Towards combinatorial framework for composite 5G communication challenge system

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1 author:

Mark Sh. Levin
Russian Academy of Sciences

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Mark Sh. Levin

The paper addresses analysis and composition of 5G communication technology challenges and key enabling technologies for 5G. First, a literature survey on the 5G challenges is presented. Second, aggregation/hierarchical forecasting schemes are briefly described. Third, a general hierarchical structure over 5G communication challenges is examined. The structure is a basis to design a hierarchical composite 5G challenge system. Fourth, a design example for the composite 5G challenge system based on optimization approaches (e.g., location, allocation, placement, scheduling, convex optimization, mixed integer programming) is consider. This example is based on hierarchical morphological design method. The suggested material (i.e., framework/approach) may be used as a prototype for various applied domains and may be very prospective in engineering/CS education.

Keywords: communication, 5G generation, technological challenges, optimization, combinatorial optimization, forecasting, morphological design

Contents

1. Introduction

1.1. Preliminaries

Table 1 contains a list of some recent survey publications on 5G challenges/key technologies and related system issues. This paper focuses on combinatorial framework/approach for the analysis and composition of 5G communication technology improvement activities based on optimization.

A literature survey on the 5G challenges is presented. In addition, aggregation/hierarchical forecasting schemes are briefly described. In the paper, combinatorial framework for improvement/forecasting of modular systems is proposed as follows:

(1) hierarchical (tree-like) model of the examined system (here: 5G communication technology challenges system);

(2) assessment of improvement actions as 5G challenges/key enabling technologies; and

(3) evaluation and selection of 5G improvement actions (i.e., challenges/key enabling technologies) and composition of the prospective actions above into the composite 5G improvement system (i.e., hierarchical morphological design 'bottom-up').

The considered example of composite 5G challenge system is based on the usage of optimization approaches (e.g., location, allocation, placement, scheduling, convex optimization, mixed integer programming). Hierarchical morphological design method is used in the example.

Fig. 1 illustrates the scheme of the research. The scheme components are based on heuristic (engineering) methods.

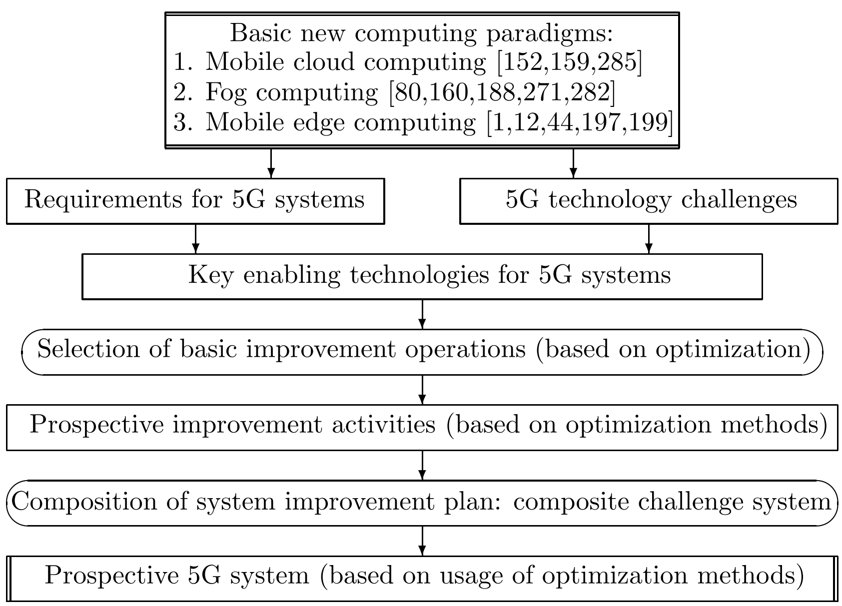

Fig. 1. General scheme of selection and composition of 5G improvement

1.2. Evolution of communication technologies

It is reasonable to point out, that evolution of communication systems generations (engineering descriptions, modeling) has been considered as a prospective topic for research, for example [103]: 1G (Voice Service), 2G (Voice + Text messages), 3G (Integrated Mobile and Internet), 4G (High Capacity Multimedia), 5G (Wireless World Wide Web). A list of some recent studies in evolution of communication systems is contained in Table 2.

2. Technology challenges

Table 3 contains four lists of challenges for 5G technology and CloudIoT which have been pointed out in basic recent literature sources.

Table 1. Recent survey publications on 5G systems (challenges/key technologies, related issues)

No.	Research	Sources
I.	Surveys and paradigms:	
1.1.	5G Internet of Things (surveys)	[178,225]
1.2.	5G mobile communication technology (surveys)	[210,304]
1.3.	Surveys on device-to-device (D2D) communication	[27,104]
1.4.	Cloud computing (surveys: architecture, mobile computing, etc.)	[94,152,159]
		[202,285]
1.5.	Survey on mobile edge computing	[1,12,199]
1.6.	Fog computing	[188,271]
1.7.	Software-defined networking paradigms in wireless networks (surveys)	[136,156]
1.8.	UltraDense networks (new wireless frontier for enabling 5G access)	[114]
1.9.	Next generation 5G wireless networks (comprehensive survey)	[8]
1.10.	5G channel measurements and models (survey)	[21,293]
1.11.	Wireless communication paradigm through software-controlled metasurfaces	[183,184]
II.	Architecture issues:	
2.1.	Survey of 5G networks: architecture and emerging technologies	[118]
2.2.	5G radio access network architecture	[201]
2.3.	Centralized network architecture for 5G mobile communication systems	[237]
2.4.	Big data network architecture and monitoring use wireless 5G technology	[143]
2.5.	Architecture for Fog computing	[188]
2.6.	Wireless heterogeneous networks (e.g., for mobile cloud computing)	[57,163]
2.7.	D2D–based heterogeneous radio access network architecture	[139]
	(for mobile cloud computing)	
2.8.	Ultra-dense network (UDN) architecture and technologies for 5G	[61]
2.9.	Architecture for software defined wireless networking	[46]
2.10.	SDN/NFV-based mobile packet core network architecture (survey)	[222]
III.	Challenges and key technologies:	
3.1.	10 key enabling technologies for 5G	[17]
3.2.	5G cellular: key enabling technologies and research challenges	[129]
3.3.	Key challenges for the radio-access network (5G on the horizon)	[82]
3.4.	Challenges in 5G (how to empower SON with big data for enabling 5G)	[135]
3.5.	Emerging technologies and research challenges for 5G wireless networks	[64]
3.6.	Basic list of challenges for 5G systems	[227]
3.7.	Key technologies for 5G wireless communication networks	[283]
3.8.	Challenges from the viewpoint of integration of IoT and cloud computing	[51]
	(CloudIoT)	
3.9.	Novel radio technology for 5G (e.g., multiple access)	[213]
3.10.	D2D communication in 5G cellular networks	[273]
	(challenges and future directions)	
3.11.	Network virtualization: research challenges	[67]
3.12.	Dense moving fog for intelligent IoT (key challenges and opportunities)	[26]
3.13.	Five disruptive technology directions for 5G	[50]
IV.	Special system issues (including optimization, AI approaches) :	
4.1.	Integration approach: IoT, cloud computing, Fog computing, big data, etc.	[48,83]
4.2.	Regulatory, standardization and industrial perspectives (survey of 5G technologies)	[213]
4.3.	Network function virtualization (management and orchestration, research challenges)	[121,203,204]
4.4.	Dynamic resource and task allocation (energy minimization in mobile cloud systems)	[159]
4.5.	Enabling intelligence in fog computing (to achieve energy and latency reduction)	[160]
4.6.	AI methods for traffic management in 5G wireless networks	[99]
4.7.	Traffic optimization for IoT	[98]
4.8.	Intelligent network optimization in wireless networking	[323]
4.9.	Network planning with robust optimization	[41]
4.10.	Cost optimal design for 5G mobile core network based on SDN and NFV	[38]
4.11.	Controller placement problem in software defined networking (survey)	[291]
4.12.	AI for 5G: research directions and paradigms	[315]
4.13.	Dual connectivity support in 5G networks (SDN based approach)	[267]

Table 2. Some researches in evolution of communication systems generations

No.	Research	Sources
I.	Engineering descriptions of system generations and evolution:	
1.1.	Evolution of mobile wireless communication networks (1G, 2G, 3G, 4G, 5G)	[254]
1.2.	Evolution of technology generations (1G, 2G, 3G, 4G, 5G)	[103,258]
1.3.	Evolution of wireless technologies (1G, 2G, 2.5G, 3G, 3.5G, 4G, 5G) (architecture and emerging technologies)	[118]
1.4.	Historical evolution (architecture issues)	[257]
1.5.	Evolution path of 4G networks	[54]
1.6.	Evolution of power trends in 5G networks (1G, 2G, 3G, 4G, 5G)	[3]
1.7.	Evolution and challenges of DNS-based CDNs	[294]
1.8.	Evolving privacy: from sensors to IoT	[192]
1.9.	Evolution toward 5G multi-tier cellular wireless networks (interference management perspective)	[128]
1.10.	Radio network evolution	[8]
1.11.	Evolution of LTE technology	[225]
1.12.	Evolution of HetNet architecture	[33]
II.	Combinatorial modeling of modular system generations and their evolution:	
2.1.	Combinatorial evolution of communication system generations	[168,170]
2.2.	Combinatorial evolution of requirements to communications systems (example)	[169]
2.3.	Combinatorial evolution of communication protocol ZigBee	[167,172]
2.4.	Combinatorial evolution of standard for multimedia information (MPEG, MPEG-2, MPEG-4)	[171]

