

On controller placement problems in communication networks: preliminary survey. Preprint

Mark Sh. Levin *

Inst. for Information Transmission Problems, Russian Academy of Sciences, Moscow 127051, Russia

The paper addresses controller placement problem in communication networks. A systematic description of the problem domain is presented (i.e., problems, models, solving strategies). Generally, the problem is based on combinatorial optimization models as network clustering and k -center (k -median) models. A traditional solving framework consists of the following stages: (1) definition of the optimal number of controllers, (2) location of the controllers, (3) definition of the controllers types, and (4) design of interconnection network over network elements (i.e., allocation of switches to controllers, design of a network over controllers). Here a special attention is targeted to support combinatorial optimization (CO) problems (e.g., location/assignment, p -center problem, clustering, covering, domination). Some basic optimization formulations (including multi-objective statements) of controller placement problems are described. Illustrations for the considered problems, models and solving schemes are presented.

Keywords: communication systems, controller placement, combinatorial optimization, heuristic, survey

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1. Introduction

In telecommunication systems infrastructures the subsystem of hierarchical control plays the significant role (e.g., [305]). The paper addresses an network control analysis and controller placement problems. (including study of tree-structured/hierarchical networks). In recent decade, the role of controller placement and assignment problems in contemporary networks has been increased. The controller placement problem in SDNs was proposed in [118]. A simplified scheme of the research is shown in Fig. 1.

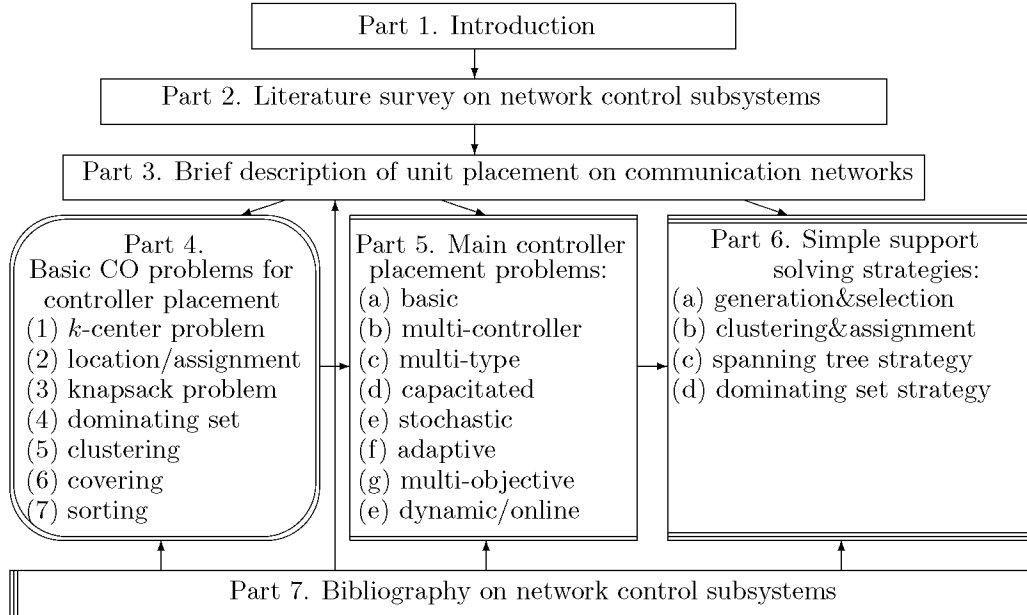


Fig. 1. Simplified scheme of research

A hierarchical illustration of controller location problem is presented in Fig. 2: (i) global controller, (ii) local (domain) controllers, (iii) clusters of nodes (switches). The node clusters above can have intersection(s) and corresponding controllers can have joint domains for the execution of control function(s) (e.g., two clusters at right side in Fig. 2). Usually two layers are considered (e.g., [11,77,167,170,266]): control plane (controllers), data plane (switches/nodes).

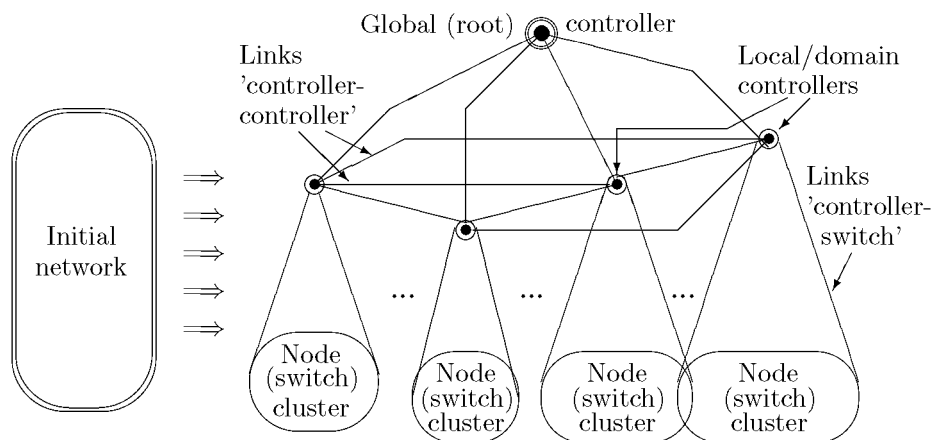


Fig. 2. Illustration for controller location problem

The controller placement problem is targeted to minimization of the cost of the network (e.g., minimization of the propagation latency, minimum control latency) while taking into account a set of constraints. The following factors are usually examined in the controller placement problems (e.g., [85,141,176,196,355]):

1. The latency of control signaling. The switches receive the instructions on how to forward the new flows. Whenever the latency between controllers and switches reaches a threshold, the latency on the whole network will increase substantially. In this case, the controller processing latency is a non-negligible factor in the total round-trip latency [277].

2. The server capacity limitation. Due to the constraints of the resources such as processors, memory, and access bandwidth, a commodity server only has the capacity to manage a limited number of switches. On the other hand, the overload of controllers may decrease the performance of SDN [355].

3. The required number of controllers. In large-scale SDN networks, a large amount of switches in data plane construct a complex networks. It is difficult for administrators to figure out how many controllers should be deployed. Some work uses the traversal searching method to iteratively find the best performance number, which may lead to high time consumption [44].

4. Fault tolerance. Unlike the traditional network architecture, the switches do not have control ability due to the split architecture of SDN. Each switch is assigned a controller. Therefore whenever a switch loses the connection to its controller, it will no longer receive any new routing instructions and thus drop all packets [368].

5. Inter-controller communication. In multi-controller SDNs, each switch is controlled by a specific controller. If a controller wants to send messages to a switch controlled by another controller, the controllers need to communicate with each other [80].

Therefore, the inter-controller communication affects the performance in end-to-end communication between disparate switches controlled by different controllers.

A traditional solving framework of the controller placement in communication networks consists of the following stages: (1) definition of the optimal number of controllers, (2) location of the controllers, (3) definition of the controllers types, and (4) design of interconnection network over network elements (i.e., allocation of switches to controllers, design of a network over controllers).

In general, the controller placement problem is considered as follows (e.g., [359]). The following is given: $G = (V, E, S)$, where V is the controller set, E is the switch set, S is the link set. The problem formulation is:

Find the number of controllers $n = |V|$, and the mapping $V \rightarrow S$ in the network (i.e., location of the controllers in the network).

A scheme of combinatorial optimization based approaches and controller placement problems is depicted in Fig. 3.

