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ORIGINAL RESEARCH

Composite Technology Challenge System for Optimization in 5G Communications

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Abstract
The significance of approaches for improvement of systems/products has been increased. In the article, a modular technology challenge system is proposed as a basis for the system improvement process. The combinatorial framework for designing a modular technology challenge system is described: (1) collection of information items (literature sources on technology challenges/key technologies); (2) designing a hierarchy over the set of information items; (3) selection of the sub-hierarchy while taking into account the specified topic(s); (4) composition of a required information item configuration as technology challenge system. The composition stage is based on morphological design. An applied realistic numerical example illustrates the usage of the proposed framework to design a 5G technology challenge system as a set of the selected related optimization actions.

Keywords Combinatorial framework · Technology challenge system · Heuristic · 5G communications

Introduction

Preliminaries

In recent decades, the significance of the following two processes has been increased: (1) improvement of existing systems/products and (2) movement from an existing system/product generation to the next system/product generation (i.e., paradigm shift). Many research efforts are targeted to descriptions and studies of the processes above: technological challenges, possible prospective system/product changes. Evidently, the above-mentioned efforts are based on information analysis of the corresponding applied domains. Fig. 1 illustrates the system/product improvement stage and its information support. Thus, dynamic analysis of research topics is widely used in many domains, for example: (a) information sciences [141], (b) software product lines [88], (c) knowledge-based systems [213], (d) operations research [112], (e) applied intelligence [211].

In this paper, a combinatorial framework of structuring a set of technological challenges for a certain research domain is examined. The framework consists of four basic stages: (1) collection of information items on the basis of literature sources (e.g., papers and patents which correspond to key technologies or technological challenges); (2) designing a hierarchy over the set of information items; (3) selection of the sub-hierarchy while taking into account the specified topic(s); (4) designing a technology challenge system as a configuration of the selected and related information items (i.e., technology challenges). The suggested combinatorial framework is illustrated by consideration of a 5G technology challenge system (while taking into account optimization methods). Note, combinatorial evolution of communication technology generations (i.e., 1G, 2G, 3G, 4G, 5G, 6G) is described in [119]. Scheme of the research is shown in Fig. 2. This paper is based on a preliminary technical report [120].

Generalized Combinatorial Framework

The examined combinatorial framework was proposed in [120] (Fig. 3):

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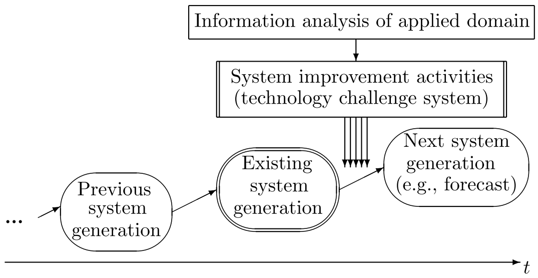

Fig. 1 Illustration for system improvement

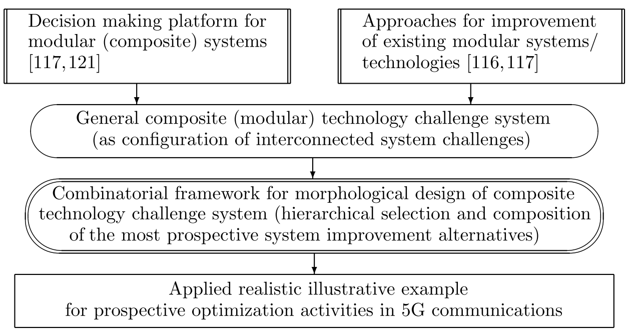

Fig. 2 Scheme of the research

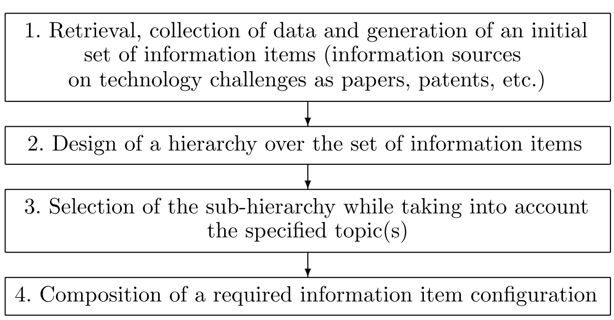

Fig. 3 Framework for designing a technology challenge system

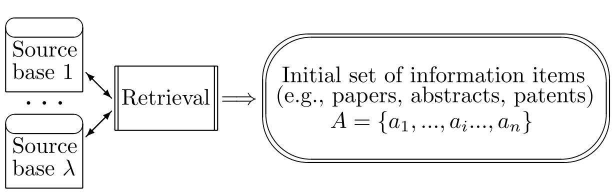

Fig. 4 Retrieval and collection of initial information items

1. Generation of an initial set of information items (information sources as papers, patents, etc.): $A = \{a_1, \dots, a_i \dots, a_n\}$ (Fig. 4).