Table 3. Basic challenges for 5G technology and CloudIoT

No.	Research	Sources
I.	5G total technology challenges:	
1.1.	Mobile computing for 5G (from clouds to edges)	[197,199]
1.2.	Challenges on wireless heterogeneous networks for mobile cloud computing	[163]
1.3.	Content caching techniques for 5G systems	[39,284]
1.4.	Mobile edge computing, fog et al.	[242]
1.5.	Opportunities and challenges of software-defined mobile networks in network security	[190]
1.6.	Mobile cloud computing applications: perspectives and challenges	[285]
1.7.	Mobile edge computing: challenges for future virtual network embedding algorithms	[44]
1.8.	Research opportunities (Fog and IoT)	[62]
1.9.	Interference management for D2D communication and its challenges in 5G networks	[224]
1.10.	Usage of intelligent techniques (data analytics, machine learning, optimization, multi-agent learning, etc.)	[160]
II.	Basic list of challenges for 5G systems: (1) data rates and network capacity expansion with energy optimization; scalability and flexibility (HetNets); (3) single channel for both UL and DL (duplex channel); (4) handling interference (HetNets, CRNs, full duplex, D2D communication); (5) environmentally friendly Cloud-RAN (C-RAN), visual light communication (VLC), mmWave, separation of indoor and outdoor users, D2D communication, mMIMO architecture, full duplex radio; (6) low latency and high reliability (caching methods, VLC, mmWave, mMIMO,fast handover techniques, D2D communication); (7) network performance optimization; (8) economic impacts; (9) high mobility and handoff solutions (e.g., inter-tier, intra-tier and multi-RATs handoff mechanisms and mechanism for secure handoff); (10) Self-healing infrastructures; (11) QoS; (12) Security and privacy of the network and UEs	[227]
III.	Challenges from the viewpoint of integration of IoT and cloud computing (CloudIoT): (1) security and privacy; (2) heterogeneity; (3) performance; (4) reliability; (5) large scale; (6) legal and social aspects; (7) big data analytics; (8) sensor networks; (9) monitoring; (10) Fog computing.	[51]
IV.	Key enabling technologies in 5G-IoT: (1) 5G and IoT architecture: data plane, control plane; (2) wireless network function virtualization; (3) heterogeneous networks (4) direct D2D; (5) advanced spectrum sharing and interference management; millimeter Wave (mmWave); (7) mobile edge computing; (8) narrowband IoT; (9) optimization and AI methods (optimization, machine learning, artificial NNs).	[178]

2.1. Resources, requirements and criteria

It may be reasonable to point out some basic resources in contemporary communication systems, for example: (a) time, (b) energy, (c) spectrum , and (d) cost. Evidently, the usage (sharing) of the resources can be improved by the optimization approaches. The list of the corresponding engineering design/management problems involves the following: (1) sharing/location/allocation (e.g., devices, channels, frequency, energy), (2) caching, (3) configuration/reconfiguration (e.g., network topology), (4) adaptation (e.g., utilization modes), and (5) selection of the best modes/components/subsystems: selection of radio access technology, network node(s) (relay node(s), devices, channel, basic station, cloud, data center, access network, handoff/handover strategies, etc.

An evolution process of requirements for communication systems has been examined in [169]. The list of key requirements for 5G communication technology has been described in [17,75]: (1) high data rates, (2) low latency, (3) low energy consumption, (4) high stability, (5) improved connectivity and reliability, and (6) improved security. The main network quality criteria (criteria or objective functions, e.g., for optimization) are the following [283]: (i) peak data rate, (ii) geographical area coverage, (iii) spectral efficiency, (iv) QoS, (v) QoE, (vi) easy of connectivity, (vii) energy-efficiency, (viii) latency, (ix) reliability, (x) fairness of users, and (xi) implementation complexity, (xii) system lifetime (maximization).

2.2. Key enabling technologies for 5G

The list of key enabling technologies for 5G has been suggested and described in [17].

An integrated and extended list of key enabling technologies for 5G is presented (Table 4). Here, a special attention is targeted to the usage of optimization approaches.

Table 4. Key enabling technologies for 5G, part 1

No.	Enabling technology	Sources
1.	Internet of Things (IoT):	
1.1.	Surveys and general papers:	
1.1.1.	Internet of Things (IoT) (architecture, future directions, evolution)	[19,31,117,208,240]
1.1.2.	IoT and cloud computing (survey, principles)	[51,278]
1.1.3.	Integration of cloud computing and IoT - CloudIoT (surveys, challenges, open issues, IoT cloud platforms)	[51,83,240]
1.1.4.	Context aware computing for the Internet of Things (survey)	[234]
1.1.5.	Internet of Things resource management (survey)	[69]
1.1.6.	Big data analytics in IoT	[11,239,252]
1.1.7.	Key enabling technologies in 5G-IoT	[178]
1.1.8.	AI for 5G (research directions and paradigms)	[315]
1.2.	Usage of optimization approaches:	
1.2.1.	IoT-Cloud service optimization in next generation smart environments	[35]
1.2.2.	Optimization approach for adaptive monitoring in IoT environments	[272]
1.2.3.	Optimization of non-functional properties in Internet of Things applications	[221]
1.2.4.	Adaptive MCS selection and resource planning for energy-efficient communication in IoT sensing platform	[77]
1.2.5.	Graph based M2M optimization in an IoT environment	[229]
1.2.6.	Content centric networking (CNN) traffic optimization for IoT	[98]
1.2.7.	Relay selection for inter-cell interference avoidance in 5G HetNets for IoT	[79]
1.2.8.	Task allocation in IoT (evolutionary approach, consensus based approach, etc.)	[72,150]
1.2.9.	Maximum throughput and optimal power allocation in wireless powered sensor networks for IoT	[70]

Table 4. Key enabling technologies for 5G, part 2

No.	Enabling technology	Sources
2.	Device-To-Device (D2D) Communications:	
2.1.	General issues (surveys, architecture, challenges, future directions, etc.):	
2.1.1.	D2D-based heterogeneous radio access network architecture for mobile cloud computing	[139]
2.1.2.	Machine-type communications (future perspectives toward 5G systems)	[253]
2.1.3.	D2D communication in 5G cellular networks (survey, challenges, future directions)	[27,146,273]
2.1.4.	D2D communication in cellular networks (survey)	[103]
2.1.5.	Interference management for D2D communication and its challenges in 5G networks (survey)	[224]
2.1.6.	D2D communication (architecture and security issues) (survey)	[104]
2.1.7.	Design aspects of the network assisted D2D communications	[97]
2.2.	Special issues:	
2.2.1.	Device-to-device communication as an underlay to LTE-advanced networks	[88]
2.2.2.	Software defined D2D communications in virtual wireless networks	[53]
2.2.3.	D2D communication in smart cities	[176]
2.2.4.	Reciprocal-selection-based 'Win-Win' overlay spectrum-sharing scheme for D2D-enabled cellular network	[177]
2.3.	Usage of optimization approaches:	
2.3.1.	Resource management in D2D communication (optimization perspective)	[10]
2.3.2.	Resource allocation algorithms for D2D communication	[103,116]
2.3.3.	Sector-based radio resource allocation in D2D communication	[105]
2.3.4.	Interference and throughput aware resource allocation for multi-class D2D (5G networks)	[93]
2.3.5.	Energy efficient power allocation for underlaying mobile D2D communications	[322]
2.3.6.	Joint mode selection and resource allocation for D2D communications	[317]
2.3.7.	Resource sharing optimization for D2D communication underlaying cellular networks	[316]
2.3.8.	Uplink resource allocation/power allocation for D2D (multi-cell mobile networks)	[91]
2.3.9.	Optimal QoS-aware channel assignment for D2D communications	[288,289]
2.3.10.	Resource allocation (e.g., channel assignment) in D2D communication (game theory)	[147,173]
2.3.11.	resource allocation for D2D communications (multi-armed bandit problem)	[219]
3.	Radio Access Techniques:	
3.1.	General issues:	
3.1.1.	5G radio access network architecture: design guidelines and key considerations	[201]
3.1.2.	State model for 5G radio access networks	[76]
3.1.3.	Fog radio access networks	[271]
3.2.	Access in cloud radio 5G networks:	
3.2.1.	System architecture and key technologies for 5G heterogeneous cloud radio access networks	[230]
3.2.2.	Radio access network evolution in cloud mobile networks	[280]
3.2.3.	Cloud radio access network (C-RAN)	[303]
3.2.4.	Nonorthogonal multiple access in 5G systems:	
3.2.4.1.	Uplink nonorthogonal multiple access in 5G systems	[321]
3.2.4.2.	Non-orthogonal random access for 5G networks	[181]
3.2.4.3.	Uplink and downlink non-orthogonal multiple access (NOMA) systems (dynamic user clustering and power allocation)	[20]
3.3.	Virtual RATs and a flexible and tailored radio access network evolving to 5G	[59]
3.4.	Flexible 5G radio access networks (cloud technologies)	[243]
3.5.	Usage of optimization approaches:	
3.5.1.	Dynamic user clustering and power allocation (non-orthogonal multiple access (NOMA) systems)	[20]
3.5.2.	Energy efficient maximized resource allocation for opportunistic relay-aided OFDMA	[292]
3.5.3.	Use of self-organizing networks to optimize radio access networks	[266]
3.5.4.	Joint resource allocation for parallel multi-radio access in wireless HetNets	[65]
3.5.5.	Serviceability maximization in Fog radio access networks (adaptive resource balancing)	[78]
3.5.6.	Virtualized radio access networks: centralization allocation and positioning of resources	[261]