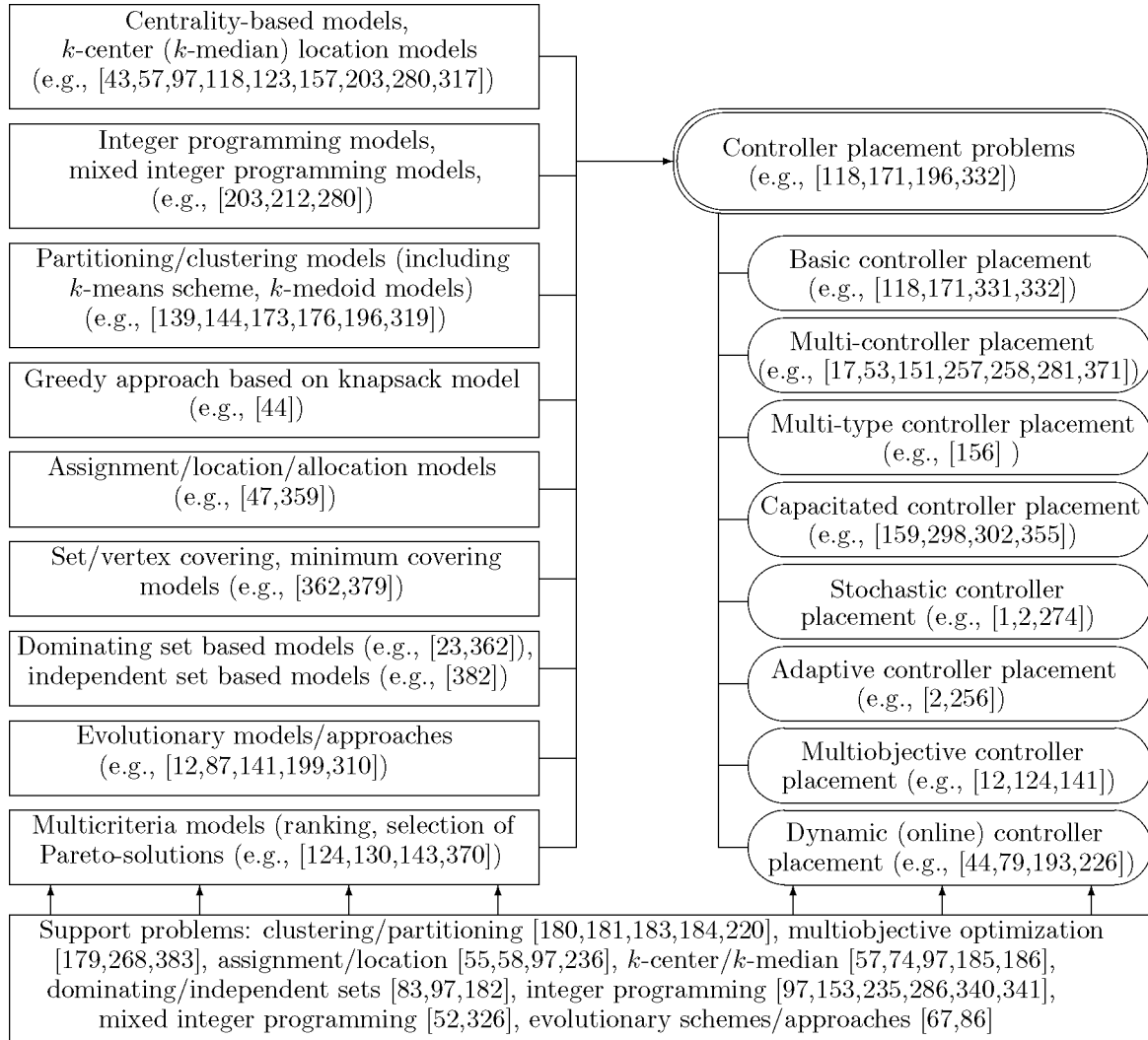


Fig. 3. Scheme: combinatorial optimization and controller placement

In the paper, a survey on controller placement problems in communication networks is presented.

2. On control in networks

2.1. Some recent studies

In recent years, the significance of distributed control/monitoring in networked systems has been increased. Here the problems of location/placement of control (monitoring, measurement, aggregation) units have a crucial central role. An illustrative scheme for the problem domain is presented in Fig. 4.

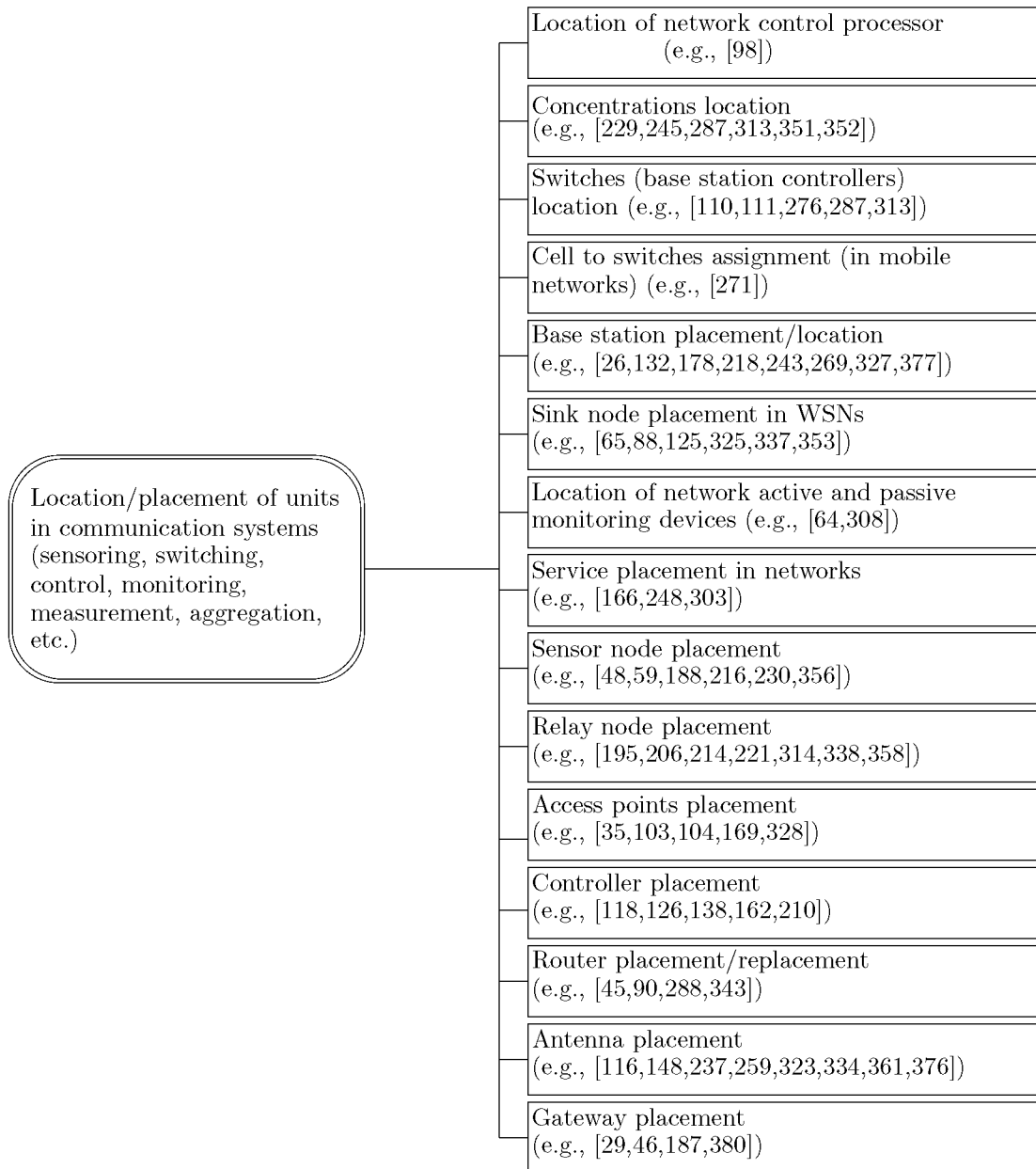


Fig. 4. Placement of network units (e.g., control, monitoring, access, integration)

Note, multi-controllers architecture are widely used in software defined networks (e.g., [129,213,254,306,371]).

Some recent studies of control/management processes in networks are listed in Table 1.