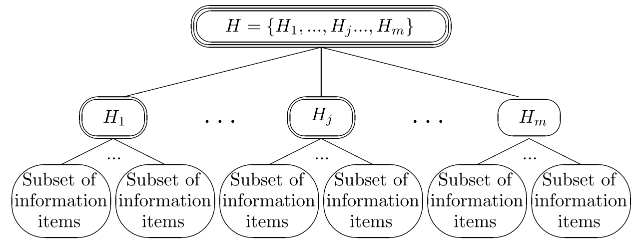

Fig. 5 Basic hierarchy of information items

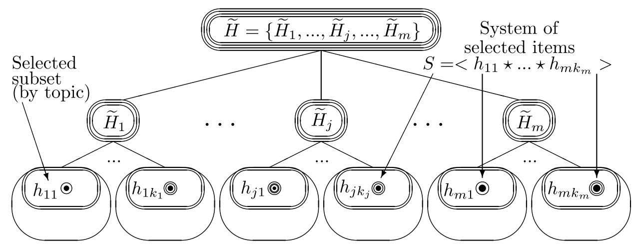

Fig. 6 Selected information items (by specified topic), item configuration

2. Design of a hierarchy over the set of information items: $H = \{H_1, \dots, H_j \dots, H_m\}, \bigcup_{j=1}^{m} \quad H_j = A$ (Fig. 5).
3. Selection of the sub-hierarchy: the item subsets by the specified topic(s): $\widetilde{H} = \{\widetilde{H}_1, \dots, \widetilde{H}_j \dots, \widetilde{H}_m\}$ where $\widetilde{H}_j \subseteq H_j \quad \forall j = \overline{1, m}$ (Fig. 6).
4. Composition of a required information item configuration: $S =< h_{11} \star \cdots \star h_{mk_m} >$ (Fig. 6).

Basic Auxiliary Optimization Approaches

Recently, optimization approaches (mainly, combinatorial optimization [42, 49, 63, 78, 117]) are widely studied and used in communications systems (e.g., [42, 80, 81, 113, 120, 133, 134, 140, 159, 166, 195]). The set of the corresponding basic auxiliary optimization approaches (i.e., problems, frameworks) is listed in Table 1. The optimization approaches are often related (e.g., by problem formulations, by applications, by solving frameworks). Note, composite optimization frameworks based of several optimization problems (e.g., selection-allocation, location-routing, scheduling and allocation, placement, and topology optimization) are used as well (e.g., [23, 66, 93, 183, 208]).

Morphological Design

Morphological analysis is a power tool for composition of multi-part (composite, modular) systems. The approach is widely used for many application domains (e.g., system

Table 1 Optimization approaches in communications (i.e., problems, models, frameworks)

No.	Optimization approach	Some network applications	Source(s)
1.	Multicriteria selection, sorting, prioritization problems	First mile access selection	[168]
		Radio access technology selection	[116]
		Modulation selection	[53]
		Mode selection for D2D communications	[208]
		Service node selection in network	[59]
		Cloud service selection	[149]
		Relay selection in 5G HetNets for IoT	[55]
		Network selection in mobile ad hoc networks	[29]
2.	Clustering/classification problems	Node clustering (e.g., for topology design)	[165]
		User clustering, hierarchical network design	[12, 117]
		Dynamic resource provisioning via clustering	[36]
		Network traffic classification	[181]
3.	Knapsack-like, multiple choice problems	Channel planning in communication systems	[102, 118]
		Modular redesign of networked systems	[117, 176]
		Improvement of communication protocol	
4.	Location/allocation/placement problems	Optimal throughput, power allocation	[47]
		Task allocation in IoT	[48, 103]
		Dynamic resource and task allocation in clouds	[110]
		Task assignment in heterogeneous clouds	[73]
		Resource allocation in UDN with massive MIMO	[202]
		Allocation of virtual resources	[156]
		Service placement in clouds	[201]
		Multicriteria allocation of users to access-points	[117]
		Placement of controllers in SDN	[108, 192]
		Antenna placement/positioning in wireless networks	[27]
5.	Coverage problems	Coverage problems in WSNs	[68, 123, 145]
		Cell coverage optimization for multicell massive MIMO	[96]
6.	Spanning tree problems (minimum spanning tree,Steiner tree, maximum leaves spanning tree)	Shortest connection networks	[49, 78, 160]
		Minimum energy broadcast/multicast trees	[64, 196]
		Network backbone design	
		Hierarchical network design	
6.	Routing problems	Routing optimization in communication networks	[37]
		Routing protocols for WSNs	[9, 11]
		Routing in green communication	[44, 199]
8.	Scheduling problems	Scheduling in multihop mmWave cellular systems	[77]
		Delay-optimal computation task scheduling for mobile-edge computing systems	[129]
		Full-duplex concurrent scheduling for mmWave wireless backhaul networks	[60]
9.	Auction optimization	Hierarchical mobile edge computing	[106]
10.	Clique problems	Broadcast congested clique	[153]
		Modular design of communication protocols and information transmission standards	[117]
11.	Independent set problems	Broadcasting, wireless/cellular networks, GPS system	[19, 35]
12.	Bin-packing problems	Packing in WiMAX systems	[118, 132]
13.	Graph optimization (e.g., partition, augmentation)	M2M optimization in IoT, graph augmentation	[50, 157]
		Utilization of bandwidth via graph partitioning	[148]
14.	Graph coloring problems	Spectrum/frequency management (e.g., frequency assignment),	[78, 95, 133]
		buffer allocation in regular dataflow networks	[83]
		Buffer minimization	[158]

Table 1 (continued)

No.	Optimization approach	Some network applications	Source(s)
15.	Connected dominating sets	Network backbone design, routing	[32, 207]
16.	Convex optimization, global optimization	Traffic optimization for IoT	[71]
		Energy optimization in relay network	[175]
17.	Mixed integer programming	Joint VNF placement and resource allocation in 5G networks	[4, 5]
18.	Optimal stopping	Stopping in cognitive cellular networks	[215]

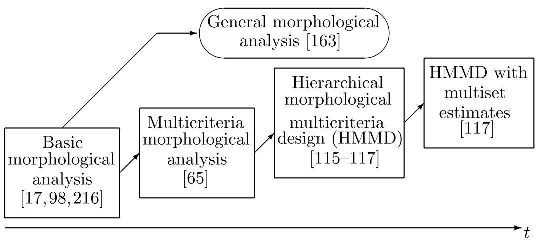

Fig. 7 Evolution of morphological analysis approaches

design, technological forecasting, management, information retrieval) (e.g., [17, 98, 116, 117, 163, 216]). A simplified evolution scheme of morphological analysis based design approaches is shown in Fig. 7.

