Towards combinatorial modeling of wireless technology generations

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The paper addresses the following problems: (1) a brief survey on wireless mobile communication technologies including evolution, history evolution (e.g., chain of system generations 0G, 1G, 2G, 3G, 4G, 5G, 6G, 7G); (2) using a hierarchical structural modular approach to the generations of the wireless communication systems (i.e., hierarchical combinatorial modeling of the communication technologies), (3) illustrative usage of two-stage combinatorial approach to improvement/forecasting of the communication technology (a version of 5G) (on the basis of multiple choice problem). Numerical examples illustrate the suggested combinatorial approach.

\textit{Keywords:} wireless communication, system generations, hierarchical structure, modular system, improvement, combinatorial optimization

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1. Introduction

Recently, in many engineering domains several technology generations are under study, design and forecasting processes. Some examples of applied system generations are pointed out in Table 1. As a result, special methods have to be suggested and used for the modeling the system generations changes/evolution and system forecasting.

| No. | Domain                               | Generations                                      | Some source(s)          |
|-----|--------------------------------------|--------------------------------------------------|-------------------------|
| 1.  | Fighter aircraft                     | 1, 2, 3, 4, 4^+, 4^{++}, 5, 6                    | [21, 44, 123]           |
| 2.  | Partiot air and missile defense systems (USA) | Patriot, Patriot PAC-2, Patriot PAC-3 | [64, 10, 29]              |
| 3.  | Anti-aircraft weapon systems (Russia) | S75, S125, S200, S300, S400, S500                | [610, 29]                |
| 4.  | Anti-aircraft weapon systems for ground forces (Russia) | “Krug”, S300V, S300VM, S300V4 | [610, 29]                |
| 5.  | Standard for multimedia information transmission | MPEG, MPEG-2, MPEG 4 | [76, 78]                |
| 6.  | Wireless mobile communication         | 0G, 1G, 2G, 3G, 4G, 4G, 5G, 6G, 7G              | [12, 30, 35, 38, 47]     |

In recent years, many research studies are targeted to issues of history and evolution of networking, challenges and forecasting in communications (including network architecture, network functions, network topology, etc.) (Table 2).

| No. | Study                                                                 | Source(s)          |
|-----|-----------------------------------------------------------------------|-------------------|
| 1.  | Modeling of topology evolutions and implication on proactive routing  | [129]             |
|     | overhead in MANETs                                                    |                   |
| 2.  | Survey on generations of mobile wireless technology                   | [19]              |
| 3.  | Evolution: 2G, 3G, 4G; challenges in the migration to 4G mobile systems | [48]              |
| 4.  | Technological changes in the innovation system towards 4G mobile service | [119]             |
|     | (including evolution: 1G, 2G, 3G, 4G)                                 |                   |
| 5.  | Evolution to 4G cellular systems (LTE-Advanced)                       | [5]               |
| 6.  | Comparative study of 3G and 4G in mobile technology                    | [62]              |
| 7.  | Evolution of wireless communication (1G, 2G, 3G, 4G, 4G; shift toward green communication) | [1]               |
| 8.  | Evolution of mobile wireless communication networks (1G, 2G, 3G, 4G, 5G) | [20, 10, 112]     |
| 9.  | Comprehensive study about evolution of different mobile generation technologies (0G to 5G mobile technology: survey) | [88]             |
| 10. | Comparative studies on 3G, 4G and 5G wireless technology              | [30]              |
| 11. | 5G on the horizon: key challenges for the radio-access network        | [27]              |
| 12. | Radio access network evolution                                       | [127]             |
| 13. | Study of next generation wireless network 6G                          | [115]             |
| 14. | Upcomming technologies: 5G and 6G                                    | [38]              |
| 15. | Future of wireless technology 6G & 7G                                 | [59]              |
| 16. | Challenges and opportunities for next generation of mobile networks  | [22, 113]         |
| 17. | Challenges and evolution of next generations wireless communication  | [130]             |
| 18. | Combinatorial approach for modular system evolution                   | [64, 67, 71, 75]  |
| 18.1 | Combinatorial evolution of MPEG-like standard for multimedia information | [75, 78]         |
| 18.2 | Combinatorial evolution and forecasting of communication protocol ZigBee | [75, 79, 80]   |
| 18.3 | Combinatorial evolution and forecasting of requirements to network topology | [76]            |
| 19. | Historical evolution of software defined networking (SDN), its architecture | [59, 117]     |
| 20. | Intellectual history of programmable networks (SDN)                   | [31, 98]          |
| 21. | History and challenges in network function virtualization             | [23, 91, 127]    |
In general (from the viewpoint of innovation processes), the following four classes of the impacts of new technologies in communications can be considered [2,15,69,73,75]:

1. **Local evolutions/modifications** (minor changes, e.g., new coding, signaling support for a higher number of antennas): 1.1. at the node level, 1.2. at the architectural level.

2. **Component changes**: disruptive changes in the design of a class of network nodes (e.g., new waveform).

3. **Architectural changes** (disruptive changes in the system architecture): 3.1. changes of nodes/node functions (e.g., new types of nodes or new functions in existing ones), 3.2. changes of system architecture (e.g., system topology), 3.3. system extension (e.g., addition of a new system part).

4. **Radical changes**: disruptive changes that have an impact at both the node and the architecture levels.

Tables 3 and Table 4 contain improvement technological directions in wireless mobile systems.