Table 1. Some recent studies of control/management processes in networks, part 1

No.	Some studies of control issues in networks	Source(s)
1.	Surveys:	
1.1.	Networked control systems (survey, recent progress)	[345]
1.2.	Cyber-physical control over wireless sensor and actuator networks	[344]
1.3.	Dynamic key management algorithms in WSNs (survey)	[357]
1.4.	Networked control systems (survey of trends and techniques, including “control over networks”)	[375]
1.5.	Survey on networked control systems (multi-hop channels)	[60,121]
1.6.	Coverage control in sensor networks	[330]
1.7.	Distributed SDN control (survey, taxonomy, challenges, architectural issues)	[41]
1.8.	Distributed SDN controller system (survey on design choice)	[233]
1.9.	Autonomic network management (current and future research directions)	[278]
1.10.	Multi-controller deployment in SDN-enabled 6G space-air-ground integrated network (including five-layer architecture)	[198]
1.11.	Controller placement problem during SDN deployment in ISP/Telco networks (survey)	[282]
1.12.	Real-time and reliable industrial control over wireless LANs (algorithms, protocols, and future directions)	[322]
1.13.	Survey on controller placement strategies	[138]
1.14.	Survey on controller placement in SDNs	[72]
2.	Architectural issues:	
2.1.	Architectures for networked control systems	[102]
2.2.	Multi-layer architecture for controllers in networks (Industry 4.0)	[366]
2.3.	Network management architecture for hybrid SDN	[279]
2.4.	Design of controller for mobile robots (modularized control architecture)	[172]
2.5.	Architecture, implementation and evaluation of join and spilt TCP for SDN networks (dynamic controlling)	[109]
2.6.	Multiple controllers architecture (in SDN, load-balancing strategy)	[346]
2.7.	Elastic distributed SDN controller architecture	[80]
2.8.	Agent-based control architectures for next generation telecommunication network infrastructures	[120]
2.9.	SDN based routing architecture for wireless mesh networks (including control plane, data plane)	[100]
2.10.	Controller-based roadside unit plane architecture (for software-defined internet of vehicles)	[215]
2.11.	Multi-level hierarchical control plane architecture in SDN	[264]
2.12.	Architecture of combination: SDN and IoT	[295]
3.	Control schemes in communication networks:	
3.1.	Centrally controlled wireless data networks	[307]
3.2.	Centrally controlled networks (adaptive computation framework)	[211]
3.3.	Energy efficient coverage control in WSNs (multi-objective genetic algorithm)	[150]
3.4.	Power control in distributed underwater wireless sensor networks (UWSN) (cooperative game)	[348]
3.5.	Distributed power control (for the downlink of multi-cell NOMA systems)	[94]
3.6.	Networked control systems with communication constraints	[30,117]
3.7.	Edge-based platoon control (including control topology)	[255]
3.8.	Optimization of the quality control station configuration	[239,240]
3.9.	Hierarchical control in sociotechnical systems	[200]
3.10.	Coverage control for mobile sensing networks	[69]
3.11.	Industrial wireless networked control systems (reliable fault tolerant-based multipath routing model)	[4]
3.12.	Power control in HetNets	[39,122,165]
3.13.	Energy aware resource control mechanism in green 6G networks	[312]
3.14.	Distributed and throughput optimal power control in wireless networks	[51]

Table 1. Some recent studies of control/management processes in networks, part 2

No.	Some studies of control issues in networks	Source(s)
4.	Control issues in software defined networks (SDNs):	
4.1.	Cross-layer access control (over SDNs)	[374]
4.2.	Network management with software defined networking	[164]
4.3.	Network management architecture for hybrid SDN	[279]
4.4.	Evaluation, performance analysis of SDN/OpenFlow network controllers	[49,291]
4.5.	Control mechanism of cloud computing (using SDN)	[231,246]
4.6.	Distributed SDN control (survey, taxonomy, challenges, architectural issues)	[41]
4.7.	Distributed SDN controller system (survey on design choice)	[233]
4.8.	Control plane of SDNs (survey)	[347]
4.9.	Distributed SDN controllers for distributed IoT	[93]
4.10.	Controller placement in multi-control 5G based on SDN/NFV architecture	[135]
4.11.	Multi-controller SDN architecture	[175,306,365]
4.12.	Survey of diverse SDN controllers, multiple SDN controllers	[11]
4.13.	Prioritized admission control with load distribution over multiple controllers for scalable SDN-based mobile networks	[175]
5.	Controller placement issues:	
5.1.	Controller placement problems	[118,171,331,332]
5.2.	Problem of placing monitoring devices as total domination in graphs	[119]
5.3.	Multicriteria controller placement problems in software defined networks	[124,143,144]
5.4.	Reliable/resilient control placement in software defined networks	[108,124,144,145,242]
5.5.	Placement of controllers in software-defined WAN (meta-heuristic)	[273]
5.6.	Controller placement for designing a distributed SDN control layer	[152]
5.7.	Capacitated controller placement problem in SDNs	[302,321,355]
5.8.	Optimizing controller placement for SDNs	[131]
5.9.	Traffic-aware dynamic controller assignment in SDN (stable matching)	[47]
5.10.	Traffic-aware dynamic controller placement using AI in SDN-based aeronautical networks	[212]
5.11.	Controller placement optimization in hierarchical distributed SDN in VANET	[203]
5.12.	Clustering for controller placement (e.g., in SDN)	[25,54,196]
5.13.	Controller placement strategies	[138]
5.14.	Controller placement issues in SDNs with different goals (survey)	[225]
5.15.	Taxonomy of controller placement problem (CPP) optimization in SDN	[294]
5.16.	Survey on controller placement in SDNs	[72]
5.17.	Dynamic controller deployment for Low Earth Orbit satellite networks (multi-objective model, objectives: minimization of controller-switch delay, maximization of network reliability)	[79]
6.	Multiple controller systems (multiple controller placement):	
6.1.	Multiple controller environments (e.g., in SDNs)	[17,129,174,254,258,371]
6.2.	Multi-controller based software-defined networking (survey)	[129]
6.3.	Survey on software defined networking with multiple controllers	[371]
6.4.	SDN architectures with multiple controllers	[53,175,365,371]
6.5.	Multi-controller placement for load balancing in software-defined wide area network (SDWAN)	[354]
6.6.	Load-balancing multiple controllers mechanism for SDN	[213,283]
6.7.	Machine intelligence approach for load balancing in multi-controller based SDN	[306]

Table 1. Some recent studies of control/management processes in networks, part 3

No.	Some studies of control issues in networks	Source(s)
7.	Scheduling issues in control systems:	
7.1.	Scheduling of networked control systems	[329]
7.2.	Scheduling in sensor node and controller node for wireless networked control systems	[315]
7.3.	Controlled service scheduling scheme for user-centric SDN-based IoT	[19]
8.	Some special studies:	
8.1.	Co-design of Safe Networked Control Systems	[284]
8.2.	Wireless LAN transmitter location under the threat of jamming attacks (optimal location)	[285]
8.3.	Stability of networked control systems	[28,81,367]
8.4.	Power control in heterogeneous ultra-dense networks	[202]
8.5.	Supervisory control synthesis (in model-based systems engineering)	[37]
8.6.	Cooperative controllers (for highway)	[241]
8.7.	Hybrid control design for linear networked systems	[34]
8.8.	Controllers for stochastic systems	[274]
8.9.	Controller area networks	[99,107,373]
8.10.	Traffic control/management in communications	[219]
8.11.	Optimal control for networked control systems with Markovian packet losses	[115]
8.12.	Rate control algorithms	[289]
8.13.	Control policies for energy-efficient remote health monitoring (wireless body area network)	[42]
8.14.	Taxonomy of node placement approaches in sensor networks (relay nodes, controllers, sink nodes)	[88]
8.15.	Review of the control plane scalability in software defined networking	[6]
8.16.	Multiobjective robust controller synthesis approach	[36]

2.2. Illustration of multi-layer network architecture with control

The basic versions of topological control paradigms are shown in Fig. 5. (e.g., [76]).