Here the combinatorial framework (as combinatorial modular morphological design) is based on Hierarchical Multicriteria Morphological Design (HMMD) method (e,g., [115–117]). A basic simplified version of HMMD is used. In HMMD method (combinatorial synthesis), the considered system consists of the following: (1) systems parts or components (modules) and corresponding design alternatives (DAS) for each component; (2) interconnection/compatibility (IC) of DAs which are included into the same system or the system part. The basic assumptions of HMMD 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 (parts, modules); and (d) quality estimates of system components and IC are evaluated by the same 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., composite system solutions).

Thus, system S consisting of m parts (components) $P(1), \dots, P(i), \dots, P(m)$ is considered. A set of design alternatives (DAs) is generated for each system part above (i.e., leaf node). The problem is:

Find composite design alternative $S = S(1) \star \cdots \star S(i) \star \cdots \star S(m)$: 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}, $1 \le j_1 \ne j_2 \le m$) in S, $n(S) = (n_1, \dots, n_r, \dots n_k)$, where n_r is the number of DAs of the rth quality in S ($\sum_{r=1}^{k} n_r = m$). Nondominated by $N(S)$ composite solutions are searched for (i.e., Pareto-efficient solutions). The problem is NP-hard and enumerative methods may be used (e.g., while taking into account a reduced dimension by problem partition/decomposition) and heuristics. A simplified numerical example of morphological design is shown in Fig. 8: ordinal estimates of DAs are depicted in parentheses in Fig. 8a, positive ordinal compatibility estimates are depicted in Fig. 8b. The Pareto-efficient solutions are: $S_1 = X_2 \star Y_1 \star Z_2$, $N(S_1) = (2;2,0,1)$; $S_2 = X_3 \star Y_1 \star Z_3$, $N(S_2) = (3;1,1,1)$. $S_3 = X_3 \star Y_2 \star Z_1$, $N(S_3) = (1;3,0,0)$.

Note, HMMD approach versions and their applications by various real-world examples are described in many publications (e.g., [116, 117]).

Example of Composite Challenge System

Figure 9 illustrates the design scheme of challenge system for 5G technology (while taking into account the topic "optimization methods"). The scheme solving components are based on heuristic (engineering) methods.

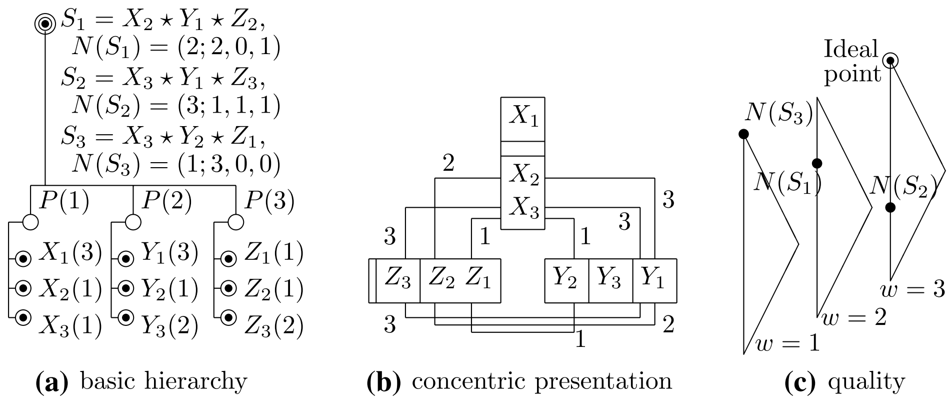

Fig. 8 Illustrative example of hierarchical morphological design

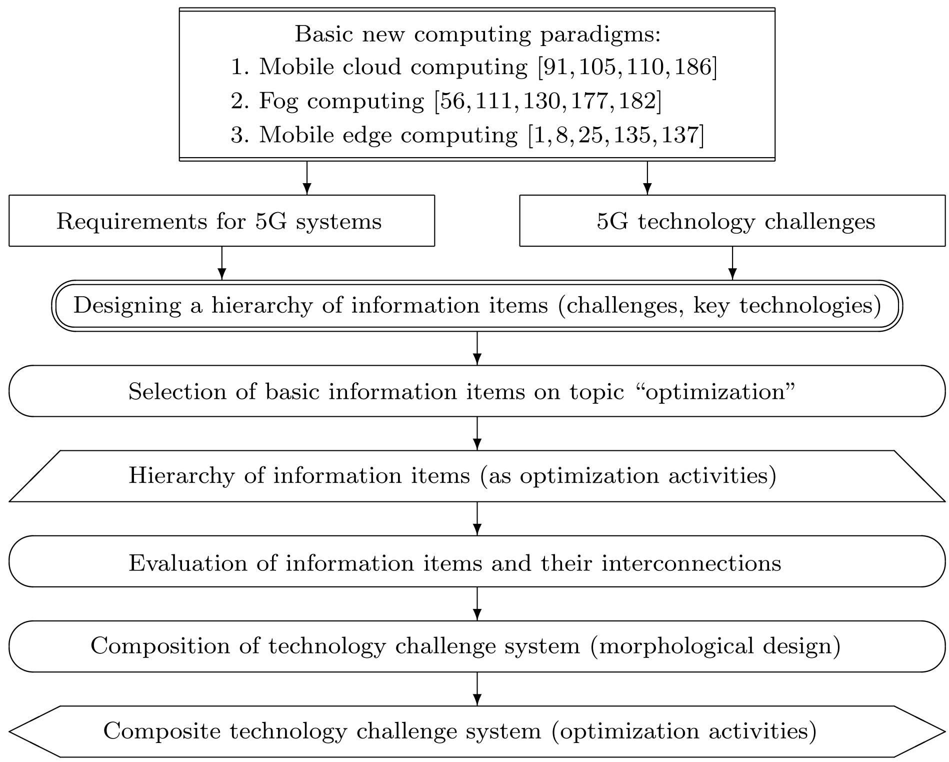

Fig. 9 General design scheme of challenge system for 5G technology

5G Technology Challenges

Table 2 contained an illustrative list of basic literature sources on 5G systems and corresponding challenges/key technologies. In addition, 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. The corresponding design/management problems are 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).