**Table 3.** Improvement technological directions in wireless mobile systems, part I

| No. | Technological direction                                                                 | Source(s) |
|-----|----------------------------------------------------------------------------------------|-----------|
| I.  | Development directions in 5G (movement from 4G to 5G):                                  | [84,122]  |
| 1.1 | New radio-interfaces, methods for sending and receiving:                                 |           |
| 1.1.1 | new methods of frequency modulation                                                   |           |
| 1.1.2 | coordination of pomeh based on prospective receiver methods                            |           |
| 1.2  | New network architecture:                                                               |           |
| 1.2.1 | building of small sots (one point - one user)                                         |           |
| 1.2.2 | central architecture:                                                                  |           |
|      | (a) cloud radio-access networks (RAN) based on SDR                                    |           |
|      | and coordinated central controllers,                                                   |           |
|      | (b) cloud basic networks CN based on SDN                                               |           |
| 1.2.3 | multidimensional antennas MIMO                                                         |           |
| 1.2.4 | evolution technologies MIMO: MIMO active/3D antennas                                    |           |
| 1.2.5 | physical division of traffic and control between layers of control and information transmission |   |
| 1.3  | New principles and conditions of spectrum usage:                                      |           |
| 1.3.1 | usage of new frequency bandwidth (since 6 to 60 GHz)                                   |           |
| 1.3.2 | flexible common usage of frequency resources                                           |           |
| 1.4  | Smart and adaptive communication networks:                                             |           |
| 1.4.1 | usage of mobile applications with their optimization for decreasing the cost of radio-access |   |
| 1.4.2 | allocation and management of resources in heterogeneous networks                       |           |
| 1.4.3 | inter-network joint work for different radio-access technologies                       |           |
| 1.4.4 | self-adaptation and self-optimization networks                                         |           |
| II. | Disruptive technology directions for 5G:                                                | [15]      |
| 2.1  | Device-centric architectures                                                           |           |
| 2.2  | Millimeter wave (mmWave)                                                               |           |
| 2.3  | Massive-MIMO                                                                         |           |
| 2.4  | Smarter devices                                                                       |           |
| 2.5  | Native support for Machine-to-Machine (M2M) communication                               |           |
| III. | 5G technology advantages:                                                             | [53]      |
| 3.1  | **Category 1** (real time performance): fast response time, low jitter, latency and delay, and high availability. |   |
| 3.2  | **Category 2** (critical infrastructure): high reliability, priority access, very wide area coverage. |   |
| 3.3  | **Category 3** (very high speed broadband): Gigabit data rates, high quality coverage, multispectrum service. |   |
| 3.4  | **Category 4** (IoT, M2M): more connected devices, deep indoor coverage, signaling efficiency. |   |
| 3.5  | **Category 5** (virtualized infrastructure): Software defined network, scalable, low-cost systems. |   |
Table 4. Improvement technological directions in wireless mobile systems, part II

| No. | Technological direction                                                                 | Source(s) |
|-----|-----------------------------------------------------------------------------------------|-----------|
| IV. | Advantages of 5G as future preferred network:                                              | [30]      |
| 4.1 | User personalization (high data transfer rates, access to large repository of data and services, flexibility) |
| 4.2 | Terminal and network heterogeneity (different types of access networks, e.g., WiMAX, WiFi, UMTS) |
| 4.3 | High performance (wireless download speeds)                                               |
| 4.4 | Interoperability (unified global standard, global mobility and service portability, i.e., different services from different service providers) |
| 4.5 | Intelligent networking (hybrid networks utilizing both the Wireless LAN concept and WAN design, ubiquitous network coverage to users at high speed) |
| 4.6 | Network convergence (convergence with both devices and services)                          |
| 4.7 | Lower power consumption                                                                  |
| V.  | Seven technical directions/advantages aiming at augmentation of the wireless worlds intelligence: | [27]      |
| 5.1 | RAT evolution,                                                                           |
| 5.2 | cell shrinking,                                                                          |
| 5.3 | composite wireless infrastructure,                                                       |
| 5.4 | heterogeneous networks,                                                                  |
| 5.5 | flexible spectrum management,                                                            |
| 5.6 | exploiting cloud concept,                                                                |
| 5.7 | introduction to intelligence                                                             |
| VI. | Basic advantages of 6G technology:                                                       | [38,43,55] |
| 6.1 | Ultra fast access of Internet                                                            | [115]     |
| 6.2 | Data rate - up to 10-11 Gbps                                                            |
| 6.3 | Home automation and related applications                                                  |
| 6.4 | Smart homes, smart cities, smart villages                                                |
| 6.5 | Home based ATM systems                                                                  |
| 6.6 | Satellite to satellite communication                                                     |

Traditionally, studies of change/improvement/evolution for applied technical systems are based on engineering analysis of existing technologies and basic trends for future systems improvements. Recently, an approach of combinatorial modeling for evolution and forecasting of modular systems has been suggested by the author [65,66,67,68,71,75,76]. This combinatorial approach is based on the following: (i) hierarchical modular presentation (as tree-based morphological structure with alternatives for leaf vertices) of the examined system, (ii) analysis of system changes or change items OPERATIONS (e.g., between neighbor system generations), (iii) assessment of the system changes (change items/operations) upon criteria (e.g., cost, prospective utilities); (iv) modeling of the system improvement/forecasting process as combinatorial optimization problems: (a) multicriteria selection of the best change items, (b) selection of the best change items while taking into account the total resource requirement for the selected items (knapsack-like models); (c) selection of the best change items while taking into account the compatibility among the selected items (morphological clique problem). Note, special mathematical studies of discrete processes in evolution based on trees with application to phylogeny (including trees, metric on tree spaces, composition and decomposition of trees, compatibility of trees) are contained in [115].