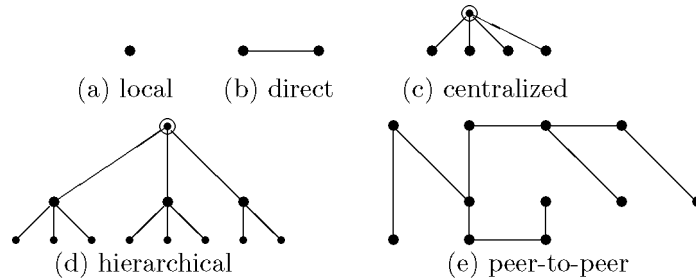


Fig. 5. Control paradigms for local and coordinated control

Further here some illustration examples of multi-layer (hierarchical) network architecture with control layers/units are presented. In Fig. 6, a simplified multi-layer architecture of SDNs with a control layer is shown (e.g., [11,49,77,78,170,266]).

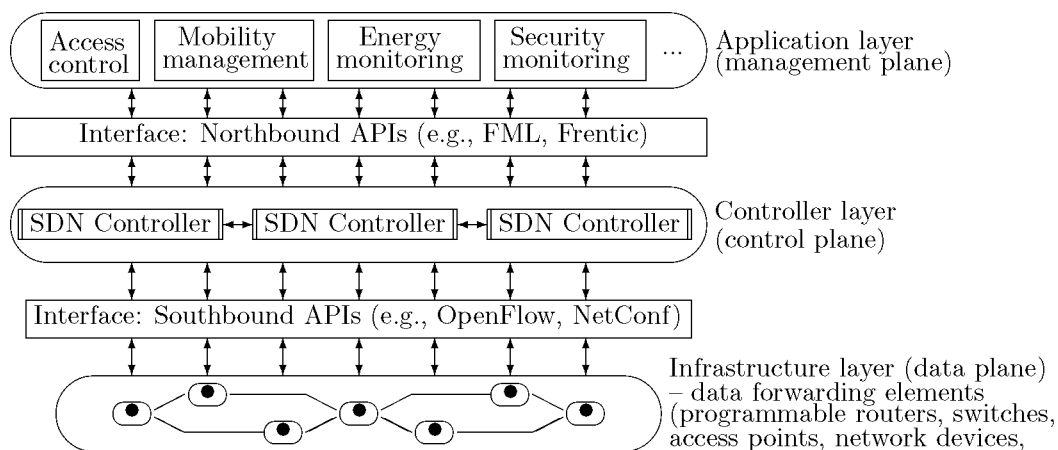


Fig. 6. Simplified multi-layer architecture of SDNs

An illustration of SDN-based IoT architecture is depicted in Fig. 7 (e.g., [295]).

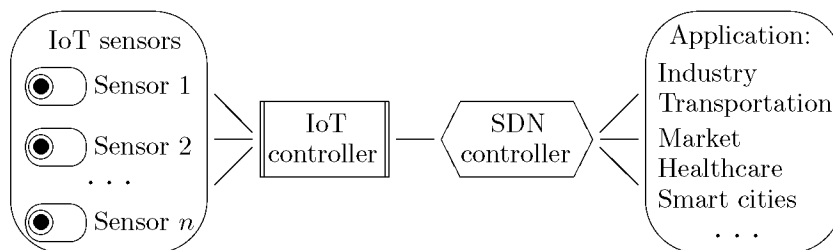


Fig. 7. Simplified SDN-IoT architecture

An illustrative example of hierarchical network control in SDN assisted ON (opportunistic network) architecture is described in [73,342] (Fig. 8).

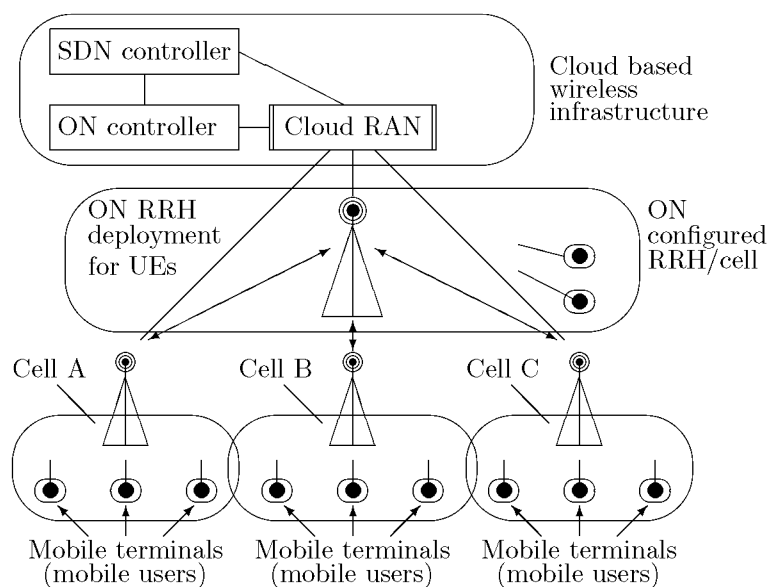


Fig. 8. SDN assisted ON architecture (hierarchical control)

A simplified scheme of SDN-IoT integration (including a control part) is depicted in Fig. 9 (e.g., [93]).

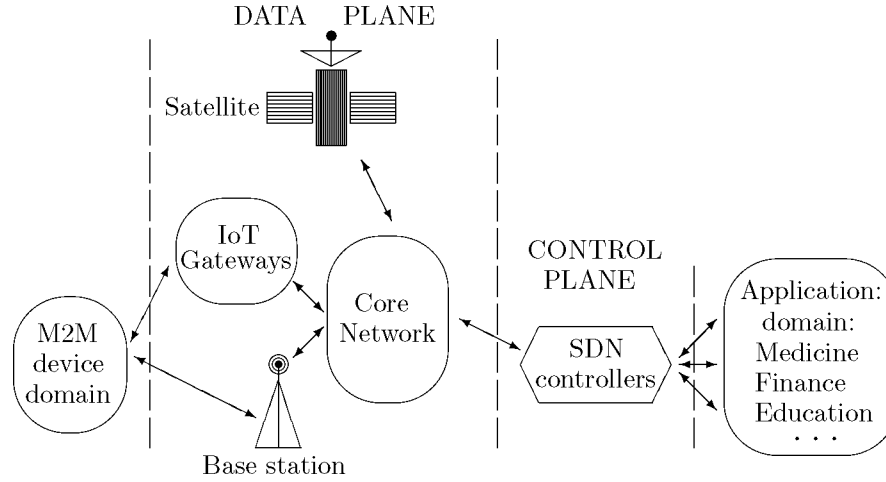


Fig. 9. Simplified scheme of SDN-IoT integration

2.3. Decentralized control

Decentralization of control in hierarchical systems plays an important role in many research domains [105]: economics, management, decision making, mathematical modeling, engineering, operations research (mathematical programming).

Some studies on distributed (decentralized) control/management processes in networks are pointed out in Table 2.

Table 2. Some recent studies of distributed control-management in networks

No.	Studies of distributed control-management in networks	Source(s)
1.	Control decentralization in hierarchical systems	[105]
2.	Distributed coordination control of traffic network flow	[372]
3.	Distributed flow management in SDNs	[50]
4.	Design of robust controllers on the grid (multiobjective evolutionary approach)	[293]
5.	Coordinated session-based admission control with statistical learning for multi-tier internet applications	[228]
6.	Replica server placement algorithms for content delivery networks (placement models)	[272]
7.	Optimal placing of the information-technological reserve (ITR) in distributed data processing systems (i.e., placement of the ITR copies in computer networks) (p -median models)	[304]
8.	Design and simulation of a mobile radio network with distributed control	[38]
9.	Merging control in networks (multi-agent systems)	[113]
10.	Design of hierarchical decentralized controllers to guarantee the structural stability of chemical plants	[84]
11.	Adaptive load balancing scheme for SDN controllers (distribution of traffic load in the controllers)	[250]
12.	Top-down approach to distributed control of discrete-event systems	[56]
13.	Distributed SDN controllers in distributed IoT	[93]
14.	Hierarchical controllers in internet of vehicles	[217]

2.4. Literature survey of control/management processes in networks

Table 3 contains a list of some recent studies of control/management processes in networks.