Table 4. Key enabling technologies for 5G, part 3

No.	Enabling technology	Sources
4.	Wireless Software Defined Networking (W-SDN):	
4.1.	General issues:	
4.1.1.	SoftAir: A software defined networking architecture for 5G wireless systems	[15]
4.1.2.	Wireless software-defined networks (W-SDNs) and network function virtualization (NFV) for 5G cellular systems	[16]
4.1.3.	Software-defined networking (comprehensive survey)	[156]
4.1.4.	Mobile SDNs (surveys)	[182,233]
4.1.5.	Opportunities and challenges of software-defined mobile networks in network security	[190]
4.1.6.	Energy efficient topology management in software defined wireless sensor network (SD-WSN)	[84]
4.1.7.	Adaptive resource management and control in SDNs	[279]
4.1.8.	SDN/NFV-based mobile packet core network architecture (survey)	[222]
4.2.	Usage of optimization approaches:	
4.2.1.	Cost optimal design for 5G mobile core network based on SDN and NFV	[38]
4.2.2.	Placement of controllers in SDNs	[2,130,157,291]
4.2.3.	Multiple spectra allocation based on wireless SDNs	[290]
4.2.4.	Routes replacement in SDN	[86]
5.	Network Function Virtualization:	[16]
5.1.	General issues:	
5.1.1.	Surveys of network virtualization	[68,180]
5.1.2.	Network function virtualization (challenges and opportunities for innovation)	[121]
5.1.3.	Network function virtualization (state-of-the art and research challenges)	[203]
5.1.4.	Management and orchestration challenges in network functions virtualization	[204]
5.1.5.	Wireless software-defined networks (W-SDNs) and network function virtualization (NFV) for 5G cellular systems	[16]
5.1.6.	Network Function Virtualization networking	[194]
5.1.7.	5G wireless network virtualization: architecture and trial environment	[92]
5.1.8.	Mobile virtual private networks (VPN) technologies (survey)	[23]
5.1.9.	SDN/NFV-based mobile packet core network architecture (survey)	[222]
5.2.	Usage of optimization approaches:	
5.2.1.	Cost optimal design for 5G mobile core network based on SDN and NFV	[38]
5.2.2.	Resource allocation in network function virtualization	[287]
5.2.3.	Functions placement problem (applying NFV and SDN to LTE mobile core gateways)	[37]
5.2.4.	Joint VNF placement and resource allocation in 5G (including vertical services)	[6,7]
5.2.5.	Deploying chains of virtual network functions	[158]
5.2.6.	Delay-aware VNF placement and chaining based on flexible resource allocation approach	[22]
5.2.7.	Resource allocation in NFV (comprehensive survey)	[125]
5.2.8.	Placement of virtual mobile functions over cloud infrastructure	[87]
5.2.9.	Optimal placement of virtualized cellular network functions	[262]
5.2.10.	User mobility-aware virtual network function placement for virtual 5G network infrastructure	[268]
5.2.11.	Combined virtual core network function placement and topology optimization	[42,43]
5.2.12.	Multi-step model for migration and resource reallocation in virtialized network infrastructure	[149]

Table 4. Key enabling technologies for 5G, part 4

No.	Enabling technology	Sources
6.	Big Data & Mobile Cloud Computing:	
6.1.	Surveys, general papers::	
6.1.1.	Mobile cloud computing (survey)	[94]
6.1.2.	Communicating while computing: distributed mobile cloud computing over 5G heterogeneous networks	[34]
6.1.3.	Challenges in 5G: how to empower SON with big data for enabling 5G	[135]
6.1.4.	Big data network architecture and monitoring use wireless 5G technology	[143]
6.1.5.	Mobile cloud computing application models (survey)	[152]
6.1.6.	Cloud assisted HetNets toward 5G wireless networks	[320]
6.1.7.	Radio access network evolution in cloud mobile networks	[280]
6.1.8.	Wireless heterogeneous networks for mobile cloud computing	[163]
6.1.9.	Energy-efficient fault tolerant data storage and processing in mobile cloud	[58]
6.1.10.	Dynamic energy-aware cloudlet-based mobile cloud computing model for green computing	[100]
6.2.	Usage of optimization approaches:	
6.2.1.	DREAM: Dynamic resource and task allocation for energy minimization in mobile cloud systems	[159]
6.2.2.	Inter-layer per-mobile optimization of cloud mobile computing: (message-passing approach)	[151]
6.2.3.	Joint optimization of radio and computational resources for multicell mobile cloud computing	[250]
6.2.4.	Energy-aware task assignment for mobile cyber-enabled applications in heterogeneous cloud computing	[101]
6.2.5.	Secure optimization in cloud computing (optimization)	[286]
6.2.6.	Cooperative resource management in mobile cloud computing	[144,318]
6.2.7.	Service placement and load dispatching in mobile cloud systems	[310]
6.2.8.	Optimization using swarm intelligence and dynamic graph partitioning in IoE infrastructure: Fog computing and cloud computing (optimization: (i) connection issues as time delay, network congestion, (ii) bandwidth, (iii) capabilities)	[217]
6.2.9.	Resource allocation for efficient management of data centers for cloud computing	[45]
6.2.10.	Optimal allocation of virtual resources in cloud computing networks	[228]
7.	Mobile edge computing:	
7.1.	Surveys, general papers:	
7.1.1.	Mobile edge computing (survey, analysis, challenges)	[242]
7.1.2.	Collaborative mobile edge computing in 5G networks (new paradigms, scenarios, and challenges)	[277]
7.1.3.	Mobile edge computing (MEC) (communication perspective)	[199]
7.1.4.	Mobile edge computing (survey and research outlook)	[1,197]
7.1.5.	Dynamic computation offloading for mobile-edge computing with energy harvesting devices	[196]
7.1.6.	Promise of edge computing	[255]
7.1.7.	Mobile-edge computing in smart homes	[281]
7.1.8.	Mobile-edge computing architecture (the role of MEC in the IoT)	[246]
7.1.9.	Edge computing aware NOMA for 5G networks	[154]
7.2.	Usage of optimization approaches:	
7.2.1.	Joint optimization of radio and computational resources for multicell mobile-edge computing	[214]
7.2.2.	Hierarchical mobile edge computing (auction-based profit maximization approach)	[153]
7.2.3.	Joint task offloading scheduling and transmit power allocation for mobile-edge computing systems (flow shop scheduling, convex optimization)	[198]
7.2.4.	Delay-optimal computation task scheduling for mobile-edge computing systems	[186]
7.2.5.	Task offloading, load balancing, resource allocation in mobile edge computing enabled IoT networks	[179]