This article focuses on using the above-mentioned author combinatorial approach to generations of wireless mobile communication systems (system modeling and changes). The described numerical illustrative examples (for generations of mobile communication system, for the system improvement process) can be used as a basis for the future modular system analysis (i.e., improvement, forecasting).
2. Generations of wireless communication systems

In recent years, several special research projects have paid attention to evolution of wireless communication systems (e.g., [13,30,35,48,52,61,88,112,115,119,130]). Evolution of wireless communications is based on communication standard generations. Basic evolution chain of wireless technology generations is presented in Fig. 1, a network-like evolution process is depicted in Fig. 2.

Table 5 contains descriptions of the generations: 0G → 1G → 2G → 3G → 4G → 5G → 6G → 7G.
Table 5. Generations of wireless mobile communication

| No. | Generation                              | Brief description, features/attributes                                                                 | Source(s) |
|-----|-----------------------------------------|--------------------------------------------------------------------------------------------------------|-----------|
| 0.  | 0G technology (classical mobile telephony systems) | (1) PTT (Push to Talk), (2) MTS (Mobile telephone system), (3) IMTS (Improved Mob. telephone system), (4) AMTS (Adv. Mob. telephone system), etc. | [13,60]  |
| 1.  | 1G technology (cellphones, analog wireless) | AMPS (Analog Mobile Phone System) FDMA (Frequency Division Multiple Access)                           | [13,38,112] |
| 2.  | 2G technology (digital wireless, GPRS, EDGE) |                                                                                                       | [13,38,93] |
| 2.1 | Basic 2G                                | GSM standard (circuit switched domain): (a) TDMA (Time Division Multiple Access), (b) CDMA (Code Division Multiple Access) | [13,38,17] |
| 2.2 | 2.5G GPRS (General Packet Radio Service) | Packet switched domain: (a) WAP, (b) MMS, (c) SMS                                                      | [13,38]   |
| 2.3 | 2.75G EDGE (Enhanced Data rates for GSM Evolution) |                                                                                                       | [13]      |
| 3.  | 3G technology (Broad Band, IP Tech):     | Enhancements (over 2.5G): (1) enhancement of audio and video streaming, (2) several times higher data speed, (3) video-conferencing support, (4) Web and WAP browsing at higher speed, (5) IPTV (TV through the Internet) support. | [13,24,38,46] |
| 3.1 | Basic 3G                                | Versions: (1) W-CDMA, (2) GSM-EDGE, (3) UMTS, (4) DECT, (5) WiMAX, (6) CDMA 2000.                    | [13,38]   |
| 3.2 | 3.5G-HSDPA (High-Speed Downlink Packet Access), W-CDMA | For higher data transfer speed, implementations: AMC, MIMO, HARQ                                         | [13,38]   |
| 3.3 | 3.75G-HSUPA (High-Speed Uplink Packet Access), UMTS/ WCDMA uplink evolution | Enhancements: P2P data applications (e.g., mobile e-mail, real-time P2P games), faster downloading Internet service, etc. | [13,38]   |
| 4.  | 4G technology:                          |                                                                                                       | [13,18,19] |
| 4.1 | Basic 4G (LTE, WiMAX, WiFi) (enhanced WiMAX, 802.16, 3GPP, 3GPP2) (Internet), service dynamic access | More bandwidth & services offers; technologies: BDMA (Band Division Multiple Access), CDMA; services: MMS, entertainment services; Digital television in high definition, etc. | [13,38,10] |
| 4.2 | 4.5G (LTE Advanced Pro) (4.5G)          | Frequency bandwidth 1800 MHz 2100 MHz, Mobile Internet speed 100 Mbit/sec                            | [13,38]   |
| 5.  | 5G technologies:                        |                                                                                                       | [13,18,19] |
| 5.1 | Basic 5G technologies (IPv4): WLAN, 802.16 (WMAN), WPAN (Internet), LTE-E (Long-Term Evolution-Enhanced), Heterogeneous networks (HetNet), asynchronous HetNet scenario | New mobile revolution (high speed access) (cell phones with very high bandwidth), Services: OWA, OTP, Multimedia, entertainment, radio broadcasting, Digital Television, etc. | [13,18]   |
| 5.2 | Mob. cloud computing & 5G               | 3-tier heterogeneous MEC system                                                                       | [13,38]   |
| 5.3 | Mob. edge computing (MEC)&5G            |                                                                                                       | [13,38]   |
| 6.  | 6G technology:                          | Air-fiber technology, superfast broadband, etc.                                                      | [13,38]   |
| 7.  | 7G technology:                          | Satellite functions for mobile communication (space roaming)                                          | [13,38]   |

3. Hierarchical structural models in communications

3.1. Examples of hierarchical multi-layer network architecture

Evidently, contemporary networks have multi-layer architecture/structure (i.e., functional/operational description, topology) [25,32,63,70,75,96,110,120]. From the “engineering” viewpoint, the following hier-
Hierarchical layers can be considered [70, 75, 96, 120] (Fig. 3):

1. Backbone network.
2. Set of regional network clusters as interconnected network segments including the following: (a) additional centers (i.e., hubs), (b) cross-connections, and (c) bridges.
3. Access network/network segment (cluster): (e.g., bi-connected topology, about 20 nodes).
4. Distributed network: a simple hard topology (e.g., bus, star, tree, ring).
5. Layer of end-users (clients).

![Fig. 3. Example of multi-layer communication network](image)

A three-layer network topology based on central hub subnetwork is depicted in Fig. 4: (1) layer of terminal nodes (clients/end users), (2) layer of hubs and/or composite hubs, and (3) layer of subnetwork of central hubs.