Note, key requirements for 5G communication technology are described in [10, 52]: (1) high data rates, (2) low latency, (3) low energy consumption, (4) high stability, (5) improved connectivity and reliability, and (6) improved security. The following main network quality criteria (criteria or objective functions) are usually considered [184]: (1) peak data rate, (2) geographical area coverage, (3) spectral efficiency, (4) QoS, (5) QoE, (6) easy of connectivity, (7) energy-efficiency, (8) latency, (9) reliability, (10) fairness of users, (11) implementation complexity, and (12) system lifetime (maximization).

Table 2 Survey publications on 5G systems (challenges/key technologies, related issues)

No.	Research	Sources
I.	Surveys and paradigms:	
1.1.	5G Internet of Things (surveys)	[124, 154]
1.2.	5G mobile communication technology (surveys)	[144, 197]
1.3.	Surveys on device-to-device (D2D) communication	[16, 75]
1.4.	Cloud computing (surveys: architecture, mobile computing, etc.)	[70, 105, 110] [139, 186]
1.5.	Survey on mobile edge computing	[1, 8, 137]
1.6.	Fog computing	[130, 177]
1.7.	Software-defined networking paradigms in wireless networks (surveys)	[94, 107]
1.8.	UltraDense networks (new wireless frontier for enabling 5G access)	[82]
1.9.	Next generation 5G wireless networks (comprehensive survey)	[6]
1.10.	5G channel measurements and models (survey)	[13, 194]
1.11.	Wireless communication paradigm through software-controlled metasurfaces	[126, 127]
II.	Architecture issues:	
2.1.	Survey of 5G networks: architecture and emerging technologies	[85]
2.2.	5G radio access network architecture	[138]
2.3.	Centralized network architecture for 5G mobile communication systems	[162]
2.4.	Big data network architecture and monitoring use wireless 5G technology	[99]
2.5.	Architecture for Fog computing	[130]
2.6.	Wireless heterogeneous networks (e.g., for mobile cloud computing)	[39, 114]
2.7.	D2D–based heterogeneous radio access network architecture (for mobile cloud computing)	[97]
2.8.	Ultra-dense network (UDN) architecture and technologies for 5G	[41]
2.9.	Architecture for software defined wireless networking	[28]
2.10.	SDN/NFV-based mobile packet core network architecture (survey)	[151]
III.	Challenges and key technologies:	
3.1.	10 key enabling technologies for 5G	[10]
3.2.	5G cellular: key enabling technologies and research challenges	[90]
3.3.	Key challenges for the radio-access network (5G on the horizon)	[57]
3.4.	Challenges in 5G (how to empower SON with big data for enabling 5G)	[92]
3.5.	Emerging technologies and research challenges for 5G wireless networks	[45]
3.6.	Basic list of challenges for 5G systems	[155]
3.7.	Key technologies for 5G wireless communication networks	[184]
3.8.	Challenges from the viewpoint of integration of IoT and cloud computing	[34]
3.9.	Novel radio technology for 5G (e.g., multiple access)	[146]
3.10.	D2D communication in 5G cellular networks (challenges and future directions)	[179]
3.11.	Network virtualization: research challenges	[46]
3.12.	Dense moving fog for intelligent IoT (key challenges and opportunities)	[15]
3.13.	Five disruptive technology directions for 5G	[33]
IV.	Special system issues (including optimization, AI approaches) :	
4.1.	Integration approach: IoT, cloud computing, Fog computing, big data, etc.	[30, 58]
4.2.	Regulatory, standardization and industrial perspectives (survey of 5G)	[146]
4.3.	Network function virtualization (management and orchestration, research challenges)	[87, 142, 143]
4.4.	Dynamic resource and task allocation (energy minimization in mobile cloud systems)	[110]
4.5.	Enabling intelligence in fog computing (to achieve energy and latency reduction)	[111]
4.6.	AI methods for traffic management in 5G wireless networks	[72]
4.7.	Traffic optimization for IoT	[71]
4.8.	Intelligent network optimization in wireless networking	[214]
4.9.	Network planning with robust optimization	[24]

Table 2 (continued)

No.	Research	Sources
4.10.	Cost optimal design for 5G mobile core network based on SDN and NFV	[21]
4.11.	Controller placement problem in software defined networking (survey)	[192]
4.12.	AI for 5G: research directions and paradigms	[205]
4.13.	Dual connectivity support in 5G networks (SDN based approach)	[172]