Table 4. Key enabling technologies for 5G, part 5

No.	Enabling technology	Sources
8.	Green Communications:	
8.1.	General issues (principles, architecture, etc.:	
8.1.1.	Green Communications. Principles, Concepts and Practice	[247]
8.1.2.	Energy efficient 5G green network with planned multi-tier architecture	[258]
8.1.3.	Green data centers	[138]
8.1.4.	Green cloudlet network (distributed green mobile cloud network)	[265]
8.1.5.	Dynamic energy-aware cloudlet-based mobile cloud computing model for green computing	[100]
8.2.	Usage of optimization approaches:	
8.2.1.	Optimization of green energy utilization for cellular networks (hybrid energy supplies)	[120]
8.2.2.	Energy-efficient mobile network design and planning (optimization of cell size, optimization of cell parameters)	[236]
8.2.3.	Energy-efficient mobile network design and planning (adaptive strategies to change the network layout, re-location)	[236]
8.2.4.	Optimal stopping problem (delay-tolerant cognitive cellular networks)	[325]
8.2.5.	Green routing/switching	[63]
8.2.6.	Optimization routing algorithm for green communication in underground mines	[307]
8.2.7.	Dynamic resource provisioning for energy efficiency in wireless access networks (cluster-based approaches, etc)	[52]
8.2.8.	Resource allocation for green cognitive radios (energy efficiency maximization)	[312]
8.2.9.	Power Optimization in 5G networks (green communication)	[3]
8.2.10.	Joint power allocation&relay selection strategy for 5G network (green communication)	[4,110]
9.	Massive MIMO:	
9.1.	Surveys, general papers:	
9.1.1.	Massive MIMO for next generation wireless systems	[162]
9.1.2.	Overview of massive MIMO: benefits and challenges	[193]
9.1.3.	MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing	[263]
9.1.4.	MIMO techniques in WiMAX and LTE (feature overview)	[174]
9.1.5.	Realizing ultra-massive MIMO communication in the (0.06-10) terahertz band	[18]
9.1.6.	Full-dimension MIMO (FD-MIMO) for next generation cellular technology	[216]
9.1.7.	Spatial domain management and massive MIMO coordination in 5G SDN	[264]
9.1.8.	Multiuser MIMO HetNets	[175]
9.1.9.	Pilot power allocation through user grouping in multi-cell massive MIMO systems	[187]
9.1.10.	Multipath multihop mmWave backhaul in ultra-dense small-cell network	[245]
9.2.	Usage of optimization approaches:	
9.2.1.	Global energy efficiency (EE) optimization of massive MIMO systems	[185]
9.2.2.	Global energy efficiency optimization for wireless-powered massive MIMO aided multiway AF relay networks	[270]
9.2.3.	Optimal design of energy-efficient multi-user MIMO systems	[49]
9.2.4.	Energy efficient power allocation massive MIMO:	
9.2.4.1.	Energy efficient power allocation algorithm for downlink massive MIMO	[324]
9.2.4.2.	Power allocation optimization for energy efficient massive MIMO aided multi-pair decode-and-forward relay systems	[269]
9.2.4.3.	Energy-efficient power control algorithms in massive MIMO cognitive radio networks (maximum network energy efficiency (EE), nonlinear differentiable fractional programming problem)	[74]
9.2.5.	Energy-efficient resource allocation in ultra-dense networks with massive MIMO	[311]
9.2.6.	Energy-efficient resource allocation for wireless powered massive MIMO system with imperfect channel estimation (CSI) (optimal power and time allocation, nonlinear fractional programming)	[55]
9.2.7.	Throughput optimization for massive MIMO systems powered by wireless energy transfer	[308]
9.2.8.	Cell coverage optimization for the multicell massive MIMO uplink	[137]
9.2.9.	Power optimization using massive MIMO and small cells approach in different deployment scenarios	[119]
9.2.10.	Sum rate maximization in massive MIMO two-way relay networks	[148,215]

Table 4. Key enabling technologies for 5G, part 6

No.	Enabling technology	Sources
10.	Ultra-Densification (Ultra-dense networks UDNs):	
10.1.	General issues (surveys, architecture, challenges, future directions, etc.):	
10.1.1.	Network densification: the dominant theme for wireless evolution into 5G	[47]
10.1.2.	UDN architecture and technologies for 5G	[61]
10.1.3.	5G ultra-dense cellular networks	[25,109]
10.1.4.	User-centric UDN for 5G (challenges, methodologies, directions)	[60]
10.1.5.	Survey on UDNs and emerging technologies (security challenges)	[66]
10.1.6.	5G multi-RAT LTE-WiFi ultra-dense small cells (performance dynamics, architecture, trends)	[102]
10.1.7.	Ultra-dense small cell deployments (1 Gbps/UE in cellular systems)	[191]
10.1.8.	Hyper-dense heterogeneous and small cell networks	[131]
10.1.9.	Energy efficient mobility management in dense small cells with mobile edge	[306]
10.1.10.	Content delivery over ultra-dense networks	[326]
10.1.11.	UDNs in millimeter-wave frequencies	[32]
10.1.12.	Ultra-dense multiuser networks	[189]
10.1.13.	Multipath multihop mmWave backhaul in ultra-dense small-cell network	[245]
10.1.14.	UltraDense networks: The new wireless frontier for enabling 5G access	[114]
10.2.	Usage of optimization approaches:	
10.2.1.	Joint optimization of resource management and interference control in UDNs	[60]
10.2.2.	Mobility robustness optimization in intra-frequency 5G ultra dense networks	[274]
10.2.3.	Energy efficiency maximization in dense small cell networks	[312]
10.2.4.	Energy-efficient resource allocation in ultra-dense networks with massive MIMO	[311]
10.2.5.	Cooperative distributed optimization for the hyper-dense small cell deployment	[305]
11.	Millimeter Wave & Terahertz band:	[112,238,263]
11.1.	Surveys, general papers:	
11.1.1.	Millimeter-wave beamforming as enabling technology for 5G cellular communications: theoretical feasibility and prototype results	[241]
11.1.2.	Terahertz band (next frontier for wireless communications)	[13]
11.1.3.	TeraNets (ultra-broadband communication networks in the terahertz band)	[14]
11.1.4.	Multi-ray channel modeling and wideband characterization for wireless communications in the terahertz band	[122]
11.1.5.	Multi-wideband waveform design for distance-adaptive wireless communications in the terahertz band	[123]
11.1.6.	High power terahertz and millimeter-wave oscillator design (systematic approach)	[211]
11.1.7.	UDNs in millimeter-wave frequencies	[32]
11.1.8.	Modulation for terahertz band communication in nanonetworks	[141]
11.1.9.	Energy-harvesting nanonetworks in terahertz band	[314]
11.1.10.	Channel modeling and capacity analysis for wireless nanonetworks in the terahertz band	[140]
11.1.11.	Performance analysis of nanosensor networks at THz frequencies	[5]
11.1.12.	Low-latency HetNets with millimeter-wave communications	[309]
11.1.13.	5G new radio capabilities for directional access at mmWave frequencies	[249]
11.2.	Usage of optimization approaches:	
11.2.1.	Scheduling in dynamic duplex multihop mmWave cellular systems	[106]
11.2.2.	Joint parameter optimization for perpetual nanonetworks and maximum network capacity	[313]
11.2.3.	Alternative minimization for hybrid precoding in millimeter wave MIMO systems	[319]
11.2.4.	QoS-aware full-duplex concurrent scheduling for mmWave wireless backhaul networks	[85]

3. Note on aggregate/hierarchical forecasting

In recent decades, the significance of technological forecasting methods for complex modular systems has been increased. It may be reasonable to point out some basic approaches in this domain. here, a special attention is targeted to aggregate/hierarchical forecasting methods. The following objects of the forecasting processes can be examined: (a) value, (b) value vector, (c) structure or system structure (e.g., chain, tree, graph, morphological structure). It is reasonable to point out basic forecasting approaches/schemes:

Scheme 1. Forecasting of a value (on the basis of value sequence/stream $a(\tau_1)$, $a(\tau_2)$,..., $a(\tau_n)$, the resultant forecast: a^f, Fig. 2).

Scheme 2. Aggregation of initial values a_1, a_2,..., a_n, the resultant aggregated value: a^a, (Fig. 3);

Scheme 3. Two-stage forecasting-aggregation scheme:

(3.1) forecasting of a value on the basis of value sequences/streams: stream 1: $a^1(\tau_1)$, $a^1(\tau_2)$,...,$a^1(\tau_n)$, stream 2: $a^2(\tau_1)$, $a^2(\tau_2)$,...,$a^2(\tau_n)$, ..., stream 1: $a^m(\tau_1)$,$a^m(\tau_2)$,...,$a^m(\tau_n)$; the obtained forecasts for the streams are: a^{1f}, a^{2f},..., a^{mf};

(3.2) aggregation of the obtained forecast-values, the obtained resultant forecast is: a^{fa} (Fig. 4);

Scheme 4. Two-stage aggregation-forecasting scheme:

(4.1) aggregation of the initial streams into the resultant aggregated stream $a^a(\tau_1)$,$a^a(\tau_2)$,...,$a^a(\tau_n)$;

(4.2) forecasting of a value (based on the obtained aggregated value stream), the result: a^{af} (Fig. 5).

Concurrently, close research efforts in aggregate/hierarchical forecasting approaches/research directions are briefly pointed out as well (a brief literature survey and taxonomy, Table 5).