![Fig. 4. Three-layer network architecture](image)

An illustrative scheme of functional multi-layer architecture for 5G system is depicted in Fig. 5 [82].
Table 6 contains a description of hierarchical six-layer architecture of space information networks (SINs) \[39\,83\,106\,132\].

**Table 6. Hierarchy of space information networks (SINs) \[39\,83\,106\,132\]**

| No. | Layer | Networks/Systems |
|-----|-------|------------------|
| I.  | Satellite layers: | GEO backbone networks: |
|     |       | (i) distributed satellite clusters DSCs, |
|     |       | (ii) service enhanced satellite networks, |
|     |       | (iii) navigation satellites |
|     | 1.1. | Geostationary orbits (high 36 000 km) |
|     |     | (geostationary satellites) |
|     | 1.2. | Medium earth orbits (high 30 000 km) |
|     |     | (medium orbit satellites) |
|     | 1.3. | Low earth orbits (low-orbit satellites) |
|     |     | 'Central network hubs' |
|     | II.  | Near space (600 km) |
|     |     | 'Hubs' for lower-level networks |
|     |     | deep-space explorers |
|     | III. | Stratospheric layer (20 km): |
|     | IV.  | Air (e.g., airplanes) (10 km) |
|     | V.   | Low-attitude terminals (e.g., balloons) (< 1000 m) |
|     | VI.  | Ground systems and nodes (0 km) |
|     |     | balloon networks |
|     |     | Systems: |
|     |     | (a) operation and control networks, |
|     |     | (b) access networks, |
|     |     | (c) ground information grid networks, |
|     |     | (d) information processing centers, |
|     |     | (e) air traffic control centers, |
|     |     | (f) community region networks, |
|     |     | (g) ground users. |
3.2. General hierarchical structural models of communication technology

Generally, seven-layer Open System Interconnection model (OSI model) is considered as a basic conceptual model for telecommunication and computer systems [89,134]:

**Layer 1.** Physical layer (L1): Protocol data unit: Bit. **Functions:** Transmission and reception of raw bit streams over a physical medium.

**Layer 2.** Data link layer (L2): Protocol data unit: Frame. **Functions:** Reliable transmission of data streams between two nodes connected by a physical layer.

**Layer 3.** Network layer (L3): Protocol data unit: Packet. **Functions:** Structuring and managing a multi-node network, including addressing, routing, and traffic control.

**Layer 4.** Transport layer (L4): Protocol data unit: Segment, Datagram. **Functions:** Reliable transmission of data segments between points on a network (including segmentation, acknowledgement and multiplexing).

**Layer 5.** Session layer (L5): Protocol data unit: Data. **Functions:** Managing communication sessions (i.e., controlling the dialogs (connections) between computers; exchange of information between two nodes).

**Layer 6.** Presentation layer (L6): Protocol data unit: Data. **Functions:** Translation of data between a networking service and an application.

**Layer 7.** Application layer (L7): Protocol data unit: Data. **Functions:** resource sharing, remote access file access, etc.

Thus, the structure of the communication system S can be presented as the corresponding seven-part morphological hierarchy (Fig. 6), where for each layer κ = 1,7 alternative implementation versions are: L₁, L₂, ..., L₇.

Another hierarchical internetworking model for enterprise networks (a three-layer model for network design) has been proposed by Cisco [109] (Fig. 7):

1. **Access layer:** connecting client nodes (e.g., workstations) to the network.
2. **Distribution layer** (work group layer): management of routing, filtering, and QoS policies, management of individual branch-office WAN connections.
3. **Core layer** (core network): high-speed, highly redundant forwarding services to move packets between distribution-layer devices in different regions of the network (core network devices manage the highest-speed connections).
For example, the following simplified morphological hierarchical structure can be considered (Fig. 8):

0. System \( S = A \ast D \ast C \):
1. Access layer \( A = E \ast T \): 1.1. client nodes \( E \), 1.2. connections \( T \).
2. Distribution layer \( D = M \ast B \):
   2.1. Management \( M = R \ast F \ast Q \): 2.1.1 routing \( R \), 2.1.2. filtering \( F \), 2.1.3. QoS policies \( Q \).
   2.2. Branch-office WAN connections \( B \).
3. Core layer (core WAN) \( C = H \ast K \):
   3.1. highest-speed connections between distribution-layer devices \( H \),
   3.2. core network topology \( K \).

\[
\begin{align*}
S &= A \ast D \ast C \\
A &= E \ast T \\
D &= M \ast B \\
M &= R \ast F \ast Q \\
B &= T \\
C &= H \ast K
\end{align*}
\]

Fig. 8. Structure of three-layer model for enterprise network

In recent years, the following multi-part structure of wireless mobile technologies is examined (simplified version) \( P_{1}^{3}, P_{5}^{3}, \ldots, P_{12}^{3}, P_{15}^{3}, P_{18}^{3} \) (Fig. 9):