Table 3 Challenges for 5G technology and CloudIoT

No.	Research	Sources
I.	5G total technology challenges:	
1.1.	Mobile computing for 5G (from clouds to edges)	[135, 137]
1.2.	Challenges on wireless heterogeneous networks for mobile cloud computing	[114]
1.3.	Content caching techniques for 5G systems	[22, 185]
1.4.	Mobile edge computing, fog et al.	[164]
1.5.	Opportunities and challenges of software-defined mobile networks network security	[131]
1.6.	Mobile cloud computing applications: perspectives and challenges	[186]
1.7.	Mobile edge computing: challenges for future virtual network embedding algorithms	[25]
1.8.	Research opportunities (Fog and IoT)	[43]
1.9.	Interference management for D2D communication and its challenges in 5G networks	[152]
1.10.	Usage of intelligent techniques (data analytics, machine learning, optimization, multi-agent learning, etc.)	[111]
II.	Basic list of challenges for 5G systems: (1) data rates and network capacity expansion with energy optimization; (2) 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, massive MIMO 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	[155]
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	[34]
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) narrow band IoT; (5) direct D2D; (6) advanced spectrum, sharing and interference management; (7) millimeter Wave (mmWave); (8) mobile edge computing; (9) optimization and AI methods (optimization, machine learning, artificial NNs)	[124]

Four integrated lists of challenges for 5G technology (based on recent literature) are presented in Table 3. Note, our basic illustrative set of information items as technology challenges for 5G communications was described in [120]. An examined general hierarchical structure of composite 5G challenge system is depicted in Fig. 10 [120].

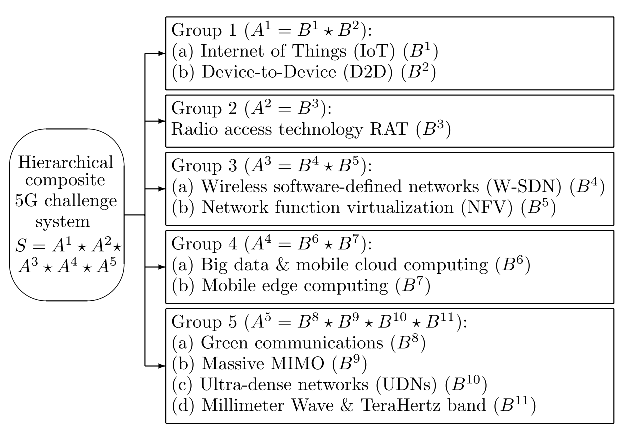

Fig. 10 General hierarchical structure of composite 5G challenge system

Optimization Based Composite 5G Challenge System

Tables 4 and 5 contain the selected 5G challenges (local DAs) based on topic "optimization". Here, the illustrative estimates are based on expert judgment: (1) ordinal scale [1, 2, 3] for DAs, (2) ordinal scale [0, 1, 2, 3] for DAs compatibility. Note, the high values of DAs compatibility correspond to the case when the challenges are based on the same (or close) optimization model/approach.

The examined structure of the composite (modular) system is (Fig. 11, design alternative X_0 corresponds to the absence of an activity, illustrative ordinal estimates of DAs are shown in parentheses as priorities in Tables 4 and 5):

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): $B^1_0(3)$, $B^1_1(2)$, $B^1_2(2)$, $B^1_3(3)$, $B^1_4(2)$, $B^1_5(2)$, $B^1_6(2)$, $B^1_7(1)$, $B^1_8(3)$, $B^1_9(1)$;

1.2. B^2 (D2D): $B^2_0(3)$, $B^2_1(2)$, $B^2_2(2)$, $B^2_3(2)$, $B^2_4(1)$, $B^2_5(2)$, $B^2_6(1)$, $B^2_7(2)$, $B^2_8(2)$, $B^2_9(2)$, $B^2_{10}(2)$.

2. $A^2 = B^3$ (RAT): $B^3_0(3)$, $B^3_1(1)$, $B^3_2(3)$, $B^3_3(2)$, $B^3_4(2)$, $B^3_5(2)$.

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

3.1. B^4 (W-SDN): $B^4_0(3)$, $B^4_1(1)$, $B^4_2(1)$, $B^4_3(2)$, $B^4_4(2)$;

3.2. B^5 (NFV): $B^5_0(3)$, $B^5_1(2)$, $B^5_2(2)$, $B^5_3(2)$, $B^5_4(2)$, $B^5_5(2)$, $B^5_6(2)$, $B^5_7(2)$, $B^5_8(2)$, $B^5_9(2)$, $B^5_{10}(1)$.

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

4.1. B^6 (Big Data and Mobile Cloud Computing): $B^6_0(3)$, $B^6_1(1)$, $B^6_2(2)$, $B^6_3(2)$, $B^6_4(3)$, $B^6_5(2)$, $B^6_6(2)$, $B^6_7(1)$, $B^6_8(2)$, $B^6_9(1)$, $B^6_{10}(2)$;

4.2. B^7 (Mobile edge computing): $B^7_0(3)$, $B^7_1(3)$, $B^7_2(2)$, $B^7_3(3)$, $B^7_4(3)$, $B^7_5(1)$.

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

5.1. B^8 (Green Communication): $B^8_0(3)$, $B^8_1(3)$, $B^8_2(3)$, $B^8_3(1)$, $B^8_4(3)$, $B^8_5(2)$, $B^8_6(3)$, $B^8_7(3)$, $B^8_8(3)$, $B^8_9(2)$;

5.2. B^9 (Massive MIMO): $B^9_0(3)$, $B^9_1(3)$, $B^9_2(3)$, $B^9_3(3)$, $B^9_4(2)$, $B^9_5(1)$, $B^9_6(2)$, $B^9_7(2)$, $B^9_8(2)$;

5.3. B^{10} (UDN): $B^{10}_0(3)$, $B^{10}_1(1)$, $B^{10}_2(2)$, $B^{10}_3(2)$, $B^{10}_4(2)$, $B^{10}_5(2)$;

5.4. B^{11} (Millimeter Wave and TeraHertz): $B^{11}_0(3)$, $B^{11}_1(1)$, $B^{11}_2(2)$, $B^{11}_3(3)$, $B^{11}_4(2)$.

Illustrative ordinal estimates of DAs pair compatibilities (based on author expert judgment) are contained in Tables 6, 7, 8, 9, 10, and 11.