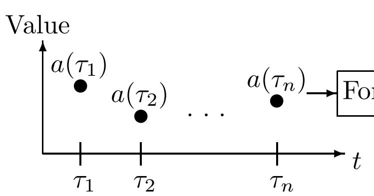

Fig. 2. Basic forecasting scheme

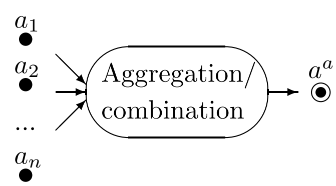

Fig. 3. Simplified aggregation scheme

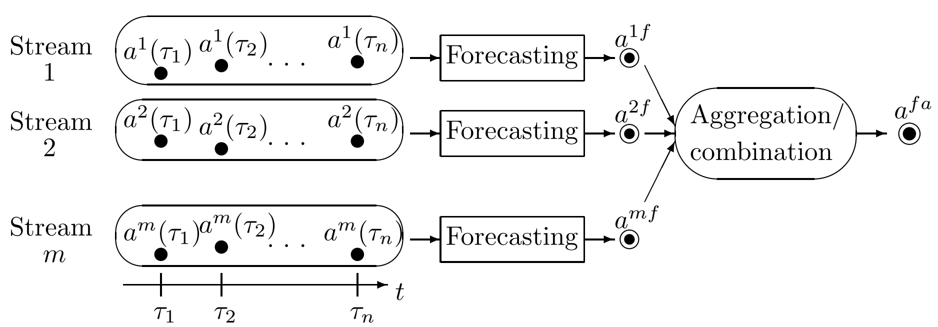

Fig. 4. Two-stage forecasting-aggregation scheme

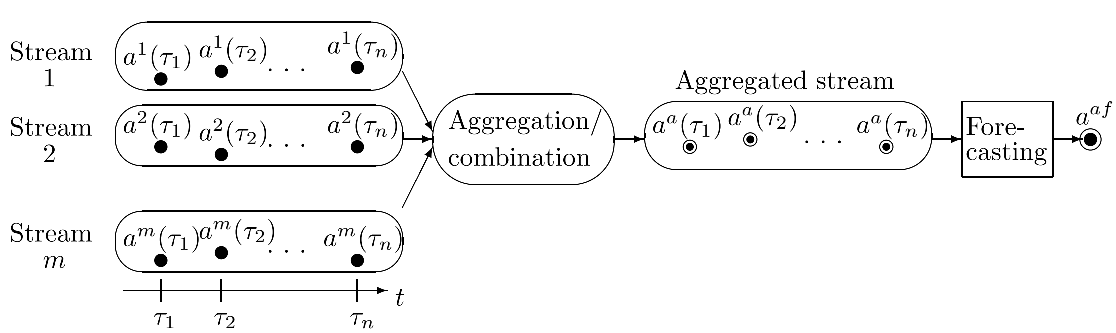

Fig. 5. Two-stage aggregation-forecasting scheme

Table 5. Research directions in aggregate/hierarchical forecasting, part 1

No.	Research direction	Sources
I.	Hierarchical forecasting:	
1.1.	Hierarchical forecasting (issues and use guidelines)	[96]
1.2.	Integrated hierarchical forecasting	[232]
1.3.	Combination of aggregate forecasting with the bottom-up forecasting (stochastic/statistical approach)	[259]
1.4.	Forecasting with temporal hierarchies (for time series forecasting)	[30]
1.5.	Determining an optimal hierarchical forecasting model	[218]
1.6.	Hierarchical forecasts for tourism	[29]
1.7.	Effect of correlation between demands on hierarchical forecasting	[56]
1.8.	Optimally reconciling forecasts in a hierarchy	[133]
1.9.	Top–down versus bottom–up forecasting strategies	[251]
1.10.	Effectiveness of top-down strategy for forecasting autoregressive demands	[299]
1.11.	Analytical evaluation of top–down versus bottom–up forecasting (in production planning framework)	[300]
1.12.	Development of hierarchical forecasting method for predicting spare parts demand	[212]
1.13.	Revisiting top-down versus bottom-up forecasting	[145]
1.14.	Fast computation of reconciled forecasts for hierarchical and grouped time series	[134]
1.15.	Modified top-down approach for hierarchical forecasting in a beverage supply chain (modification of top-down approach)	[209]
II.	Combination of forecasts:	
2.1.	Combing forecasts (reviews, issues, annotated-bibliography)	[71,226,275]
2.2.	Combination of forecasts (basic methods)	[36,40,220]
2.3.	Combining exponential smoothing forecasts using Akaike weights	[155]
2.4.	Optimal forecast combinations:	
2.4.1.	Optimal forecast combinations under general loss functions and forecast error distributions	[89]
2.4.2.	Optimal forecast combination under regime switching	[90]
2.4.3.	Optimal combination forecasts for hierarchical time series	[132]
2.5.	Bayesian and non-Bayesian methods for combining models and forecasts	[207]
2.6.	Forecast combinations for intermittent demand	[235]
2.7.	Sensitivity of weights in combining forecasts	[302]
2.8.	Aggregation, disaggregation and combination of forecasts	[295]
2.9.	Combination of long term and short term forecasts	[24]
2.10.	Combination of forecasts using self-organizing algorithms	[124]
2.11.	Selecting among forecasts and their combinations	[127]
2.12.	Benchmarking approach to forecast combination	[276]
2.13.	Nonstationarity on combined forecasts	[205]
2.14.	Combined forecast-inventory control procedure for spare parts	[126]
III.	Aggegate (disaggregate) forecasting (including consensus forecast):	
3.1.	Aggregation and proration in forecasting	[256]
3.2.	Aggregating subjective forecasts (empirical results)	[28]
3.3.	Aggregatedisaggregate approach to forecasting	[223]
3.4.	Demand forecasting by temporal aggregation	[244]
3.5.	Temporal aggregation on estimates and forecasts of fractionally integrated processes (Monte-Carlo study)	[260]
3.6.	Aggregation, disaggregation and combination of forecasts	[295]
3.7.	Aggregation, disaggregation and forecasting performance	[327]
3.8.	Bayesian consensus forecasts of macroeconomic variables	[9]
3.9.	Averages of forecasts	[142,195]
3.10.	Aggregate variable time series forecast strategies with specific subaggregate time series statistical correlation	[95]

Table 5. Research directions in aggregate/hierarchical forecasting, part 2

No.	Research direction	Sources
IV.	Composite and special methods:	
4.1.	Integrating judgmental forecasts with statistical methods	[113]
4.2.	Combination of aggregate forecasting with the bottom-up forecasting (stochastic/statistical approach)	[259]
4.3.	Optimal forecasting groups	[161]
4.4.	Forecasting hierarchical and grouped time series through trace minimization	[296]
4.5.	Aggregation and combined forecasting to improve seasonal demand forecasts	[81]
4.6.	Disaggregation methods to expedite product line forecasting	[115]

In addition, it is reasonable to point out a list of research in evaluation/comparison/selection of forecast methods (Table 6).

Table 6. Evaluation / comparison / selection of forecast methods

No.	Research	Sources
1.	Evaluating forecast performance in an inventory control system	[107]
2.	Evaluation of forecasting methods for intermittent parts demand in the field of aviation (a predictive model)	[111]
3.	Comparison of alternative forecasting strategies for multi-stage production-inventory systems	[206]
4.	Selecting the best periodic inventory control and demand forecasting methods for low demand items	[248]
5.	Analytical evaluation of top–down versus bottom–up forecasting in a production planning framework	[300]
6.	Effectiveness of top-down strategy for forecasting autoregressive demands	[297]
7.	Evaluation of hierarchical forecasting for substitutable products	[298]
8.	Analytical evaluation of top-down versus bottom-up forecasting in a production planning framework	[301]
9.	Impact of aggregation level on forecasting performance	[328]
10.	Comparative study of demand forecasting techniques for military helicopter spare parts	[200]

Evidently, the considered four forecasting schemes can be used for other objects (i.e., value vector, system structure) as well. A simplified scheme for forecasting of structure stream is depicted in Fig. 6 [166,167,168,169,170,172].

Here, the system structure consists of its parts/components and their relations (i.e., a graph model $G(A,E)$ where A is the set of system components, E is the set of edges/arcs). Thus, the initial system structure stream is: $< G_{\tau_1}, G_{\tau_2}, ..., G_{\tau_n} >$.

The considered forecasting procedure is based on the following stages:

Stage 1. generation of a set of system improvement operations (e.g., for the next system generation) (on the basis of an analysis of system structure stream).

Stage 2. Selecting a subset of system improvement operations.

Stage 3. Synthesis of the system forecast as a composition of the best (more prospective) system improvement operations. As a result, a set of k Pareto-efficient solutions can be obtained: G^f_1,G^f_2,...,G^f_k.

Here, two combinatorial optimization models can be used: knapsack line problem, morphological clique problem (e.g., while taking into account their compatibility).

Stage 4. Aggregation of the Pareto-efficient system (i.e, system structure) forecasts to obtain the resultant aggregated system (i.e., system structure) forecast G^{af}.

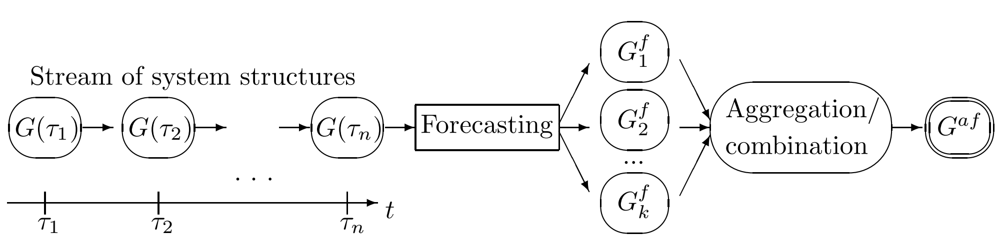

Fig. 6. Simplified scheme for forecasting of structure stream

4. Example of composite challenge system

4.1. General composite 5G challenge system

A hierarchical structure of composite 5G challenge system is shown in Fig. 7. Note it is reasonable to conduct a special study to design the 5G hierarchical structure (or an ontology of 5G challenges).