\[
\begin{align*}
S &= P_{1}^{1} \ast P_{2}^{1} \ast P_{3}^{1} \ast P_{4}^{1} \ast P_{5}^{1} \ast P_{6}^{1} \ast P_{7}^{1} \ast P_{8}^{1} \\
S^{1G} &= P_{1}^{1} \ast P_{2}^{1} \ast P_{3}^{1} \ast P_{4}^{1} \ast P_{5}^{1} \ast P_{6}^{1} \ast P_{7}^{1} \ast P_{8}^{1} \\
S^{2G} &= P_{1}^{2} \ast P_{2}^{2} \ast P_{3}^{2} \ast P_{4}^{2} \ast P_{5}^{2} \ast P_{6}^{2} \ast P_{7}^{2} \ast P_{8}^{2} \\
S^{3G} &= P_{1}^{3} \ast P_{2}^{3} \ast P_{3}^{3} \ast P_{4}^{3} \ast P_{5}^{3} \ast P_{6}^{3} \ast P_{7}^{3} \ast P_{8}^{3} \\
S^{4G} &= P_{1}^{4} \ast P_{2}^{4} \ast P_{3}^{4} \ast P_{4}^{4} \ast P_{5}^{4} \ast P_{6}^{4} \ast P_{7}^{4} \ast P_{8}^{4} \\
S^{5G} &= P_{1}^{5} \ast P_{2}^{5} \ast P_{3}^{5} \ast P_{4}^{5} \ast P_{5}^{5} \ast P_{6}^{5} \ast P_{7}^{5} \ast P_{8}^{5} \\
S^{6G} &= P_{1}^{6} \ast P_{2}^{6} \ast P_{3}^{6} \ast P_{4}^{6} \ast P_{5}^{6} \ast P_{6}^{6} \ast P_{7}^{6} \ast P_{8}^{6} \\
S^{7G} &= P_{1}^{7} \ast P_{2}^{7} \ast P_{3}^{7} \ast P_{4}^{7} \ast P_{5}^{7} \ast P_{6}^{7} \ast P_{7}^{7} \ast P_{8}^{7}
\end{align*}
\]

Fig. 9. Structure of wireless mobile system generations

0. Wireless mobile system \( S = P_{1}^{1} \ast P_{2}^{1} \ast P_{3}^{1} \ast P_{4}^{1} \ast P_{5}^{1} \ast P_{6}^{1} \ast P_{7}^{1} \ast P_{8}^{1} \):
1. Part 1 (definition/technology) \( P_{1}^{1} \): analog cellular technology \( P_{1}^{1} \), digital cellular technology (digital narrow band circuit data) \( P_{2}^{1} \), packet data \( P_{3}^{1} \), digital broadband packet data & IP technology \( P_{4}^{1} \), all IP very high throughput \( P_{5}^{1} \), flat IP network \( P_{6}^{1} = P_{1}^{1} \ast P_{5}^{1} \).
2. Part 2 (data bandwidth/throughput speed/data rates) \( P_{2}^{2} \): 2 kbps \( P_{7}^{2} \), 64 kbps \( P_{8}^{2} \), 400 kbps to 30 Mbps \( P_{9}^{2} \), 3-5 Mbps, 100 Mbps (WiFi) \( P_{10}^{2} \), 200 Mbps to 1 Gbps \( P_{11}^{2} \), approx 20 Gbps \( P_{12}^{2} \).
3. Part 3 (service) \( P_{3}^{3} \): mobile telephony (voice) \( P_{13}^{3} \), digital voice \( P_{14}^{3} \), SMS \( P_{15}^{3} \), higher capacity packetized data \( P_{16}^{3} \), digital voice & SMS & higher capacity packetized data \( P_{17}^{3} = P_{14}^{3} \ast P_{15}^{3} \), integrated high quality audio, video and data \( P_{18}^{3} \), dynamic information access, wearable devices \( P_{19}^{3} \), AI capability \( P_{20}^{3} \), dynamic information access, wearable devices & AI capability \( P_{21}^{3} = P_{19}^{3} \ast P_{20}^{3} \).
In this paper, the following hierarchical structure of wireless mobile technologies is suggested (simplified version) (Fig. 10):

![Hierarchical Structure Diagram]

**Definition**

0. Wireless mobile system \( S = B^1 \times B^2 \times B^3 \times B^4 \):

1. Definition \( B^1 = B^{11} \times B^{12} \):
   - 1.1. technology \( B^{11} \): analog cellular technology \( B^{11} \), digital cellular technology (digital narrow band circuit data) \( B^{12} \), packet data \( B^{13} \), digital broadband packet data & IP technology \( B^{14} \), all IP very high throughput \( B^{15} \), flat IP network \( B^{16} = B^{14} \times B^{15} \).
   - 1.2. switching \( B^{12} \): circuit \( B^{121} \), packet \( B^{122} \), circuit & packet \( B^{123} = B^{121} \times B^{122} \), all packet \( B^{124} \).

2. Services \( B^2 = B^{21} \times B^{22} \):
   - 2.1. service \( B^{21} \): mobile telephony (voice) \( B^{211} \), digital voice \( B^{212} \), SMS \( B^{213} \), higher capacity packetized data \( B^{214} \), digital voice & SMS & higher capacity packetized data \( B^{215} \), integrated high quality audio, video, and data \( B^{216} \), dynamic information access, wearable devices \( B^{217} \), AI capability \( B^{218} \), dynamic information access, wearable devices & AI capability \( B^{219} = B^{217} \times B^{218} \).
   - 2.2. cloud computing \( B^{22} \): none \( B^{221} \), cloud computing \( B^{222} \).

3. Data transmission & access \( B^3 = B^{31} \times B^{32} \):
   - 3.1. data bandwidth/throughput speed/data rates \( B^{31} \): 2 kbps \( B^{311} \), 64 kbps \( B^{312} \), 400 kbps to 30 Mbps \( B^{313} \), 3-5 Mbps, 100 Mbps (WiFi) \( B^{314} \), 200 mbps to 1 Gbps \( B^{315} \), approx 20 Gbps \( B^{316} \).
   - 3.2. multiplexing/access technology \( B^{32} \): FDMA \( B^{321} \), TDMA \( B^{322} \), FDMA & TDMA \( B^{323} = B^{321} \times B^{322} \), CDMA \( B^{324} \), TDMA & CDMA \( B^{325} = B^{321} \times B^{322} \), OFDMA \( B^{326} \), LAS-CDMA \( B^{327} \), OFDMA & LAS-CDMA \( B^{327} = B^{326} \times B^{327} \).