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: $A^2_1 = B^3_1$.
3. For subsystem A^3: $A^3_1 = B^4_1 \star B^5_{10}$, $N(A^3_1) = (3;2,0,0)$.
4. For subsystem A^4: $A^4_1 = B^6_1 \star B^7_5$, $N(A^4_1) = (3;2,0,0)$; $A^4_2 = B^6_9 \star B^7_5$, $N(A^4_2) = (3;2,0,0)$.
5. For subsystem A^5: $A^5_1 = B^8_3 \star B^9_5 \star B^{10}_1 \star B^{11}_1$, $N(A^5_1) = (1;4,0,0)$; $A^5_2 = B^8_8 \star B^9_7 \star B^{10}_5 \star B^{11}_2$, $N(A^5_2) = (3;0,3,1)$.

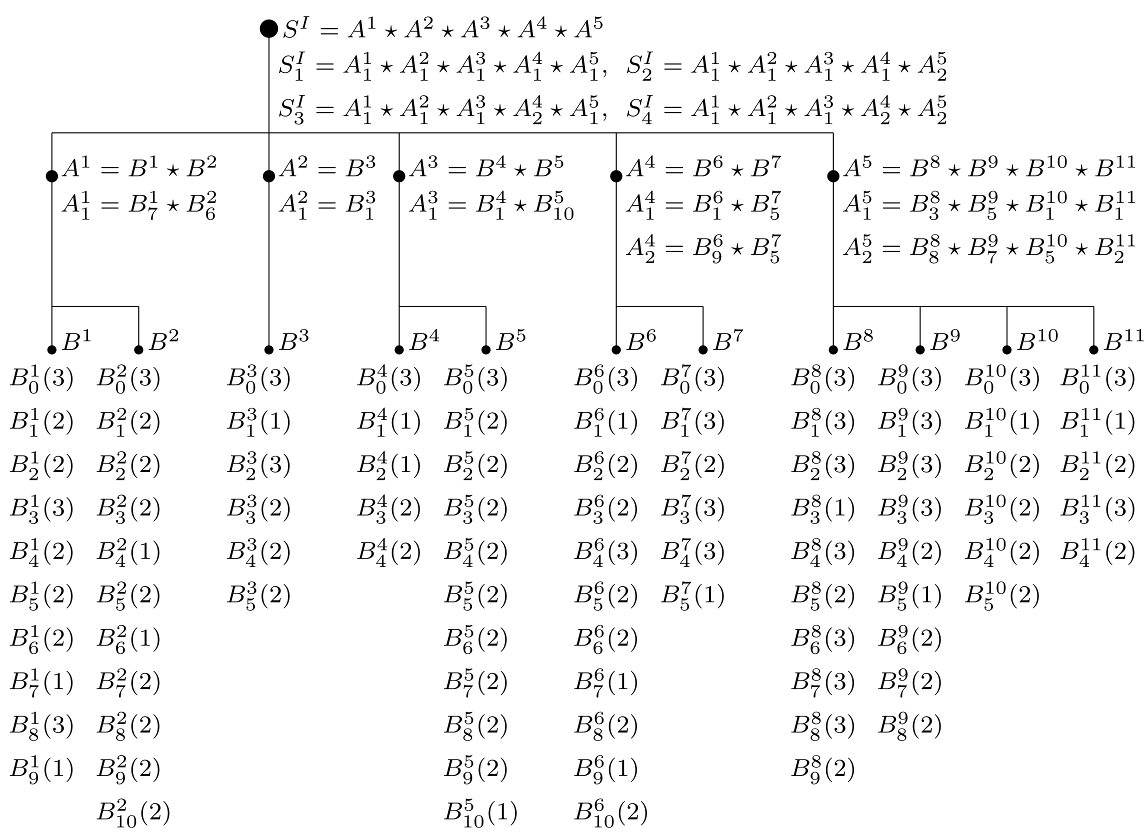

Fig. 11 Morphological hierarchical structure of composite 5G challenge system

Table 4 5G alternative improvement activities based on optimization approaches, part 1