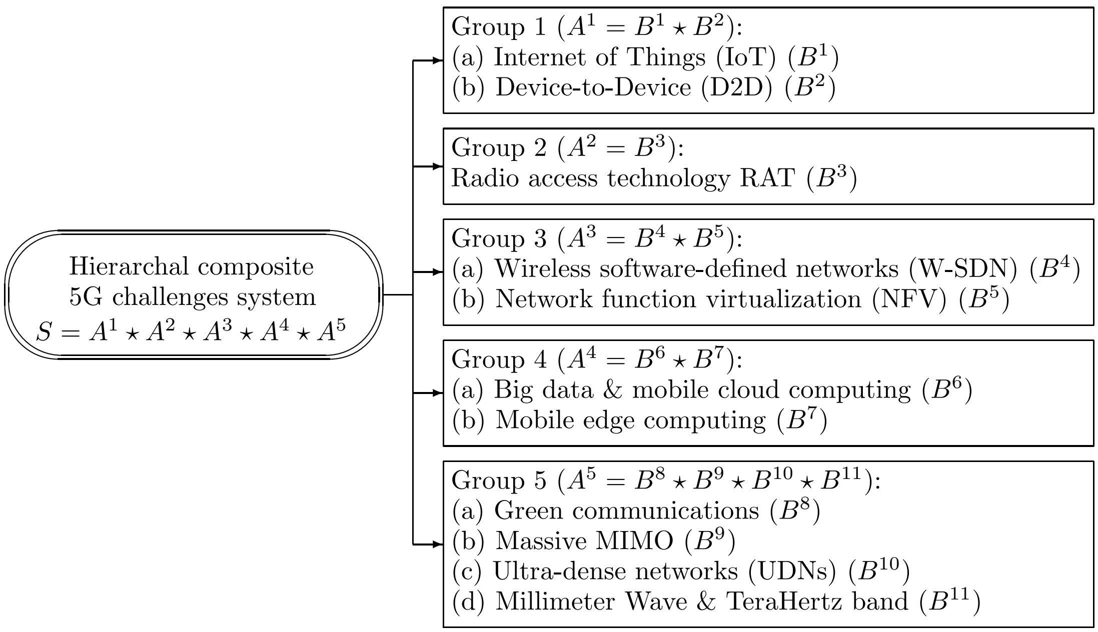

Fig. 7. General hierarchical structure of composite 5G challenge system

4.2. Basic auxiliary optimization approaches

It may be reasonable to point out the set of basic auxiliary optimization approaches (i.e., models, problems, frameworks) which are used in 5G communication technologies and their improvements (obtained in the basis of literature from Table 3 and Table 4) (e.g., [73,108,167]):

(1) knapsack problem, its modifications (e.g., multicriteria problems, problems under uncertainty, dynamical problems);

(2) multicriteria selection, prioritization;

(3) multiple choice problem, its versions (e.g., multicriteria problems, problems under uncertainty, dynamical problems);

(4) location/allocation/placement problems (e.g., generalized problems, multicriteria problems, problems under uncertainty, dynamical problems);

(5) coverage problems (e.g., multicriteria problems, problems under uncertainty, dynamical problems);

(6) routing problems;

(7) auction problems;

(8) clique problem, its versions (e.g., morphological clique problem);

(9) nonlinear fractional programming problems;

(10) convex optimization;

(11) mixed integer linear programming; and

(12) mixed integer nonlinear programming.

4.3. Morphological design

here, the combinatorial framework (as combinatorial modular morphological design) is based on Hierarchical Multicriteria Morphological Design method (HMMD) that has been described in (e,g., [164,165,167]). A basic simplified version of HMMD is used.

In HMMD method (combinatorial synthesis) the considered system consists of the following:

(i) systems parts or components (modules) and corresponding design alternatives (DAS) for each component;

(ii) interconnection/compatibility (IC) of DAs which are included into the same system or the system part.

Basic assumptions are the following: (a) a tree-like structure of the system; (b) a composite estimate for system quality that integrates components (subsystems, parts, modules) qualities and qualities of IC (compatibility) across subsystems; (c) monotonic criteria for the system and its components (modules); (d) quality estimates of system components and IC are evaluated by coordinated ordinal scales. The designations are: (1) design alternatives (DAs) for nodes of the model; (2) priorities of DAs ($r = \overline{1,k}$; 1 corresponds to the best level of quality); (3) an ordinal compatibility estimate for each pair of DAs ($w = \overline{0,l}$; l corresponds to the best level of quality).

The phases of HMMD are:

Phase 1. design of the tree-like system model.

Phase 2. generation of DAs for leaf nodes of the model.

Phase 3. hierarchical selection and composing of DAs into composite DAs for the corresponding higher level of the system hierarchy.

Phase 4. analysis and improvement of composite DAs (i.e., system solutions).

Let S be a system consisting of m parts (components): $P(1), ..., P(i), ..., P(m)$. A set of design alternatives (DAs) is generated for each system part above. The problem is:

Find composite design alternative $S = S(1) \star ... \star S(i) \star ... \star S(m)$ one representative design alternative $S(i)$ for each system component/part $P(i)$, $i = \overline{1,m}$) with non-zero IC estimates between the representative DAs.

A discrete domain of the integrated system excellence is based on the vector: $N(S) = (w(S); n(S))$, where $w(S)$ is the minimum of pairwise compatibility between DAs which correspond to different system components (i.e., $\forall\ P_{j_1}$ and P_{j_2}, $1 \leq j_1 \neq j_2 \leq m$) in S, $n(S) = (n_1, ..., n_r, ...n_k)$, where n_r is the number of DAs of the rth quality in S ($\sum_{r=1}^{k} n_r = m$). Composite solutions are searched for which are nondominated by $N(S)$ (i.e., Pareto-efficient solutions).

4.4. Optimization based composite 5G challenge system

Table 7 contains the selected 5G challenges based on optimization approaches as the initial set of basic 5G improvement activities.

Further, an example of the hierarchical composite 5G challenge (improvement) system is examined. The estimates of DAs and their ordinal compatibilities are based on expert judgment and have only illustrative character. Here the design alternative (DAs) as a local challenge/improvement action corresponds to element (the number-notation) from Table 4. The composite (modular) system is (design alternative X_0 corresponds to the absence of an activity) (Fig. 8; ordinal estimates of DAs are are shown in parentheses).

0. $S^I = A^1 \star A^2 \star A^3 \star A^4 \star A^5$:

1. $A^1 = B^1 \star B^2$:

1.1. B^1 (IoT): B^1_0 (None), B^1_1 (1.2.1.), B^1_2 (1.2.2.), B^1_3 (1.2.3.), B^1_4 (1.2.4.), B^1_5 (1.2.5.), B^1_6 (1.2.6.), B^1_7 (1.2.7.), B^1_8 (1.2.8.), B^1_9 (1.2.9.);

1.2. B^2 (D2D): B^2_0 (None), B^2_1 (2.3.1.), B^2_2 (2.3.2.), B^2_3 (2.3.3.), B^2_4 (2.3.4.), B^2_5 (2.3.5.), B^2_6 (2.3.6.), B^2_7 (2.3.7.), B^2_8 (2.3.8.), B^2_9 (2.3.9.), B^2_{10} (2.3.10.), B^2_{11} (2.3.11.).

2. $A^2 = B^3$ (RAT): B^3_0 (None), B^3_1 (3.5.1.), B^3_2 (3.5.2.), B^3_3 (3.5.3.), B^3_4 (3.5.4.), B^3_5 (3.5.5.), B^3_6 (3.5.6.).

3. $A^3 = B^4 \star B^5$:

3.1. B^4 (W-SDN): B^4_0 (None), B^4_1 (4.2.1.), B^4_2 (4.2.2.), B^4_3 (4.2.3.), B^4_4 (4.2.4.).

3.2. B^5 (NFV): B^5_0 (None), B^5_1 (5.2.1.), B^5_2 (5.2.2.), B^5_3 (5.2.3.), B^5_4 (5.2.4.), B^5_5 (5.2.5.), B^5_6 (5.2.6.), B^5_7 (5.2.7.), B^5_8 (5.2.8.), B^5_9 (5.2.9.), B^5_{10} (5.2.10.), B^5_{11} (5.2.11.), B^5_{12} (5.2.12.).

4. $A^4 = B^6 \star B^7$:

4.1. B^6 (Big Data & Mobile Cloud Computing): B^6_0 (None), B^6_1 (6.2.1.), B^6_2 (6.2.2.), B^6_3 (6.2.3.), B^6_4 (6.2.4.), B^6_5 (6.2.5.), B^6_6 (6.2.6.), B^6_7 (6.2.7.), B^6_8 (6.2.8.), B^6_9 (6.2.9.), B^6_{10} (6.2.10.).

4.2. B^7 (Mobile edge computing): B^7_0 (None), B^7_1 (7.2.1.), B^7_2 (7.2.2.), B^7_3 (7.2.3.), B^7_4 (7.2.4.), B^7_5 (7.2.5.).

5. $A^5 = B^8 \star B^9 \star B^{10} \star B^{11}$:

5.1. B^8 (Green Communication): B^8_0 (None), B^8_1 (8.2.1.), B^8_2 (8.2.2.), B^8_3 (8.2.3.), B^8_4 (8.2.4.), B^8_5 (8.2.5.), B^8_6 (8.2.6.), B^8_7 (8.2.7.), B^8_8 (8.2.8.), B^8_9 (8.2.9.), B^8_{10} (8.2.10.).

5.2. B^9 (Massive MIMO): B^9_0 (None), B^9_1 (9.2.1.), B^9_2 (9.2.2.), B^9_3 (9.2.3.), B^9_4 (9.2.4.), B^9_5 (9.2.5.), B^9_6 (9.2.6.), B^9_7 (9.2.7.), B^9_8 (9.2.8.), B^9_9 (9.2.9.), B^9_{10} (9.2.10.).