Table 3. Some recent studies of control/management processes in networks (combinatorial models), part 2

No.	Some studies of control issues in networks	Source(s)
3.	Dynamic control/management:	
3.1.	Dynamic controlling in networks (SDN)	[109]
3.2.	Dynamic bandwidth management in single-hop ad hoc wireless networks	[290]
3.3.	Switched dynamics	[75]
3.4.	Issues of mobility management in networks	[101,238]
3.5.	Dynamic traffic control expert system	[339]
3.6.	Supervisory controller design in timed-transition Petri nets	[33]
3.7.	Dynamic power management in cluster system (Markov decision process)	[232]
3.8.	Resource controller problem in networks	[9]
3.9.	Controller and estimator for dynamic networks	[168]
3.10.	Dynamic channel allocation for efficient power management (control) in multi-channel IEEE 802.16 networks (WiMAX)	[27]
3.11.	Optimal sensor placement for target tracking	[216]
4.	Topology control/management in networks:	
4.1.	Topology control in WSNs:	
4.1.1.	Topology control for WSNs	[63,147,261]
4.1.2.	Topology control for two-tiered WSNs	[177]
4.1.3.	Topology management in large and dense real-time WSNs	[208]
4.1.4.	Topology control for two-tier wireless sensor networks	[234]
4.2.	Topology control in Ad Hoc Networks:	
4.2.1.	Topology control problems for Ad Hoc networks (algorithmic aspects)	[70,205]
4.2.2.	Topology control and routing in Ad Hoc networks	[260]
4.3.	Distributed topology control techniques for low interference and energy efficiency in WSNs	[68]
4.5.	Probabilistic and highly efficient topology control algorithms	[189,190]
4.5.	Largest connected-topology minimum interference topology control problem (in cognitive radio networks)	[349]
4.7.	Topology control for dynamic clusters in MANET	[262]
4.10.	Topology control for WSNs (virtual backbone)	[333]
5.	Cluster-based control/management:	
5.1.	Cluster-based control channel allocation in opportunistic cognitive radio networks (spectrum opportunity clustering design, maximum edge biclique model)	[201]
5.2.	Cluster control of heterogeneous thermostatically controlled loads using tracer limits	[133]
5.3.	Clustering scheme for hierarchical control in multi-hop wireless networks	[40]
5.4.	k -hop clustering scheme for the optimal common control channel assignment problem (cognitive radio networks)	[350]

Table 3. Some recent studies of control/management processes in networks (combinatorial models), part 3

No.	Some studies of control issues in networks	Source(s)
6.	Some control issues in contemporary networks:	
6.1.	Access control for IoT networks	[96]
6.2.	Common control channel design in cognitive radio networks (clustering, biclique model, balancing)	[207]
6.3.	Delay gradient based congestion control for IoT	[265]
6.4.	Distributed flow management in SDNs	[50]
6.5.	Power management in virtualized datacenter (power management, server heterogeneity controls, server virtualization controls, etc)	[222]
6.6.	Dynamic controlling in networks (SDN)	[109]
6.7.	Multi-layer architecture for controllers in networks (Industry 4.0)	[366]
6.8.	Power control (e.g., for connected vehicles)	[106]
6.9.	Performance analysis of SDN/OpenFlow controllers	[49]
6.10.	Load-balancing multiple controllers mechanism for software-defined networking multiple controller environment with hierarchical control plane	[213]
6.11.	Controller design for data center network	[318]
6.12.	Energy-efficient management techniques in cloud data centers (DCs), current challenges: static management, dynamic management (for hardware level, for virtualization/software level)	[112]
6.15.	Hierarchical SDN controllers with adaptive offload	[292]
6.16.	Coverage control of sensor networks in IoT	[336]
6.17.	Distributed SDN controllers in distributed IoT (edge computing, federated learning)	[93]
7.	Virtual machine placement problems:	
7.1.	Efficient resource allocation as virtual machine placement	[15]
7.2.	Secure virtual machine placement in cloud data centers	[10]
7.3.	Optimistic virtual machine placement in cloud data centers (queuing approach)	[247]
7.4.	Energy-efficient dynamic Virtual Machine Placement in data centers	[21]
7.5.	Virtual machine placement in data center networks (minimizing connection cost)	[95]
7.6.	Virtual machine placement (multi-objective reinforcement learning)	[253]
7.7.	Virtual machine placement in cloud computing (imperialist competitive algorithm)	[146]
7.8.	Virtual machine consolidated placement (multiobjective biogeography-based optimization)	[378]
7.9.	Virtual machine placement in cloud computing (chemical reaction optimization)	[191]
7.10.	Virtual machine placement and migration in cloud environments (optimization, survey)	[91]
7.11.	Multi-objective communication-aware optimization for virtual machine placement in cloud datacenters	[89]
7.12.	Predictive Anti-Correlated Placement Algorithm (PACPA) for VM placement (cloud data centers)	[134]
7.13.	Optimizing virtual machine placement for energy and SLA in clouds (using utility functions)	[227]
7.14.	Hybrid energy-aware virtual machine placement algorithm for cloud environments	[5]
7.15.	Survey on the use of preferences for virtual machine placement in cloud data centers	[18]
8.	Virtual network function (VNF) placement in networks:	
8.1.	VNF and CHF placement in 5G (recent advances, future trends)	[31]
8.2.	Efficient VNF placement in network function virtualization	[251]
8.3.	User mobility-aware VNF placement for virtual 5G network infrastructure	[311]
8.4.	Combining deep reinforcement learning with graph neural networks for optimal VNF placement	[309]
8.5.	VNFs placement and routing optimization	[7]
8.6.	Survey on wireless SDNs (W-SDNs) and network function virtualization (NFV) for 5G cellular systems	[16]

3. On controller placement studies

3.1. Recent controller placement and assignment studies

Some recent controller placement and assignment studies are listed in Table 4.

Table 4. Some recent controller placement and assignment studies, part 1

No.	Controller placement and assignment study	Source(s)
1.	Basic problems, surveys:	
1.1.	Basic controller placement problem	[118,171,331]
1.2.	Controller placement problems in software defined networking (surveys)	[126,174,210] [296,332]
1.3.	Controller placement in SDNs (comprehensive surveys)	[162]
1.4.	Taxonomy of controller placement problem (CPP) optimization in SDN	[294]
1.5.	Min-cover based controller placement approach (for reliable control network in SDN)	[379]
1.6.	Distributed controller placement in SDN	[137,197,362,369]
1.7.	Survey on SDN controller placement strategies	[138]
1.8.	SDN architectures with multiple controllers	[53]
1.9.	Robust controller placement for link failure in SDNs (Pareto-efficient solutions)	[130]
1.10.	Controller placement issues in SDNs with different goals (comprehensive survey)	[225]
1.11.	Survey of controller placement problem in SDN-IoT network	[3]
1.12.	Optimizing SDN controller to switch latency for controller placement problem	[382]
1.13.	Review and future directions on controller placement in software defined emerging SDNs (including satellite communication networks)	[71]
2.	Contemporary problems:	
2.1.	Optimal models for the controller placement problem in SDNs	[114,131,277]
2.2.	Reliability-aware controller placement for SDNs	[267]
2.3.	Energy-aware controller placement problem in SDNs	[128]
2.4.	Load balanced controller placement problem in SDNs	[127]
2.5.	Controller placement problem for wireless SDN	[85]
2.6.	SDN-controller placement for D2D communications	[204]
2.7.	Reliable control placement in SDNs	[144,145]
2.8.	Controller placement optimization in hierarchical distributed software defined vehicular networks	[203]
2.9.	Cost-effective controller placement in software-defined multihop wireless networking (deep reinforcement learning)	[364]
2.10.	Hierarchical controllers in internet of vehicles model	[217]
2.11.	Multi-controller placement in software-defined networking	[258]
3.	Capacitated controller placement problems:	
3.1.	Capacitated SDN controller placement problem	[301]
3.2.	Capacitated controller placement problem in SDNs	[355]
3.3.	Capacity and load aware SDN controller placement in heterogeneous environments	[156]
3.4.	Control plane delay minimization-based capacitated controller placement algorithm for SDN	[61]
3.5.	Capacity-aware and delay-guaranteed resilient controller placement for software-defined WANs	[316]
3.6.	Network cost optimization-based capacitated controller deployment for SDN	[62]
4.	Controller placement in large scale networks:	
4.1.	Controller placement problem in large scale SDNs	[176,196]
4.2.	Controller placement in software defined wide area networks	[335]
4.3.	Density cluster based approach for controller placement in large-scale SDNs	[196]
4.4.	Optimal controller placement in large scale SDNs software (based on modified NSGA-II)	[142]
4.5.	Controller placement in large-scale SDN (parameter optimization, heuristics, PSO)	[192]

