques can achieve secure optimizations by enabling secure exchange of the inherent metrics and decisions.

Federated and transfer learning. Federated learning can simplify network automation by processing learning models (e.g., on COTS hardware installed at the edge) instead of handling large training datasets to reduce the time and energy costs of the proactive self-coordination. Further, transfer learning will allow capitalizing on the experience gained in avoiding or resolving previous SON conflicts to address new but similar ones [2].

Extended reality (XR) based simulations. XR environments can simulate or emulate realistic scenarios in which a network equipment operates under typical real-time conditions. The resulting observations can be further improved using knowledge and experience gained from historical information of similar equipment together with contextual data provided by AI techniques. This can enhance the predefined rules and policies implemented at the design stage to identify potential SONFs conflicts.

Collective intelligence. Conventional AI techniques are leveraged by each SONF to selfishly benefit its own actions, and can cooperate with the remaining SONFs for global performance. Consequently, SONs will need to handle an inherent communication overhead. In the next decade, self-coordination will leverage the power of the collective intelligence wherein local information (e.g., current and historical parameters and observations) are the basis for each SONF to decide on its optimal actions that constructively impact the entire SON functioning without the need for direct communications between the involved SONFs [14]. This can enable a truly proactive coordination of various SONFs with minimum or no overhead and loose coupling. For instance, the whole SON can be modelled based on a game-theoretic approach and then deep reinforcement learning techniques can be applied to converge to the optimal action for each SONF. This combination has been successfully explored in [15] for the case of inter-cell interference avoidance. However, research still needs to deal with the slow convergence speed of evolutionary methods and neural networks (e.g., via offline training), and minimize the amount of data locally needed to achieve the global benefit.

Sustainability and energy efficiency. There is always an interplay between network performance and the corresponding
energy efficiency [2]. One way to resolve the potential conflicts is to define priorities. Coordination between SONFs attempting to optimize performance and others attempting to optimize energy usage will be an important area of future work given a goal of sustainable networks.

**Human factor.** SONs aim at reducing human intervention in system optimization related tasks, but a human in the self-coordination process is indispensable to prevent system malfunction since machines cannot be endowed with self-consciousness [6]. For a successful operational mode, human intervention should be in the highest level loops, and ideally should not intervene at the lowest levels characterized by tighter constraints in terms of speed and responsiveness. Moreover, and besides autonomous learning, human experts can also contribute to enriching the coordination rules fed into the network.

### V. Conclusion

In this paper we analyzed the problem of managing complex networks more efficiently. As it can be seen from history, a potential solution is H-SON, which combines weak centralized control and distributed control so that the different feedback loops are almost isolated from each other to guarantee the stability of the network. Thus we discuss the potential and the promises of H-SONs for an improved self-coordination to avoid and resolve possible conflicts. We provided an in-depth landscape analysis of past and current standardization activities related to SONs and the inherent self-coordination functionality within various standardization organizations to explore the harmonization possibilities. Finally, we summarized the challenges and the future technological trends for the development of SONs over the next decade. An important challenge is to adapt the network to the correct degree of centralization between centralized and distributed networks depending on the situation in the network environment.

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