5.3. B^{10} (UDN): B^{10}_0 (None), B^{10}_1 (10.2.1.), B^{10}_2 (10.2.2.), B^{10}_3 (10.2.3.), B^{10}_4 (10.2.4.), B^{10}_5 (10.2.5.).

5.4. B^{11} (Millimeter Wave & TeraHertz): B^{11}_0 (None), B^{11}_1 (11.2.1.), B^{11}_2 (11.2.2.), B^{11}_3 (11.2.3.), B^{11}_4 (11.2.4.).

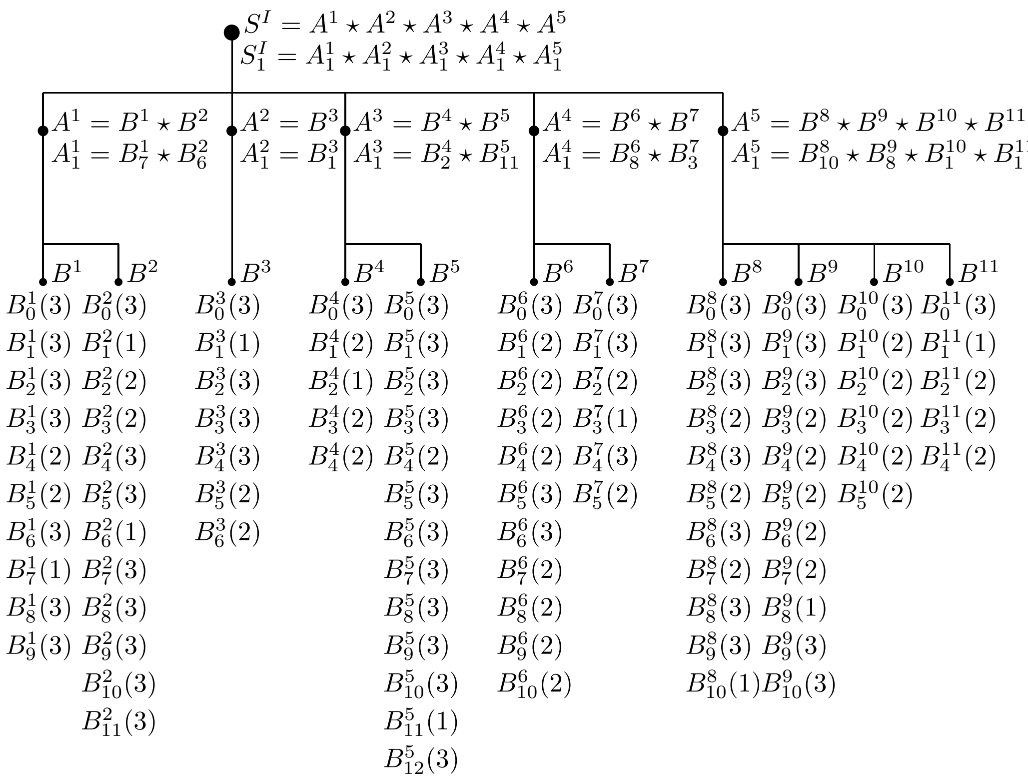

Fig. 8. Morphological hierarchical structure of composite 5G challenge system

Illustrative ordinal estimates of pair compatibilities are contained in Table 8, Table 9, Table 10. Table 11, and Table 12.

As a result, the following Pareto-efficient composite DAs for system parts are obtained:

1. For subsystem A^1: $A^1_1 = B^1_7 \star B^2_6$, $N(A^1_1) = (3; 2, 0, 0)$.
2. For subsystem A^2: $A^2_1 = B^3_3$.
3. For subsystem A^3: $A^3_1 = B^4_2 \star B^5_{11}$, $N(A^3_1) = (3; 2, 0, 0)$.
4. For subsystem A^4: $A^4_1 = B^6_8 \star B^7_3$, $N(A^4_1) = (3; 2, 0, 0)$.
5. For subsystem A^5: $A^5_1 = B^8_{10} \star B^9_8 \star B^{10}_1 \star B^{11}_1$, $N(A^5_1) = (3; 3, 1, 0)$.

For composition of the resultant system solution compatibility estimates are not used. The resultant solution (composite 5G challenge system based on optimization approaches) is:

$S^I_1 = A^1_1 \star A^2_1 \star A^3_1 \star A^4_1 \star A^5_1$.

Table 7. Basic 5G alternative improvement activities based on optimization approaches, part 1

Notation (Table 4)	DAs	Optimization problem(s)	Breaf description	Sources
	B^1_0	None	None	
1.2.1	B^1_1	Optimization	IoT-Cloud service optimization	[35]
1.2.2	B^1_2	Optimization	adaptive monitoring in IoT	[272]
1.2.3	B^1_3	Optimization	Optimization of non-functional properties in IoT	[221]
1.2.4	B^1_4	Selection, planning	Modulation selection, resource planning	[77]
1.2.5	B^1_5	Graph optimization	M2M optimization in IoT	[229]
1.2.6	B^1_6	Optimization	Traffic optimization for IoT	[98]
1.2.7	B^1_7	Selection	Relay selection in 5G HetNets for IoT	[79]
1.2.8	B^1_8	Allocation	Task allocation in IoT	[72,150]
1.2.9	B^1_9	Allocation	Optimal throughput, power allocation	[70]
	B^2_0	None	None	
2.3.1	B^2_1	Optimization	Resource management in D2D	[10]
2.3.2	B^2_2	Allocation	Resource allocation for D2D	[103,116]
2.3.3	B^2_3	Location/allocation	Sector-based radio resource allocation (D2D)	[105]
2.3.4	B^2_4	Allocation	Interference&throughput aware resource allocation for multi-class D2D	[93]
2.3.5	B^2_5	Allocation	Power allocation for mobile D2D	[322]
2.3.6	B^2_6	Selection, allocation	Mode selection&resource allocation	[317]
2.3.7	B^2_7	Optimization	Resource sharing for D2D (cellular network)	[316]
2.3.8	B^2_8	Allocation	Uplink resource/power allocation for D2D	[91]
2.3.9	B^2_9	Assignment	QoS-aware channel assignment for D2D	[288,289]
2.3.10	B^2_{10}	Assignment	Channel assignment in D2D (game models)	[147,173]
2.3.11	B^2_{11}	Multi-armed bandit	Resource allocation for D2D communications	[219]
	B^3_0	None	None	
3.5.1	B^3_1	Clustering, allocation	User clustering, power allocation	[20]
3.5.2	B^3_2	Allocation	Resource allocation	[292]
3.5.3	B^3_3	Optimization	Optimization of RAN	[266]
3.5.4	B^3_4	Allocation	resource allocation in wireless HetNets	
3.5.5	B^3_5	Adaptive balancing	Serviceability maximization in Fog networks	[78]
3.5.6	B^3_6	Allocation, positioning	Resource positioning (virtualized networks)	[261]
	B^4_0	None	None	
4.2.1	B^4_1	Optimal design	Optimal design for 5G mobile SDN	
4.2.2	B^4_2	Location	Placement of controllers in SDN	[2,130,157,291]
4.2.3	B^4_3	Allocation	Multi-spectra allocation (wireless SDN)	[290]
4.2.4	B^4_4	Routes replacement	Replacing several dependent routes in SDN	[86]
	B^5_0	None	None	
5.2.1	B^5_1	Optimization	Cost optimal design for core network	[38]
5.2.2	B^5_2	Chaining/allocation	Service function chaining, resource allocation	[287]
5.2.3	B^5_3	Placement	Functions placement (mobile core gateways)	[37]
5.2.4	B^5_4	Generalized assignment problem, MILP	Joint VNF placement&resource allocation in 5G networks (including vertical services)	[6,7]
5.2.5	B^5_5	Deployment	Deploying chains of VNFs	[158]
5.2.6	B^5_6	Allocation	VNF placement and chaining	[22]
5.2.7	B^5_7	Allocation	Resource allocation in NFV	[125]
5.2.8	B^5_8	Placement	Placement of virtual mobile functions over cloud infrastructure	[87]
5.2.9	B^5_9	Placement	Placement of virtualized network functions	[262]
5.2.10	B^5_{10}	Placement	Virtual network function placement	[268]
5.2.11	B^5_{11}	Placement, design	Function placement&topology optimization	[42,43]
5.2.12	B^5_{12}	Reallocation	Resource reallocation	[149]

Table 7. Basic 5G alternative improvement activities based on optimization approaches, part 2