4. Networking \( B^4 = B^{41} \times B^{42} \times B^{43} \times B^{44} \):
   - 4.1. core network \( B^{41} \): PSTN \( B^{411} \), GSM \( B^{412} \), PSTN & GSM \( B^{413} = B^{411} \times B^{412} \), packet N/W \( B^{414} \), Internet \( B^{415} \), packet N/W & Internet \( B^{416} = B^{414} \times B^{415} \), satellite network \( B^{417} \), packet N/W & Internet &
satellite network \( B^4_{8} = B^{41}_{5} \& B^{41}_{7} \).

4.2. handoff \( B^{42} \): horizontal \( B^{42}_{2} \), vertical \( B^{42}_{3} \), horizontal & vertical \( B^{42}_{3} = B^{42}_{2} \& B^{42}_{7} \).

4.3. heterogeneous networks (HetNets) \( B^{43} \): none \( B^{43}_{1} \), aggregation of different networks (HetNets) \( B^{43}_{2} \).

4.4. space communication \( B^{44} = B^{441} \& B^{442} \).

4.4.1. satellite network \( B^{441} \): none \( B^{441}_{1} \), telecommunication network \( B^{442} \), earth imaging \( B^{441}_{2} \), navigation \( B^{442} \), telecommunication & earth imaging & navigation \( B^{441} = B^{441}_{2} \& B^{441}_{4} \& B^{441}_{7} \).

4.4.2. satellite functions \( B^{442} \): none \( B^{442}_{1} \), satellite roaming \( B^{442}_{2} \).

As a result, the following modular system descriptions can be examined:

1. Change/improvement \( S^1G \) = \((B^{1}_{11} \& B^{1}_{12}) \& (B^{1}_{21} \& B^{1}_{22}) \& (B^{1}_{31} \& B^{1}_{32}) \& (B^{1}_{41} \& B^{1}_{42} \& B^{1}_{43} \& B^{1}_{442})),
2. Change/improvement \( S^2G \) = \((B^{2}_{11} \& B^{2}_{12}) \& (B^{2}_{21} \& B^{2}_{22}) \& (B^{2}_{31} \& B^{2}_{32}) \& (B^{2}_{41} \& B^{2}_{42} \& B^{2}_{43} \& B^{2}_{442})),
3. Change/improvement \( S^3G \) = \((B^{3}_{11} \& B^{3}_{12}) \& (B^{3}_{21} \& B^{3}_{22}) \& (B^{3}_{31} \& B^{3}_{32}) \& (B^{3}_{41} \& B^{3}_{42} \& B^{3}_{43} \& B^{3}_{442})),
4. Change/improvement \( S^4G \) = \((B^{4}_{11} \& B^{4}_{12}) \& (B^{4}_{21} \& B^{4}_{22}) \& (B^{4}_{31} \& B^{4}_{32}) \& (B^{4}_{41} \& B^{4}_{42} \& B^{4}_{43} \& B^{4}_{442})),
5. Change/improvement \( S^5G \) = \((B^{5}_{11} \& B^{5}_{12}) \& (B^{5}_{21} \& B^{5}_{22}) \& (B^{5}_{31} \& B^{5}_{32}) \& (B^{5}_{41} \& B^{5}_{42} \& B^{5}_{43} \& B^{5}_{442})),
6. Change/improvement \( S^6G \) = \((B^{6}_{11} \& B^{6}_{12}) \& (B^{6}_{21} \& B^{6}_{22}) \& (B^{6}_{31} \& B^{6}_{32}) \& (B^{6}_{41} \& B^{6}_{42} \& B^{6}_{43} \& B^{6}_{442})),
7. Change/improvement \( S^7G \) = \((B^{7}_{11} \& B^{7}_{12}) \& (B^{7}_{21} \& B^{7}_{22}) \& (B^{7}_{31} \& B^{7}_{32}) \& (B^{7}_{41} \& B^{7}_{42} \& B^{7}_{43} \& B^{7}_{442})).

4. Illustrative example of two-stage system improvement

In this section, an illustrative example of two-stage system improvement for 5G communication technology is described: \( S^5G \) \(\Rightarrow\) \((S^{5G_{adv-1}} \rightarrow S^{5G_{adv-2}})\), where \( S^{5G_{adv-1}} \) is the system after the improvement stage 1, \( S^{5G_{adv-2}} \) is the system after the improvement stage 2. This kind of the improvement problem may be of interest to a communication company/organization.

Note, seven basic combinatorial engineering frameworks (design of system hierarchical model, system evaluation, detection of system bottlenecks, system design, system improvement, multistage system design, combinatorial modeling of system evolution, system forecasting) for modular systems have been suggested in [24, 41, 75]. The considered two stage scheme (framework) for two-stage modular system improvement (or forecasting) is depicted in Fig. 11.