DAs	Approach	Breaf description	Priority	Source
B_0^1	None	None	3	
B_1^1	Optimization	IoT-Cloud service optimization	2	[18]
B_2^1	Optimization	Adaptive monitoring in IoT	2	[178]
B_3^1	Optimization	Optimization of non-functional properties in IoT	3	[150]
B_4^1	Selection, planning	Modulation selection, resource planning	2	[53]
B_5^1	Graph optimization	M2M optimization in IoT	2	[157]
B_6^1	Optimization	Traffic optimization for IoT	2	[71]
B_7^1	Selection	Relay selection in 5G HetNets for IoT	1	[55]
B_8^1	Allocation	Task allocation in IoT	3	[48, 103]
B_9^1	Allocation	Optimal throughput, power allocation	1	[47]
B_0^2	None	None	3	
B_1^2	Optimization	Resource management in D2D	2	[7]
B_2^2	Allocation	Resource allocation for D2D	2	[74, 84]
B_3^2	Location/allocation	Sector-based radio resource allocation (D2D)	2	[76]
B_4^2	Allocation	Interference and throughput aware resource allocation for multi-class D2D	1	[69]
B_5^2	Allocation	Power allocation for mobile D2D	2	[212]
B_6^2	Selection, allocation	Mode selection and resource allocation	1	[208]
B_7^2	Optimization	Resource sharing for D2D (cellular network)	2	[206]
B_8^2	Allocation	Uplink resource/power allocation for D2D	2	[67]
B_9^2	Assignment	QoS-aware channel assignment for D2D	2	[189, 190]
B_{10}^2	Assignment	Channel assignment in D2D (game models)	2	[101, 122]
B_0^3	None	None	3	
B_1^3	Clustering, allocation	User clustering, power allocation	1	[12]
B_2^3	Allocation	Resource allocation	3	[193]
B_3^3	Optimization	Optimization of RAN	2	[171]
B_4^3	Adaptive balancing	Serviceability maximization in Fog networks	2	[54]
B_5^3	Allocation, positioning	Resource positioning (virtualized networks)	2	[169]
B_0^4	None	None	3	
B_1^4	Optimal design	Optimal design for 5G mobile SDN	1	[21]
B_2^4	Location	Placement of controllers in SDN	1	[108, 192]
B_3^4	Allocation	Multi-spectra allocation (wireless SDN)	2	[191]
B_4^4	Routes replacement	Replacing several dependent routes in SDN	2	[61]
B_0^5	None	None	3	
B_1^5	Optimization	Cost optimal design for core network	2	[21]
B_2^5	Chaining/allocation	Service function chaining, resource allocation	2	[188]
B_3^5	Placement	Functions placement (mobile core gateways)	2	[20]
B_4^5	Generalized assignment, MILP	Joint VNF placement and resource allocation in 5G networks (including vertical services)	2	[4, 5]
B_5^5	Deployment	Deploying chains of VNFs	2	[109]
B_6^5	Allocation	VNF placement and chaining	2	[14]
B_7^5	Allocation	Resource allocation in NFV	2	[89]
B_8^5	Placement	Placement of virtual mobile functions over cloud infrastructure	2	[62]
B_9^5	Placement	Placement of virtualized network functions	2	[170, 173]
B_{10}^5	Placement, design	Function placement and topology optimization	1	[23]

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

DAs	Approach	Brief description	Priority	Source
B_0^6	None	None	3	
B_1^6	Allocation	Dynamic resource and task allocation (clouds)	1	[110]
B_2^6	Optimization	Inter-layer optimization of clouds	2	[104]
B_3^6	Optimization	Joint analysis of radio and computer resources	2	[167]
B_4^6	Assignment	Task assignment (heterogeneous clouds)	3	[73]
B_5^6	Optimization	Secure optimization in clouds	2	[187]
B_6^6	Optimization	Cooperative resource management	2	[100, 209]
B_7^6	Placement	Service placement in clouds	1	[201]
B_8^6	Graph partition	Utilization of bandwidth	2	[148]
B_9^6	Allocation	Management of data centers	1	[26]
B_{10}^6	Location	Allocation of virtual resources	2	[156]
B_0^7	None	None	3	
B_1^7	Optimization	Joint analysis of radio and computer resources	3	[147]
B_2^7	Auction optimization	Hierarchical edge computing	2	[106]
B_3^7	Scheduling, allocation	Task scheduling and power allocation	3	[136]
B_4^7	Scheduling	Delay-optimal computation task scheduling	3	[129]
B_5^7	Balancing, allocation	Task offloading, load balancing, resource allocation	1	[125]
B_0^8	None	None	3	
B_1^8	Optimization	Optimization of cell size	3	[161]
B_2^8	Layout, relocation	Adaptive change of network layout	1	[161]
B_3^8	Optimal stopping	Stopping in cognitive cellular networks	3	[215]
B_4^8	Routing/switching	Green routing/switching	2	[44]
B_5^8	Routing	Routing in green communication	3	[199]
B_6^8	Clustering	Dynamic resource provisioning	3	[36]
B_7^8	Allocation	Resource allocation	3	[203]
B_8^8	Optimization	Power optimization in green communication	2	[2]
B_9^8	Allocation, selection	Power allocation, relay selection	1	[3, 79]
B_0^9	None	None	3	
B_1^9	Global optimization	Energy optimization of massive MIMO	3	[86, 128]
B_2^9	Global optimization	Energy optimization in relay network	3	[175]
B_3^9	Optimization	Optimal energy design of MIMO system	3	[31]
B_4^9	Allocation	Power allocation in massive MIMO	2	[51, 174]
B_5^9	Location	Resource allocation in UDN (massive MIMO)	1	[202]
B_6^9	Allocation	Resource allocation for massive MIMO	2	[38]
B_7^9	Optimization	Throughput optimization for massive MIMO	2	[200]
B_8^9	Covering	Cell coverage for multicell massive MIMO	2	[96]
B_0^{10}	None	None	3	
B_1^{10}	Optimization	Resource management, interference (UDN)	1	[40]
B_2^{10}	Optimization	Robustness optimization in UDN	2	[180]
B_3^{10}	Maximization	Energy maximization (dense cells)	2	[203]
B_4^{10}	Allocation	Energy resource allocation (UDN)	2	[202]
B_5^{10}	Optimization	Hyper-dense cell deployment	2	[198]
B_0^{11}	None	None	3	
B_1^{11}	Scheduling	Scheduling in multihop mmWave systems	1	[77]
B_2^{11}	Optimization	Maximum nanonetwork capacity	2	[204]
B_3^{11}	Optimization	Min precoding in mmWave MIMO systems	3	[210]
B_4^{11}	Concurrent scheduling	QoS-aware full-duplex concurrent scheduling for mmWave wireless backhaul networks	2	[60]