Notation (Table 4)	DAs	Optimization problem(s)	Breaf description	Sources
	B_0^6	None	None	
6.2.1	B_1^6	Allocation	Dynamic resource&task allocation (clouds)	[159]
6.2.2	B_2^6	Optimization	Inter-layer optimization of clouds	[151]
6.2.3	B_3^6	Optimization	Joint analysis of radio&computer resources	[250]
6.2.4	B_4^6	Assignment	Task assignment (heterogeneous clouds)	[101]
6.2.5	B_5^6	Optimition	Secure optimization in clouds	[286]
6.2.6	B_6^6	Optimition	Cooperative resource management	[144,318]
6.2.7	B_7^6	Placement	Service placement in clouds	[310]
6.2.8	B_8^6	Optimization, partiion	Utilization of bandwidth (graph partitioning)	[217]
6.2.9	B_9^6	Allocation	Management of data centers	[45]
6.2.10	B_{10}^6	Location	Allocation of virtual resources	[228]
	B_0^7	None	None	
7.2.1	B_1^7	Optimization	Joint analysis of radio&computer resources	
7.2.2	B_2^7	Auction optimization	Hierarchical edge computing	[153]
7.2.3	B_3^7	Scheduling, allocation	Task scheduling and power allocation	[198]
7.2.4	B_4^7	Scheduling	Delay-optimal computation task scheduling	[186]
7.2.5	B_5^7	Balancing, allocation	Task offloading, load balancing, resource allocation	[179]
	B_0^8	None	None	
8.2.1	B_1^8	Optimization	Green energy for cellular networks	[120]
8.2.2	B_2^8	Optimization	Optimization of cell size	[236]
8.2.3	B_3^8	Layout, relocation	Adaptive change of network layout	[236]
8.2.4	B_4^8	Optimal stopping	Stopping in cognitive cellular networks	[325]
8.2.5	B_5^8	Routing/switching	Green routing/switching	[63]
8.2.6	B_6^8	Routing	Routing in green communication	[307]
8.2.7	B_7^8	Clustering	Dynamic resource provisioning	[52]
8.2.8	B_8^8	Allocation	Resource allocation	[312]
8.2.9	B_9^8	Optimization	Power optimization in green communication	[3]
8.2.10	B_{10}^8	Allocation, selection	Power allocation, relay selection	[4,110]
	B_0^9	None	None	
9.2.1	B_1^9	Global optimization	Energy optimization of massive MIMO	[185]
9.2.2	B_2^9	Global optimization	Energy optimization in relay network	[270]
9.2.3	B_3^9	Optimization	Optimal energy design of MIMO system	[49]
9.2.4	B_4^9	Allocation	Power allocation in massive MIMO	[74,269,324]
9.2.5	B_5^9	Location	Resource allocation in UDN (massive MIMO)	[311]
9.2.6	B_6^9	Allocation	Resource allocation for massive MIMO	[55]
9.2.7	B_7^9	Optimition	Throughput optimization for massive MIMO	[308]
9.2.8	B_8^9	Covering	Cell coverage for multicell massive MIMO	[137]
9.2.9	B_9^9	Optimization	Power optimization (different deployments)	[119]
9.2.10	B_{10}^9	Optimization	Sum rate maximization in massive MIMO	[148,215]
	B_0^{10}	None	None	
10.2.1	B_1^{10}	Optimition	Resource management, interference (UDN)	[60]
10.2.2	B_2^{10}	Optimization	Robustness optimization in UDN	[274]
10.2.3	B_3^{10}	Maximization	Energy maximization (dense cells)	[312]
10.2.4	B_4^{10}	Allocation	Energy resource allocation (UDN)	[311]
10.2.5	B_5^{10}	Optimization	Hyper-dense cell deployment	[305]
	B_0^{11}	None	None	
11.2.1	B_1^{11}	Scheduling	Scheduling in multihop mmWave systems	[106]
11.2.2	B_2^{11}	Optimization	Maximum nanonetwork capacity	[313]
11.2.3	B_3^{11}	Optimiation	Min precoding in mmWave MIMO systems	[319]
11.2.4	B_4^{11}	Concurrent scheduling	QoS-aware full-duplex concurrent scheduling for mmWave wireless backhaul networks	[85]

Table 8. Estimates of ordinal compatibility between DAs for $A^1 = B^1 \star B^2$

	B^2_0	B^2_1	B^2_2	B^2_3	B^2_4	B^2_5	B^2_6	B^2_7	B^2_8	B^2_9	B^2_{10}	B^2_{11}
B^1_0	3	2	2	2	2	2	2	2	2	2	2	2
B^1_1	1	3	1	1	1	1	1	3	2	1	1	1
B^1_2	1	1	1	1	1	1	1	1	2	3	3	2
B^1_3	1	1	1	1	1	1	1	1	2	1	1	1
B^1_4	2	1	1	1	1	1	1	2	2	3	3	2
B^1_5	2	2	2	2	2	2	2	2	2	3	3	2
B^1_6	1	3	1	1	1	1	1	3	2	1	3	2
B^1_7	2	2	2	2	2	3	2	2	2	3	3	2
B^1_8	2	2	3	3	3	3	3	2	3	3	3	2
B^1_9	2	2	3	3	3	3	3	2	3	3	3	2

Table 9. Estimates of ordinal compatibility between DAs for $A^3 = B^4 \star B^5$

	B^5_0	B^5_1	B^5_2	B^5_3	B^5_4	B^5_5	B^5_6	B^5_7	B^5_8	B^5_9	B^5_{10}	B^5_{11}	B^5_{12}
B^4_0	3	1	1	1	1	1	1	1	1	1	1	1	1
B^4_1	1	2	2	2	2	2	2	2	2	2	2	2	2
B^4_2	1	3	3	3	3	3	3	3	3	3	3	3	3
B^4_3	1	3	3	3	3	3	3	3	3	3	3	3	3
B^4_4	1	2	2	2	2	2	2	2	2	2	2	2	2

Table 10. Estimates of ordinal compatibility between DAs for $A^4 = B^6 \star B^7$

	B^6_0	B^6_1	B^6_2	B^6_3	B^6_4	B^6_5	B^6_6	B^6_7	B^6_8	B^6_9	B^6_{10}
B^7_0	3	1	1	1	1	1	1	1	1	1	1
B^7_1	1	1	1	1	1	1	1	1	1	1	1
B^7_2	1	2	2	2	2	2	2	2	2	2	2
B^7_3	1	2	2	2	3	2	2	2	3	3	3
B^7_4	1	2	2	2	2	2	2	2	2	2	2
B^7_5	1	3	3	3	3	3	3	3	3	3	1

Table 11. Estimates of ordinal compatibility between DAs for $A^5 = B^8 \star B^9 \star B^{10} \star B^{11}$, part 1

	B^9_0	B^9_1	B^9_2	B^9_3	B^9_4	B^9_5	B^9_6	B^9_7	B^9_8	B^9_9	B^9_{10}
B^8_0	3	1	1	1	1	1	1	1	1	1	1
B^8_1	1	1	1	1	2	1	1	2	2	2	3
B^8_2	1	1	1	2	2	2	2	2	2	2	2
B^8_3	1	1	1	2	2	2	2	2	2	2	2
B^8_4	1	1	1	1	1	1	1	2	2	2	2
B^8_5	1	1	1	1	2	1	1	2	2	2	1
B^8_6	1	2	1	1	2	1	1	2	2	2	2
B^8_7	1	1	1	1	2	1	1	2	2	2	2
B^8_8	1	1	1	1	2	1	1	2	2	2	1
B^8_9	1	2	1	1	2	1	1	1	2	2	2
B^8_{10}	1	2	1	1	2	1	1	2	3	2	2

Table 12. Estimates of ordinal compatibility between DAs for $A^5 = B^8 \star B^9 \star B^{10} \star B^{11}$, part 2

	B^{10}_0	B^{10}_1	B^{10}_2	B^{10}_3	B^{10}_4	B^{10}_5	B^{11}_0	B^{11}_1	B^{11}_2	B^{11}_3	B^{11}_4
B^8_0	3	1	1	1	1	1	3	1	1	1	1
B^8_1	1	1	1	1	2	1	1	2	2	2	2
B^8_2	1	1	1	1	2	1	1	2	2	2	2
B^8_3	1	2	1	1	2	1	1	1	1	1	2
B^8_4	1	1	1	1	2	1	1	2	1	2	2
B^8_5	1	1	1	1	2	1	1	2	1	2	2
B^8_6	1	2	1	1	2	1	1	2	2	2	2
B^8_7	1	1	1	1	2	1	1	2	2	2	2
B^8_8	1	1	1	1	2	1	1	2	2	2	2
B^8_9	1	2	1	1	2	1	1	2	2	2	2
B^8_{10}	1	3	2	2	2	2	1	3	2	2	2

5. Conclusion

This paper describes a combinatorial framework for selection and composition of 5G improvement actions (challenges/key emerging technologies) based on optimization methods to obtain a composite challenge system. An illustrative example for design of the composite 5G challenge system is presented. Evidently, this approach can be used for other complex technological systems in various domains. Note, various other forecasting methods (including aggregation/hierarchical approaches) can be successfully used in system forecasting as well. The presented material has a preliminary character and can be improved and extended. It may be reasonable to consider the following future research directions: (1) special study to design a hierarchy (or ontology) of technological systems and their challenges; (2) study of composite innovations as combination of modular innovation activities (e.g., challenges/key technologies); (3) study of multi-stage composite technology challenge(s) systems; and (4) using the suggested combinatorial framework in education.

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Author address:
Mark Sh. Levin, Institute for Information Transmission Problem, Russian Academy of Sciences
http://www.mslevin.iitp.ru/ email: mslevin@acm.org