![Fig. 11. Two-stage system improvement (forecasting) scheme](image-url)

In general, it is possible to generate (e.g., engineering analysis) a set of change/improvement activities (operations), for example as in Table 7: \( \mathcal{O} = \{O_1, ..., O_4, ..., O_{17}\} \).
Table 7. Generated improvement activities (based on data from Table 3, Table 4)

| No. | Change/improvement (forecasting) activity                                         | Notation |
|-----|----------------------------------------------------------------------------------|----------|
| 1.  | Implementation of central architecture:                                          |          |
| 1.1 | (a) cloud radio-access networks (RAN) based on SDR and coordinated central controllers | O₁       |
| 1.2 | (b) cloud basic networks CN based on SDN                                          | O₂       |
| 2.  | Multidimensional antennas MIMO                                                    | O₃       |
| 3.  | Flexibility, adaptivity, heterogeneity:                                          |          |
| 3.1 | (i) flexible common usage of frequency resources                                  | O₄       |
| 3.2 | (ii) terminal and network heterogeneity (different types of access networks, e.g., WiMAX, WiFi, UMTS) | O₅       |
| 3.3 | (iii) allocation and management of resources in heterogeneous networks            | O₆       |
| 3.4 | (iv) inter-network joint work for different radio-access technologies             | O₇       |
| 3.5 | (v) self-adaptation and self-optimization networks                                | O₈       |
| 3.6 | (vi) smart homes, smart cities, smart villages                                    | O₉       |
| 4.  | Device-centric architectures                                                      | O₁₀      |
| 5.  | Very wide area coverage                                                          | O₁₁      |
| 6.  | User personalization (high data transfer rates, access to large repository of data and services, flexibility) | O₁₂      |
| 7.  | Interoperability (unified global standard, global mobility and service portability, i.e., different services from different service providers) | O₁₃      |
| 8.  | Network convergence (convergence with both devices and services)                  | O₁₄      |
| 9.  | Lower power consumption                                                           | O₁₅      |
| 10. | Ultra fast access of Internet                                                     | O₁₆      |
| 11. | Satellite to satellite communication                                              | O₁₇      |

Here, a modular system improvement is examined. The initial technology generation under examination is: \( S^{5G} = (B_1^{11} \times B_1^{22}) \times (B_2^{11} \times B_2^{22}) \times (B_3^{11} \times B_3^{22}) \times (B_4^{11} \times B_4^{22}) \times (B_5^{11} \times B_5^{22}) \times (B_6^{11} \times B_6^{22}) \times (B_7^{11} \times B_7^{22}) \times (B_8^{11} \times B_8^{22}) \times (B_9^{11} \times B_9^{22}) \times (B_{10}^{11} \times B_{10}^{22}) \). The following technology components of \( S^{5G} \) can be considered for the change/improvement (or forecasting): (1) service \( B_{8}^{21} \); (2) data bandwidth/throughput speed/data rates \( B_3^{31} \); (3) multiplexing/access technology \( B_5^{32} \); (4) core network \( B_4^{11} \); (5) satellite network \( B_1^{41} \); and (6) satellite functions \( B_7^{42} \). Thus, two series system improvement (forecasting) problems can be considered (a simplified case, knapsack-like models as multiple choice problems): for stage 1 and for stage 2.

**Problem 1.** Structure of composite improvement \( S^{5G} \Rightarrow S^{5Gadv₁} \) for stage 1 is depicted in Fig. 12. Descriptions of the improvement operations and their estimates are contained in Table 8.

The corresponding multiple choice model for \( S^{5G} \Rightarrow S^{5Gadv₁} \) is \((q_1 = 2, q_2 = 2, q_3 = 4, q_4 = 4, q_5 = 5, b_1^{constr} = 19.0)\):

\[
\text{max} \sum_{t=1}^{6} \sum_{j=1}^{q_t} x_{t,j} \ 	ext{s.t.} \ \sum_{t=1}^{6} \sum_{j=1}^{q_t} x_{t,j} b_{1,j} \leq b_1^{constr}, \ \sum_{j=1}^{q_t} x_{t,j} \leq 1 \ \forall t = 1,6, \ \forall j = 1, q_t, \ \forall x_{t,j} \in \{0,1\}.
\]

A simplified greedy heuristic is used (i.e., series packing of items via value \( \frac{c_{t,j}}{b_{1,j}} \)).

![Fig. 12. Composite improvement \( S^{5G} \Rightarrow S^{5Gadv₁} \)](image-url)
### Table 8. Change operations for $S^5G \Rightarrow S^5G_{adv,1}$ (stage 1)