Table 4. Some recent controller placement and assignment studies, part 2

No.	Controller placement and assignment study	Source(s)
5.	Dynamic controller placement/assignment studies:	
5.1.	Controller placement in multi-control 5G based on SDN/NFV architecture (dynamic capacitated controller placement problem)	[135]
5.2.	Dynamic controller assignment in software defined internet of vehicles (through multi-agent deep reinforcement learning)	[360]
5.3.	Dynamic controller assignment in LEO satellite based SDN (using multi-agent deep reinforcement learning)	[226]
5.4.	Dynamic assignment of software-defined controllers in vehicle networks an evolutionary game approach	[149]
5.5.	Dynamic controller provisioning in SDNs	[44]
6.	Multiobjective (multicriteria) controller placement problems:	
6.1.	Survey of multiobjective controller placement problems in SDNs	[174]
6.2.	Multicriteria controller placement problems in SDNs	[143,144]
6.3.	Pareto-optimal resilient controller placement in SDN-based core networks	[124]
6.4.	Multiobjective controller placement in SDNs (genetic algorithms)	[12,141]
6.5.	MCDM scheme (Analytical Network Process) for controller placement	[22]
6.6.	Multiple criteria analysis of controller placement problem in SDNs (AHP technique)	[143]
6.7.	Multi-objective optimization controller placement problem in Internet-oriented SDNs	[370]
6.8.	Multiobjective controller placement in SDNs (adaptive heuristic)	[13]
6.9.	Optimal controller placement in large scale SDNs software (multicriteria combinatorial optimization model)	[142]
6.10.	Multi-objective controller placements for latency minimization of both primary and backup paths in SDNs (evolutionary approach)	[87]
6.11.	Multi-objective placement of SDN controllers (optimization of cost and network performance in WSNs)	[310]
7.	Controller placement problems under uncertainty:	
7.1.	Stochastic controller placement problems in wireless/cellular SDNs	[1,2]
7.2.	Robust controller placement and assignment in SDNs (stochastic problem)	[2]
7.3.	Failure-based controller placement in SDNs (decision under uncertainty)	[244]
8.	Special controller placement studies:	
8.1.	Controller placement problem for robust SDNs	[280]
8.2.	Adaptive controller placement (for wireless sensor-actuator networks)	[256]
8.3.	Inter-controller consensus in the placement of distributed SDN controllers	[369]
8.4.	Elastic distribution of SDN/NFV controllers (for 5G cloud management systems)	[14,80]
8.5.	Improving resilience of controller placement with minimum backup capacity in SDNs	[161]
8.6.	SDN controller placement with delay-overhead balancing in wireless edge networks	[252]
8.7.	Flow processing-aware controller placement in wireless DenseNets	[32]
8.8.	QoS-Guaranteed controller placement in SDN (e.g., delay minimization)	[66,381]
8.9.	Exploring the impact of critical programmability on controller placement for software-defined wide area networks	[82]
8.10.	Controller placement in SDN using game theory and discrete hybrid metaheuristic algorithm	[155]
8.11.	Survival backup strategy for controller placement in SDNs	[24]
8.12.	Comparative analysis of SDN controller placement problem (IoT-specific tactics and generalized solutions)	[324]

3.2. Basic combinatorial approaches for controller placement

Table 5 contains a list of basic solving approaches for controller placement problems.

Table 5. Basic solving approaches for controller placement problems, part 1

No.	Method	Source(s)
1.	Basic solving methods:	
1.1.	Min-cover based controller placement approach	[379]
1.2.	K -means-based network partitioning algorithm	[331]
1.3.	Density cluster based approach	[196]
1.4.	Heuristic approaches (e.g., partitioning based)	[176]
1.6.	Centrality based algorithms for controller placements (in software defined wide area networks)	[8]
1.7.	Betweenness centrality & hierarchical clustering for distributed SDN controller placement	[20]
2.	Optimization approaches:	
2.1.	Taxonomy of controller placement problem (CPP) optimization in SDN	[294]
2.2.	GAs with particle swarm optimization based mutation for distributed controller placement	[197]
2.3.	GA for controller placement in software-defined multi-hop wireless networks	[365]
2.4.	Novel controller placement algorithm based on network portioning concept and hybrid discrete optimization algorithm for multi-controller SDNs	[92]
2.5.	Parameter optimization model of heuristic algorithms (PSO) for controller placement in large-scale SDN	[192]
2.6.	Whale optimization for controller placement in SDN-WAN	[320]
2.7.	Bio-inspired multiverse optimization approach for controller placement in SDN	[249]
2.8.	Constrained evolutionary multiobjective optimization techniques for reliable controller placement in SDN	[270]
2.9.	Joint placement latency optimization of the control plane (mixed-integer linear programming)	[263]
2.10.	Multi-objective antlion algorithm for controller placements in SDNs	[154]
3.	Heuristics:	
3.1.	Heuristic approaches for the reliable controller placement problem	[299]
3.2.	Evaluating heuristic techniques as a solution of controller placement problem in SDN	[300]
3.3.	Using heuristics to the controller placement problem in software-defined multihop wireless networking	[363]
3.4.	Heuristic resource allocation algorithm for controller placement in multi-control 5G based on SDN/NFV architecture	[135]
3.5.	Parameter optimization model of heuristic algorithms (PSO) for controller placement in large-scale SDN	[192]
3.6.	Meta-heuristic approach for multi-controller placement in satellite SDN	[151]
3.7.	Nature-inspired metaheuristic algorithms for resilience controller placement in SDNs (experimental comparison of four nature-inspired metaheuristics)	[224]
3.8.	Efficient greedy heuristic approach for fault-tolerant distributed controller placement in scalable SDN architecture	[275]
3.9.	PSO and TLBO based reliable placement of controllers in SDN	[297]
3.10.	Metaheuristics (SA-MCSDN) optimizer for multi-controller placement in SDNs	[258]
4.	Evolutionary approaches:	
4.1.	Genetic algorithms for controller placement in SDNs	[12,87,141]
4.2.	Evolutionary multi-objective placement of SDN controllers in WSNs	[310]
4.3.	Multi-objective evolutionary optimization for cost-effective controller placement	[199]