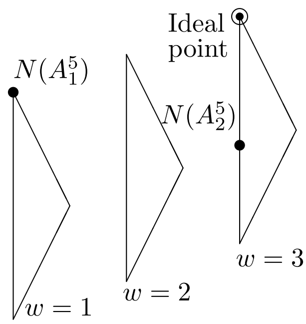

Fig. 12 Quality of A^5

Figure 12 illustrates quality of two Pareto-efficient solutions for subsystem A^5. Further, compatibility estimates are not used for composition of the resultant system solutions. The obtained resultant solutions (composite 5G challenge systems based on optimization approaches) are:

$S_1^I = A_1^1 \star A_1^2 \star A_1^3 \star A_1^4 \star A_1^5$;

$S_2^I = A_1^1 \star A_1^2 \star A_1^3 \star A_1^4 \star A_2^5$;

$S_3^I = A_1^1 \star A_1^2 \star A_1^3 \star A_2^4 \star A_1^5$; and

$S_4^I = A_1^1 \star A_1^2 \star A_1^3 \star A_4^4 \star A_2^5$.

Conclusion

This paper describes a combinatorial framework for selection and composition of technology challenges/key technologies based on optimization methods to design a composite technology challenge system. A numerical illustrative example for an optimization based modular technology challenges system in 5G communications is presented.

Table 6 Estimates of ordinal compatibility between DAs for $A^1 = B^1 \star B^2$

	B_0^2	B_1^2	B_2^2	B_3^2	B_4^2	B_5^2	B_6^2	B_7^2	B_8^2	B_9^2	B_{10}^2
B_0^1	3	1	1	1	1	1	1	1	1	1	1
B_1^1	1	1	3	1	1	1	1	3	1	1	1
B_2^1	1	1	3	1	1	1	1	3	1	1	1
B_3^1	1	1	3	1	1	1	1	3	1	1	1
B_4^1	1	1	1	1	1	1	3	1	1	1	1
B_5^1	1	1	3	1	1	1	1	3	1	1	1
B_6^1	1	1	3	1	1	1	1	3	1	1	1
B_7^1	1	1	1	1	1	1	3	1	1	1	1
B_8^1	1	1	3	3	3	3	3	1	3	2	2
B_9^1	1	1	3	3	3	3	3	1	3	2	2

Table 7 Estimates of ordinal compatibility between DAs for $A^3 = B^4 \star B^5$

	B_0^5	B_1^5	B_2^5	B_3^5	B_4^5	B_5^5	B_6^5	B_7^5	B_8^5	B_9^5	B_{10}^5
B_0^4	3	1	1	1	1	1	1	1	1	1	1
B_1^4	1	2	1	1	1	1	1	1	1	1	3
B_2^4	1	1	3	2	2	2	3	3	3	3	2
B_3^4	1	1	3	2	2	2	3	3	3	3	2
B_4^4	1	2	2	2	2	2	2	2	2	2	2

Table 8 Estimates of ordinal compatibility between DAs for $A^4 = B^6 \star B^7$

	B_0^6	B_1^6	B_2^6	B_3^6	B_4^6	B_5^6	B_6^6	B_7^6	B_8^6	B_9^6	B_{10}^6
B_0^7	3	1	1	1	1	1	1	1	1	1	1
B_1^7	1	1	3	3	1	3	3	1	3	1	1
B_2^7	1	2	2	2	2	2	2	2	2	2	2
B_3^7	1	3	2	2	3	2	2	3	2	3	3
B_4^7	1	2	2	2	2	2	2	2	2	2	2
B_5^7	1	3	2	2	3	2	2	3	2	3	3

Table 9 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^8_0	3	1	1	1	1	1	1	1	1
B^8_1	1	3	3	3	1	1	1	3	1
B^8_2	1	1	1	1	3	3	3	1	2
B^8_3	1	1	1	1	1	1	1	1	1
B^8_4	1	1	1	1	1	1	1	1	1
B^8_5	1	1	1	1	1	1	1	1	1
B^8_6	1	1	1	1	1	1	1	1	2
B^8_7	1	1	1	1	3	3	1	1	2
B^8_8	1	3	3	3	1	1	1	3	1
B^8_9	1	1	1	1	3	3	3	1	2

Table 10 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	1	3	3	1
B^8_2	1	1	1	1	3	1	1	2	2	2	2
B^8_3	1	1	1	1	1	1	1	1	1	1	1
B^8_4	1	1	1	1	1	1	1	2	1	1	2
B^8_5	1	1	1	1	1	1	1	2	1	1	2
B^8_6	1	1	1	1	1	1	1	1	1	1	1
B^8_7	1	1	1	1	3	1	1	1	1	1	1
B^8_8	1	3	3	3	1	3	1	1	3	3	1
B^8_9	1	1	1	1	3	1	1	1	1	1	1

Table 11 Estimates of ordinal compatibility between DAs for $A^5 = B^8 \star B^9 \star B^{10} \star B^{11}$, part 3

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

Note, the paper suggests firstly an important step to structuring the processes of the system improvement and/or system paradigm shift to design a hierarchical modular technology challenge system (instead of listing the prospective challenges and key technologies). Evidently, the suggested approach can be used for complex technological systems in various domains.

It may be reasonable to consider the following future research directions: (1) investigation of technology challenge systems in various computer science/engineering domains; (2) special study for designing a hierarchy (or ontology) of technology challenges; (3) examination of the combinatorial framework under uncertainty; (4) designing a special computer-aided system to support the suggested combinatorial framework; (5) study of composite innovations as combination of modular innovation activities (e.g., challenges/key technologies); (6) study of multi-stage composite technology challenge(s) systems; and (7) using the suggested combinatorial framework and its applications in computer science/engineering education (e.g., for student projects).

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Compliance with Ethical Standards

Conflict of interest The author states that there is no conflict of interest.

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