| No. | System component | Alternative under change | Change/improvement item/operation | Change/improvement stage | Binary variable | Profit $c_{i,j}$ | Cost $b_{i,j}$ |
|-----|------------------|--------------------------|-----------------------------------|--------------------------|----------------|----------------|----------------|
| 1.  | $B_2^{21}$ (service) | $B_2^{21}$ | $U_1^1 : None$ | $x_{1,1}$ | 0.0 | 0.0 |
|     |                  | $B_2^{21}$ | $U_2^1 : B_8^{21} \rightarrow B_9^{21}$ | $x_{1,2}$ | 2.0 | 3.0 |
| 2.  | $B_2^{31}$ (data bandwidth/throughput speed/data rates) | $B_2^{31}$ | $U_1^1 : None$ | $x_{2,1}$ | 0.0 | 0.0 |
|     |                  | $B_2^{31}$ | $U_2^1 : B_5^{31} \rightarrow B_6^{31}$ | $x_{2,2}$ | 4.0 | 5.0 |
| 3.  | $B_3^{32}$ (multiplexing/access technology) | $B_3^{32}$ | $U_1^2 : None$ | $x_{3,1}$ | 0.0 | 0.0 |
|     |                  | $B_3^{32}$ | $U_2^3 : B_5^{32} \rightarrow B_6^{32}$ | $x_{3,2}$ | 1.0 | 2.0 |
|     |                  | $B_3^{32}$ | $U_3^3 : B_5^{32} \rightarrow B_7^{32}$ | $x_{3,3}$ | 3.6 | 4.0 |
|     |                  | $B_3^{32}$ | $U_4^3 : B_5^{32} \rightarrow B_8^{32}$ | $x_{3,4}$ | 3.6 | 6.0 |
| 4.  | $B_4^{41}$ (core network) | $B_4^{41}$ | $U_1^4 : None$ | $x_{4,1}$ | 0.0 | 0.0 |
|     |                  | $B_4^{41}$ | $U_2^4 : B_5^{41} \rightarrow B_6^{41}$ | $x_{4,2}$ | 3.6 | 6.0 |
|     |                  | $B_4^{41}$ | $U_3^4 : B_5^{41} \rightarrow B_7^{41}$ | $x_{4,3}$ | 7.0 | 7.0 |
|     |                  | $B_4^{41}$ | $U_4^4 : B_5^{41} \rightarrow B_8^{41}$ | $x_{4,4}$ | 9.0 | 12.0 |
| 5.  | $B_5^{441}$ (satellite network) | $B_5^{441}$ | $U_1^5 : None$ | $x_{5,1}$ | 0.0 | 0.0 |
|     |                  | $B_5^{441}$ | $U_2^5 : B_5^{441} \rightarrow B_6^{441}$ | $x_{5,2}$ | 5.0 | 5.0 |
|     |                  | $B_5^{441}$ | $U_3^5 : B_5^{441} \rightarrow B_7^{441}$ | $x_{5,3}$ | 5.6 | 7.0 |
|     |                  | $B_5^{441}$ | $U_4^5 : B_5^{441} \rightarrow B_8^{441}$ | $x_{5,4}$ | 6.0 | 8.0 |
|     |                  | $B_5^{441}$ | $U_5^5 : B_5^{441} \rightarrow B_9^{441}$ | $x_{5,5}$ | 14.0 | 20.0 |

The resultant solution is ($I_1 = U_1^1 \cdot U_2^1 \cdot U_3^3 \cdot U_4^4 \cdot U_5^5$):

$$S^{5G}_{adv,1} = (B_9^{11} \cdot B_4^{12}) \cdot (B_5^{21} \cdot B_7^{32}) \cdot (B_8^{31} \cdot B_9^{32}) \cdot (B_4^{41} \cdot B_3^{12} \cdot B_2^{43} \cdot (B_2^{41} \cdot B_1^{442}))$$

This modular system is a basis for the improvement (forecasting) at stage 2.

**Problem 2.** Structure of composite improvement $S^{5G}_{adv,2} \Rightarrow S^{5G}_{adv,2}$ for stage 2 is depicted in Fig. 13. Descriptions of the improvement operations and their estimates are contained in Table 9. The corresponding multiple choice model for $S^{5G}_{adv,2} \Rightarrow S^{5G}_{adv,2}$ is ($q_1 = 2$, $q_2 = 2$, $q_3 = 4$, $q_4 = 2$, $b_{2,\text{const}str} = 17.5$):

$$\max \sum_{i=1}^{4} \sum_{j=1}^{q_i} y_{i,j} c_{i,j} \quad \text{s.t.} \quad \sum_{i=1}^{4} \sum_{j=1}^{q_i} y_{i,j} b_{i,j} < b_{2,\text{const}str}, \quad \sum_{j=1}^{q_i} y_{i,j} \leq 1 \quad \forall i = 1,4, \quad \forall j = 1, q_i, \quad \forall y_{i,j} \in \{0,1\}$$

Here, a simplified greedy heuristic (i.e., series packing of items via value $\frac{c_{i,j}}{b_{i,j}}$). The resultant solution is: ($I_2 = V_1^1 \cdot V_2^2 \cdot V_3^3 \cdot V_4^4$): $S^{5G}_{adv,2} = (B_9^{11} \cdot B_4^{12}) \cdot (B_5^{21} \cdot B_7^{32}) \cdot (B_8^{31} \cdot B_9^{32}) \cdot (B_4^{41} \cdot B_3^{12} \cdot B_2^{43} \cdot (B_2^{41} \cdot B_1^{442}))$.

Thus, the following two-stage improvement (forecasting) strategy (as a chain) is obtained):

$$\forall : S^{5G}_{adv,2} \Rightarrow S^{5G}_{adv,2} \Rightarrow S^{5G}_{adv,2}$$

**Fig. 13.** Composite improvement $S^{5G}_{adv,2} \Rightarrow S^{5G}_{adv,2}$
In general, more complex models can be used at each improvement (or forecasting) stage (e.g., multi-criteria models, combinatorial synthesis approach). As a result, several solutions can be obtained and the structure of the improvement (forecasting) strategy(ies) will be more complex (e.g., tree, parallel-series graph, network).

5. Conclusion

The article describes an attempt to examine the evolution of wireless mobile communication technologies/systems on the basis of the author combinatorial approach. The approach is based on a hierarchical modular model of the system under study and an analysis of changes between the system generations to collect a set of basic change operations (change items). The application numerical illustrative examples are based on expert judgment.

Some future research directions can include the following: 1. analysis of system improvement/evolution (or forecasting) for complex applied systems in various domains (e.g., software engineering, data based management systems, computer engineering); 2. special analysis (i.e., improvement, evolution, forecasting processes) of subsystems, for example: (i) multi-antenna technologies (e.g., MIMO, MU-MIMO), (ii) multiple HetNets (at the same area), (iii) network architecture/topology, and (iv) multiplexing/access technologies; 3. analysis of correlations between two fields: (a) improvement/evolution/forecasting processes, (b) innovation processes and innovation cycles; 4. designing a special support computer-aided tool to implement the described combinatorial approach; and 5. usage of the considered approach to structural system evolution and forecasting in education (CS, applied mathematics, engineering, management).

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