Table 5. Basic solving approached for controller placement problems, part 2

No.	Method	Source(s)
5.	Multiobjective (multicriteria) methods:	
5.1.	Pareto-optimal resilient controller placement	[124]
5.2.	Multiobjective genetic algorithms	[12,87,141]
5.3.	Hybrid NSGA-II for solving multiobjective controller placement	[12]
5.4.	Multi-start hybrid non-dominated sorting GA-II (MHNSGA-II) (multicriteria combinatorial optimization model)	[142]
5.5.	Analytical Network Process approach	[22]
5.6.	Multiple criteria analysis of controller placement problem in SDNs (using AHP technique)	[143]
5.7.	Multi-objective optimization approach	[370]
5.8.	Adaptive multiobjective heuristic	[13]
5.9.	Evolutionary multi-objective placement of SDN controllers for optimizing cost and network performance in WSNs	[310]
5.10.	Pareto-optimal solutions for robust controller placement for link failure in SDNs	[130]
5.11.	Cost-effective controller placement scheme for software-defined vehicular networks (multi-objective evolutionary optimization, GA)	[199]
6.	AI-based method (machine learning, etc.):	
6.1.	Deep reinforcement learning for cost-effective controller placement in multihop wireless SDN	[364]
6.2.	Deep reinforcement learning based controller placement and optimal edge selection in SDN-based multi-access edge computing environments	[194]
6.3.	Reinforcement learning for dynamic controller deployment in LEO satellite networks	[79]
6.4.	AI techniques for traffic-aware dynamic controller placement (SDN-based aeronautical networks)	[212]
7.	Special methods:	
7.1.	Cooperative game theory based network partitioning approach	[160]
7.2.	Simulated annealing strategy for reliable controller placement in SDNs	[223]
7.3.	New GSO based method for SDN controller placement problem	[321]
7.4.	Clustering for controller placement (e.g., in SDN)	[25,54,196]
7.5.	Novel framework for capacitated SDN controller placement (balancing latency and reliability with PSO algorithm)	[301]
7.6.	Game theory and discrete hybrid metaheuristic algorithm for controller placement problem	[155]

4. Some basic formulations of controller placement problem

4.1. Basic parameters of controller placement problem

The basic list of problem parameters involves the following:

- (1) type of controllers: one type, multiple types;
- (2) type of network topology: tree-like topology, hierarchy, general network;
- (3) type of controllers layer: simple layer as controllers set, layer of connected controllers, layer as two tier controller set (local controllers, bottom-layer controllers); and
- (4) type of objective(s): one criterion (cost), multiple criteria.

4.2. Basic criteria/requirement in controller placement problems

In recent years controller placement problems have been examined under multiple criteria/requirements (e.g., [2,22,143,144,154,174,210,294]) (Fig. 10).

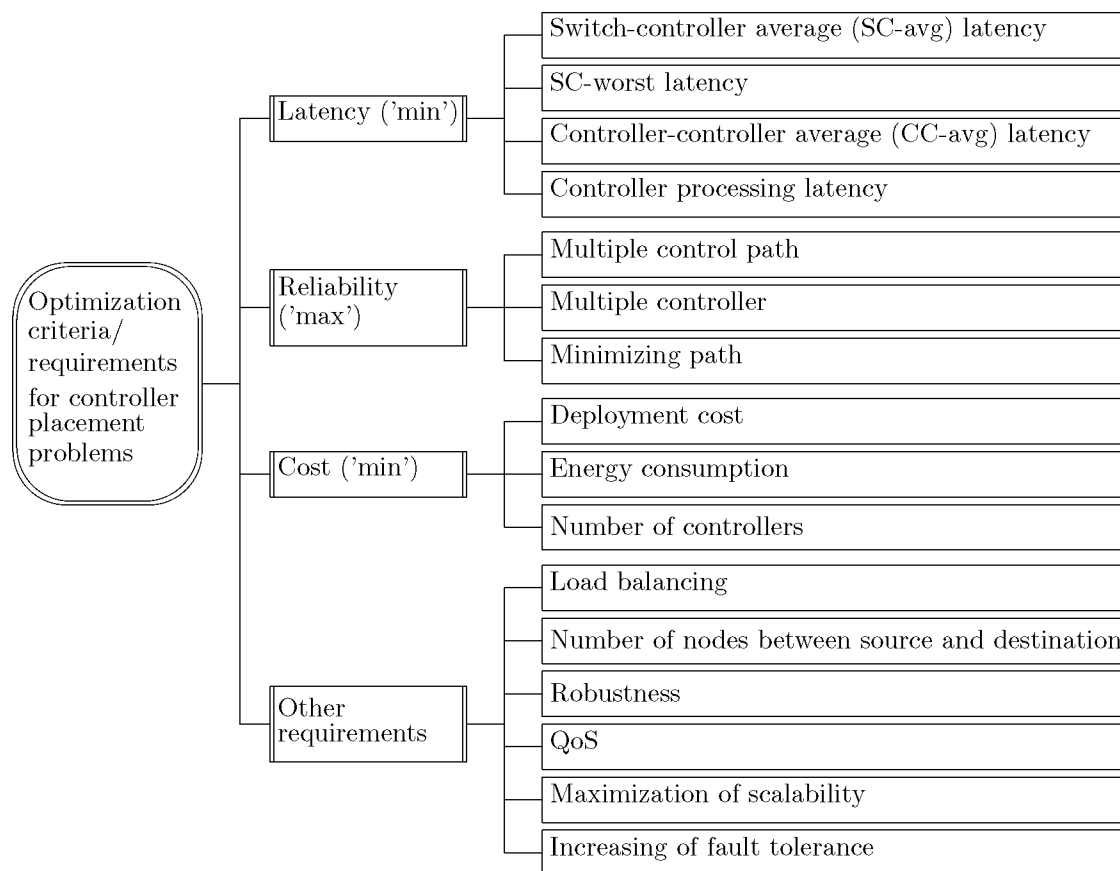


Fig. 10. Basic optimization criteria/requirements

4.3. Basic description and notations

Here the basic mathematical formulations of controller placement problem are described. The models are based on the following basic works [118,263]. Note that the considered optimization models are based on k -center problem (e.g., [185,186]) and the minimum k -means problem (e.g., [140]).

Usually the following notations are used [263]:

1. the initial graph (network) nodes/switches:
 - (1.1.) $G = (A, E)$, A is a set of all nodes/switches ($A = \{a_1, \dots, a_i, \dots, a_n\}$), E is the set of physical edges (links) between the nodes,
 - (1.2.) $B = \{b_1, \dots, b_\xi, \dots, b_k\}$ ($k < n$), is the set of installed controllers $B \subset A$.
2. $d_{i,j}$ is a distance between nodes $a_i, a_j \in A$ (here the distance is considered as a shortest path between the nodes).

3. $x_{i,\xi}$ is a binary variable: $x_{i,\xi} = 1$ if the node (switch) $a_i \in A$ is mapped (connected) to controller $b_\xi \in B$ and $x_{i,\xi} = 0$ otherwise.
4. $y_{i,\xi}$ is a binary variable: $y_{i,\xi} = 1$ if controller $b_\xi \in B$ is located at node $a_i \in A$ and $y_{i,\xi} = 0$ otherwise.
5. τ_{cs} is 'controller-switch' latency.
6. τ_{cc} is 'controller-controller' latency (or 'inter-controller' latency).
7. η_{cc} is the number of possible links between controllers, the number is $k(k-1)/2$.

4.4. Two basic formulations of controller placement problem

The basic controller placement problem was proposed in [118]. The joint latency optimization controller placement problem was described in [263]: In the problem the basic assumption is:

'The controller is collocated with a switch and each switch is managed by a single controller'.

Here (joint placement optimization) the goal is to find an optimal trade-off between (i.e., two objectives): (a) switch-controller latency τ_{cs} , and (b) inter-controller latency τ_{cc} . In [263] the objective functions are integrated with special weights/coefficients λ and $(1-\lambda)$ ($\lambda \in [0, 1]$):

$$\min (\lambda \tau_{cs} + (1 - \lambda) \tau_{cc}). \quad (1)$$

The following objectives are under consideration:

1. The latency between controllers and switches:

1.1. Average case latency scenario. The average latency between controllers and their assigned switches:

$$\tau_{cs}^a = (\sum_{a_i \in A, b_\xi \in B} d_{i,\xi} x_{i,\xi}) / (n - k) \quad (2)$$

The corresponding model is the minimum k -means problem.

1.2. Worst case latency scenario. The objective is to minimize the maximum latency between controllers and their assigned switches:

$$\tau_{cs}^w = \max_{b_\xi \in B} (d_{i,\xi} x_{i,\xi}) \quad a_i \in A, \quad b_\xi \in B \quad (3)$$

2. Inter-controller communication latency:

2.1. Average case latency scenario. The average inter-controller latency is minimized. The number of possible path among controllers is: $\eta_{cc} = k(k-1) / 2$. Here the average latency is:

$$\tau_{cc}^a = (\sum_{a_i \in A, b_\xi \in B} d_{i,\xi} x_{i,i} y_{\xi,\xi}) / \eta_{cc} \quad (4)$$

2.2. Worst case latency scenario. Here the longest distance between controllers is taken into account. The optimization problem is to minimize the maximum latency among controllers. The objective function is:

$$\tau_{cc}^w = \max_{b_\xi \in B} (d_{i,\xi} x_{i,\xi} y_{\xi,\xi}) \quad a_i \in A, \quad b_\xi \in B \quad (5)$$

In the models the following constraints are used as well:

$$\sum_{b_\xi \in B} = 1, \quad \forall a_i \in A \quad (6)$$

$$\sum_{a_i \in A} = 1, \quad \forall b_\xi \in B \quad (7)$$

$$y_{i,\xi} \leq x_{i,\xi}, \quad \forall a_i \in A, \quad \forall b_\xi \in B \quad (8)$$

$$x_{i,\xi}, y_{i,\xi} \in \{0, 1\} \quad i = \overline{1, n}, \quad \xi = \overline{1, k} \quad (9)$$

Here the above-mentioned constraints are used for the following:

- (a) constraint (6): every switch is assigned to exactly one controller;
- (b) constraint (7): each controller is located onto exactly one switch;
- (c) constraint (8): each switch a_i is mapped to controller b_ξ if controller b_ξ is placed at switch a_i ;
- (d) constraint (9): decision variables are binary (equal to 0 or 1).

Finally the following objective functions are examined in basic optimization models:

Problem 1. The basic controller placement problem (minimization of latency between switches and controllers; average case latency scenario) [118]:

$$\min \tau_{cs}^a. \quad (10)$$

Problem 2. The basic controller placement problem (minimization of latency between switches and controllers; worst case latency scenario) [118]:

$$\min \tau_{ts}^w. \quad (11)$$

Problem 3. Joint optimization of latency between switches and controllers and inter-controller latency - between controllers (for average case latency scenario) [263]:

$$\min (\lambda \tau_{cs}^a + (1 - \lambda) \tau_{cc}^a). \quad (12)$$

Problem 4. Joint optimization of latency between switches and controllers and inter-controller latency - between controllers (for worst case latency scenario) [263]:

$$\min (\lambda \tau_{cs}^w + (1 - \lambda) \tau_{cc}^w). \quad (13)$$

4.5. Two evident bi-criteria models

The evident bi-criteria optimization controller placement problems are as follows:

Problem 5. Two-criteria (vector) joint optimization of latency between switches and controllers and inter-controller latency - between controllers (for average case latency scenario):

$$(\min \tau_{cs}^a, \min \tau_{cc}^a). \quad (14)$$

Problem 6. Two-criteria (vector) joint optimization of latency between switches and controllers and inter-controller latency - between controllers (for worst case latency scenario):

$$(\min \tau_{cs}^w, \min \tau_{cc}^w). \quad (15)$$

4.6. On multi-criteria models

Evidently, the examination of multi-criteria (multi-objective) controller placement models is a vital contemporary research direction. Here the considered optimization models can be extended by the combination of the described criteria/requirements.

5. Some simple support solving strategies

There is an initial graph $A = (A, E)$ (A is a set of vertices, E is a set of edges). The problem consists in selection of a vertex subset $A' \subseteq A$ to locate the controller points. On the other hand, the problem is close to cluster head selection problem (Fig. 11). It is possible to consider the clustering (balanced clustering) of the initial network and assignment for obtained clusters the controller points (as an analogue of cluster heads). Clearly, an additional structure (e.g., hierarchical structure) over the controller points can be design as well.

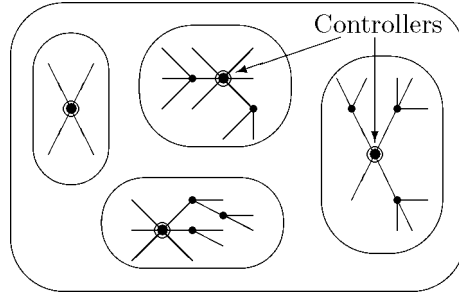


Fig. 11. Placement of controller points

The following simple support solving strategies can be listed:

Strategy 1. Basic placement (generation and selection) of controller points:

Step 1.1. Generation of controller points candidates $B \subseteq A$.

Step 1.2. Selection of the controller points $A' \subseteq B$ while taking into account attributes of the selected controller points and connections of the points to all other vertices $B = A \setminus A'$.

Strategy 2. Clustering-based strategy for placement of controller points (clustering and assignment/selection) (e.g., on the basis of k -means-based clustering approach [331]):

Step 2.1. Balanced clustering the initial graph to obtain clustering solution S (i.e., covering the graph G).

Step 2.2. Assignment/selection of the controller point for each cluster.

Strategy 3. Spanning tree (tree-like structure) based strategy for placement (location) of controller points:

Step 3.1. Designing the minimum spanning tree (or tree-like structure) T for the initial graph G .

Step 3.2. Balanced clustering the obtained T to obtain the clustering solution S^t .

Step 3.3. Assignment/selection of the controller point for each cluster.

Strategy 4. Combined degree-based with independent dominating set approach for controller placement problem (in SDN). Here a node degree-based algorithm named High Degree with Independent Dominating Set (HDIDS) for the controller placement problem is proposed [23]:

Step 4.1. Determining candidate controller instances by selecting those nodes with highest node degree.

Step 4.2. Partitioning the network into multiple domains, one controller per domain, exploiting the independent dominating set approach to ensure a distribution of controllers with lowest response times.

6. Some studies on clustering based controllers placement

Some studies of clustering based controllers placement are listed in Table 6.

Table 6. Some studies of clustering based controller placement

No.	Study	Support clustering scheme	Source(s)
1.	Controller placement in SDNs	Partitioning the network to maximize end-to-end latency between controllers and their associated switches	[331,332,335]
2.	Controller placement problem in large-scale SDNs	Density cluster based approach	[196]
3.	Framework for reliable controller placement in SDNs	Multicriteria clustering approach	[144]
4.	Multiobjective controller placement	Multicriteria network clustering (AHP)	[22]
5.	Controller placement in SDNs	Hierarchical k -means clustering	[173]
6.	Controller placement in SDNs	Spectral clustering	[209]
7.	Controller placement in SDNs	Fuzzy k -means clustering	[319]
8.	Distributed controller placement in SDN	Cluster leader election	[137]
9.	Controller placement based on cooperative games (for SDNs)	Network partitioning	[160]

7. Conclusion

This paper focuses on a systematic structured survey on controller placement problem in communication networks. Concurrently, an integrated glance to control/management issues in networks is presented as well. A general research effort is targeted to the usage of composite solving schemes based on combinatorial optimization models (i.e., clustering, k -center models, assignment/location, covering, domination/independent sets, knapsack problem, covering, multicriteria ranking -sorting). Two basic controller placement problem formulations are described. A special preliminary section contains a structured description for basic requirements and objectives which are used in controller placement problems. Some simplified support heuristic strategies are briefly described.

It may be reasonable to consider the following future research directions:

- (1) examination of other problem statements for controller placement problem (including problems under uncertainty);
- (2) an extended study of various solving schemes/frameworks for controller placement problem;
- (3) description and analysis of computing experiments for solving the controller placement problem in various modes (i.e., statical modes, dynamic/online mode);
- (4) consideration of placement problems in other networks (e.g., in electricity systems); and
- (5) using the controller placement problem in engineering and IT educational courses and projects.

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Author work address: Mark Sh. Levin, Kharkevich Inst. for Information Transmission Problem, Russian Academy of Sciences, 19 Bolshoy Karetny lane, Moscow 127051, Russia

Author home address: Mark Sh. Levin, Sumskey Proezd 5-1-103, Moscow 117208, Russia
<http://www.mslevin.iitp.ru/> email: mslevin@acm.org